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UNIVERSIDADE D COIMBRA

Tyre4BuildIns Calculation Tool

USER GUIDE

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LIST OF SYMBOLS

A_{w}	Area of external walls [m^2]
d	Thickness [m]
CDD	Cooling Degree Days [℃]
CoP	Coefficient of Performance
EER	Energy Efficiency Ratio
$E_{\mathrm{final}}^{\mathrm{imp}}$	Final energy consumed by climatization systems to compensate the amount of heat transferred through the improved wall, by transmission [kWh]
$E_{\mathrm{final}}^{\mathrm{ref}}$	Final energy consumed by climatization systems to compensate the amount of heat transferred through the reference wall, by transmission [kWh]
E_{saved}	Saved final energy [kWh]
G_{BF}	Glazing area of the back facade [%]
G_{LF}	Glazing area of the left facade [%]
G_{MF}	Glazing area of the main facade [%]
G_{RF}	Glazing area of the right facade [%]
HDD	Heating Degree Days [℃]
$H_{\mathrm{tr,i}}$	Overall heat transfer coefficient by transmission in the heating season [W/℃]
$H_{\mathrm{tr,v}}$	Overall heat transfer coefficient by transmission in the cooling season [W/℃]
L_{BF}	Length of the back facade [m]
L_{LF}	Length of the left facade [m]
L_{MF}	Length of the main facade [m]
L_{RF}	Length of the right facade [m]
L_{v}	Duration of the cooling season [h]
$Q_{\mathrm{tr}}^{\mathrm{cooling}}$	Heat transfer by transmission in the cooling season [kWh]
$Q_{\mathrm{tr}}^{\mathrm{heating}}$	Heat transfer by transmission in the heating season [kWh]
R	Thermal resistance [m^2·K·W^{-1}]
R_{se}	Outer surface thermal resistance [m^2·K·W^{-1}]
R_{si}	Inner surface thermal resistance [m^2·K·W^{-1}]
T_{avg}	Daily average temperatures [℃]
T_{max}	Daily maximum temperature [℃]
T_{min}	Daily minimum temperature [℃]
T_{ref}	Reference temperature [℃]
U	Thermal transmittance coefficient [W·m^{-2}·K^{-1}]
W_{AC}	Weight of acquisition costs [%]
W_{EC}	Weight of energy consumption [%]
W_{EI}	Weight of environmental impacts [%]
λ	Thermal conductivity [W·m^{-1}·K^{-1}]
$\theta_{\mathrm{v,ext}}$	Average external air temperature for the cooling season [℃]
$\theta_{\mathrm{v,ref}}$	Reference indoor temperature during the cooling season [℃]

LIST OF ACRONYMS

AC	Acquisition Cost
ADPE	Abiotic Resources Depletion Potential – Elements
ADPF	Abiotic Resources Depletion Potential – Fossil Fuels
AP	Acidification Potential
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CDD	Cooling Degree Days
CoP	Coefficient of Performance
EC	Energy Consumption
EER	Energy Efficiency Ratio
EI	Environmental Impacts
EP	Eutrophication Potential
EPS	Expanded Polystyrene
ETICS	External Thermal Insulation Composite System
FE	Final Evaluation
GWP	Global Warming Potential
HDD	Heating Degree Days
HF	Height of each Floor
NF	Number of Floors
ODP	Ozone Depletion Potential
OSB	Oriented Strand Board
POCP	Photochemical Ozone Creation Potential
TBS	Thermal Break Strips
XPS	eXtruded PolyStyrene

1. INTRODUCTION

Tyre4BuildIns Calculation Tool was developed within the Tyre4BuildIns research project [1]. The Tyre4BuildIns - *Recycled tyre rubber resin-bonded for building insulation systems towards energy efficiency* - research project is focused on the use of recycled tyre rubber for the development of an innovative and sustainable thermal insulation material that promotes the increase of energy efficiency of buildings. The research work performed is essentially directed towards improving the performance of LSF (Lightweight Steel Framed) constructions, acting in four main research areas: i) thermal behaviour and energy efficiency; ii) development of new thermal insulation solutions; iii) acoustic behaviour and noise attenuation, and; iv) sustainability and life cycle analysis.

This research project started in July 2018 and has a total duration of four years (3+1). The research work, involving Civil Engineering and Chemical Engineering, is carried out in the Departments of Civil Engineering (DEC) and Chemical Engineering (DEQ) of the Faculty of Science and Technology of the University of Coimbra. Furthermore, the project is integrated in two research centres: i) ISISE - Institute for Sustainability and Innovation in Structural Engineering, and; ii) CIEPQPF - Centre for Research in Chemical Processes and Forest Products Engineering. Funding is provided by the European Regional Development Fund (ERDF) through the Competitiveness and Internationalisation Operational Programme - COMPETE and by national funds through the FCT - Foundation for Science and Technology. More information can be found on the project website: www.tyre4buildins.dec.uc.pt.

Tyre4BuildIns Calculation Tool evaluates the performance of Lightweight Steel Framed (LSF) walls, regarding thermal behaviour, energy efficiency, environmental impacts and costs. Therefore, this tool comparatively evaluates the performance of two LSF walls: (1) a reference wall (Solution A), and; (2) a thermally improved wall (Solution B). The assessment of these two LSF walls is performed considering four features: (1) thermal transmittance (Module 1); (2) energy benefits (Module 2); (3) life-cycle assessment (Module 3), and; (4) cost-benefit analysis (Module 4). Furthermore, a fifth module (Module 5) performs a multicriteria analysis that provides help to decide what is the best solution in an overall perspective.

This document is a user guide for the Tyre4BuildIns Calculation Tool, being organized in seven main chapters, as explained next. After this brief introduction, the framework of the tool is presented, including the general structure, its format and layout, as wells as their Excel worksheets. Then, the inputs of the Calculation Tool are described and after the calculation methodology and their respective outputs are also described. Next, the computational accuracy of this Tool is verified for each one of the five calculation models. In Chapter 6, a design example is presented. To conclude, some final remarks are provided in Chapter 7, which are followed by the list of bibliographic references used in this document.

2. CALCULATION TOOL FRAMEWORK

2.1. General structure

The general structure of this tool, namely the identification and location of the main inputs and outputs, is illustrated in Figure 1.

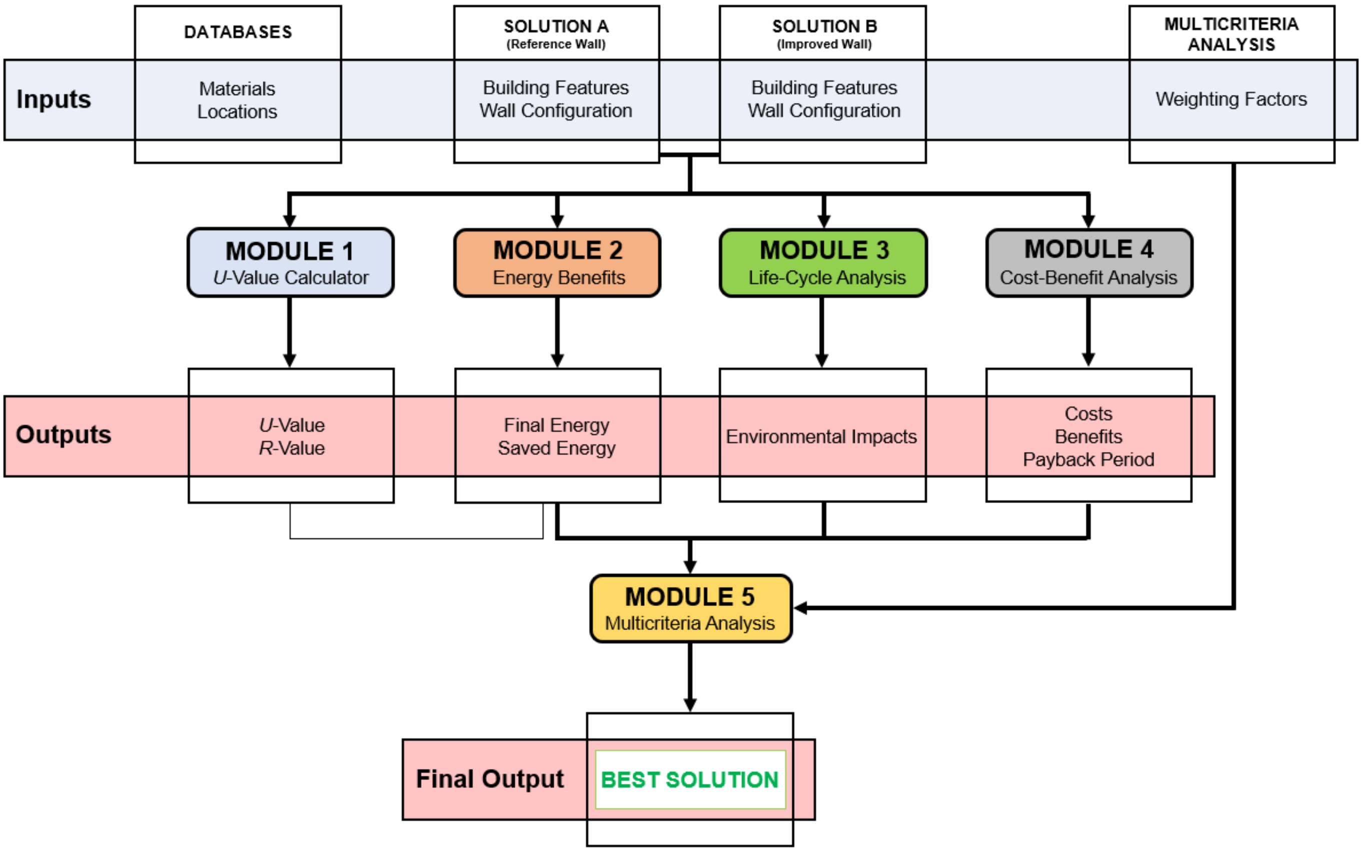


Figure 1 – General organization framework of the calculation tool.

The first step for the operation of the tool is the inputs definition. The inputs required to run the tool are grouped into 3 sets: i) definition of a reference LSF wall (Solution A); ii) definition of an improved LSF wall (Solution B), and; iii) definition of the weighting factors of the multicriteria analysis. For the definition of the LSF walls under analysis (solution A and Solution B), besides the configuration of the LSF wall, some features related with the building where the wall will be installed should be also inserted. Moreover, the weighting factor values for the multicriteria analysis should be also defined. These factors express the importance attributed to the parameters under evaluation and should be defined on two levels: i) weighting factors for the final results of Modules 2 to 4, and; ii) weighting factors for the environmental indicators of Module 3.

The outputs of this calculation tool are organised into 5 calculation modules. The Module 1 - *U-Value Calculator*, computes the thermal transmittance (and the thermal resistance) of the LSF walls using five analytical calculation methods. Module 2 - *Energy Benefits*, provides the predicted saved energy in terms of final energy (electricity), resulting from the use of the thermally improved LSF wall solution, instead of the reference solution with a lower thermal performance. Module 3 - *Cost-Benefit Analysis*, calculates the total cost from the cost of each material that constitutes each LSF wall solution under analysis, and estimates the monetary benefit provided by the saved energy previously assessed in Module 2. Module 4 - *Life-Cycle Analysis*, estimates the environmental impacts associated with the LSF wall solutions considered, based on a life-cycle analysis. Finally, Module 5 - *Multicriteria Analysis* performs a multicriteria analysis considering the results obtained in the Modules 2, 3 and 4 and provides the overall evaluation of each LSF wall solution analysed, indicating which is the most favourable solution.

2.2. Format and layout

Tyre4BuildIns Calculation Tool was developed in *Microsoft Excel* format and the general layout of the tool is presented in Figure 2.

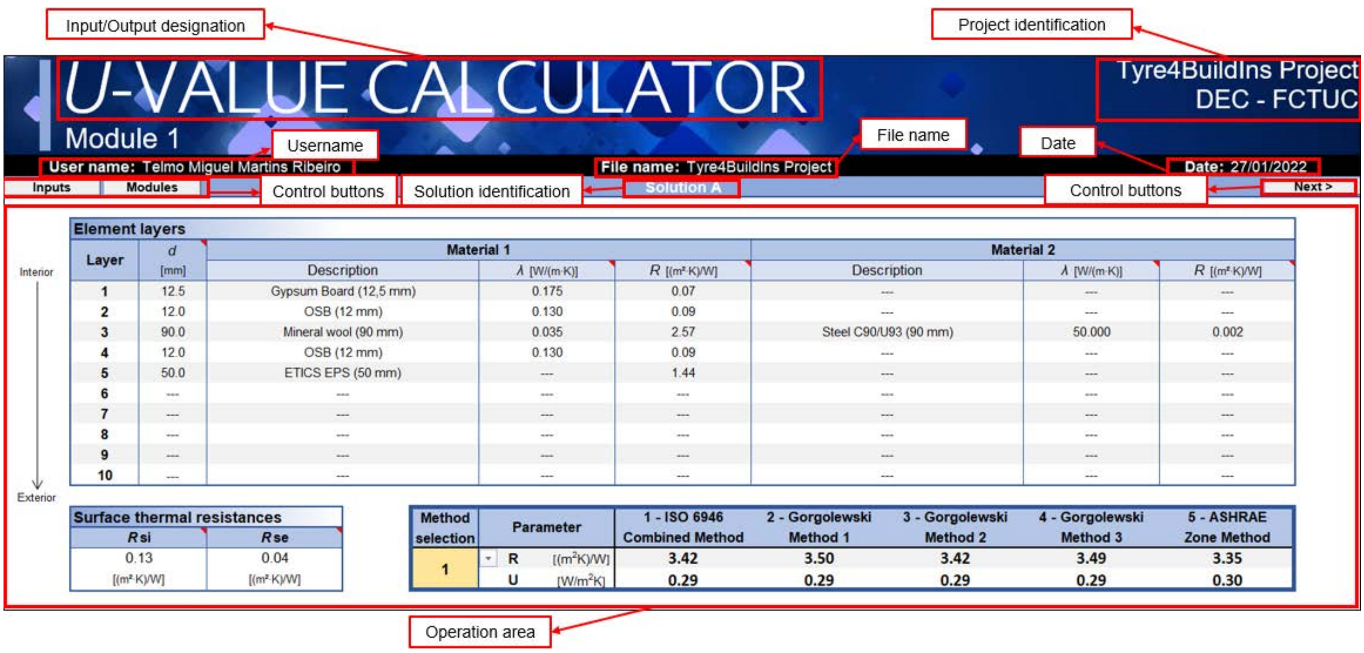


Figure 2 – Tyre4BuildIns Calculation Tool general layout.

From top to bottom of the worksheet, the first strip displays the name of the input or output and project identification. Then, a black strip is reserved for the information related to the workbook being used, namely, the username, the file name and the date. Next, there is a strip containing the control buttons and, when applicable, the identification of the solution being analysed. Finally, the remaining space is the tool's operating area, where all the data related to each worksheet is displayed. The control buttons adopted are intended to facilitate the “navigation” within the Excel tabs of the tool. The control buttons of the tool and their respective functions are shown in Table 1.

Table 1 – Control buttons and respective functions.

Control Button	Function
Add Location	Go to *Location Database* tab to add a new location
Add Material	Go to *Materials Database* tab to add new material
Back	Go to the previous tab
Inputs	Go to the *Inputs* first tab
Modules	Go to Modules tab
Next	Go to the next tab
Start Menu	Go to *Start Menu* tab

Moreover, this Calculation Tool uses a colour coding to facilitate the interpretation of input or output cells. The colour coding adopted is described in Table 2.

Table 2 – Implemented colour coding.

Cell colour	Meaning
	Generic input
	Dropdown list input
	Input from a database
	Output value

Regarding the organisation of the information within the Calculation Tool, four levels can be considered, as illustrated in Table 3: i) worksheet; ii) section; iii) area, and; iv) field.

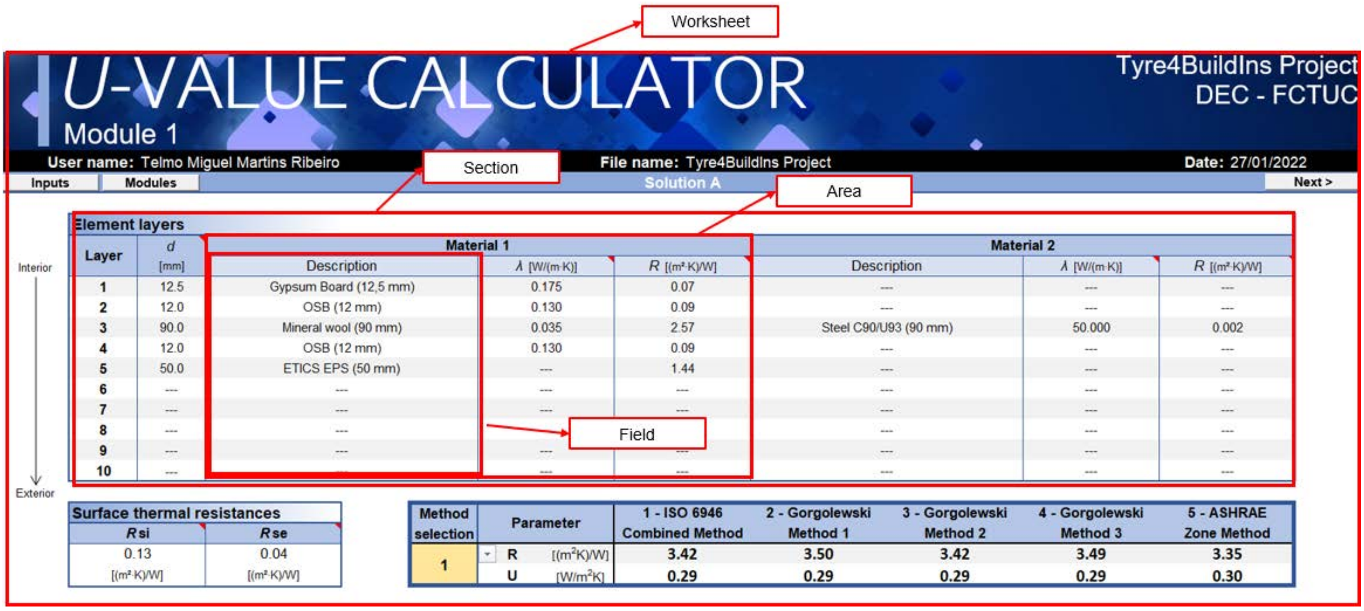


Figure 3 – Organization levels of the tool information: worksheet, section, area and field.

2.3. Worksheets

The Tyre4BuildIns Calculation Tool workbook is composed by 21 worksheets organized into four categories, depending on their type of function: i) Introduction; ii) Inputs; iii) Outputs; iv) Databases, and; v) Calculation. The identification and the function of each tab of Tyre4BuildIns Calculation Tool worksheet are shown in Table 3. In Figure 4, the groups of tabs existing in the tool are displayed.

Table 3 – Identification and function of the worksheets.

Category	Worksheet identification	Function
Introduction	HomePage	Tyre4BuildIns Calculation Tool logo; Tyre4BuildIns Project identification; Authors
	Start Menu	Username; File name; Date
Inputs	SA_Inp1	Solution A (Reference) inputs for building features
	SA_Inp2	Solution A (Reference) inputs for LSF wall configuration
	SB_Inp1	Solution B (Improved) inputs for building features
	SB_Inp2	Solution B (Improved) inputs for LSF wall configuration
	MCA_Inp	MultiCriteria Analysis inputs (weights)
Outputs	Modules	Selection of Modules 1-5
	SA_UCalc	Module 1 – *U*-value Calculator for Solution A
	SB_UCalc	Module 1 – *U*-value Calculator for Solution B
	Energy	Module 2 – Energy Benefits Computation
	SA_LCA	Module 3 – Life-Cycle Analysis for Solution A
	SB_LCA	Module 3 – Life-Cycle Analysis for Solution B
	Comp_LCA	Module 3 – Life-Cycle Analysis comparison
	SA_CostBen	Module 4 – Cost-Benefit Analysis for Solution A
	SB_CostBen	Module 4 – Cost-Benefit Analysis for Solution B
	Comp_CostBen	Module 4 – Cost-Benefit Analysis comparison
	MCA	Module 5 – MultiCriteria Analysis
Databases	Mat_DB	Materials DataBase
	Loc_DB	Locations DataBase
Calculation	Calculation	Tool calculation process

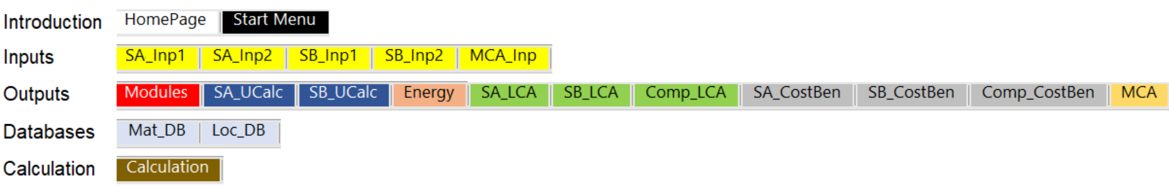


Figure 4 – Tabs and colours of the Calculation Tool.

3. INPUTS DESCRIPTION

3.1. LSF Wall Configurations: (A) Reference and (B) Improved

The comparative analysis performed by this tool requires the definition of a reference LSF wall (identified as Solution A) and an improved LSF wall (identified as Solution B). The improvement defined in Solution B should be (or usually is) in terms of thermal performance, i.e., higher thermal resistance when compared to Solution A. The input data for a specific solution is carried out through the definition of two sets of parameters: (i) *Building Features*, and; (ii) *Wall Configuration*, as detailed next.

3.1.1 Building Features Inputs

The building features of Solution A and Solution B are defined in the [*SA_Inp1*] (Figure 5) and [*SB_Inp1*] worksheets, respectively. These worksheets aim to define a set of parameters related to the building where the LSF wall under analysis is inserted. In [*Location*] section, the location of the building is defined, selecting one of two options: i) *Portugal*, or; ii) *Other locations*.

In the [*1 – Portugal*] input area (left side), the municipality where the building is located, as well as its altitude should be defined. For the municipality and altitude defined, the tool displays the respective annual Heating Degree Days (HDD) and Cooling Degree Days (CDD), in ˚C, with a reference temperature of 18 ℃ and 25 ℃, respectively, based on the Portuguese legal requirement for the energy performance of residential buildings "*REH – Regulamento de Desempenho Energético dos Edifícios de Habitação*" [2].

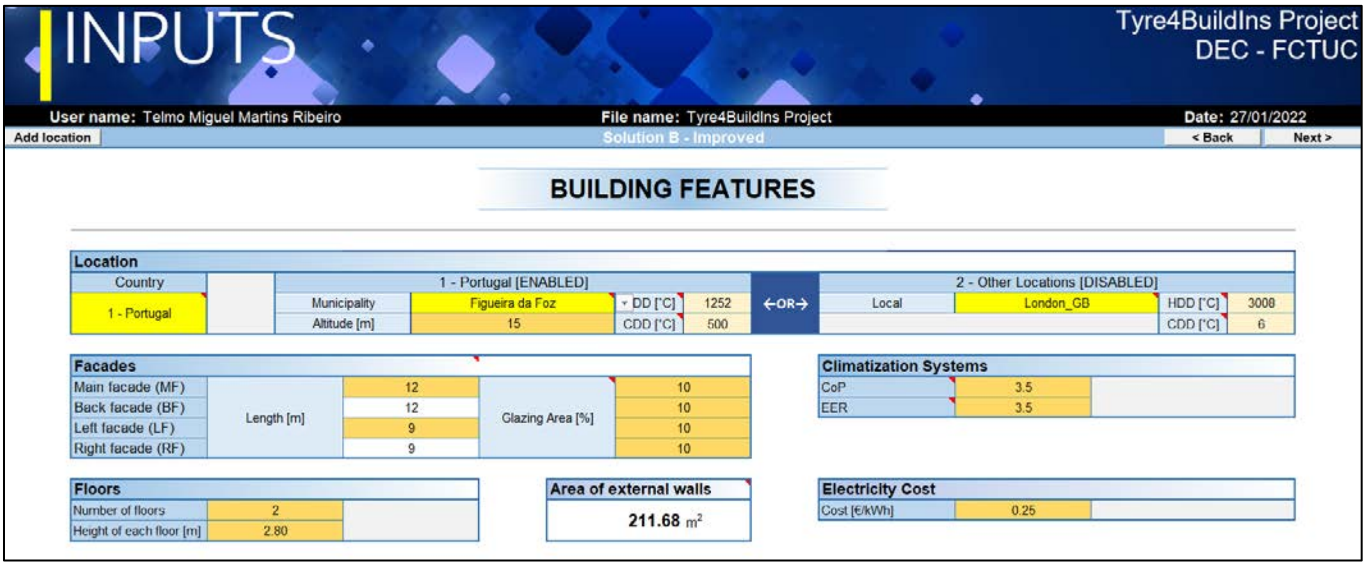


Figure 5 – Print-screen of the [SA_Inp1] worksheet: Inputs of building features for Solution A (Reference).

In the [*2 - Other Locations*] input area (right side), other locations worldwide previously added to the [*Loc_DB*] worksheet can be selected. Likewise, the respective annual HDD and CDD are displayed, being its calculation performed using the methodology suggested by UK Met Office [3]. The equations adopted for the calculation of HDD and CDD, are shown in Table 4 and Table 5, respectively. In this tool, the HDD were calculated using a reference temperature (T_{ref}) of 18 ℃ and the daily CDD were calculated using a T_{ref} of 25 ℃, based on hourly values. Furthermore, the daily average temperature T_{avg} was calculated as (T_{max} + T_{min})/2, where T_{max} is the daily maximum temperature and T_{min} is the daily minimum temperature. The annual HDD and CDD were determined by the summation of the daily HDD and CDD, respectively, along the year.

This calculation tool already has a weather database for 15 worldwide cities, as will be later presented in Section 3.4 (Locations Database).

Table 4 – UK Met Office equations to calculate the Heating Degree-Days [3].

Case	Condition	Daily HDD	
1	$T_{max} \leq T_{ref}$	$HDD = T_{ref} - T_{avg}$	(1)
2	$T_{avg} \leq T_{ref} < T_{max}$	$HDD = [(T_{ref} - T_{\min})/2] - [(T_{max} - T_{ref})/4]$	(2)
3	$T_{min} < T_{ref} < T_{avg}$	$HDD = (T_{ref} - T_{\min})/4$	(3)
4	$T_{min} \geq T_{ref}$	$HDD = 0$	(4)

T_{ref} = 18 ˚C; T_{avg} = (T_{max} + T_{min})/2.

Table 5 – UK Met Office equations for calculating the Cooling Degree-Days [3].

Case	Condition	Daily CDD	
1	$T_{max} \leq T_{ref}$	$CDD = 0$	(5)
2	$T_{avg} \leq T_{ref} < T_{max}$	$CDD = (T_{max} - T_{ref})/4$	(6)
3	$T_{min} < T_{ref} < T_{avg}$	$CDD = [(T_{max} - T_{ref})/2] - [(T_{ref} - T_{min})/4]$	(7)
4	$T_{min} \geq T_{ref}$	$CDD = T_{avg} - T_{ref}$	(8)

T_{ref} = 25 ˚C; T_{avg} = (T_{max} + T_{min})/2.

The [*Facades*] input section (Figure 5) aims to define the length, in meters, of the building facades and the respective glazing area (in percentage relative to the facade wall area). In this tool, in order to simplify the calculation, only buildings with a rectangular floor geometry are allowed. Thus, only the following four facades are considered: i) Main Facade (L_{MF}); ii) Back Facade (L_{BF}); iii) Left Facade (L_{LF}), and; iv) Right Facade (L_{RF}). Since the floor geometry of the building is rectangular, only the length of the main and left facades needs to be defined. The glazing area (G) should be relative to the wall area and it is expressed in percentage. The number of floors (NF) and the height of each floor (HF) should be defined in the [*Floors*] input section. Using the values introduced in these fields, the tool calculates and displays the area of external walls (A_w), through the expression:

$$A_w = 0.01 \times [L_{MF} \times (100 - G_{MF}) + L_{BF} \times (100 - G_{BF}) + L_{LF} \times (100 - G_{LF}) + L_{RF} \times (100 - G_{RF})] \times NF \times HF \quad (9)$$

where L_x is the length of facade *x*, G_x is the glazing area percentage of facade *x*, NF is the number of floors and HF is the height of each floor.

The [*Climatization Systems*] input section (Figure 5) aims to define the Coefficient of Performance (CoP) and the Energy Efficiency Ratio (EER) of the climatization systems used in the building. The CoP and EER represent the ratio that measures the energy efficiency of the heating and cooling systems, respectively. Finally, in the [*Electricity Cost*] input field (Figure 5), the cost of the electricity per kilowatt-hour should be defined.

A summary of the parameters that need to be defined in the [*SA_Inp1*] or [*SB_Inp1*] worksheets is presented in Table 6.

Table 6 – List of the Building Features input parameters.

Parameter	Description	Unit
Location		
Country	Selection between "1 – *Portugal*" or "2 – *Other Locations*"	---
Municipality (1 - Portugal)	Selection of the Portuguese municipality	---
Altitude (1 - Portugal)	Altitude of the building location	m
City (2 - Other Locations)	Location of the building under analysis	---
Facades		
Main facade length	Length of the main facade	m
Main facade glazing area	Ratio between glazing area and facade area (main facade)	%
Back facade length	Length of the back facade	m
Back facade glazing area	Ratio between glazing area and facade area (back facade)	%
Left facade length	Length of the left facade	m
Left facade glazing area	Ratio between glazing area and facade area (left facade)	%
Right facade length	Length of the right facade	m
Right facade glazing area	Ratio between glazing area and facade area (right facade)	%
Floors		
Number of floors	---	---
Height of each floor	---	m
Climatization Systems		
CoP – Coefficient of Performance	Ratio that measures the energy efficiency of the heating system	---
EER – Energy Efficiency Ratio	Ratio that measures the energy efficiency of the cooling system	---
Electricity Cost		
Cost	Cost of the electrical energy per kWh	€/kWh

3.1.2. Wall Configuration Inputs

The wall configurations of Solution A and Solution B are defined in the [*SA_Inp2*] (Figure 6) and [SB_*Inp2*] worksheets, respectively. These worksheets aim to define the configuration of the LSF wall solution, by layers, and other wall related parameters, namely, the stud spacing of the steel structure and the width of the thermal break strips.

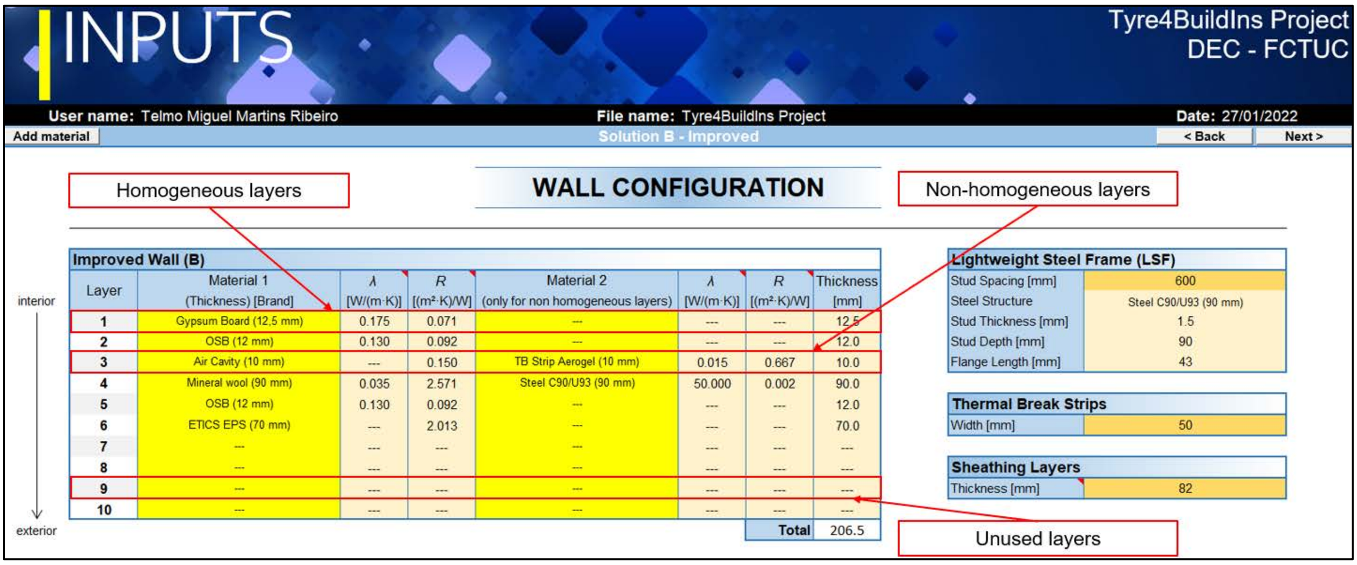


Figure 6 – Layout of the [Wall Configuration] inputs.

In the [Reference Wall (A)] input section (Figure 6), the definition of the LSF wall, layer by layer, is performed. The composition of each layer is made through the selection of materials from a database existing in the tool (Materials Database). This database, presented in more detail in Section 3.3, contains a set of branded materials, with a predefined thickness and the respective thermal conductivity values (or R-values). This tool allows to define two types of layers: i) homogeneous layers (only 1 material), or; ii) heterogeneous layers (2 materials). The assembly of each layer must be carried out as explained in Table 7.

Table 7 – Instructions for the LSF wall layer assembly.

Layer type	Instruction
Homogeneous layers (1 material)	The material must be defined in the [*Material 1*] field, while the [*Material 2*] field must be filled with "---"[1].
Non-homogeneous layers (2 materials)	The predominant material must be defined in the field [*Material 1*], while the other material must be defined in the [*Material 2*] field[1].
Unused layers	All unused layers must be filled with "---"[1].

[1] See the layout example in Figure 6.

The [*Lightweight Steel Frame (LSF)*] input section (Figure 6) allows to define the spacing between the vertical studs of the steel structure (stud spacing) and displays the main features of the selected steel structure, namely, the stud thickness, the stud depth and the flange length. The width of the thermal break strips (if applicable) should be defined in the [*Thermal Break Strips*] input section (Figure 6). Finally, in the [*Sheathing Layers*] input section, the thicker thickness regarding to the inner or outer sheathing layers is displayed. This value is used for the operation of the U-Value Calculator module, in the framework of the ASHRAE Zone Method [4].

3.2. Multicriteria Analysis

The weighting factors used in the multicriteria analysis are defined in the [*MCA_Inp*] worksheet (Figure 7). The weighting factors should express the given importance to each parameter under evaluation and they are defined in two categories: i) Calculation Modules, and; ii) Environmental Indicators.

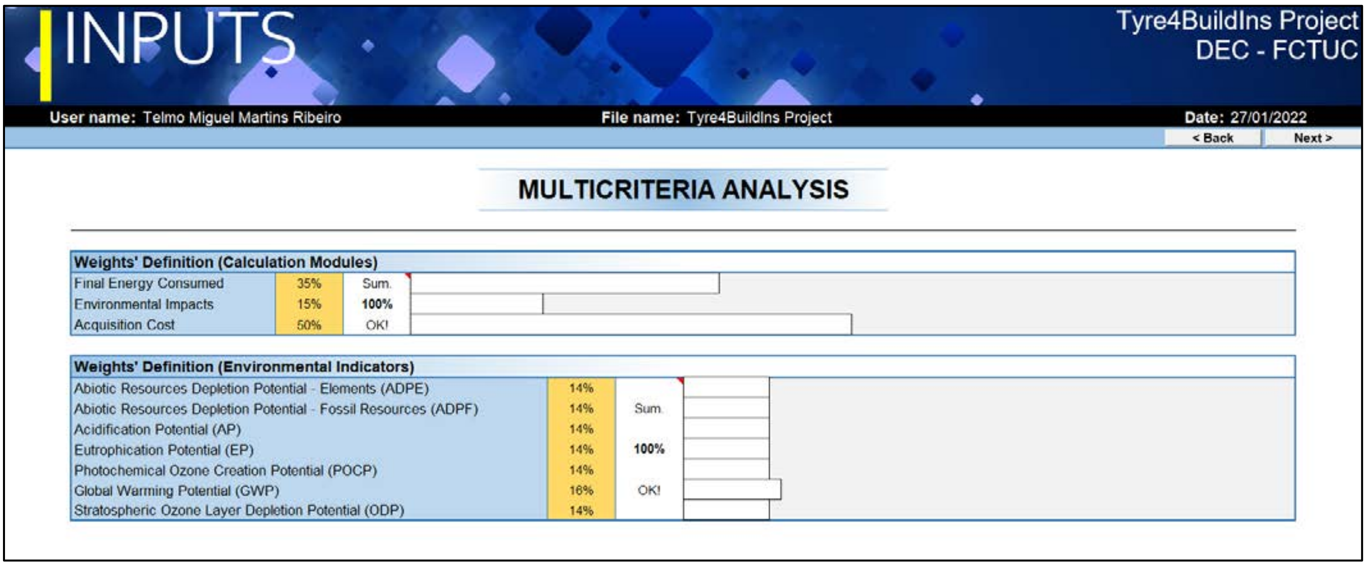
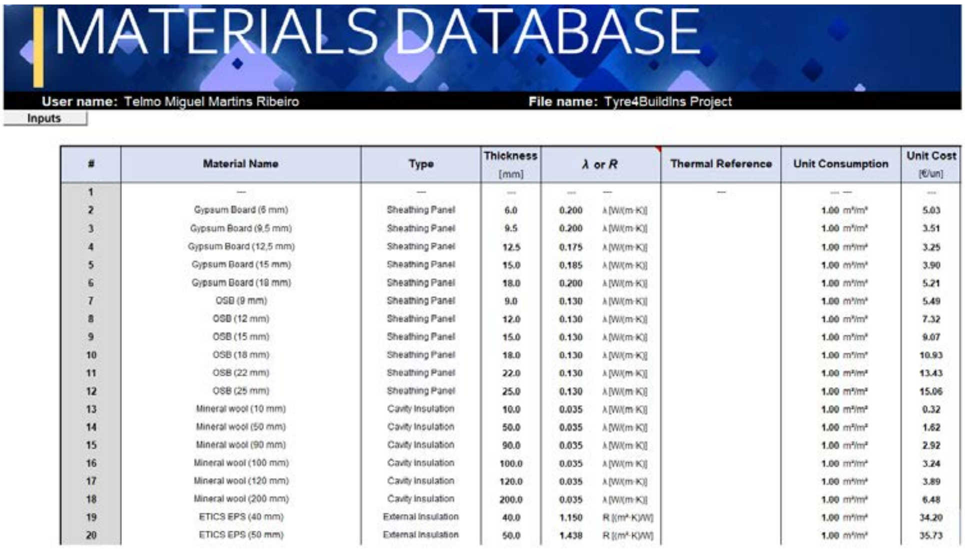


Figure 7 – Layout of the [MCA_Inp] input worksheet.

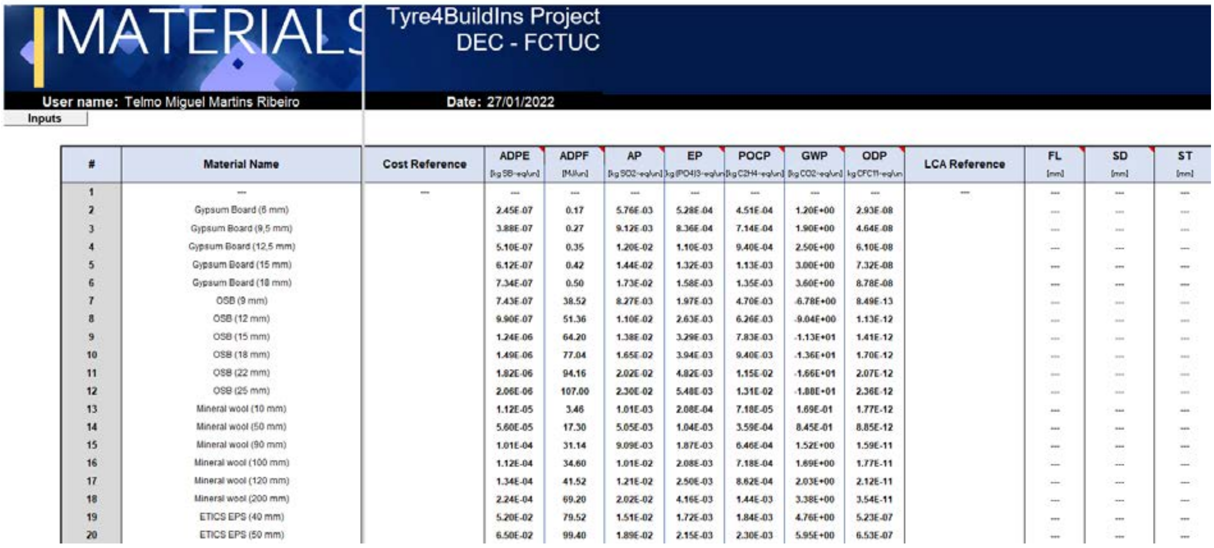
The weights referring to the modules should be defined in the [*Weight's Definition (Modules)*] input section (Figure 7) and express the relative importance regarding three criteria: energy consumption, environmental impacts and acquisition cost. Moreover, the weights for the environmental impacts express the relative importance between the environmental indicators considered in the life-cycle analysis (Module 3) and should be defined in the [*Weight's Definition (Environmental Indicators)*] input section. The weight values must be expressed in percentage and, for each category, the sum of the weights must be equal to 100%.

3.3. Materials Database

This database contains the materials that can be used in the walls and it is based in [*Mat_DB*] input worksheet (Figure 8). The database already contains a set of available materials, however new materials can be added manually at the bottom of the database. Each material is characterised by a set of parameters that ensure the correct functioning of the tool. A description of each parameter existing in the materials database is presented in Table 8.



#	Material Name	Type	Thickness [mm]	λ or R		Thermal Reference	Unit Consumption	Unit Cost [€/un]
1	---	---	---	---	---	---	--- ---	---
2	Gypsum Board (6 mm)	Sheathing Panel	6.0	0.200	λ [W/(m·K)]		1.00 m²/m²	5.03
3	Gypsum Board (9,5 mm)	Sheathing Panel	9.5	0.200	λ [W/(m·K)]		1.00 m²/m²	3.51
4	Gypsum Board (12,5 mm)	Sheathing Panel	12.5	0.175	λ [W/(m·K)]		1.00 m²/m²	3.25
5	Gypsum Board (15 mm)	Sheathing Panel	15.0	0.185	λ [W/(m·K)]		1.00 m²/m²	3.90
6	Gypsum Board (18 mm)	Sheathing Panel	18.0	0.200	λ [W/(m·K)]		1.00 m²/m²	5.21
7	OSB (9 mm)	Sheathing Panel	9.0	0.130	λ [W/(m·K)]		1.00 m²/m²	5.49
8	OSB (12 mm)	Sheathing Panel	12.0	0.130	λ [W/(m·K)]		1.00 m²/m²	7.32
9	OSB (15 mm)	Sheathing Panel	15.0	0.130	λ [W/(m·K)]		1.00 m²/m²	9.07
10	OSB (18 mm)	Sheathing Panel	18.0	0.130	λ [W/(m·K)]		1.00 m²/m²	10.93
11	OSB (22 mm)	Sheathing Panel	22.0	0.130	λ [W/(m·K)]		1.00 m²/m²	13.43
12	OSB (25 mm)	Sheathing Panel	25.0	0.130	λ [W/(m·K)]		1.00 m²/m²	15.06
13	Mineral wool (10 mm)	Cavity Insulation	10.0	0.035	λ [W/(m·K)]		1.00 m²/m²	0.32
14	Mineral wool (50 mm)	Cavity Insulation	50.0	0.035	λ [W/(m·K)]		1.00 m²/m²	1.62
15	Mineral wool (90 mm)	Cavity Insulation	90.0	0.035	λ [W/(m·K)]		1.00 m²/m²	2.92
16	Mineral wool (100 mm)	Cavity Insulation	100.0	0.035	λ [W/(m·K)]		1.00 m²/m²	3.24
17	Mineral wool (120 mm)	Cavity Insulation	120.0	0.035	λ [W/(m·K)]		1.00 m²/m²	3.89
18	Mineral wool (200 mm)	Cavity Insulation	200.0	0.035	λ [W/(m·K)]		1.00 m²/m²	6.48
19	ETICS EPS (40 mm)	External Insulation	40.0	1.150	R [(m²·K)/W]		1.00 m²/m²	34.20
20	ETICS EPS (50 mm)	External Insulation	50.0	1.438	R [(m²·K)/W]		1.00 m²/m²	35.73



#	Material Name	Cost Reference	ADPE [kg SB-eq/un]	ADPF [MJ/un]	AP [kg SO2-eq/un]	EP [kg (PO4)3-eq/un]	POCP [kg C2H4-eq/un]	GWP [kg CO2-eq/un]	ODP [kg CFC11-eq/un]	LCA Reference	FL [mm]	SD [mm]	ST [mm]
1	---	---	---	---	---	---	---	---	---	---	---	---	---
2	Gypsum Board (6 mm)		2.45E-07	0.17	5.76E-03	5.28E-04	4.51E-04	1.20E+00	2.93E-08		---	---	---
3	Gypsum Board (9,5 mm)		3.88E-07	0.27	9.12E-03	8.36E-04	7.14E-04	1.90E+00	4.64E-08		---	---	---
4	Gypsum Board (12,5 mm)		5.10E-07	0.35	1.20E-02	1.10E-03	9.40E-04	2.50E+00	6.10E-08		---	---	---
5	Gypsum Board (15 mm)		6.12E-07	0.42	1.44E-02	1.32E-03	1.13E-03	3.00E+00	7.32E-08		---	---	---
6	Gypsum Board (18 mm)		7.34E-07	0.50	1.73E-02	1.58E-03	1.35E-03	3.60E+00	8.78E-08		---	---	---
7	OSB (9 mm)		7.43E-07	38.52	8.27E-03	1.97E-03	4.70E-03	-6.78E+00	8.49E-13		---	---	---
8	OSB (12 mm)		9.90E-07	51.36	1.10E-02	2.63E-03	6.26E-03	-9.04E+00	1.13E-12		---	---	---
9	OSB (15 mm)		1.24E-06	64.20	1.38E-02	3.29E-03	7.83E-03	-1.13E+01	1.41E-12		---	---	---
10	OSB (18 mm)		1.49E-06	77.04	1.65E-02	3.94E-03	9.40E-03	-1.36E+01	1.70E-12		---	---	---
11	OSB (22 mm)		1.82E-06	94.16	2.02E-02	4.82E-03	1.15E-02	-1.66E+01	2.07E-12		---	---	---
12	OSB (25 mm)		2.06E-06	107.00	2.30E-02	5.48E-03	1.31E-02	-1.88E+01	2.36E-12		---	---	---
13	Mineral wool (10 mm)		1.12E-05	3.46	1.01E-03	2.08E-04	7.18E-05	1.69E-01	1.77E-12		---	---	---
14	Mineral wool (50 mm)		5.60E-05	17.30	5.05E-03	1.04E-03	3.59E-04	8.45E-01	8.85E-12		---	---	---
15	Mineral wool (90 mm)		1.01E-04	31.14	9.09E-03	1.87E-03	6.46E-04	1.52E+00	1.59E-11		---	---	---
16	Mineral wool (100 mm)		1.12E-04	34.60	1.01E-02	2.08E-03	7.18E-04	1.69E+00	1.77E-11		---	---	---
17	Mineral wool (120 mm)		1.34E-04	41.52	1.21E-02	2.50E-03	8.62E-04	2.03E+00	2.12E-11		---	---	---
18	Mineral wool (200 mm)		2.24E-04	69.20	2.02E-02	4.16E-03	1.44E-03	3.38E+00	3.54E-11		---	---	---
19	ETICS EPS (40 mm)		5.20E-02	79.52	1.51E-02	1.72E-03	1.84E-03	4.76E+00	5.23E-07		---	---	---
20	ETICS EPS (50 mm)		6.50E-02	99.40	1.89E-02	2.15E-03	2.30E-03	5.95E+00	6.53E-07		---	---	---

Figure 8 – Materials database layout.

Table 8 – Materials database parameters.

Parameter	Description
Material Name	Material designation (thickness) [Manufacturer]
Type	Type of material regarding its main function, organized by categories: - LSF Structure - Cavity insulation - External insulation - Sheathing panel - Thermal break strip - Air cavity - Others
Thickness [mm]	Thickness of the material, in mm
λ [units] or R [units]	Thermal conductivity (λ) or thermal resistance (R) of the material
Thermal Reference	Source of thermal conductivity (λ) or thermal resistance (R) values
Unit Consumption	Consumption of the material per unit area of wall Two options: m/m² or m²/m²

Unit Cost [€/un]	Unit cost of the material
Cost Reference	Source of the unit cost value
Environmental indicators	Environmental indicators values associated to the material in the LCA Product Stage: - Abiotic resources Depletion Potential - Elements (ADPE) - Abiotic resources Depletion Potential - Fossil Resources (ADPF) - Acidification Potential (AP) - Eutrophication Potential (EP) - Photochemical Ozone Creation Potential (POCP) - Global Warming Potential (GWP) - stratospheric Ozone layer Depletion Potential (ODP)
LCA Reference	Source of the LCA environmental indicator values
Steel stud dimensions [mm]	Dimensions of the LSF steel studs (only applicable for “LSF Structure” type materials): - Flange Length (FL) - Stud Depth (SD) - Steel Thickness (ST)

3.4. Locations Database

The Locations Database contains the locations (beyond Portugal) available in the tool and it is based in [*Loc_DB*] input worksheet (Figure 9). For each location, the database contains the values of the Heating Degree Days (HDD) and Cooling Degree Days (CDD), for a temperature reference of 18 ˚C and 25 ˚C, respectively, being its calculation performed using the methodology suggested by UK Met Office [3]. The database already contains several European cities. However, new locations can be added manually at the bottom of the database, introducing the respective HDD and CDD.

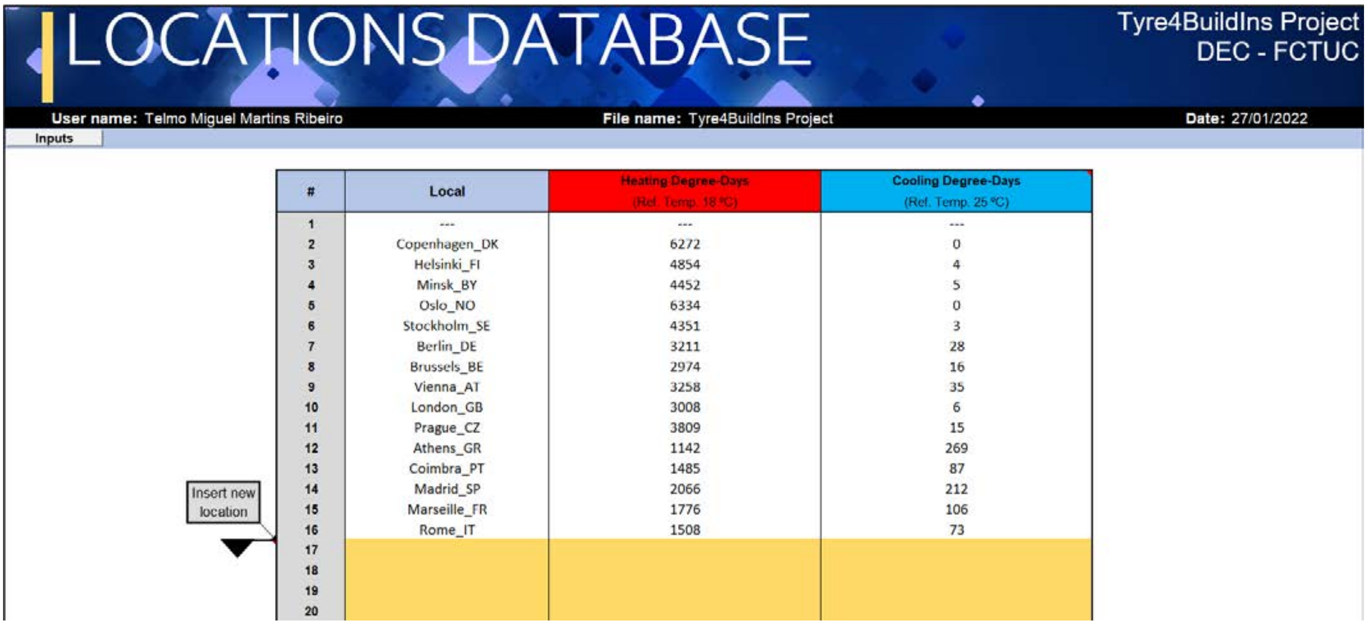


Figure 9 – Locations database layout.

4. CALCULATION METHODOLOGY AND OUTPUTS

4.1. Module 1 – U-value Calculator

Module 1 – U-value Calculator (Figure 10) determines the thermal transmittance (and thermal resistance) of the LSF walls under analysis. This first module presents the configuration of the LSF wall organized by layers with an indication of the respective thickness (d). For each layer, information on the thermal conductivity, λ (if applicable) and thermal resistance value (R) for the constituent materials are indicated. According to ISO 6946 (2017), the values of 0.13 and 0.04 $m^2 \cdot K/W$ were adopted for the inner and outer surface thermal resistances, respectively, being these values also displayed in the layout of Module 1.

The thermal transmittance (U-value) defines, under a steady-state heat transfer condition, the heat flux transmitted, perpendicularly to the wall surface and per unit area, through a given building element subject to a temperature gradient of 1 K, being expressed in $W/(m^2 \cdot K)$. Moreover, the thermal resistance (R-Value) can be determined from the inverse of the U-Value, being expressed in $m^2 \cdot K/W$.

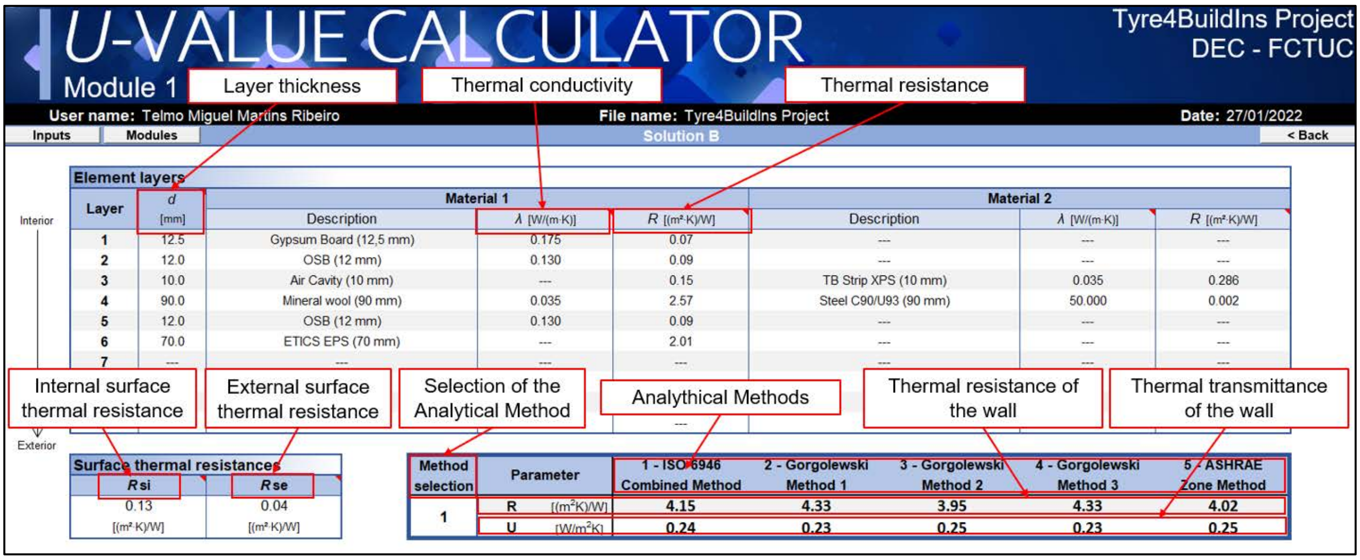


Figure 10 – Layout of Module 1: U-value Calculator (Solution B – Improved LSF wall).

When the building element is made with homogeneous material layers and the heat flux is unidirectional, the U-value can be determined by:

$$U = \frac{1}{R} = \frac{1}{R_{si} + \sum_j R_j + R_{se}} \tag{9}$$

where, R_{si} [m^2·K·W^{-1}] represents the inner surface thermal resistance, R_j [m^2·K·W^{-1}] represents the thermal resistance of layer j of construction element, and R_{se} [m^2·K·W^{-1}] represents the outer surface thermal resistance. The thermal resistance of each layer, R_j, [m^2·K·W^{-1}] is determined by the expression:

$$R_j = \frac{d_j}{\lambda_j} \tag{10}$$

where d_j [m] is the layer j thickness and λ [W·m^{-1}·K^{-1}] is the material thermal conductivity of the layer j.

In the case of LSF walls, the building element is composed by a mix of homogeneous and heterogeneous layers, being the calculation of the U-value more complex. In this tool, the calculation of the U-value of LSF walls is performed using five analytical methods: i) ISO 6946 Combined Method [5]; ii) Gorgolewski Method 1 [6]; iii) Gorgolewski Method 2 [6]; iv) Gorgolewski Method 3 [6] and; v) ASHRAE Zone Method [4]. A detailed explanation of these five methods can be found in a previous publication [7] of the Tyre4BuildIns research project [1].

4.2. Module 2 – Energy Benefits

This module (layout illustrated in Figure 11) evaluates the energy benefits obtained when improving the thermal behaviour of a wall. This module performs the calculation of the energy saved when adopting a thermally improved wall (Solution B), compared to a reference wall (Solution A).

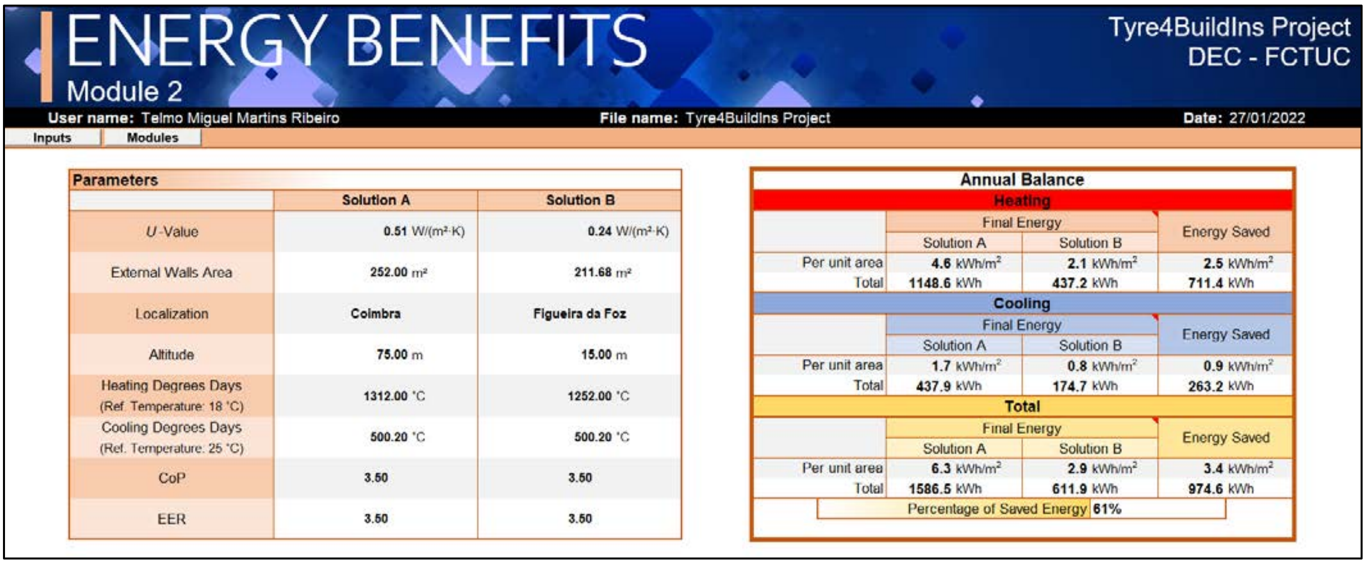


Figure 11 – Layout of Module 2: Energy Benefits.

The saved energy is quantified in terms of final energy consumed by the climatization system (e.g., electricity) and the results are presented per year, and per heating and cooling season. The quantification of the annual saved energy can be estimated according to the expression,

$$E_{saved} = E_{final}^{ref} - E_{final}^{imp} \tag{11}$$

where, E_{final}^{ref} [kWh] represents the final energy consumed by climatization systems to compensate the amount of heat transferred through the reference wall, by transmission and E_{final}^{imp} [kWh] represents the final energy consumed by climatization systems to compensate the amount of heat transferred through the improved wall, by transmission, in kWh.

The final energy E_{final} [kWh] consumed by climatization systems, annually, can be obtained through,

$$E_{final} = \frac{Q_{tr}^{heating}}{CoP} + \frac{Q_{tr}^{cooling}}{EER} \tag{12}$$

where $Q_{tr}^{heating}$ [kWh] represents the heat transfer by transmission through the wall from inside to outside environment, $Q_{tr}^{cooling}$ [kWh] represents the heat transfer by transmission through the wall from outside to inside environment, CoP is the Coefficient of Performance for heating mode, and EER is the Energy Efficiency Ratio for cooling mode.

4.2.1. Portuguese Locations

When the building is located in Portugal, the heat transfer by transmission through the construction element (e.g., wall) is determined using the Portuguese legal requirement for the energy performance of housing buildings "*REH – Regulamento de Desempenho Energético dos Edifícios de Habitação*" [8]. Thus, the determination of the heat transfer by transmission, for the heating season, can be obtained by,

$$Q_{tr}^{heating} = Q_{tr,i} = \frac{H_{tr,i} \cdot HDD \cdot 0.024}{1000} \tag{13}$$

where, $H_{tr,i}$ [W/˚C] is the overall heat transfer coefficient by transmission in the heating season and HDD [˚C] represents the heating degree-days for the building location, for a temperature reference of 18 ˚C. Moreover, for the cooling season, the heat transfer by transmission is given by,

$$Q_{tr}^{cooling} = Q_{tr,v} = \frac{H_{tr,v} \cdot (\theta_{v,ref} - \theta_{v,ext}) \cdot L_v}{1000} \tag{14}$$

where, $H_{tr,v}$ [W/˚C] is the overall heat transfer coefficient by transmission in the cooling season, $\theta_{v,ref}$ [˚C] is the reference indoor temperature for calculating the energy demand in the cooling season (equal to 25 ˚C), $\theta_{v,ext}$ [˚C] is the average outside air temperature for the cooling season, and L_v [h] represents the duration of cooling season (4 months, 2928 hours).

4.2.2. Other Locations

For situations in which the wall under analysis is inserted in a building located beyond Portugal, the heat transfer by transmission through the construction element, for heating and cooling seasons, can be determined by expressions (15) and (16), respectively:

$$Q_{tr}^{heating} = \frac{H_{tr,h} \cdot HDD \cdot 0.024}{1000} \tag{15}$$

$$Q_{tr}^{cooling} = \frac{H_{tr,c} \cdot CDD \cdot 0.024}{1000} \tag{16}$$

where, $H_{tr,h}$ [W/˚C] is the overall heat transfer coefficient by transmission in the heating season, HDD [˚C] is the heating degree-days for the building location, for a temperature reference of 18 ˚C, $H_{tr,c}$ [W/˚C] is the overall heat transfer coefficient by transmission in the cooling season and CDD [˚C] is the cooling degree-days for the building location, for a temperature reference of 25 ˚C.

For each solution, this module displays information about 8 parameters (Figure 11): i) U-value; ii) external walls area; iii) location; iv) elevation; v) heating degree-days (HDD); vi) cooling degree-days (CDD); vii) coefficient of performance (CoP), and viii) energy efficiency ratio (EER). Furthermore, the energy saved per season and annually are presented, as well as the percentage of energy that was saved by using the thermally improved wall.

4.3. Module 3 – Life-Cycle Analysis

This module assesses the environmental impacts associated with the evaluated LSF walls. The quantification of the environmental impacts is carried out considering a functional unit of 1 m^2 of LSF wall and the results are displayed for each constituent material and for the global configuration of the wall. The seven indicators considered to assess the environmental impacts are presented in Table 9.

Table 9 – Environmental impact indicators considered in Module 3.

Environmental impact indicator	Unit
Abiotic Resources Depletion Potential – Elements (ADPE)	kg Sb eq
Abiotic Resources Depletion Potential – Fossil Fuels (ADPF)	MJ
Acidification Potential (AP)	kg SO_2 eq
Eutrophication Potential (EP)	kg $(PO_4)_3$- eq
Photochemical Ozone Creation Potential (POCP)	kg C_2H_4 eq
Global Warming Potential (GWP)	kg CO_2 eq
Stratospheric Ozone Layer Depletion Potential (ODP)	kg CFC-11 eq

The calculation of environmental impacts focuses on the "Product Stage" of the LCA [9]. Therefore, it covers three stages: A1 – Raw material extraction; A2 – Transport to the manufacturer, and; A3 – Manufacturing. Stage A1 includes the extraction and processing of all raw materials and energy which occur upstream from the manufacturing process. Stage A2 – considers the transport of the raw materials to the manufacturing site, including road, boat and/or train transportations of each raw material. Finally, Stage A3 includes the provision of all materials, products and energy, as well as waste processing up to the end-of waste state or disposal of final residues during the product stage. This module includes the manufacture of products and the production of packaging material is also considered at this stage. The processing of any waste arising from this stage is also included.

Module 3 (Life-Cycle Analysis) comprises three worksheets: [*LCA_SA*], [*LCA_SB*] and [*LCA_Total*]. The [*LCA_SA*] (Figure 12) and [*LCA_SB*] (Figure 13) worksheets display the environmental impacts related to Solution A and Solution B, respectively. Moreover, the [*LCA_Total*] (Figure 14) presents an overview and comparison of the two solutions.

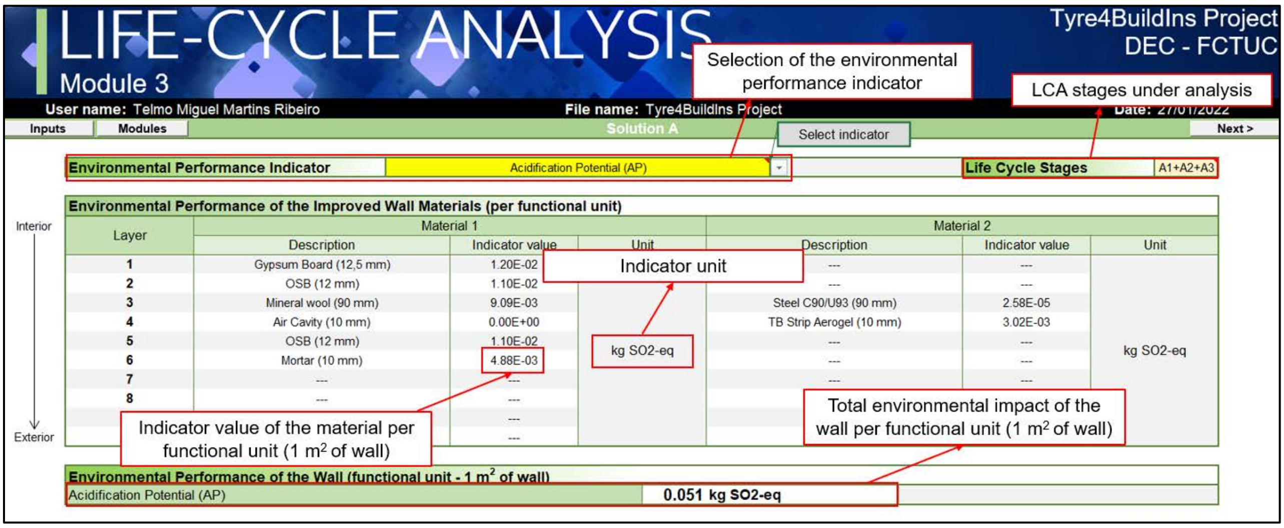


Figure 12 – Layout of Module 3: Life-Cycle Analysis (Solution A – Reference LSF wall).

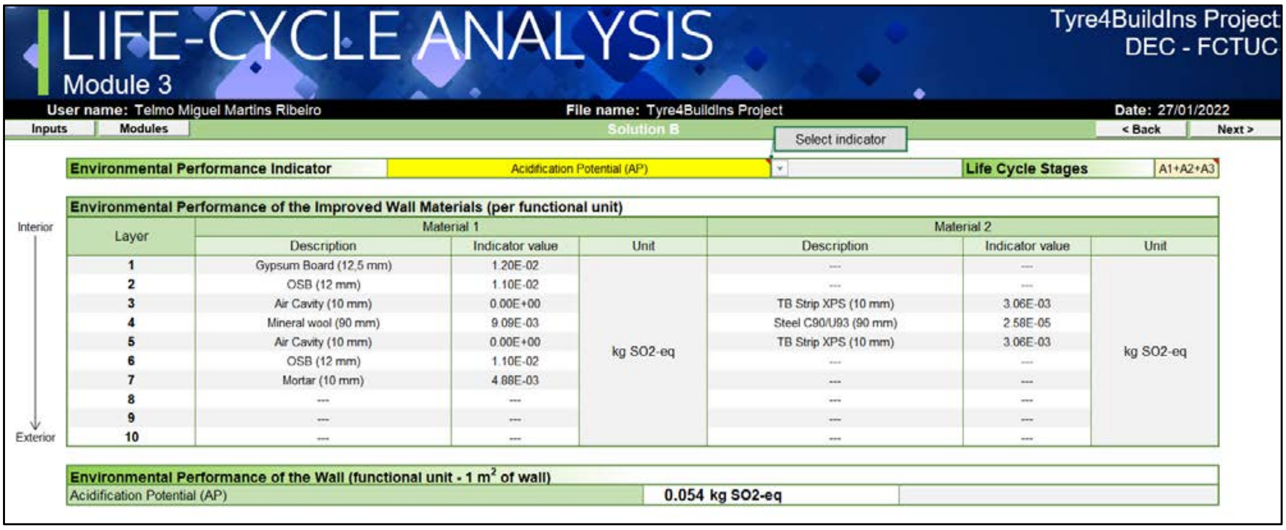


Figure 13 – Layout of Module 3: Life-Cycle Analysis (Solution B – Improved LSF wall).

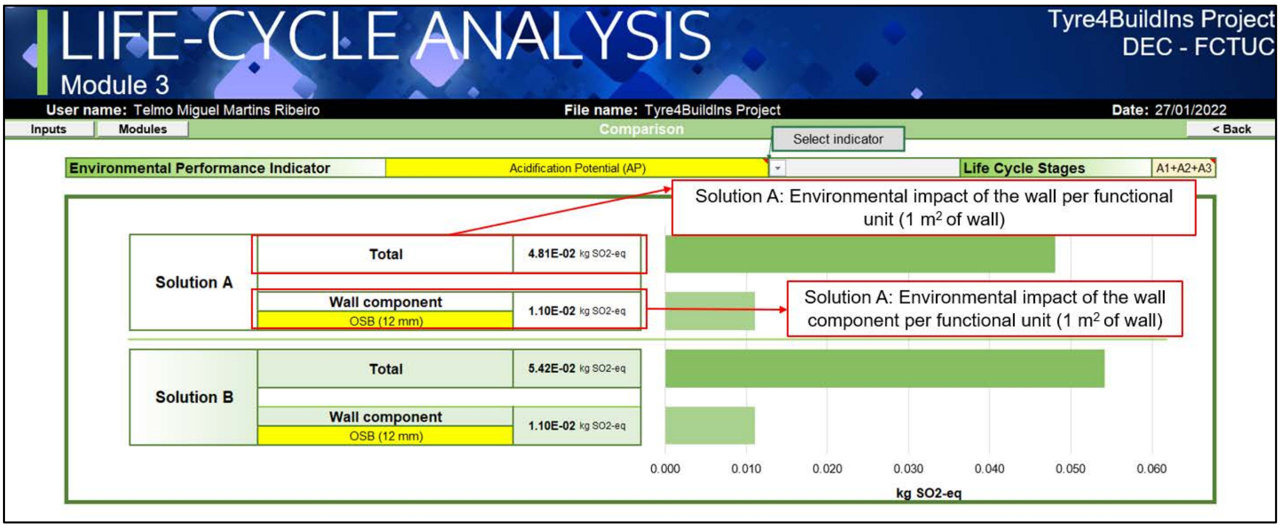


Figure 14 – Layout of Module 3: Life-Cycle Analysis (Comparison).

4.4. Module 4 – Cost-Benefit Analysis

Module 4 – Cost-Benefit Analysis aims to evaluate the monetary balance when using the thermally improved wall (Solution B), instead of the reference wall (Solution A). This module calculates the costs, in terms of materials, of the two LSF walls considered and the monetary benefits achieved in terms of electrical energy saved (calculated in Module 2) when using the thermally improved wall. Regarding costs, this module presents the unit cost and the unit consumption for each constituent material, as well as the total cost of the wall. This information is displayed in [*CostBen_SA*] worksheet (Figure 15) and [*CostBen_SB*] worksheet (Figure 16) for Solution A and Solution B, respectively. The annual benefits are calculated considering the electrical energy saved and the electricity cost. The [*CostBen_Total*] worksheet (Figure 17) presents an overview of the costs and the annual benefits, and also indicates the payback period for the walls under analysis, i.e., the period of time until the annual benefits outweigh the additional cost involved in the thermally improved wall.

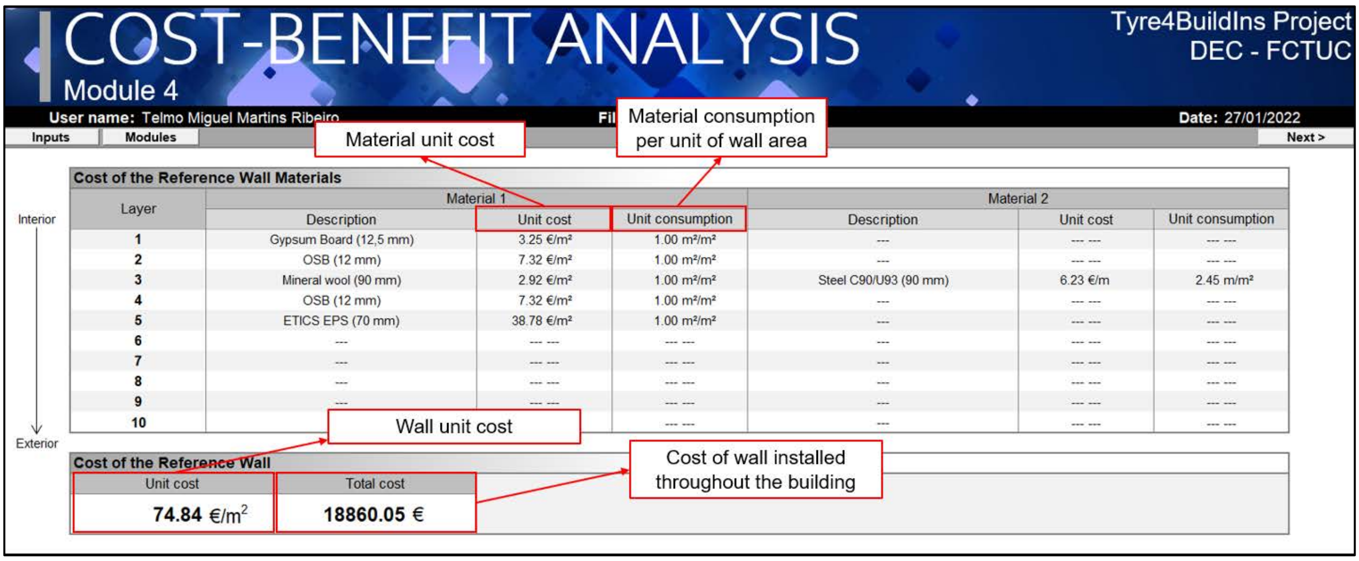


Figure 15 – Layout of Module 4: Cost-Benefit Analysis (Solution A – Reference LSF wall).

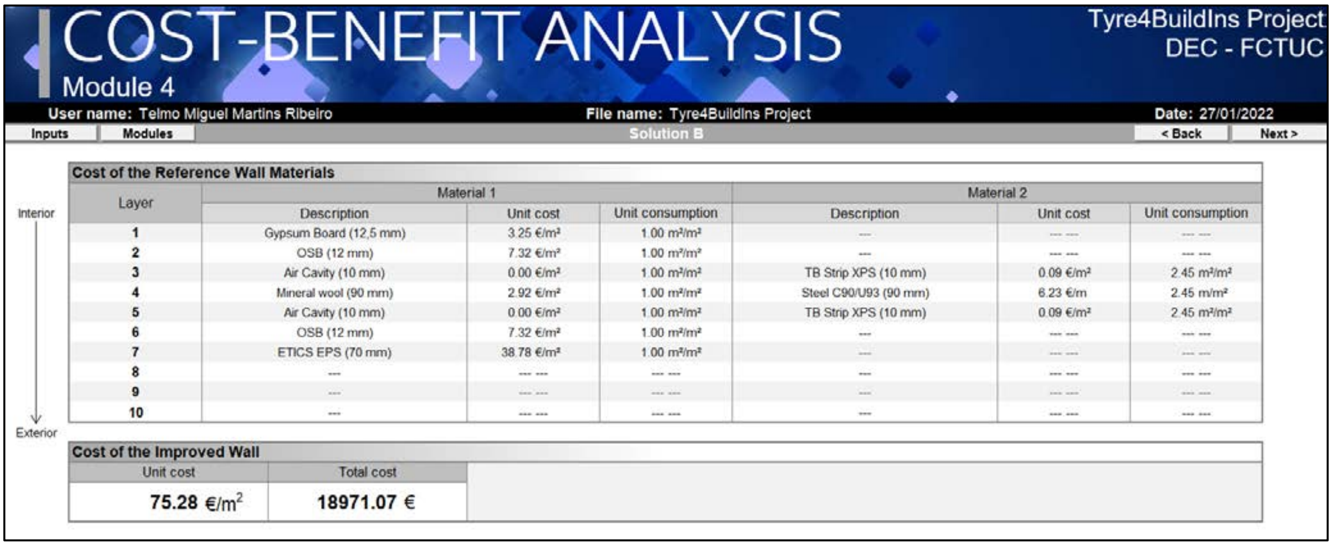


Figure 16 – Layout of Module 4: Cost-Benefit Analysis (Solution B – Improved LSF wall).

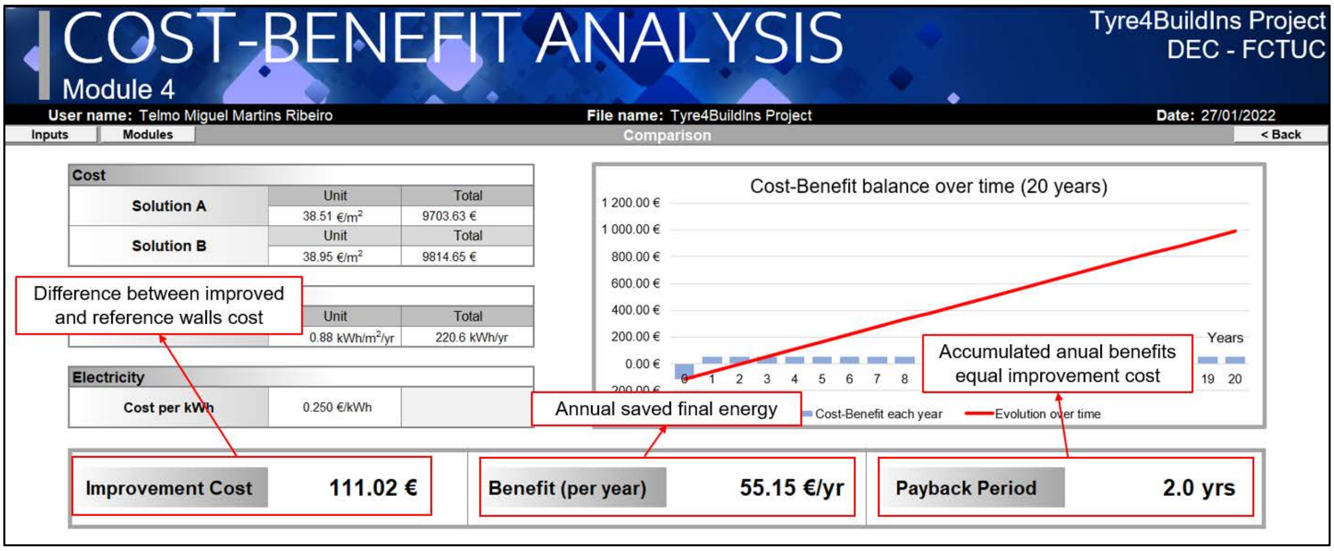


Figure 17 – Layout of Module 4: Cost-Benefit Analysis (Comparison).

4.5. Module 5 – Multicriteria Analysis

Module 5 – Multicriteria Analysis (Figure 18) determines the most favourable LSF wall configuration (Solution A or B) considering three criteria: energy consumption, environmental impacts and acquisition cost, considering the previously defined weights. The values of each criteria, for solutions A and B, are displayed in two matrixes (Figure 18): Decision Matrix and Standardized Decision Matrix. In the Decision Matrix, the values of energy consumption and acquisition cost by wall unit area, and the average weighted (by the weights defined in the inputs stage) of the environmental impacts, quantified within a scale 0 to 1, are displayed (Figure 18). In the Standardized Decision Matrix, the values of each criteria are adjusted on a scale 0 to 1 (Figure 18), where higher values mean great benefits. The quantification of the criteria on a scale of 0 to 1 is carried out through a linear normalisation, using the expression (17),

$$r_{ij} = \frac{min_i x_{ij}}{x_{ij}} \tag{17}$$

where, r_{ij} is the normalised value of criterion i and solution j, $min_i x_{ij}$ is the minimum original value of criterion i, and x_{ij} is the original value of criterion i and solution j.

The evaluation of each solution is performed using a weighted average, where the influence that each one of these aspects has in the multicriteria analysis is imposed through the attribution of the weights defined in the inputs stage of the tool (see Section 3.2). Thus, the final evaluation (FE) of each solution, can be determined by:

$$FE = EC \times W_{EC} + EI \times W_{EI} + AC \times W_{AC} \tag{18}$$

where, EC [dimensionless] is the standardized value of the energy consumption, W_{EC} is the respective energy consumption weight (in %), EI [dimensionless] is the standardized value of the environmental impacts, W_{EI} is the respective environmental impacts weight (%), AC [dimensionless] is the standardized value of the acquisition cost, and W_{AC} is the respective energy consumption weight (%). The final evaluation is presented on a scale from 0 to 1 and the best solution corresponds to the highest value.

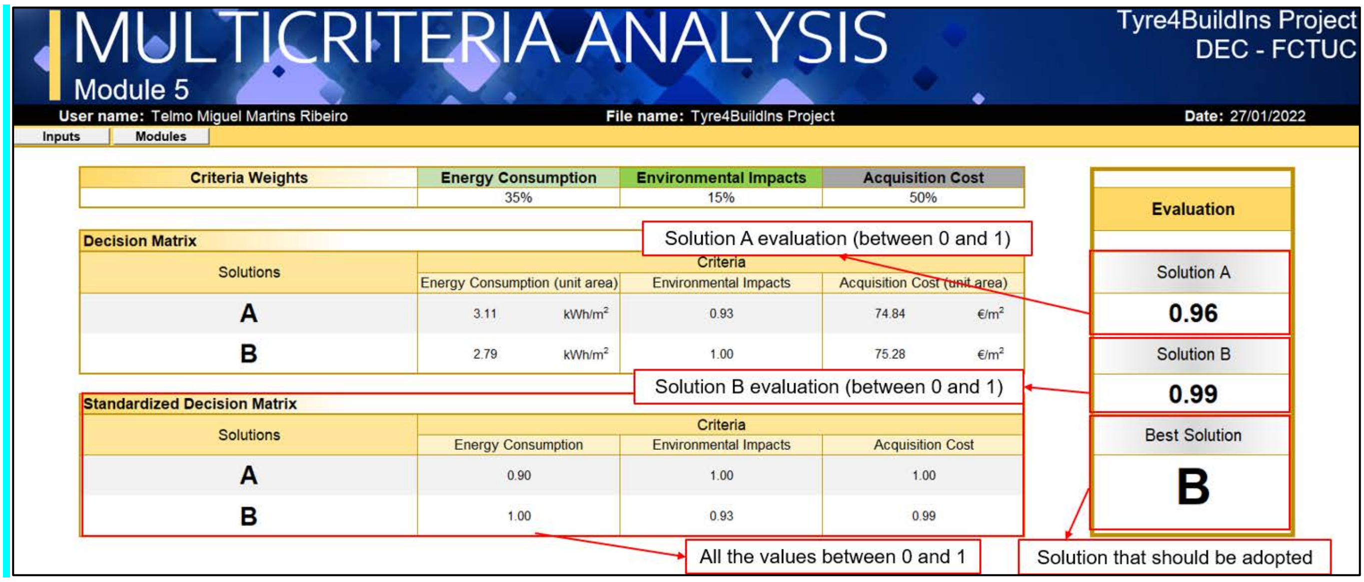


Figure 18 – Layout of Module 5: Multicriteria Analysis.

5. COMPUTATIONAL ACCURACY VERIFICATIONS

5.1. Framework

In this chapter, the accuracy verification of the five modules of the Tyre4BuildIns Calculation Tool is performed. The main purpose of these verifications is to demonstrate that the calculation methodologies used have been correctly programmed and that the results provided by the tool are reliable. For each module, particular cases are presented and the results provided by the tool are compared with the results obtained by performing the calculation procedure step by step. Additionally, in Module 1 – U-value Calculator, a comparison is made between the thermal resistance values obtained by the calculation tool (using simplified analytical methods) and the thermal resistance values calculated using numerical simulations in THERM software (THERM, 2022).

In Table 10, the references of the parameter values associated with each material used in this dissertation are presented.

Table 10 – References used for the materials parameter values.

Material	Thermal reference	Cost reference	LCA reference
Gypsum Plasterboard (12.5 mm)	[10]	[10]	[11]
OSB (12 mm)	[12]	[12]	[13]
Mineral Wool (90 mm)	[14]	[14]	[15]
Steel Stud (C90 x 43 x 15 x 1.5 mm)	[16]	[16]	[16]
ETICS EPS (50 mm)	[17]	[17]	[18]
Finishing Option (5 mm)	[17]	[17]	---
Mortar (5 mm)	[19]	---	---
XPS TB Strip (10 mm)	[20]	[20]	[21]
EPS (50 mm)	[22]	[22]	---

5.2. Module 1 – U-value Calculator

The composition of the LSF wall considered in Module 1 verification is presented in Table 11.

Table 11 – Module 1 verification: LSF wall composition.

Material (Inner to outer layer)	d [mm]	λ [W/(m·K)]
Gypsum Plasterboard	12.5	0.175
OSB	12	0.100
Mineral Wool | Steel Stud (C90x43x15x1.5; ss: 600 mm)	90	0.035 | 50.000
OSB	12	0.100
ETICS EPS	50	0.035
Total Thickness	176.5	

Next, the calculation procedures of the thermal resistances (R-values) using the five simplified analytical methods computed in the Tool are described.

Combined Method

$[R_{tot;upper}]$

$$\frac{1}{R_{tot;upper}} = \frac{0.0015/0.6}{0.1300 + 0.0714 + 0.0923 + 0.0018 + 0.0923 + 1.4375 + 0.0400} +$$

$$+ \frac{0.5985/0.6}{0.1300 + 0.0714 + 0.0923 + 2.5714 + 0.0923 + 1.4375 + 0.0400} =$$

$$= 0.2263\ W \cdot m^{-2} \cdot K^{-1}$$

$$R_{tot;upper} = 4.4189\ m^2 \cdot K \cdot W^{-1}$$

[$R_{inhomogeneous\ layer}$]

$$\frac{1}{R_{inhomogeneous}} = \frac{0.0015/0.6}{0.0018} + \frac{0.5985/0.6}{2.5714} = 1.7768\ W \cdot m^{-2} \cdot K^{-1}$$

$$R_{inohomogeneous} = 0.5628\ m^{2} \cdot K \cdot W^{-1}$$

[$R_{tot;lower}$]

$$R_{tot;lower} = 0.1300 + 0.0714 + 0.0923 + 0.5628 + 0.0923 + 1.4375 + 0.0400$$

$$= 2.4263\ m^{2} \cdot K \cdot W^{-1}$$

[$R_{tot;ISO}$]

$$R_{tot;ISO} = \frac{4.4189 + 2.4263}{2} = 3.42\ m^{2} \cdot K \cdot W^{-1}$$

Gorgolewski Method 1

[p factor]

$$p = 0.8\left(\frac{4.4189}{2.4263}\right) + 0.1 = 0.5392$$

[$R_{tot;gorg1}$]

$$R_{tot;gorg1} = 0.5392 \cdot 4.4189 + (1 - 0.5392) \cdot 2.4263 = 3.50\ m^{2} \cdot K \cdot W^{-1}$$

Gorgolewski Method 2

[p factor]

$$p = 0.50$$

[$R_{tot;gorg2}$]

$$R_{tot;gorg2} = 0.50 \cdot 4.4189 + (1 - 0.50) \cdot 2.4263 = 3.42\ m^{2} \cdot K \cdot W^{-1}$$

Gorgolewski Method 3

[p factor]

$$p = 0.8\left(\frac{2.4263}{4.4189}\right) + 0.44 - 0.1\left(\frac{0.043}{0.04}\right) - 0.2\left(\frac{0.6}{0.6}\right) - 0.04\left(\frac{0.09}{0.1}\right) = 0.5358$$

[$R_{tot;gorg3}$]

$$R_{tot;gorg3} = 0.5358 \cdot 4.4189 + (1 - 0.5358) \cdot 2.4263 = 3.49\ m^2 \cdot K \cdot W^{-1}$$

ASHRAE Zone Method

[$R_{tot;cav}$]

$$R_{tot;cav} = 0.1300 + 0.0714 + 0.0923 + 2.5714 + 0.0923 + 1.4375 + 0.0400$$

$$= 4.4349\ m^2 \cdot K \cdot W^{-1}$$

[w]

$$w = 0.043 + 2 \cdot 0.062 = 0.167\ m$$

[$R_{innerflange;MW}$]

$$\frac{1}{R_{innerflange;MW}} = \frac{0.043/0.167}{0.0015/50} + \frac{(0.167 - 0.043)/0.167}{0.0015/0.035} = 0.0001\ W \cdot m^{-2} \cdot K^{-1}$$

[$R_{web;MW}$]

$$\frac{1}{R_{web;MW}} = \frac{0.0015/0.167}{0.087/50} + \frac{(0.167 - 0.0015)/0.167}{0.087/0.035} = 0.1798\ W \cdot m^{-2} \cdot K^{-1}$$

$[R_{outerflange;MW}]$

$$\frac{1}{R_{outerflange;MW}} = \frac{0.043/0.167}{0.0015/50} + \frac{(0.167 - 0.043)/0.167}{0.087/50} = 0.0001\ W \cdot m^{-2} \cdot K^{-1}$$

$[R_{tot;w}]$

$$R_{tot;w} = 0.1300 + 0.0714 + 0.0923 + 0.0001 + 0.1798 + 0.0001 + 0.0923 + 1.4375 +$$

$$+ 0.0400 = 2.0435\ m^2 \cdot K \cdot W^{-1}$$

$[R_{tot;ASHRAE}]$

$$\frac{1}{R_{tot;ASHRAE}} = \frac{0.167/0.600}{2.0435} + \frac{(0.600 - 0.167)/0.600}{4.4349} = 0.2989\ W \cdot m^{-2} \cdot K^{-1}$$

$$R_{tot;ASHRAE} = 3.35\ m^2 \cdot K \cdot W^{-1}$$

The summary of the results obtained above is displayed in Table 12.

Table 12 – Module 1 verification: results obtained by the calculation procedure.

	R-values [(m^2·K)/W]	U-values [W/(m^2·K)]
ISO 6946 Combined Method	3.42	0.29
Gorgolewski Method 1	3.50	0.29
Gorgolewski Method 2	3.42	0.29
Gorgolewski Method 3	3.49	0.29
ASHRAE Zone Method	3.35	0.30

The results provided by the Tyre4BuildIns Calculation Tool, for the same LSF wall, are presented in Figure 19. Analysing the results obtained, it is possible to verify that the values provided by the tool and the previously calculated values coincide, thus ensuring the reliability of the results provided by this module.

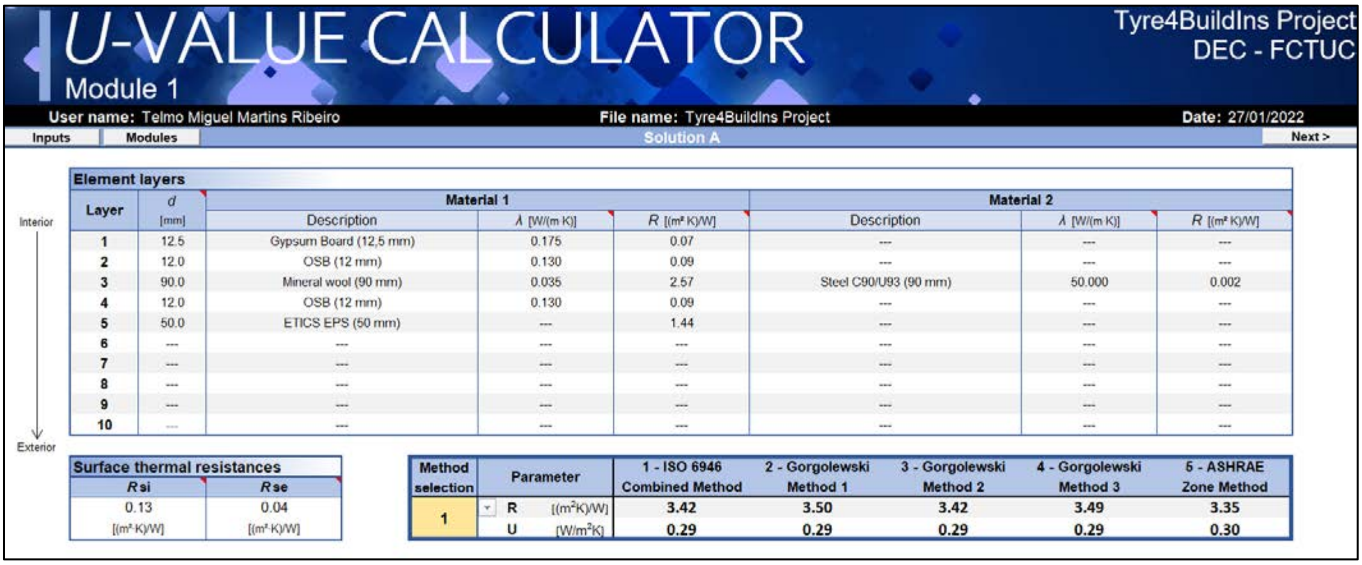


Figure 19 – Module 1 verification: Tyre4BuildIns Calculation Tool results.

Additionally, a comparison between the thermal resistance values calculated by the tool using the five analytical methods and those calculated through numerical simulations was performed. These numerical simulations were performed using bidimensional models built in the THERM finite elements software. For these verifications, three LSF walls were considered, corresponding to the three LSF construction types: i) cold frame construction (Table 13 and Figure 20); ii) warm frame construction (Table 14 and Figure 21), and; iii) hybrid construction (Table 15 and Figure 22).

Table 13 – LSF wall configuration (cold frame construction).

Material (Inner to outer layer)	d [mm]	λ [W/(m·K)]
Gypsum Plasterboard	12.5	0.175
OSB	12	0.100
Air Cavity | TB Strip XPS	10	--- | 0.034
Mineral Wool | Steel Stud (C90 x 43 x 15 x 1.5 mm; ss: 400 mm)	90	0.035 | 50.000
OSB	12	0.100
Finishing	5	0.045
Total Thickness	141.5	---

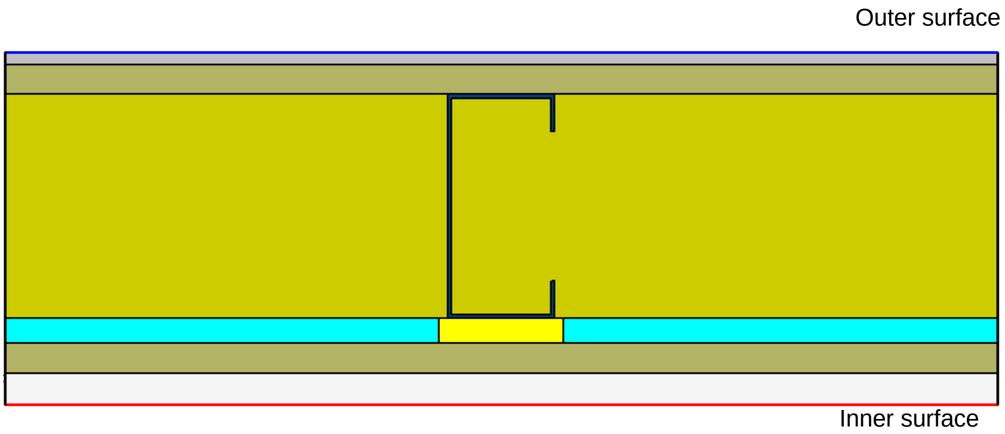


Figure 20 – LSF wall cross-section (cold frame construction).

Table 14 – LSF wall configuration (warm frame construction).

Material (Inner to outer layer)	d [mm]	λ [W/(m·K)]
Gypsum Plasterboard	12.5	0.175
OSB	12	0.100
Air Cavity | TB Strip XPS	10	--- | 0.034
Air Cavity | Steel Stud (C90 x 43 x 15 x 1.5; ss: 400 mm)	90	--- | 50.000
OSB	12	0.100
EPS	50	0.036
Finishing	5	0.045
Total Thickness	191.5	---

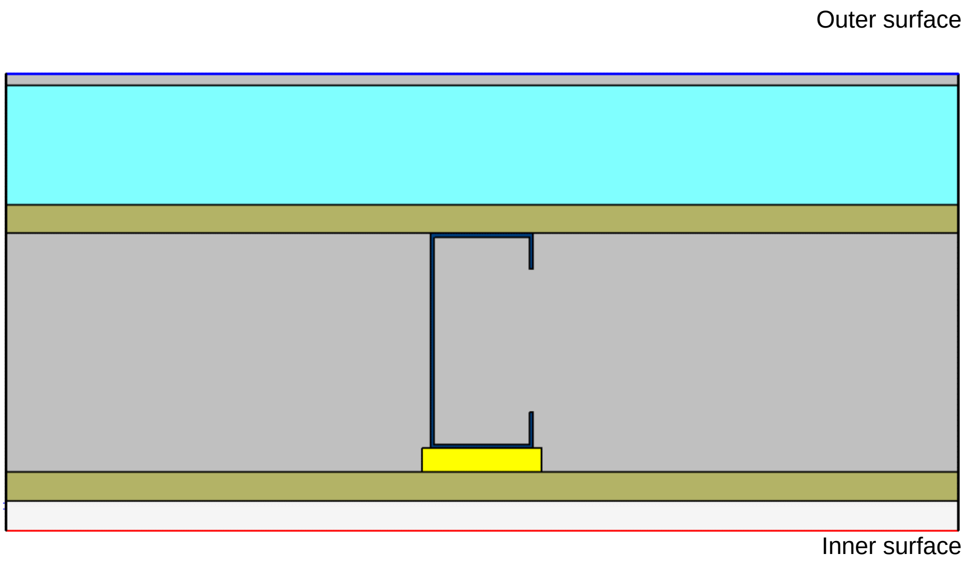


Figure 21 – LSF wall cross-section (warm frame construction).

Table 15 – LSF wall configuration (hybrid construction).

Material (Inner to outer layer)	d [mm]	λ [W/(m·K)]
Gypsum Plasterboard	12.5	0.175
OSB	12	0.100
Air Cavity | TB Strip XPS	10	--- | 0.034
Mineral Wool | Steel Stud (C90 x 43 x 15 x 1.5 mm; ss: 400 mm)	90	0.035 | 50.000
OSB	12	0.100
EPS	50	0.036
Finishing	5	0.045
Total Thickness	191.5	---

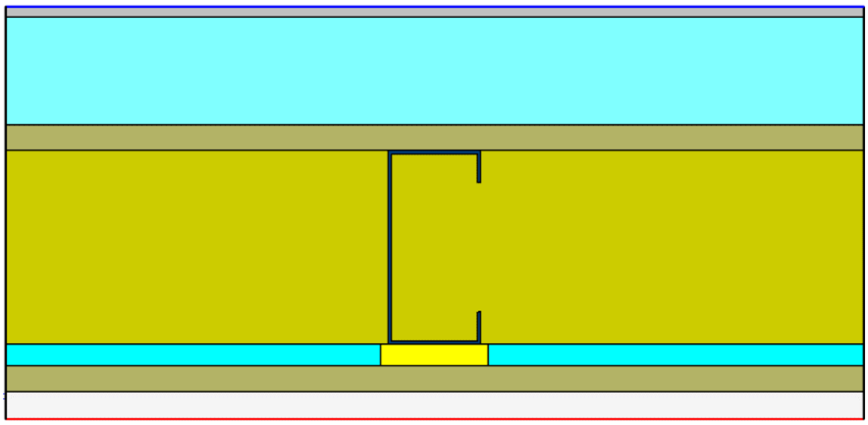


Figure 22 – LSF wall cross-section (hybrid construction).

The U-values obtained, as well as the absolute and percentage differences, for the three LSF walls through numerical simulations (THERM) and using the five analytical methods computed within the tool are presented in Table 16. In addition, for a better visualization of the differences obtained, the percentage differences are displayed graphically in Figure 23.

Table 16 – Thermal transmittance values, U: numerical simulations (THERM) vs analytical methods computed within the Tyre4BuildIns Tool.

LSF Wall Type					Warm	Cold	Hybrid
THERM		U-value		[W/(m2·K)]	0.486	0.475	0.272
Tool	ISO 6946 Combined Method	U-Value		[W/(m2·K)]	0.490	0.476	0.285
		Difference	Absolute	[W/(m2·K)]	0.004	0.001	0.012
			Percentage	[%]	1%	0%	4%
	Gorgolewski Method 1	U-Value		[W/(m2·K)]	0.486	0.545	0.280
		Difference	Absolute	[W/(m2·K)]	0.000	0.070	0.008
			Percentage	[%]	0%	15%	3%
	Gorgolewski Method 2	U-Value		[W/(m2·K)]	0.491	0.630	0.303
		Difference	Absolute	[W/(m2·K)]	0.005	0.155	0.031
			Percentage	[%]	1%	33%	11%
	Gorgolewski Method 3	U-Value		[W/(m2·K)]	0.487	0.620	0.298
		Difference	Absolute	[W/(m2·K)]	0.001	0.144	0.026
			Percentage	[%]	0%	30%	10%
	ASHRAE Zone Method	U-Value		[W/(m2·K)]	0.492	0.570	0.318
		Difference	Absolute	[W/(m2·K)]	0.006	0.095	0.046
			Percentage	[%]	1%	20%	17%

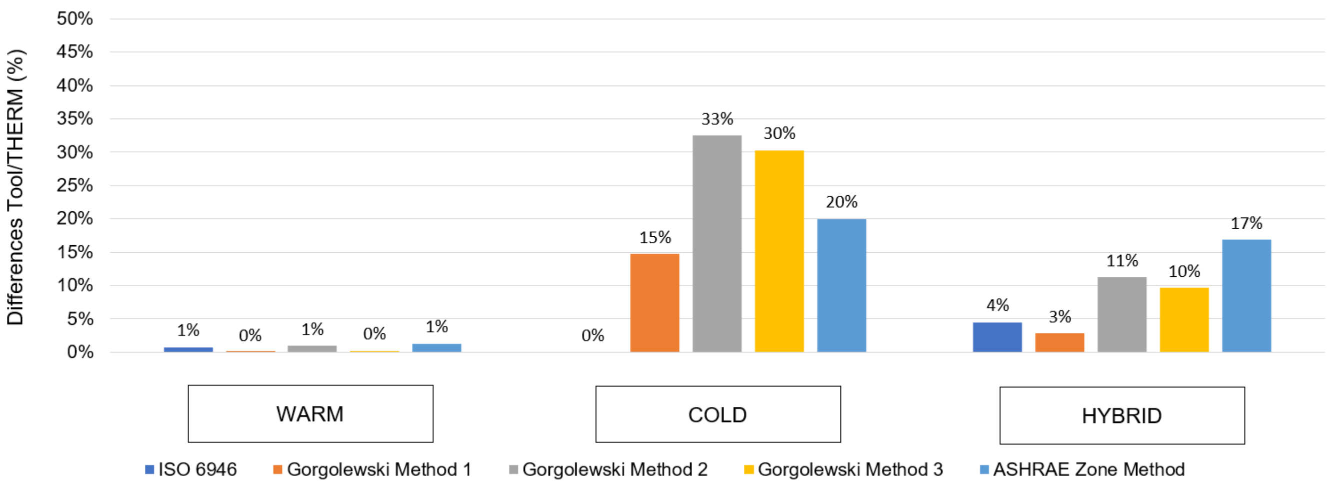


Figure 23 – Percentage differences between the Calculation Tool and the THERM U-values.

The results displayed in Figure 23 allow to verify that, for all the cases evaluated, the U-values provided by the Calculation Tool are higher than the ones provided through numerical simulations, exhibiting a conservative trend.

Analysing by type of LSF construction, the closest approximation between the values of THERM and the tool is reached in the wall with thermal insulation only from the outside (warm frame construction). In this type of construction, the results obtained present maximum percentage differences equal to 1%. On the other hand, the cold frame type construction, characterised by the presence of thermal insulation only in the interior cavity, registered the highest differences in four of the five analytical modules considered. The largest percentage difference was registered in Gorgolewski Method 2 (33%), while the best approximation with the numerical simulations was verified in the ISO 6946 Combined Method (~ 0%). Moreover, in the wall with thermal insulation in the internal cavity and from the outside (hybrid construction), the percentage differences change between 3% (Gorgolewski Method 1) and -17% (ASHRAE Zone Method).

Although these results give an idea of which type of construction and which analytical methods provide more reliable results, it is important to note that for other LSF wall configurations the differences from numerical simulations may vary significantly. Nevertheless, since these deviations are within the error range observed in a previous research work and published in a journal article by Santos et al. (2020), it can be concluded that the Tyre4BuildIns Calculation Tool is providing accurate results regarding the U-values simplified calculations using the analytical methods.

5.3. Module 2 – Energy Benefits

The verification of Module 2 was performed considering two LSF walls solutions, whose parameters are presented in Table 17.

Table 17 – Module 2 verification: parameters of the two LSF walls solutions considered.

	Solution A	**Solution B**
U-value	0.29 W/(m^2·K)	0.24 W/(m^2·K)
External Walls Area	252 m^2	252 m^2
Localization	Madrid	Rome
Heating Degree Days	2066 °C	1508 °C
Cooling Degree Days	212 °C	73 °C
CoP	3.50	3.50
EER	3.50	3.50

The calculation procedure for the calculation of the final energy balance considering these two solutions is presented next.

Solution A

[$Q_{tr}^{heating}$ | from Equation 13]

$$Q_{tr}^{heating} = \frac{0.2921 \cdot 252 \cdot 2066 \cdot 24}{1000} = 3649.839\ kWh$$

[$Q_{tr}^{cooling}$ | from Equation 14]

$$Q_{tr}^{cooling} = \frac{0.2921 \cdot 252 \cdot 212 \cdot 24}{1000} = 374.524\ kWh$$

[E_{final} | from Equation 12]

$$E_{final} = \frac{3648.839}{3.5} + \frac{374.524}{3.5} = 1150\ kWh$$

Solution B

[$Q_{tr}^{heating}$ | from Equation 13]

$$Q_{tr}^{heating} = \frac{0.2408 \cdot 252 \cdot 1508 \cdot 24}{1000} = 2196.188\ kWh$$

[$Q_{tr}^{cooling}$ | from Equation 14]

$$Q_{tr}^{cooling} = \frac{0.2408 \cdot 252 \cdot 73 \cdot 24}{1000} = 106.314\ kWh$$

[E_{final} | from Equation 12]

$$E_{final} = \frac{2196.188}{3.5} + \frac{106.314}{3.5} = 658\ kWh$$

Saved Energy

[E_{saved} | from Equation (11)]

$$E_{saved} = 1150 - 658 = 492\ kWh$$

In Figure 24, the results provided by the Tyre4BuildIns Calculation Tool, considering the previous couple of solutions are shown. Comparing the final energy values provided by the tool and the values determined performing the calculation procedure, it is possible to verify that they are equal, thus ensuring the reliability of the results provided by this module.

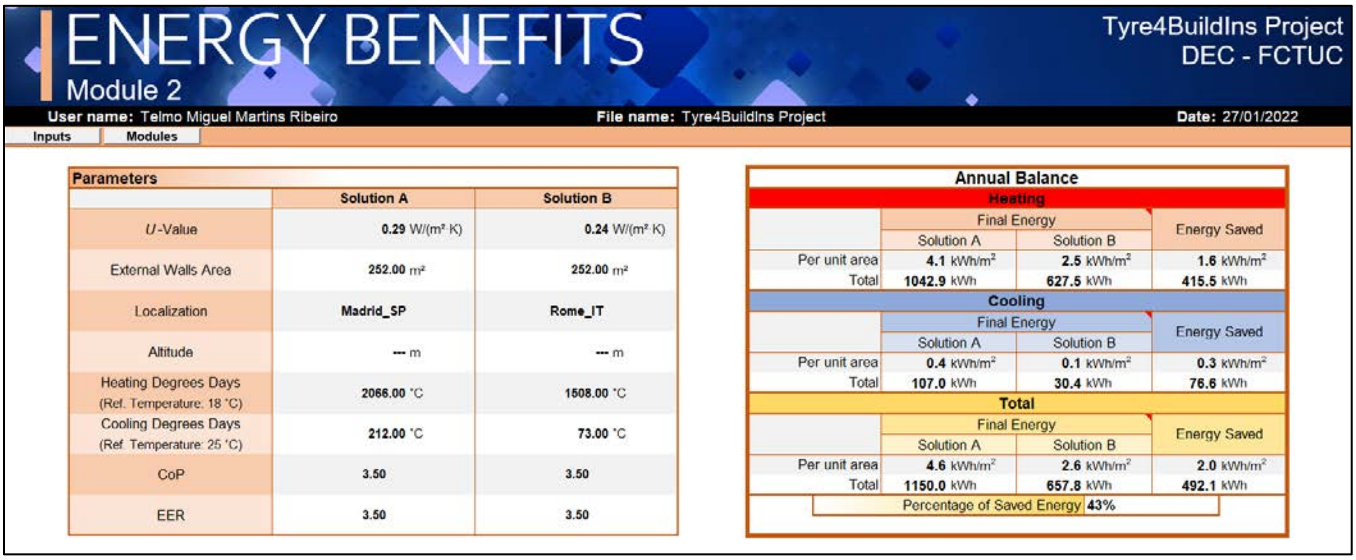


Figure 24 – Module 2 verification: Tyre4BuildIns Calculation Tool results.

5.4. Module 3 – Life-Cycle Analysis

Module 3 – Life-Cycle Analysis was verified by comparing the results provided by the tool, with the results obtained by performing the calculation procedure, for a given LSF wall.

In this verification, the environmental impact indicator used was the Acidification Potential. The composition of the LSF wall considered, as well as the respective values of the environmental impacts (per functional unit – 1 m^2 of wall) of each constituent material is presented in Table 18.

Table 18 – Composition and Acidification Potential (AP) value of the LSF wall.

Material (Inner to outer layer)	d [mm]	AP [kg·SO2-eq]
Gypsum Plasterboard	12.5	1.20E-02
OSB	12	1.10E-02
Mineral Wool | Steel Stud (C90 x 43 x 15 x 1.5 mm)	90	9.09E-03 | 2.58E-05
OSB	12	1.10E-02
Total Thickness	126.5	---

Considering the Acidification Potential (AP) values of each constituent material, the AP of the LSF wall, per functional unit, is obtained by:

$$AP = 0.012 + 0.011 + 0.00909 + 0.0000258 + 0.011 = 0.043\ \mathrm{kg} \cdot \mathrm{SO}_{2-\mathrm{eq}}$$

In Figure 25, the results provided by the calculation tool are presented. Since the results shown by the tool coincide with the results obtained through the calculation procedure, the reliability of the Module 3 is verified.

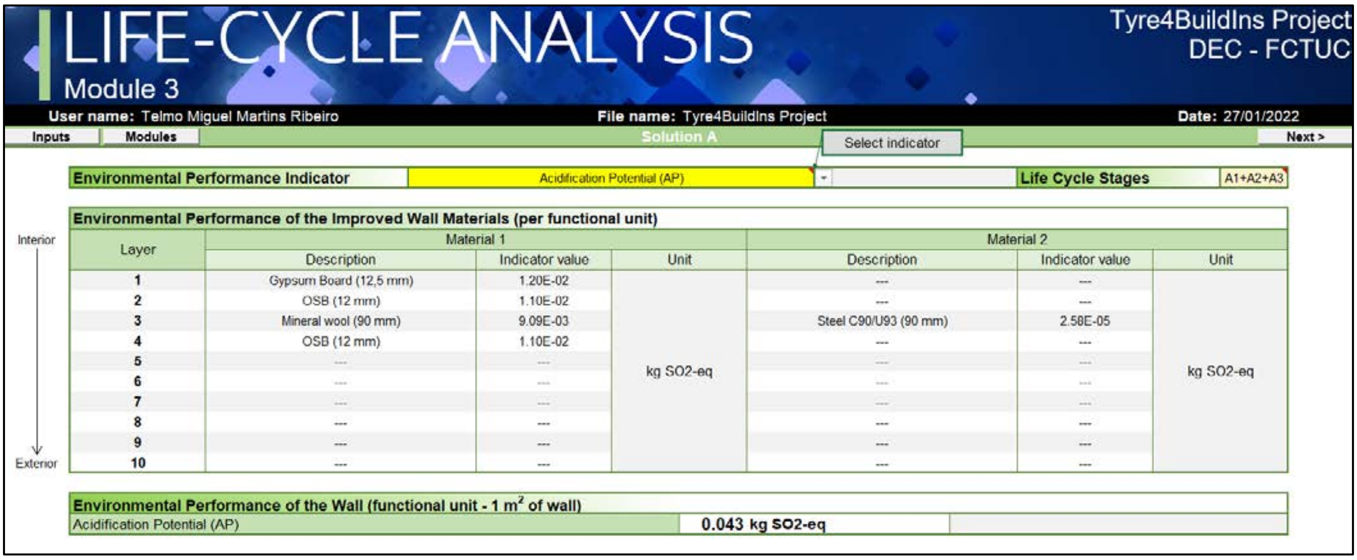


Figure 25 – Module 3 verification: print-screen of Solution A results.

5.5. Module 4 – Cost-Benefit Analysis

For the verification of Module 4 – Cost-Benefit Analysis, the cost-benefit balance of two LSF walls was evaluated through the calculation tool and compared with the results obtained by performing the calculation procedure. In this verification, a reference wall with an U-value equal to 0.51 W/(m^2·K) (ISO 6946 Combined Method) and an improved wall with an U-value equal to 0.44 W/(m^2·K) (ISO 6946 Combined Method) were considered. Moreover, the following assumptions were considering: i) total area of external walls equal to 100 m^2; ii) annual saved energy of 100 kWh, and; iii) electricity cost of 0.25 €. Table 19 and Table 20 show the composition of the reference and improved walls, respectively, as well as the respective costs of each constituent material, based on the references used.

Table 19 – Composition and unit costs of the reference wall.

Material (Inner to outer layer)	d [mm]	Unit cost [€/m^2 of wall]
Gypsum Plasterboard	12.5	3.25
OSB	12	7.32
Mineral Wool | Steel Stud (C90 x 43 x 15 x 1.5 mm)	90	2.92 | 17.06
OSB	12	7.32
Total Thickness	126.5	---

Table 20 – Composition and unit costs of the improved wall.

Material (Inner to outer layer)	d [mm]	Unit cost [€/m^2 of wall]
Gypsum Plasterboard	12.5	3.25
OSB	12	7.32
Air Cavity | TB Strip XPS	10	--- | 0.25
Mineral Wool | Steel Stud (C90 x 43 x 15 x 1.5 mm)	90	2.92 | 17.06
Air Cavity | TB Strip XPS	10	--- | 0.25
OSB	12	7.32
Total Thickness	146.5	---

Considering the unit cost values of each constituent material, the unit cost of the reference $C_{reference}^{unit}$ and improved $C_{improved}^{unit}$ walls can be obtained by:

$$C_{reference}^{unit} = 3.25 + 7.32 + 2.92 + 17.07 + 7.32 = \ 37.88 \text{ €}/m^2$$

$$C_{improved}^{unit} = 3.25 + 7.32 + 0.26 + 2.92 + 17.07 + 0.26 + 7.32 = \ 38.40 \text{ €}/m^2$$

Thus, the total cost of the reference $C_{reference}^{total}$ and improved $C_{improved}^{total}$ walls is obtained by:

$$C_{reference}^{total} = 37.88 \frac{\text{€}}{m^2} \times 100\ m^2 = 3788.00 \text{ €}$$

$$C_{improved}^{total} = 38.40 \frac{\text{€}}{m^2} \times 100 m^2 = \ 3840.00 \text{ €}$$

Consequently, the improvement cost (IC) is determined by:

$$IC = 3840.00\ € - 3788\ € = 52.00\ €$$

Regarding benefits, the annual benefit (AB) from using the thermally improved wall instead of the reference wall is calculated through,

$$AB = 0.25 \frac{€}{kWh} \times 100\ kWh = 25.00\ €$$

Finally, the payback period (PP) is given by:

$$PP = 52.00/25.00 = 2.1\ years$$

In Figure 26, the results provided by the calculation tool are presented. The results obtained by the tool and the previously calculated values coincide, thus ensuring the reliability of the results provided by this module.

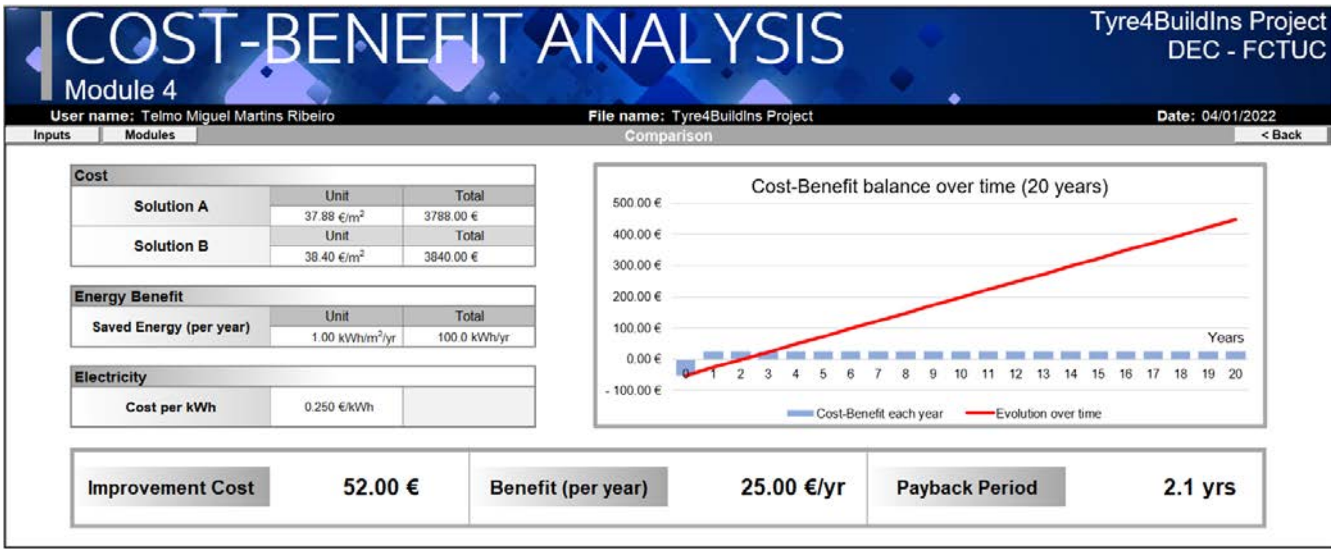


Figure 26 – Module 4 verification: print-screen of the comparison worksheet.

5.6. Module 5 – Multicriteria Analysis

The accuracy verification of Module 5 – Multicriteria Analysis was carried out by comparing the results provided by the Tool with the results obtained by performing the manual calculation procedure of the multicriteria analysis. The data considered in this verification are presented in Table 21 (criteria weights) and Table 22 (decision matrix).

Table 21 – Module 5 verification: criteria weights.

Criteria Weights	
Energy consumption	35%
Environmental impacts	15%
Acquisition cost	50%

Table 22 – Module 5 verification: decision matrix.

Decision Matrix			
Solutions	Criteria		
	Energy consumption	Environmental impacts	Acquisition costs
A	6.30 kWh/m2	0.88	36.07 €/m2
B	5.25 kWh/m2	1.00	36.51 €/m2

Using Equation (17), the standardized decision matrix presented in Table 23 was obtained.

Table 23 – Module 5 verification: standardized decision matrix.

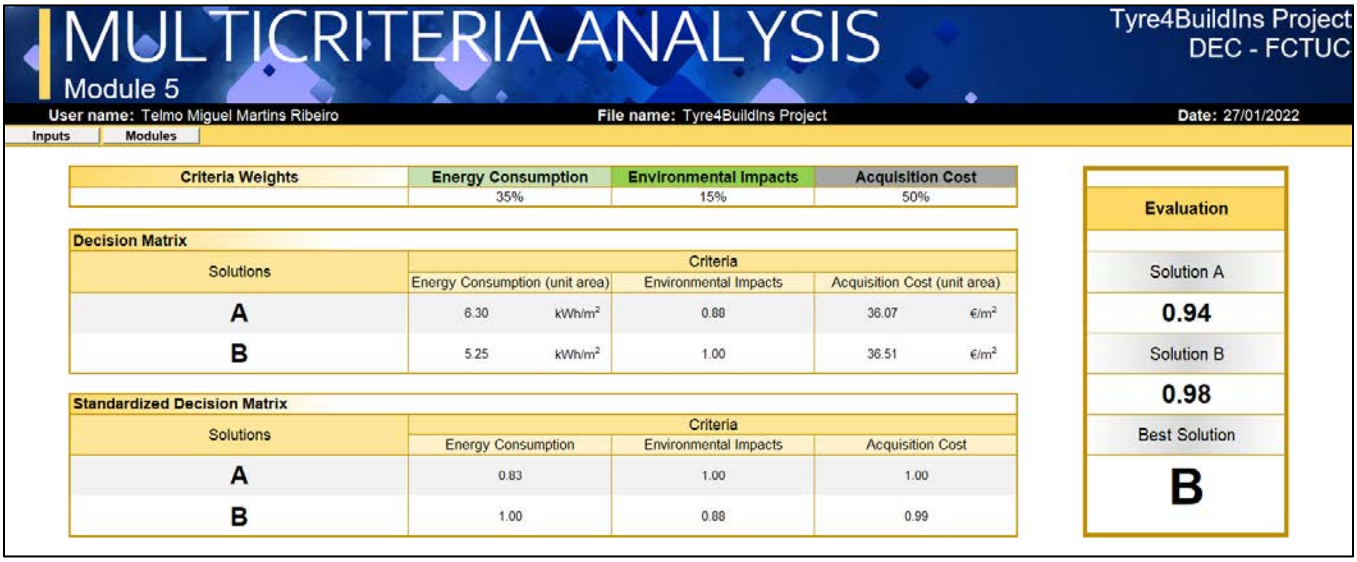
Standardized Decision Matrix			
Solutions	Criteria		
	Energy consumption	Environmental impacts	Acquisition costs
A	$5.25/_{6.30} = 0.83$	$0.88/_{0.88} = 1.00$	$36.07/_{36.07} = 1.00$
B	$5.25/_{5.25} = 1.00$	$0.88/_{1.00} = 0.88$	$36.07/_{36.51} = 0.99$

The Final Evaluation (FE) of solutions A and B is computed using Equation (18), as follows:

$$FE^{solution\ A} = 0.83 \times 0.35 + 1.00 \times 0.15 + 1.00 \times 0.50 = 0.94$$

$$FE^{solution\ B} = 1.00 \times 0.35 + 0.88 \times 0.15 + 0.99 \times 0.50 = 0.98$$

The results provided by the calculation tool are presented in Figure 27. The results obtained by the tool and the values obtained by the calculation procedure are equal, thus ensuring the reliability of the results provided by this module.



Criteria Weights	Energy Consumption	Environmental Impacts	Acquisition Cost
	35%	15%	50%

Decision Matrix

Solutions	Criteria		
	Energy Consumption (unit area)	Environmental Impacts	Acquisition Cost (unit area)
A	6.30 kWh/m²	0.88	36.07 €/m²
B	5.25 kWh/m²	1.00	36.51 €/m²

Standardized Decision Matrix

Solutions	Criteria		
	Energy Consumption	Environmental Impacts	Acquisition Cost
A	0.83	1.00	1.00
B	1.00	0.88	0.99

Evaluation
Solution A
0.94
Solution B
0.98
Best Solution
B

Figure 27 – Module 5 verification: Tyre4BuildIns Calculation Tool results.

6. DESIGN EXAMPLE

6.1. Framework

In this chapter, to demonstrate the full operation of the calculation tool, a design example is presented. Firstly, the inputs used in this example are displayed, by defining the building features and the wall configuration for Solution A (reference) and Solution B (improved), as well as the weights used in the multicriteria analysis. Then, the operation of the tool is shown, through the presentation of each one of the tabs that constitute the Tyre4BuildIns Calculation Tool.

6.2. Input Data

The input data considered in this design example for Solution A (reference) and Solution B (improved) are presented in Table 24 and Table 25, respectively. Moreover, Table 26 presents the definition of the weights for the multicriteria analysis. Regarding the building features, the same parameters were used for solutions A and B, in order to focus the analysis on the comparison between the LSF walls considered. Concerning the configuration of the two LSF walls under analysis, it was considered that both solutions have metal profiles spaced 600 mm apart and mineral wool thermal insulation in the cavity between the metal profiles (cold frame construction), plasterboard and OSB on the inner sheathing, and OSB and mortar finishing on the outer sheathing. The only difference between the two solutions is the application of XPS thermal break strips Figure 28 along the inner and outer flanges of the metal profiles in the improved solution (Solution B).

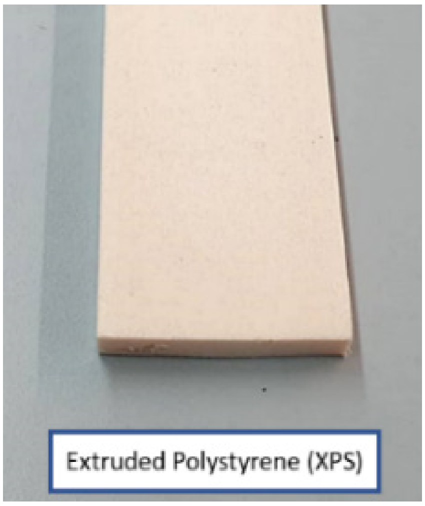


Figure 28 – Extruded polystyrene (XPS) thermal break strip.

Solution A – Reference Solution

Table 24 – Input data of Solution A – Reference configuration.

Building Features

Location

Country	Portugal
Municipality	Coimbra
Altitude	75 m

Climatization Systems

CoP	3.5
EER	3.5

Electricity Cost

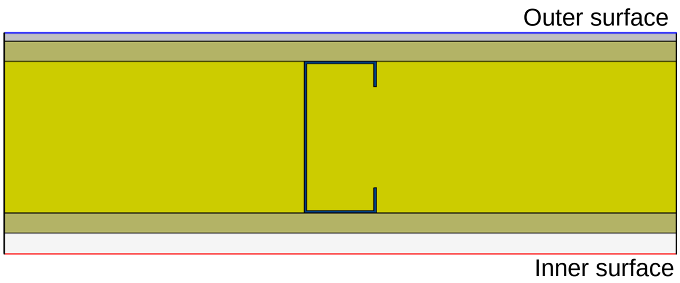
Cost	0.20 €/kWh

Facades

Main Facade (MF)	
Length	15 m
Glazing Area	10%
Back Facade (BF)	
Length	15 m
Glazing Area	10%
Left Facade (LF)	
Length	10 m
Glazing Area	10%
Right Facade (RF)	
Length	10 m
Glazing Area	10%

Wall Configuration

Material (Inner to outer layer)	d [mm]
Gypsum Plasterboard	12.5
OSB	12
Mineral Wool | Steel Stud (C90 x 43 x 15 x 1.5 mm; ss: 600 mm)	90
OSB	12
Mortar	5
Total Thickness	131.5



Solution B – Improved Solution

Table 25 – Input data of Solution B – Improved configuration.

Building Features

Location

Country	Portugal
Municipality	Coimbra
Altitude	75 m

Climatization Systems

CoP	3.5
EER	3.5

Electricity Cost

Cost	0.20 €/kWh

Facades

Main Facade (MF)

Length	15 m
Glazing Area	10%

Back Facade (BF)

Length	15 m
Glazing Area	10%

Left Facade (LF)

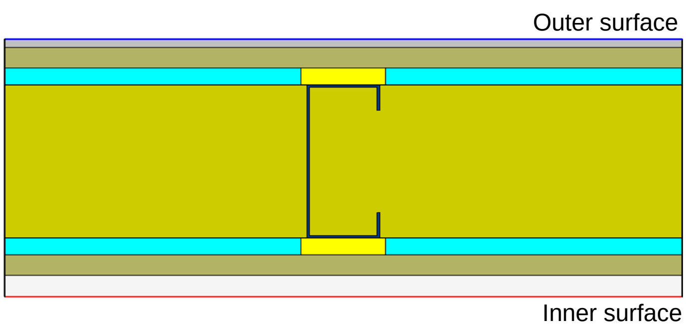
Length	10 m
Glazing Area	10%

Right Facade (RF)

Length	10 m
Glazing Area	10%

Wall Configuration

Material (Inner to outer layer)	d [mm]
Gypsum Plasterboard	12.5
OSB	12
Air Cavity | TB Strip XPS (Improvement)	10
Mineral Wool | Steel Stud (C90 x 43 x 15 x 1.5 mm; ss: 600 mm)	90
Air Cavity | TB Strip XPS (Improvement)	10
OSB	12
Mortar	5
Total Thickness	151.5



Multicriteria Analysis (Weights' definition)

Table 26 – Input data of Multicriteria Analysis.

Calculation Modules (Weights)	
Final Energy Consumed	35%
Environmental Impacts	15%
Acquisition Costs	50%
Environmental Indicators (Weights)	
Abiotic Resources Depletion Potential – Elements (ADPE)	14%
Abiotic Resources Depletion Potential – Fossil Fuels (ADPF)	14%
Acidification potential (AP)	14%
Eutrophication potential (EP)	14%
Photochemical Ozone Creation Potential (POCP)	14%
Global warming potential (GWP)	16%
Ozone Depletion Potential (ODP)	14%

6.3. Tool Operation

The operation of the tool for this example is illustrated in Figures 29 to 46, which represent print-screens of the various tabs that constitute the Tyre4BuildIns Calculation Tool.

As expected, the application of the XPS thermal break strips on the wall of Solution B, allowed to increase the thermal resistance and, consequently, to obtain 14% energy savings, compared to the performance offered by Solution A. However, in Modules 3 and 4, Solution B proved to be more unfavourable. The consideration of XPS thermal break strips in Solution B caused an increase in cost and environmental impacts, compared to Solution A. Considering the results obtained in Modules 1 to 4 and the weights defined for the multicriteria analysis, Module 5 indicates that, globally, the most favourable solution is solution B.

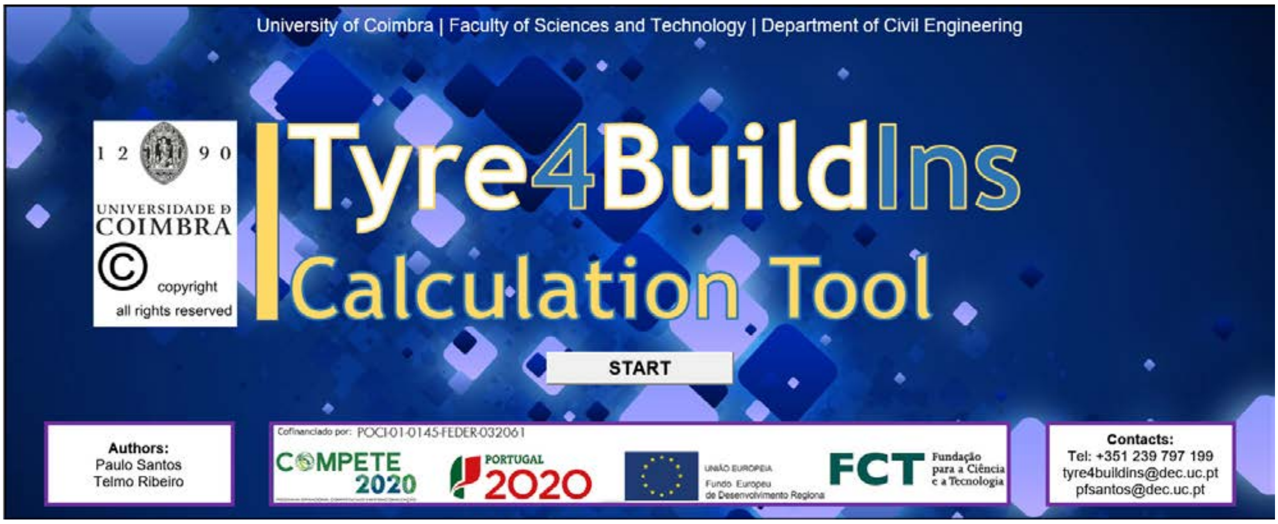


Figure 29 – Design example: Tab 1 of Tyre4BuildIns Calculation Tool.

Figure 30 – Design example: Tab 2 of Tyre4BuildIns Calculation Tool.

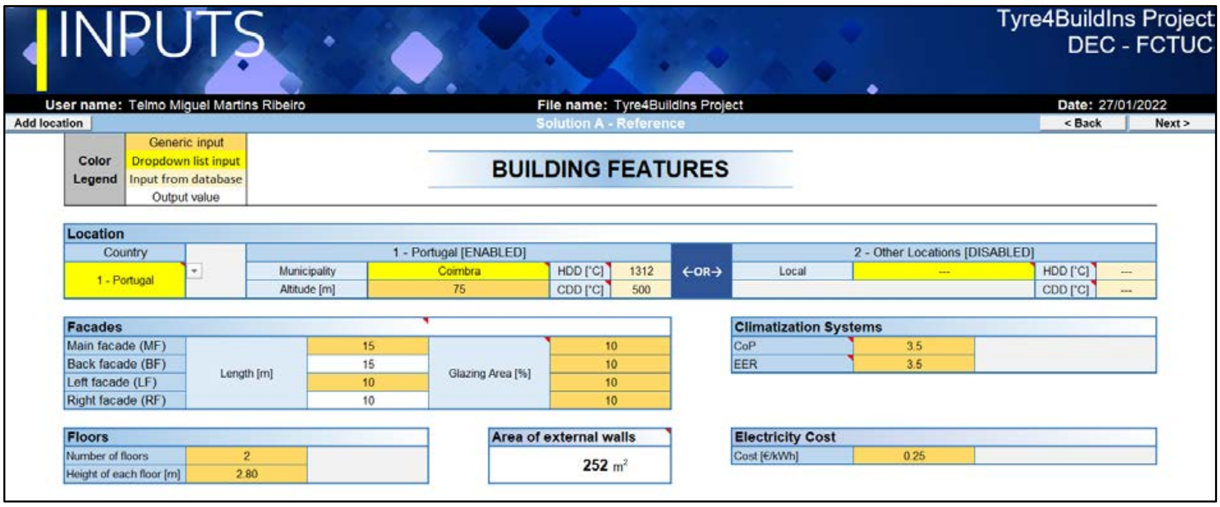


Figure 31 – Design example: Tab 3 of Tyre4BuildIns Calculation Tool.

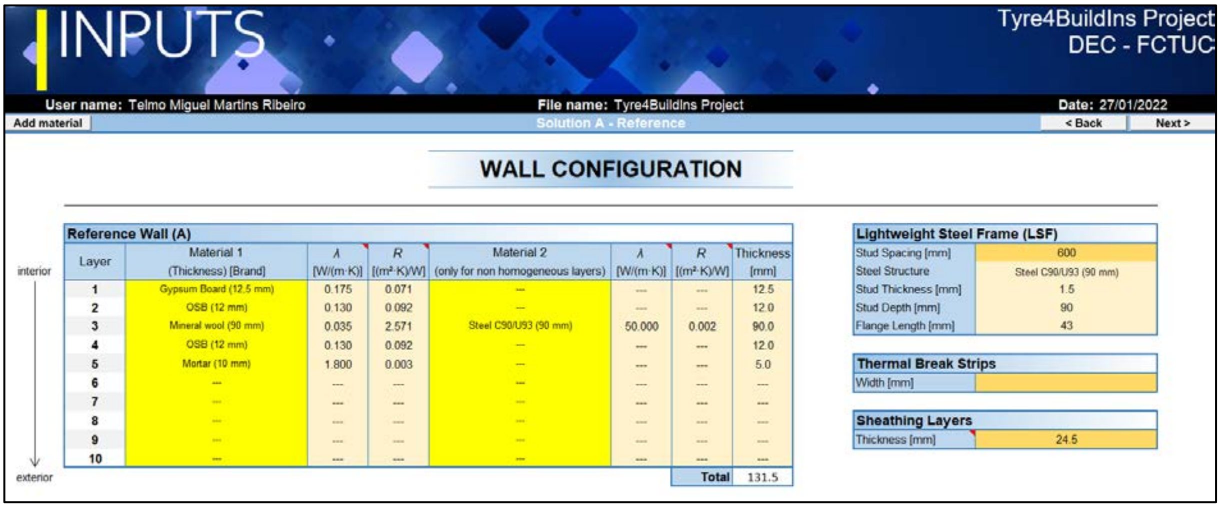


Figure 32 – Design example: Tab 4 of Tyre4BuildIns Calculation Tool.

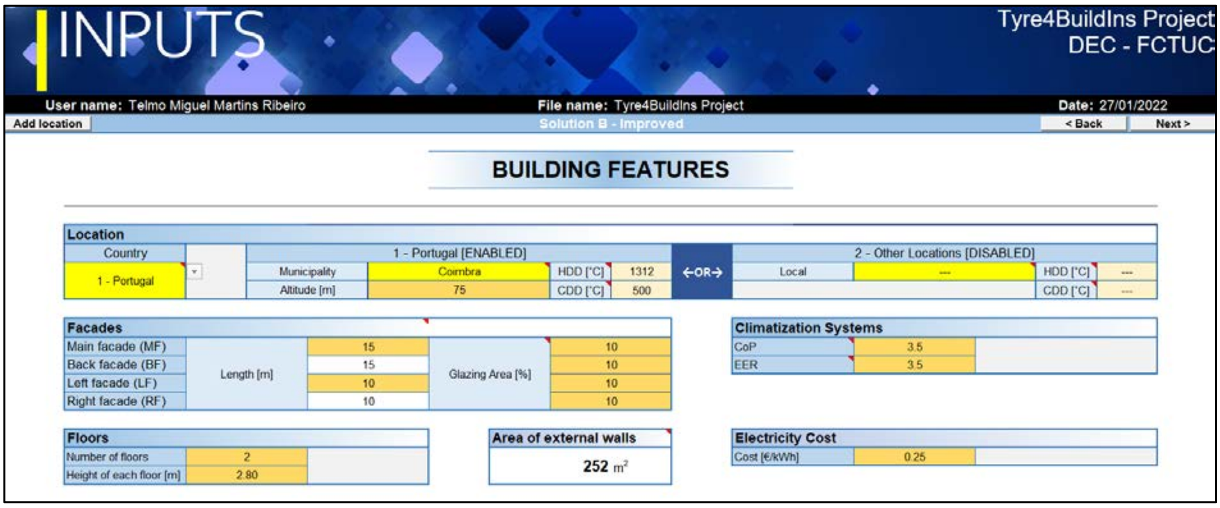


Figure 33 – Design example: Tab 5 of Tyre4BuildIns Calculation Tool.

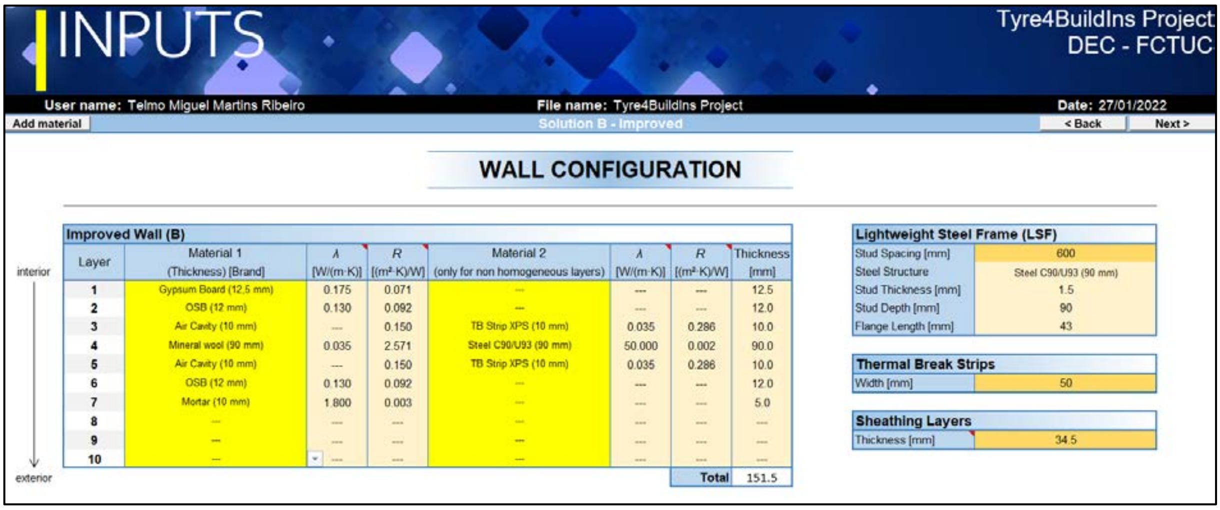


Figure 34 – Design example: Tab 6 of Tyre4BuildIns Calculation Tool.

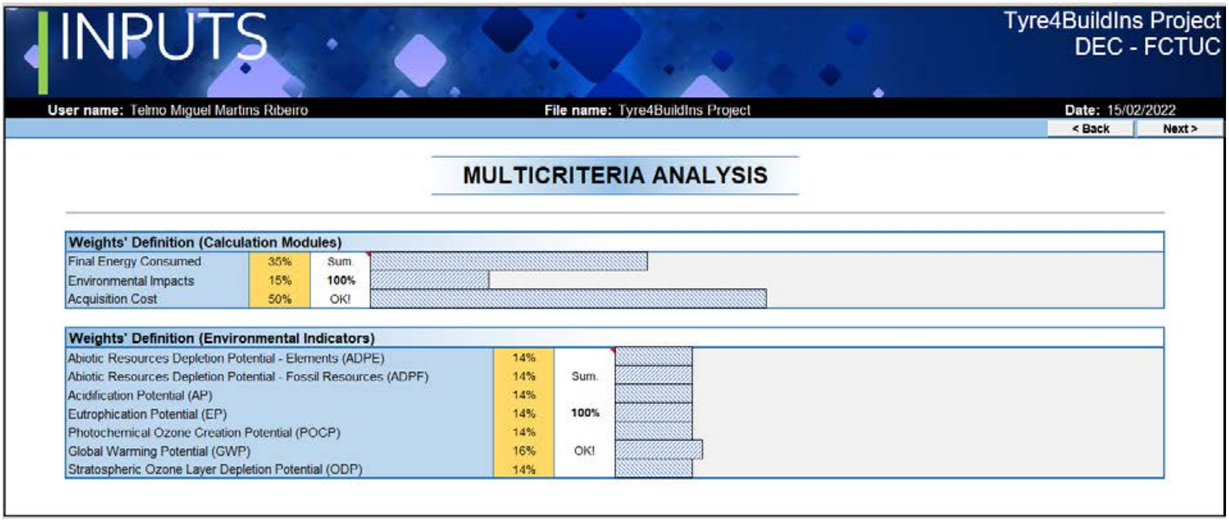


Figure 35 – Design example: Tab 7 of Tyre4BuildIns Calculation Tool.

Figure 36 – Design example: Tab 8 of Tyre4BuildIns Calculation Tool.

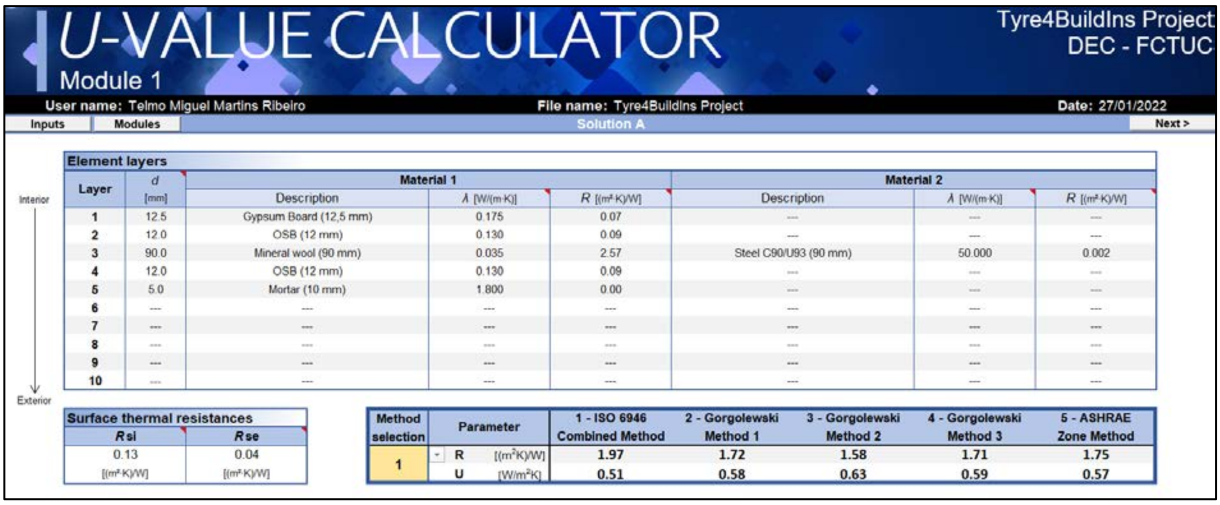
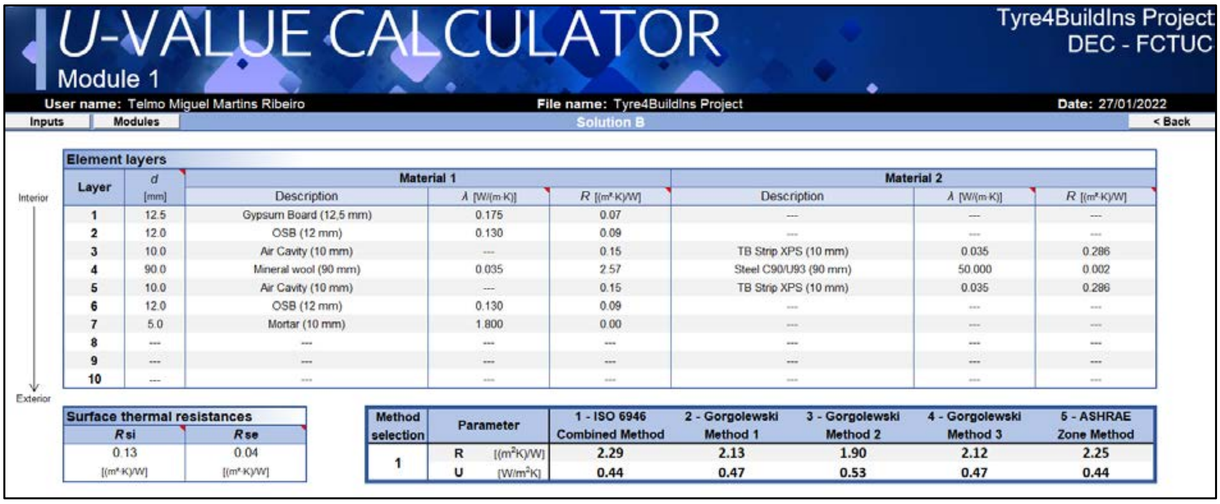


Figure 37 – Design example: Tab 9 of Tyre4BuildIns Calculation Tool.



Element layers

Layer	d [mm]	Material 1 Description	λ [W/(m·K)]	R [(m²·K)/W]	Material 2 Description	λ [W/(m·K)]	R [(m²·K)/W]
1	12.5	Gypsum Board (12,5 mm)	0.175	0.07	---	---	---
2	12.0	OSB (12 mm)	0.130	0.09	---	---	---
3	10.0	Air Cavity (10 mm)	---	0.15	TB Strip XPS (10 mm)	0.035	0.286
4	90.0	Mineral wool (90 mm)	0.035	2.57	Steel C90/U93 (90 mm)	50.000	0.002
5	10.0	Air Cavity (10 mm)	---	0.15	TB Strip XPS (10 mm)	0.035	0.286
6	12.0	OSB (12 mm)	0.130	0.09	---	---	---
7	5.0	Mortar (10 mm)	1.800	0.00	---	---	---
8	---	---	---	---	---	---	---
9	---	---	---	---	---	---	---
10	---	---	---	---	---	---	---

Surface thermal resistances

Rsi	Rse
0.13 [(m²·K)/W]	0.04 [(m²·K)/W]

Method selection	Parameter		1 - ISO 6946 Combined Method	2 - Gorgolewski Method 1	3 - Gorgolewski Method 2	4 - Gorgolewski Method 3	5 - ASHRAE Zone Method
1	R	[(m²K)/W]	2.29	2.13	1.90	2.12	2.25
	U	[W/m²K]	0.44	0.47	0.53	0.47	0.44

Figure 38 – Design example: Tab 10 of Tyre4BuildIns Calculation Tool.

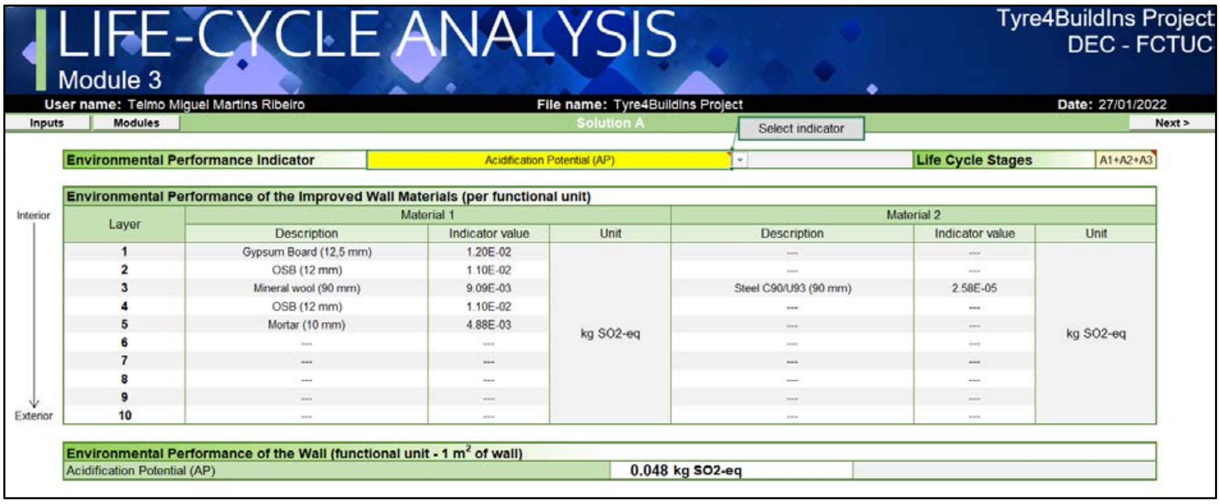
Parameters

	Solution A	Solution B
U-Value	0.51 W/(m²·K)	0.44 W/(m²·K)
External Walls Area	252.00 m²	252.00 m²
Localization	Coimbra	Coimbra
Altitude	75.00 m	75.00 m
Heating Degrees Days (Ref. Temperature: 18 °C)	1312.00 °C	1312.00 °C
Cooling Degrees Days (Ref. Temperature: 25 °C)	500.20 °C	500.20 °C
CoP	3.50	3.50
EER	3.50	3.50

Annual Balance

	Final Energy Solution A	Final Energy Solution B	Energy Saved
Heating			
Per unit area	4.6 kWh/m²	3.9 kWh/m²	0.6 kWh/m²
Total	1148.6 kWh	988.8 kWh	159.7 kWh
Cooling			
Per unit area	1.7 kWh/m²	1.5 kWh/m²	0.2 kWh/m²
Total	437.9 kWh	377.0 kWh	60.9 kWh
Total			
Per unit area	6.3 kWh/m²	5.4 kWh/m²	0.9 kWh/m²
Total	1586.5 kWh	1365.8 kWh	220.6 kWh
Percentage of Saved Energy	14%		

Figure 39 – Design example: Tab 11 of Tyre4BuildIns Calculation Tool.



Environmental Performance Indicator	Acidification Potential (AP)	Life Cycle Stages	A1+A2+A3

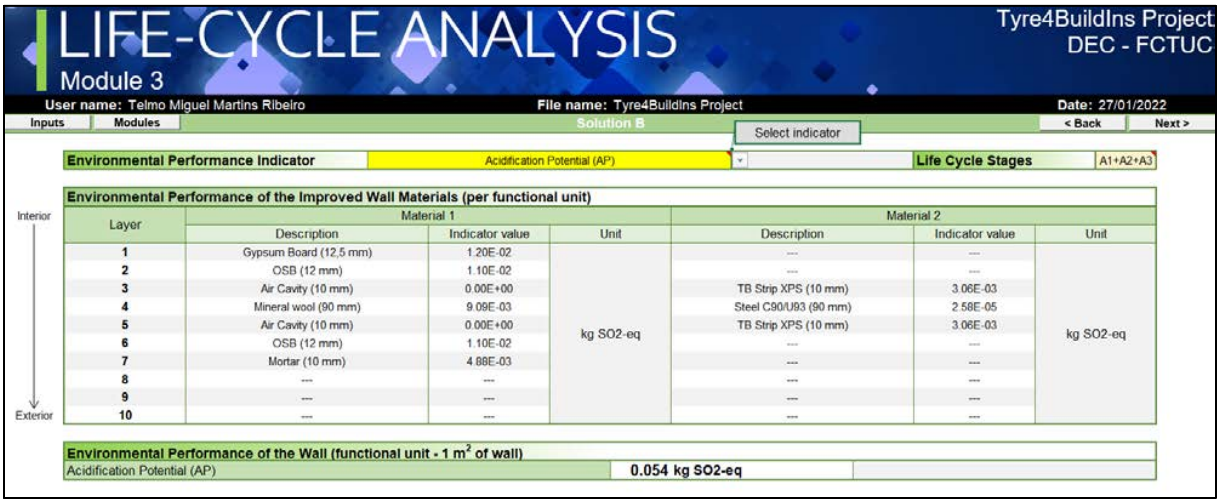
Environmental Performance of the Improved Wall Materials (per functional unit)

Layer	Material 1 Description	Indicator value	Unit	Material 2 Description	Indicator value	Unit
1	Gypsum Board (12,5 mm)	1.20E-02	kg SO2-eq	---	---	kg SO2-eq
2	OSB (12 mm)	1.10E-02		---	---	
3	Mineral wool (90 mm)	9.09E-03		Steel C90/U93 (90 mm)	2.58E-05	
4	OSB (12 mm)	1.10E-02		---	---	
5	Mortar (10 mm)	4.88E-03		---	---	
6	---	---		---	---	
7	---	---		---	---	
8	---	---		---	---	
9	---	---		---	---	
10	---	---		---	---	

Environmental Performance of the Wall (functional unit - 1 m² of wall)

Acidification Potential (AP)	0.048 kg SO2-eq

Figure 40 – Design example: Tab 12 of Tyre4BuildIns Calculation Tool.



Layer	Material 1 Description	Material 1 Indicator value	Material 1 Unit	Material 2 Description	Material 2 Indicator value	Material 2 Unit
1	Gypsum Board (12,5 mm)	1.20E-02	kg SO2-eq	---	---	kg SO2-eq
2	OSB (12 mm)	1.10E-02		---	---	
3	Air Cavity (10 mm)	0.00E+00		TB Strip XPS (10 mm)	3.06E-03	
4	Mineral wool (90 mm)	9.09E-03		Steel C90/U93 (90 mm)	2.58E-05	
5	Air Cavity (10 mm)	0.00E+00		TB Strip XPS (10 mm)	3.06E-03	
6	OSB (12 mm)	1.10E-02		---	---	
7	Mortar (10 mm)	4.88E-03		---	---	
8	---	---		---	---	
9	---	---		---	---	
10	---	---		---	---	

Environmental Performance of the Wall (functional unit - 1 m² of wall)	
Acidification Potential (AP)	0.054 kg SO2-eq

Figure 41 – Design example: Tab 13 of Tyre4BuildIns Calculation Tool.

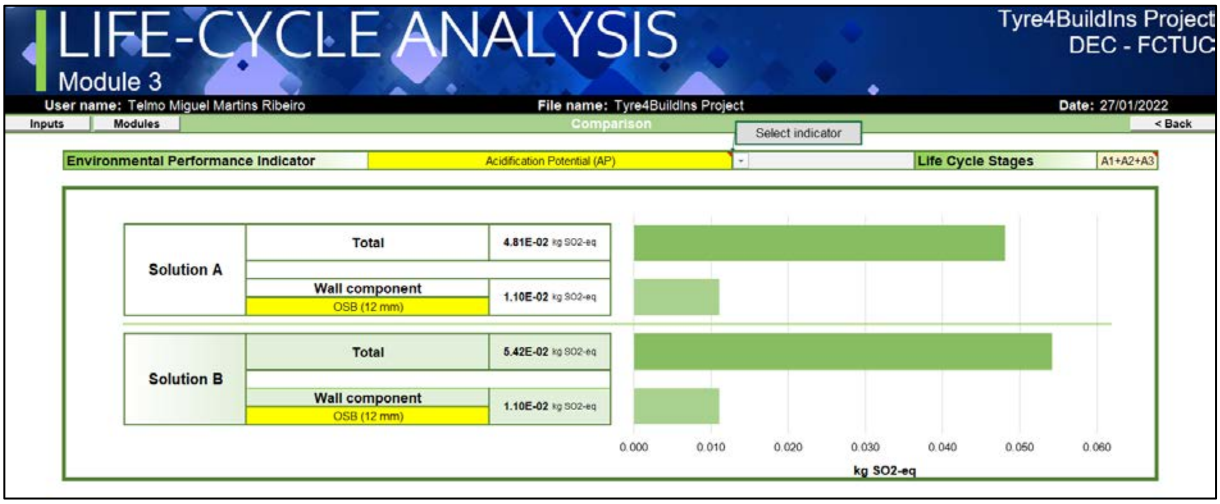
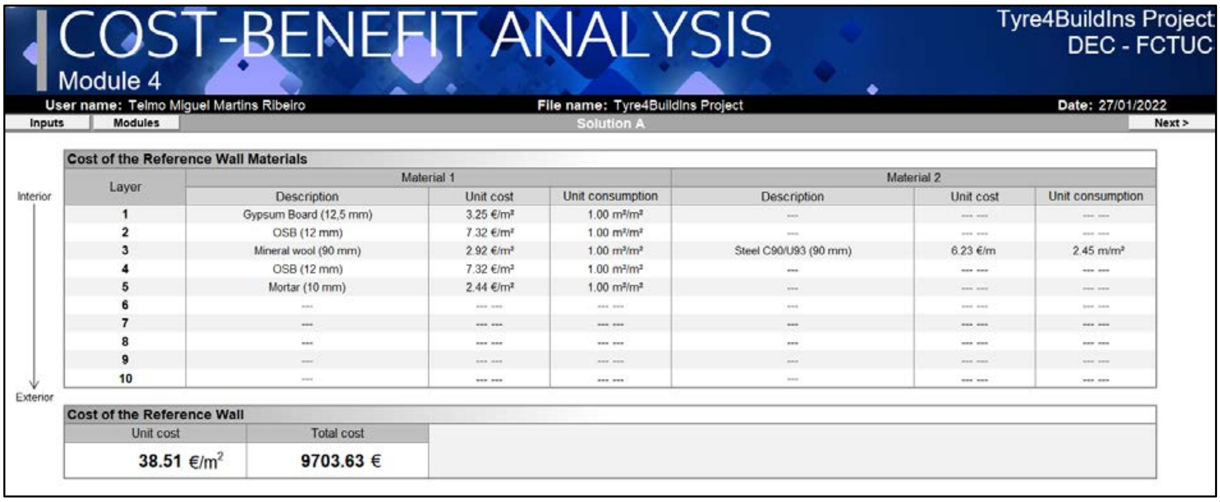


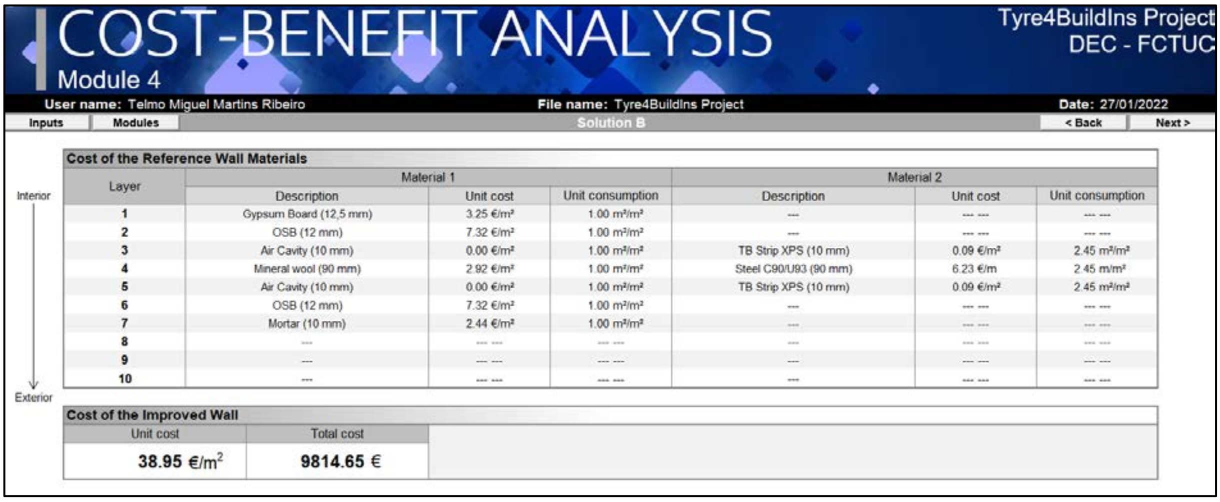
Figure 42 – Design example: Tab 14 of Tyre4BuildIns Calculation Tool.



Layer	Material 1 Description	Material 1 Unit cost	Material 1 Unit consumption	Material 2 Description	Material 2 Unit cost	Material 2 Unit consumption
1	Gypsum Board (12,5 mm)	3.25 €/m²	1.00 m²/m²	---	--- ---	--- ---
2	OSB (12 mm)	7.32 €/m²	1.00 m²/m²	---	--- ---	--- ---
3	Mineral wool (90 mm)	2.92 €/m²	1.00 m²/m²	Steel C90/U93 (90 mm)	6.23 €/m	2.45 m/m²
4	OSB (12 mm)	7.32 €/m²	1.00 m²/m²	---	--- ---	--- ---
5	Mortar (10 mm)	2.44 €/m²	1.00 m²/m²	---	--- ---	--- ---
6	---	--- ---	--- ---	---	--- ---	--- ---
7	---	--- ---	--- ---	---	--- ---	--- ---
8	---	--- ---	--- ---	---	--- ---	--- ---
9	---	--- ---	--- ---	---	--- ---	--- ---
10	---	--- ---	--- ---	---	--- ---	--- ---

Cost of the Reference Wall	
Unit cost	Total cost
38.51 €/m²	9703.63 €

Figure 43 – Design example: Tab 15 of Tyre4BuildIns Calculation Tool.



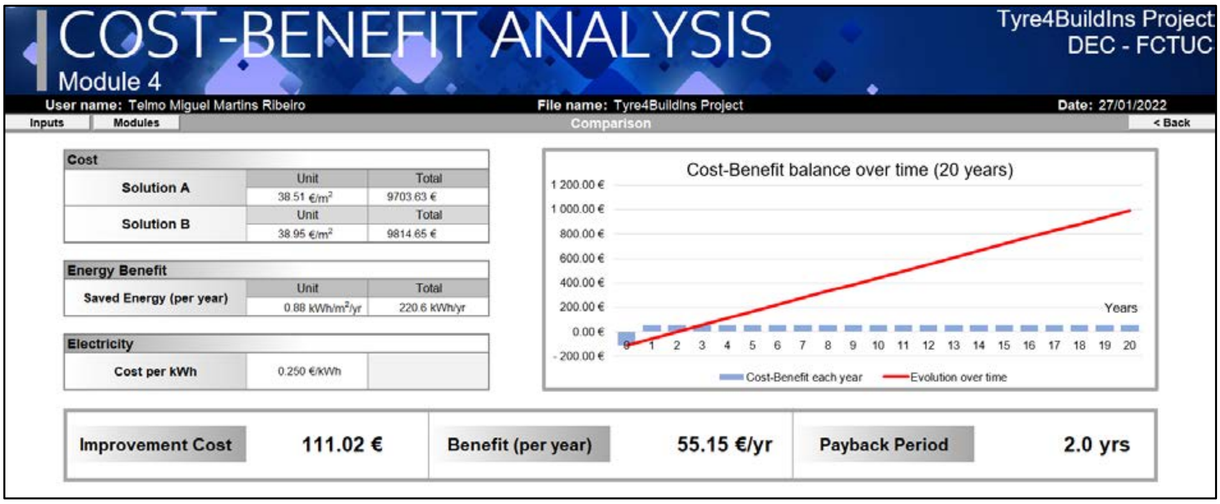
Cost of the Reference Wall Materials

Layer	Material 1 Description	Material 1 Unit cost	Material 1 Unit consumption	Material 2 Description	Material 2 Unit cost	Material 2 Unit consumption
1	Gypsum Board (12,5 mm)	3.25 €/m²	1.00 m²/m²	---	--- ---	--- ---
2	OSB (12 mm)	7.32 €/m²	1.00 m²/m²	---	--- ---	--- ---
3	Air Cavity (10 mm)	0.00 €/m²	1.00 m²/m²	TB Strip XPS (10 mm)	0.09 €/m²	2.45 m²/m²
4	Mineral wool (90 mm)	2.92 €/m²	1.00 m²/m²	Steel C90/U93 (90 mm)	6.23 €/m	2.45 m/m²
5	Air Cavity (10 mm)	0.00 €/m²	1.00 m²/m²	TB Strip XPS (10 mm)	0.09 €/m²	2.45 m²/m²
6	OSB (12 mm)	7.32 €/m²	1.00 m²/m²	---	--- ---	--- ---
7	Mortar (10 mm)	2.44 €/m²	1.00 m²/m²	---	--- ---	--- ---
8	---	--- ---	--- ---	---	--- ---	--- ---
9	---	--- ---	--- ---	---	--- ---	--- ---
10	---	--- ---	--- ---	---	--- ---	--- ---

Cost of the Improved Wall

Unit cost	Total cost
38.95 €/m²	9814.65 €

Figure 44 – Design example: Tab 16 of Tyre4BuildIns Calculation Tool.



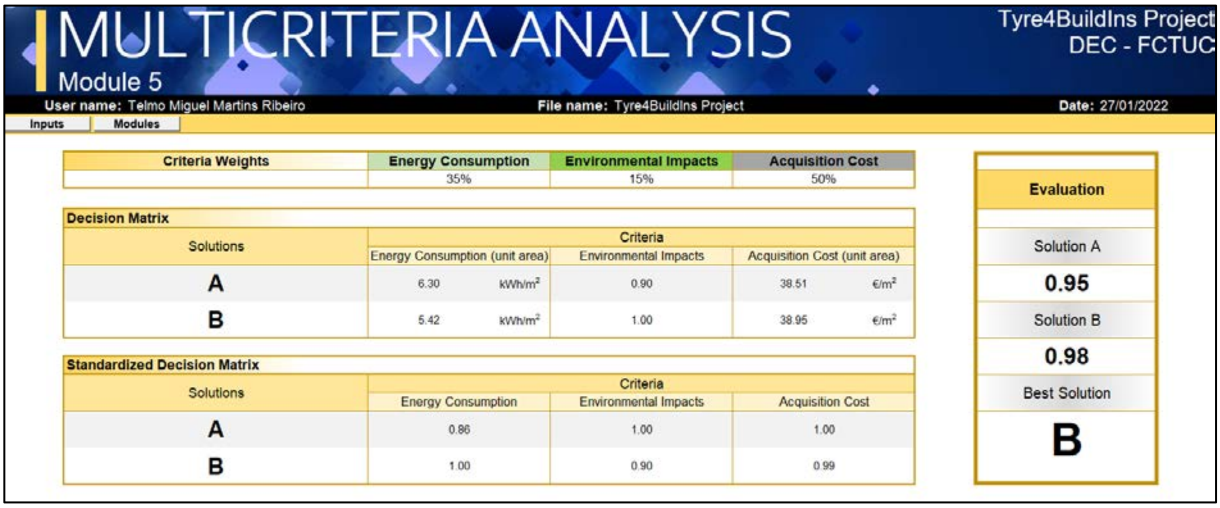
Cost	Unit	Total
Solution A	38.51 €/m²	9703.63 €
Solution B	38.95 €/m²	9814.65 €

Energy Benefit	Unit	Total
Saved Energy (per year)	0.88 kWh/m²/yr	220.6 kWh/yr

Electricity	
Cost per kWh	0.250 €/kWh

Improvement Cost	111.02 €	Benefit (per year)	55.15 €/yr	Payback Period	2.0 yrs

Figure 45 – Design example: Tab 17 of Tyre4BuildIns Calculation Tool.



Criteria Weights	Energy Consumption	Environmental Impacts	Acquisition Cost
	35%	15%	50%

Decision Matrix

Solutions	Energy Consumption (unit area)	Environmental Impacts	Acquisition Cost (unit area)
A	6.30 kWh/m²	0.90	38.51 €/m²
B	5.42 kWh/m²	1.00	38.95 €/m²

Standardized Decision Matrix

Solutions	Energy Consumption	Environmental Impacts	Acquisition Cost
A	0.86	1.00	1.00
B	1.00	0.90	0.99

Evaluation	
Solution A	0.95
Solution B	0.98
Best Solution	B

Figure 46 – Design example: Tab 18 of Tyre4BuildIns Calculation Tool.

7. FINAL REMARKS

This document contains a user guide (or instructions manual) for the Tyre4BuildIns Calculation Tool (version 1) users and should be consulted prior to using this Calculation Tool.

This user guide is organized as follows. After a brief introduction section with some background and previous framework info, the inputs were presented and described. Next, the calculation methodology was explained and the obtained outputs presented for each one of the five calculation modules. Then, the reliability of the computed values using these calculation modules was verified. In Section 6 was presented a design example to illustrate for a specific case study how to use this calculation tool and to obtain the intended outputs/results. Finally, in this last section some final concluding remarks are presented.

Notice that the correct operation of the Tyre4BuidIns Calculation Tool and the adequate reliability of the obtained results, can only be achieved by strictly following the instructions and procedures presented in this document. Additionally, being a very simplified Calculation Tool, e.g., to predict the heat losses/gains through the facade LSF walls and the consequent thermal energy computations, the obtained results/outputs could not be always reliable for all circumstances/inputs. However, as a simple comparison between two different LSF walls configurations/solutions, this Calculation Tool is further consistent and could be very useful to choose the more adequate design. Moreover, being this a first version, the authors welcome and acknowledge the communication of any bug or anomaly detected, as well as suggestions for future improvements.

REFERENCES

[1] “Tyre4BuildIns, Research project Tyre4BuildIns - ‘Recycled tyre rubber resin-bonded for building insulation systems towards energy efficiency’, University of Coimbra, PT, www.tyre4buildins.dec.uc.pt, last accessed 2021/10/20.”

[2] “REH (2013). ‘Regulamento do Desempenho Energético dos Edifícios de Habitação’. Portuguese legal requirement for the energy performance of residential buildings. Decreto-Lei n.º 118/2013, Portugal.” .

[3] J. Spinoni *et al.*, “Changes of heating and cooling degree-days in Europe from 1981 to 2100,” *Int. J. Climatol.*, vol. 38, no. December 2017, pp. e191–e208, 2018, doi: 10.1002/joc.5362.

[4] “ASHRAE. Handbook ofFundamentals (SI Edition); ASHRAE—American Society of Heating, Refrigerating and Air-conditioning Engineers: Atlanta, GA, USA, 2017.” .

[5] “ISO 6946, Building Components and Building Elements—Thermal Resistance and ThermalTransmittance—Calculation Methods; ISO—International Organization for Standardization: Geneva, Switzerland, 2017.”

[6] “Gorgolewski, M. Developing a simplified method of calculating U-values in light steel framing. Build. Environ. 2007, 42, 230–236.”

[7] P. Santos, G. Lemes, and D. Mateus, “Analytical methods to estimate the thermal transmittance of LSF walls: Calculation procedures review and accuracy comparison,” *Energies*, vol. 13, no. 4, 2020, doi: 10.3390/en13040840.

[8] “REH - Regulamento do Desempenho Energético dos Edifícios de Habitação.” .

[9] “ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework.”

[10] ‘Gyptec Ibérica – Ficha Técnica, Placa A – EN 520 (Standard)’.”

[11] “Gyproc (2020). ‘Environmental Product Declaration In accordance with EN 15804 and ISO 14025 – 12.5mm Gyproc WallBoard.’” .

[12] “Sonae Arauco (2021). https://www.sonaearauco.com/. Last accessed 2021/09/15.” .

[13] “Egger (2018). ‘Environmental Product Declaration, EGGER OSB-boards Fritz EGGER GmbH & Co. OG Holzwerkstoffe’.” .

[14] “Volcalis (2021). https://www.volcalis.pt/. Last accessed 2021/10/27.” .

[15] “Knauf (2019). ‘Environmental Product Declaration, Knauf Bulgaria EOOD – Gypsum Fibreboards’.” .

[16] “Pertecno (2021). http://www.pertecno.pt/. Last accessed 2021/09/15.” .

[17] “Cype (2021). http://www.geradordeprecos.info/. Last accessed 2021/09/15.” .

[18] Atlas (2020). “Environmental Product Declaration Atlas Etics External Thermal Insulation Composite Systems with Silicate Renders”.

[19] Santos, C., Matias, L. (2006). “ITE 50 – Coeficientes de Transmissão Térmica de Elementos das Envolventes dos Edifícios”. Laboratório Nacional de Engenharia Civil, Lisboa.

[20] “IFoam (2021). https://www.leroymerlin.pt/. Last accessed 2021/09/15.” .

[21] Danosa (2020). “Environmental Product Declaration of Danopren®Extruded Polystyrene (XPS) Insulation Board”.

[22] “Isovit (2021). https://www.leroymerlin.pt/. Last accessed 2021/09/15.” .

