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DEVELOPMENT OF A CALCULATION TOOL FOR THE PERFORMANCE EVALUATION OF LIGHTWEIGHT STEEL FRAMED (LSF) WALLS

Dissertation in the Master Course on Acoustic and Energy Efficiency for a Sustainable Construction, in the specialization of Energy and Indoor Environment, supervised by Professor Paulo Fernando Antunes dos Santos and presented to the Department of Civil Engineering of the Faculty of Sciences and Technology of the University of Coimbra.

March 2022

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DESENVOLVIMENTO DE UMA FERRAMENTA DE CÁLCULO PARA A AVALIAÇÃO DO DESEMPENHO DE PAREDES EM ESTRUTURA METÁLICA LEVE (LSF)

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ABSTRACT

The external envelope walls have a major influence on the energy efficiency of a building. These construction elements act as a barrier between the inner and outer environment, conditioning the heat exchanges which occur in the building envelope and, consequently, influencing the energy needs to establish thermal comfort in the inner environment. In the particular case of the LSF (Lightweight Steel Framed) construction system, the walls are elements of great importance for the energy efficiency of the building, since the thermal bridges originated by the high thermal conductivity of the steel structure can cause significant heat losses. For that reason, the consideration and appropriate treatment of these thermal bridges is essential for the improvement of the thermal behaviour and the energy efficiency of this constructive system. There are several mitigation strategies of these thermal bridges, such as, the application of the external thermal insulation composite system (ETICS) or the application of thermal break strips along the flanges of the metallic profiles.

However, in order to obtain a global evaluation of the performance of a wall, in addition to the issues of thermal behaviour and energy efficiency, it is also important to evaluate other aspects, such as, the monetary costs (and benefits), and the associated environmental impacts. Performing a holistic evaluation of a wall, it is possible to know its advantages and drawbacks from a perspective that covers several performance aspects, thus allowing to define the most appropriate wall solution.

This dissertation presents as main objective to develop a calculation tool for the performance evaluation of LSF walls, and was produced within the Tyre4BuildIns research project. The calculation tool, denominated *Tyre4BuildIns Calculation Tool*, was developed and is available in Microsoft Excel format and its main functionality is to perform a comparative analysis between the performance of LSF walls, considering four aspects: i) thermal transmittance coefficient (Module 1); ii) energy benefits (Module 2); iii) life-cycle analysis (Module 3) and; iv) cost-benefit analysis (Module 4). A fifth module (Module 5) performs a multicriteria analysis considering the results obtained in the previous modules and provides the overall evaluation of each LSF wall solution analysed, indicating which is the most favourable solution.

Keywords: lightweight steel framed (LSF) construction; tyre4buildins calculation tool; thermal performance; energy efficiency; life-cycle analysis; cost-benefit analysis.

RESUMO

As paredes da envolvente exterior apresentam uma grande influência na eficiência energética de um edifício. Estes elementos construtivos funcionam como uma barreira entre o ambiente exterior e interior, condicionando as trocas de calor que ocorrem na envolvente do edifício e, consequentemente, influenciando as necessidades energéticas para estabelecer o conforto térmico no ambiente interior. No caso particular do sistema construtivo em LSF (sigla proveniente do inglês e que significa *Lightweight Steel Framed*), as paredes são elementos de elevada importância para a eficiência energética do edifício, uma vez que as pontes térmicas originadas pela elevada condutibilidade térmica da estrutura metálica podem provocar significativas perdas de calor. Por essa razão, a consideração e o tratamento adequado destas pontes térmicas é essencial para a melhoria do comportamento térmico e da eficiência energética deste sistema construtivo. Atualmente, existem várias estratégias de mitigação destas pontes térmicas, tais como, a aplicação do sistema compósito de isolamento térmico pelo exterior (ETICS) ou a aplicação de tiras de corte térmico ao longo dos banzos dos perfis metálicos.

No entanto, com o objetivo de obter uma avaliação global do desempenho de uma parede, para além das questões do comportamento térmico e eficiência energética, é também importante avaliar outros aspetos, tais como, os custos (e benefícios) monetários, e os impactos ambientais associados. Fazendo uma avaliação holística da parede, é possível conhecer as suas vantagens e desvantagens de uma perspetiva que cobre vários aspetos de desempenho, permitindo, assim, definir a solução de parede mais apropriada.

Esta dissertação apresenta como objetivo principal o desenvolvimento de uma ferramenta de cálculo para a avaliação do desempenho de paredes em LSF, e foi produzida no âmbito do projeto de investigação Tyre4BuildIns. A ferramenta de cálculo, denominada *Tyre4BuildIns Calculation Tool*, foi desenvolvida e está disponível em formato *Microsoft Excel* e a sua principal funcionalidade é realizar uma análise comparativa entre o desempenho de paredes em LSF, considerando quatro aspetos: i) coeficiente de transmissão térmica (Módulo 1); ii) benefícios energéticos (Módulo 2); iii) análise de ciclo de vida (Módulo 3) e; iv) análise custo-benefício (Módulo 4). Um quinto módulo (Módulo 5) realiza uma análise multicritério considerando os resultados obtidos nos módulos anteriores e fornece a avaliação global de cada solução de parede LSF analisada, indicando qual é a solução mais favorável.

Palavras-chave: construção em estrutura metálica leve (LSF); ferramenta de cálculo tyre4buildins; desempenho térmico; eficiência energética; análise ciclo de vida; análise custo-benefício.

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LIST OF SYMBOLS

A_{w}	Area of external walls [m^{2}]
cav	Length of section CAV [m]
CDD	Cooling Degree Days [°C]
CoP	Coefficient of Performance
d	Thickness [m]
$d_{thicker}$	Thickness of the thicker sheathing side [m]
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 energy [kWh]
fl	Flange length [m]
G_{BF}	Glazing area of the back façade [%]
G_{LF}	Glazing area of the left façade [%]
G_{MF}	Glazing area of the main façade [%]
G_{RF}	Glazing area of the right façade [%]
HDD	Heating Degree Days [°C]
$H_{\mathrm{tr,i}}$	Overall heat transfer coefficient by transmission in the heating season [W/°C]
$H_{\mathrm{tr,v}}$	Overall heat transfer coefficient by transmission in the cooling season [W/°C]
L_{BF}	Length of the back façade [m]
L_{LF}	Length of the left façade [m]
L_{MF}	Length of the main façade [m]
L_{RF}	Length of the right façade [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_{ins}	Thermal resistance of insulation zone [m^{2}·K·W^{-1}]
R_{met}	Thermal resistance of metal zone [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}]
$R_{tot;ASHRAE}$	Total thermal resistance of ASHRAE Zone Method [m^{2}·K·W^{-1}]
$R_{tot;CAV}$	Total thermal resistance of section *CAV* [m^{2}·K·W^{-1}]
$R_{tot;ISO}$	Total thermal resistance of ISO 6946 Combined Method [m^{2}·K·W^{-1}]

$R_{tot;lower}$	Lower limit of the total thermal resistance [$m^2 \cdot K \cdot W^{-1}$]
$R_{tot;upper}$	Upper limit of the total thermal resistance [$m^2 \cdot K \cdot W^{-1}$]
$R_{tot;w}$	Total thermal resistance of section *W* [$m^2 \cdot K \cdot W^{-1}$]
T_{avg}	Daily average temperatures [°C]
T_{max}	Daily maximum temperature [°C]
T_{min}	Daily minimum temperature [°C]
T_{ref}	Reference temperature [°C]
U	Thermal transmittance coefficient [$W \cdot m^{-2} \cdot K^{-1}$]
w	Length of section *W* [m].
W_{AC}	Weight of acquisition costs [%]
W_{EC}	Weight of energy consumption [%]
W_{EI}	Weight of environmental impacts [%]
λ	Thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$]
$\theta_{\mathrm{v,ext}}$	average outside air temperature for the cooling season [°C]
$\theta_{\mathrm{v,ref}}$	Reference indoor temperature for calculation of the energy demand in the cooling season [°C]

LIST OF ACRONYMS

ADPE	Abiotic Resources Depletion Potential – Elements
ADPF	Abiotic Resources Depletion Potential – Fossil Resources
AP	Acidification potential
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CAV	Section CAV (ASHRAE Zone Method)
CDD	Cooling Degree Days
CoP	Coefficient of Performance
EC	European Commission
EER	Energy Efficiency Ratio
EP	Eutrophication potential
EPS	Expanded Polystyrene
ETICS	External Thermal Insulation Composite System
EU	European Union
GWP	Global warming potential
HDD	Heating Degree Days
IEA	International Energy Agency
ODP	Stratospheric Ozone Layer Depletion Potential
OSB	Oriented Strand Board
POCP	Photochemical Ozone Creation Potential
TBS	Thermal Break Strips
NF	Number of Floors
FE	Final Evaluation
EI	Environmental Impacts
AC	Acquisition Cost
EC	Energy Consumption
XPS	Extruded Polystyrene
HF	Height of each Floor
W	Section W (ASHRAE Zone Method)

1. INTRODUCTION

1.1 Framework

The implementation of a sustainable development must be the primary objective of mankind. Nowadays, one of the major threats to the environment is the growing worldwide need for energy. According to International Energy Agency (IEA, 2021), in the last three decades, the global annual energy consumption increased by approximately 4000 million tonnes of oil equivalent, with the growth trend expected to continue in the near future. This increase in the amount of energy consumed is directly linked to the growth of industrial and urban activities caused by the intensive development of several countries and the exponential increase in world population. Over the last few decades, in order to counteract this trend and guarantee a more sustainable future for the planet, many international and national policies to promote more efficient energy consumptions have been created and implemented (Schiavoni *et al*., 2016).

Since a significant part of global energy consumption and greenhouse gases emissions is associated with the residential sector, it is crucial to improve energy efficiency in this area. According to data from the European Commission (EC, 2016), energy consumption by residential buildings in the EU accounts for around 30% of total energy needs, and approximately 60% of this energy is used for heating the indoor environment. However, the buildings sector has an enormous potential for energy efficiency that has not yet been fully exploited. Harnessing that potential, large-scale implementation of energy-saving measures could achieve a significant reduction in energy consumption and greenhouse gases emissions (Schiavoni *et al*., 2016).

External walls, as part of the external envelope, are one of the most important components in the energy consumption of a building. Acting as barriers between the indoor and outdoor environment, exterior walls influence the heat exchanges between the two sides and, consequently, the energy consumption to achieve thermal comfort of interior spaces. In the particular case of Lightweight Steel Framed (LSF) construction system, the external walls have a special importance as thermal bridges originated by the high thermal conductivity of the structure's steel profiles can lead to significant heat losses through the building envelope. Thus, in LSF buildings, a thermally improved wall with an appropriate treatment of thermal bridges is essential to achieve a good thermal behaviour. However, beyond thermal behavior and energy efficiency issues, and in order to obtain a global evaluation of the wall's performance, it is also important to analyse other aspects, such as, monetary costs (and benefits), and environmental impacts. Performing a holistic evaluation of a wall, it is possible to know its advantages and drawbacks from a perspective that covers all performance aspects, allowing to define the most appropriate wall solution.

1.2 Objective

This dissertation presents as main objective to develop a calculation tool for the performance evaluation of lightweight steel framed (LSF) walls, and was produced within the Tyre4BuildIns research project (Tyre4BuildIns, 2022). The calculation tool was developed and is available in *Microsoft Excel* format and its main functionality is to perform a comparative analysis between the performance of LSF walls, considering four aspects: i) thermal transmittance (Module 1); ii) energy benefits (Module 2); iii) life-cycle analysis (Module 3) and; iv) cost-benefit analysis (Module 4). A fifth module (Module 5) performs a multicriteria analysis considering the results obtained in the previous modules and provides the overall evaluation of each LSF wall solution analysed, indicating which is the most favourable solution.

1.3 Dissertation structure

In Chapter 1 – Introduction – a general framework about the subject is carried out, the main objectives outlined for this work are identified and the dissertation structure is described.

Chapter 2 – The Lightweight Steel Framed (LSF) Construction – performs a general description of the LSF construction system, identifying the constituent materials, the assembly methods used, as well as the main advantages and disadvantages associated to this type of construction.

In turn, Chapter 3 – Tyre4BuildIns Calculation Tool – a detailed description of the Tyre4BuildIns Calculation Tool is carried out. First, a general framework of the tool is performed. Then, the inputs necessary for the operation of the tool, as well as the calculation methodologies and their respective outputs are described in detail.

In Chapter 4 – Computational Verifications – the results provided by each module are verified in order to ensure the reliability of the tool.

Chapter 5 – Design Example – presents a design example, in order to demonstrate the general operation of the tool.

Finally, Chapter 6 – Conclusions and Future Work – presents the main conclusions resulting from this dissertation and indicates suggestions for future work.

2. LIGHTWEIGHT STEEL FRAMED (LSF) CONSTUCTION

2.1 Framework

The Lightweight Steel Framed (LSF) is a construction system that presents a supporting structure composed of cold-formed galvanised steel metal profiles (Figure 1). The metal profiles of this construction system are produced from steel plates with reduced thickness, combining high mechanical strength with considerable lightness. Although still a minority in the global construction context, LSF construction has shown a growing trend, presenting a significant application in countries like the United States of America, Japan and Australia, and gaining space in the European market (Soares *et al*, 2017).

Figure 1 – LSF steel structure (Bloken, 2021a).

Compared to traditional constructions (e.g., reinforced concrete structure with brick masonry), this construction system can provide several advantages, such as: i) reduced overall weight of the construction; ii) high mechanical strength offered by steel profiles combined with their low weight; iii) strict quality control provided by factory production; iv) high potential for recycling and reusing steel, enabling a sustainable end of life cycle for this material; v) adaptation to a mass production economy; vi) ease of transport and assembly; vii) the fact that it is a "dry" construction system, reducing the risk of pathologies related to humidity; viii) the fact that metal profiles are not sensitive to humidity or biological activities, which means that steel does not suffer degradation of its resistant properties due to these factors; ix) great architectural flexibility, and; x) capacity to integrate various types and configurations of thermal insulation materials, contributing to the construction of buildings with lower energy consumption (Roque and Santos, 2017). However, although this construction system offers several advantages, there are some negative aspects that should be considered, such as thermal bridges and low thermal inertia. Thermal bridges caused by the high thermal conductivity of steel can originate significant heat losses through the building envelope and for that reason they should be considered and treated appropriately. In turn, the low thermal inertia often associated with this type of construction can lead to problems such as the overheating of interior spaces and considerable temperature fluctuations (Soares *et al.*, 2017).

The specific characteristics and numerous advantages provided by LSF construction enable it to be used in several applications, however, this construction system is especially suitable for the construction of low-rise residential buildings and for the rehabilitation of old buildings (Futureng, 2021a).

2.2 Methods of construction

The LSF construction components are produced in factory and then assembled on site. The process of assembling the building components can be carried out by three different methods (Figure 2): i) "stick build" construction; ii) panel construction; and iii) modular construction.

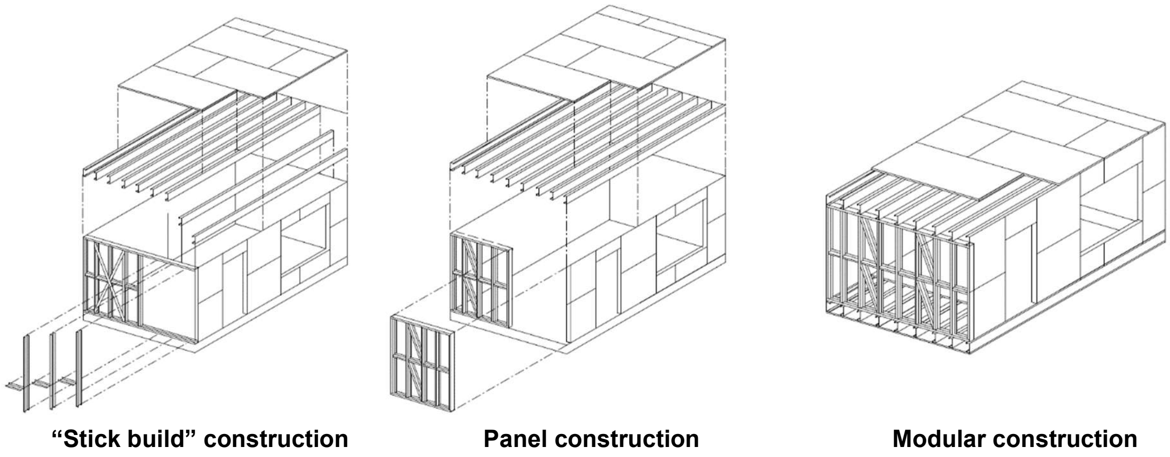


Figure 2 - Methods of construction (Grubb *et al.*, 2001).

In the "stick build" construction method, the components of the building's structural body are formed by assembling discrete elements, on site. Generally, the elements are prefabricated with the definitive assembly dimensions and drillings, being the connections made on site. Regarding panel construction, the building assembly process is carried out on-site using prefabricated wall panels, floor cassettes and roof trusses. In order to increase the speed of on-site construction, some elements, such as thermal insulating materials and sheathing layers, can be pre-applied, in factory, to the structural panels. Finally, in modular construction, complete units are prefabricated and then installed on site to form the final configuration of the building. The fabrication of these units may contain all internal finishes, fixtures and fittings, reducing construction time on site (Grubb *et al*., 2001). Furthermore, in order to combine the positive aspects of each of these methods, it is also possible to adopt hybrid construction methods, contemplating panel and modular construction, or a combination of the three methods described. The main advantages of each of the construction methods are shown Table 1.

Table 1 – Advantages of each LSF assembling methods (Soares *et al*., 2017).

LSF assembling methods: features
“Stick build” construction
‣ Possibility to accommodate construction tolerances and modifications on site ‣ Connection procedures relatively simple ‣ No need for construction site facilities associated with panel and modular construction ‣ Possibility to transport large quantities of structural elements in single loads
Panel construction
‣ Shorter construction time on site ‣ Superior quality control in production ‣ Minimisation of on-site labour costs ‣ Automations in factory production ‣ Easier and faster application of coating and finishing systems
Modular construction
‣ Lower construction costs ‣ Shorter construction time on site ‣ Increased productivity on site ‣ High certainty of meeting deadlines and budgetary constraints ‣ Reduced factory and on-site waste ‣ Increased reliability and quality
Hybrid construction (panels and modular)
‣ Optimised advantages of panel and modular construction
Hybrid construction (“stick build”, panels and modular)
‣ Optimised advantages of panel and modular construction ‣ Taller buildings and greater flexibility in internal planning

2.3 Materials

2.3.1 Types

Generally, the main materials that constitute an LSF construction can be organised into three categories (Silvestre *et al*., 2013): i) cold formed steel profiles; ii) sheathing panels (e.g., oriented stranded board (OSB) and gypsum plasterboard); and iii) insulation materials (e.g., mineral wool and expanded polystyrene). Other complementary materials such as fixing elements, waterproof and air tightness membranes, and finishing layers are also used in LSF buildings. Furthermore, in order to prevent the occurrence of ground humidity problems, concrete is used in the ground floor of this constructive system, being the foundations built using conventional methods.

2.3.2 Cold-formed steel profiles

Cold-formed steel profiles are the basic elements of LSF building structures and they are present in the constitution of the walls (facades and partitions), slabs and roofs. The strength and stiffness of these elements vary depending on some factors, such as: i) steel sheet thickness; ii) steel sheet grade; and iii) geometry of the cross section. These profiles can present various cross section geometries (Figure 3), most of them identified by a letter (U, C, Z, I,...), and they are commercialized with steel sheet thicknesses that normally vary between 0.45 mm and 6 mm (Soares *et al*., 2017).

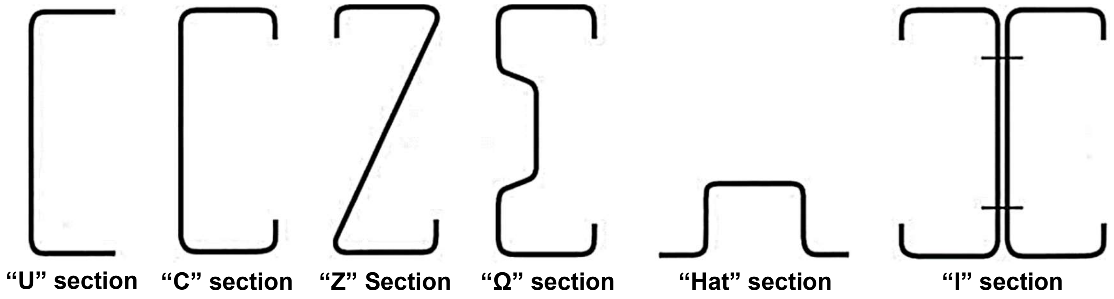


Figure 3 - Cross sections of cold-formed steel profiles (LSK, 2005).

The increase of durability of cold formed profiles of the LSF constructions is often achieved by galvanizing the surfaces of these elements, according to EN 10326, thus avoiding possible corrosion and degradation processes. The regulation of cold formed structural elements and profiled sheets is performed by the normative document EN 1993-1-3 (Eurocode 3: Design of steel structures; Part 1: General rules and rules for buildings; Subpart 3: Cold formed members and sheathing) (Simões, 2005).

2.3.3 Sheathing panels

OSB and gypsum plasterboard are the materials most commonly used as sheathing panels in LSF low-rise residential buildings (Figure 4). OSB panels, in addition to its function as sheathing layer, can also provide a structural function in load-bearing walls, contributing to the resistance of the construction to horizontal loads in the plane of the wall, such as, the wind effect (Soares *et al*., 2017). This material is applied to walls, floors and roofs and it is manufactured from wood veneers arranged in layers with perpendicular directions and joined together by adding adhesives, creating a waterproof panel with significant resistance (APA, 2022). Besides the resistance provided, these panels are light and easy to handle and install. In turn, gypsum plasterboards are often used as interior wall and ceiling cladding. These panels are produced from gypsum, water and additives that provide specific properties to the panel depending on its use (Futureng, 2021b).

a) b)

Figure 4 – Sheathing layers: a) OSB; b) gypsum plasterboard (Bloken, 2021b).

2.3.4 Joining and fastening

The joining and fastening process is a very important factor for the competitiveness of the LSF construction system, since the amount of work involved in this process may have a significant contribution to the overall cost of the construction. It is therefore essential to improve the efficiency of this process, by developing joining and fixing methods that combine effectiveness and reduced cost. The definition of the most suitable fixing method depends on several factors, such as: i) type and thickness of the connected materials; ii) loading conditions; iii) required strength of connections; iv) availability of fasteners and tools; v) material configuration; vi) local of assemblage; vii) cost; viii) durability; ix) code acceptance and; x) manufacturer's experience. Generally, the connections of LSF construction elements are made using self-drilling screws (Figure 5). In this fastening method, steel washers are frequently added in order to increase the resistant capacity of the connection with screws, and elastomeric washers can also be applied to increase the watertightness at the connection area. Furthermore, self-drilling screws are normally manufactured from heat-treated carbon-steel or from stainless steel to resist the high temperatures generated in the drilling process.

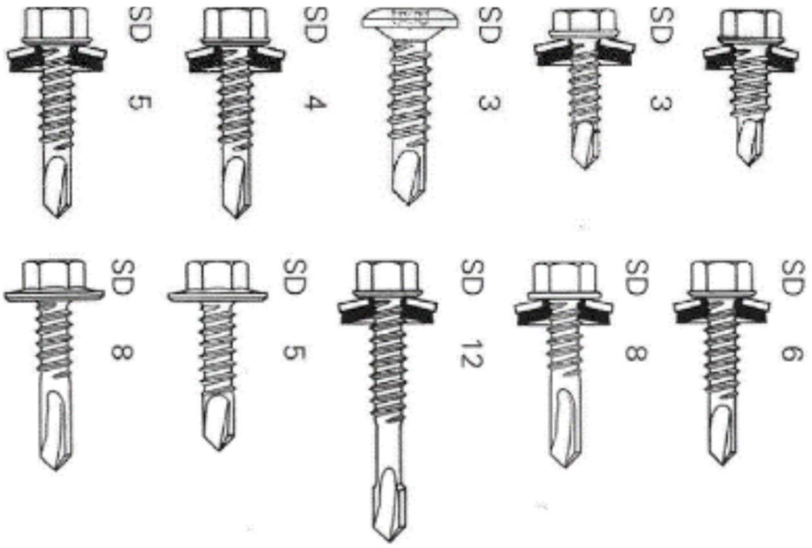


Figure 5 – Self-drilling screws (Santos *et al.*, 2012).

Other fixing methods, using pins, rivets, welds, bolts, clips and adhesives are also applied in LSF construction (LSK, 2005). Figure 6 illustrates some fixing methods used in the profile-profile and profile-panel connections.

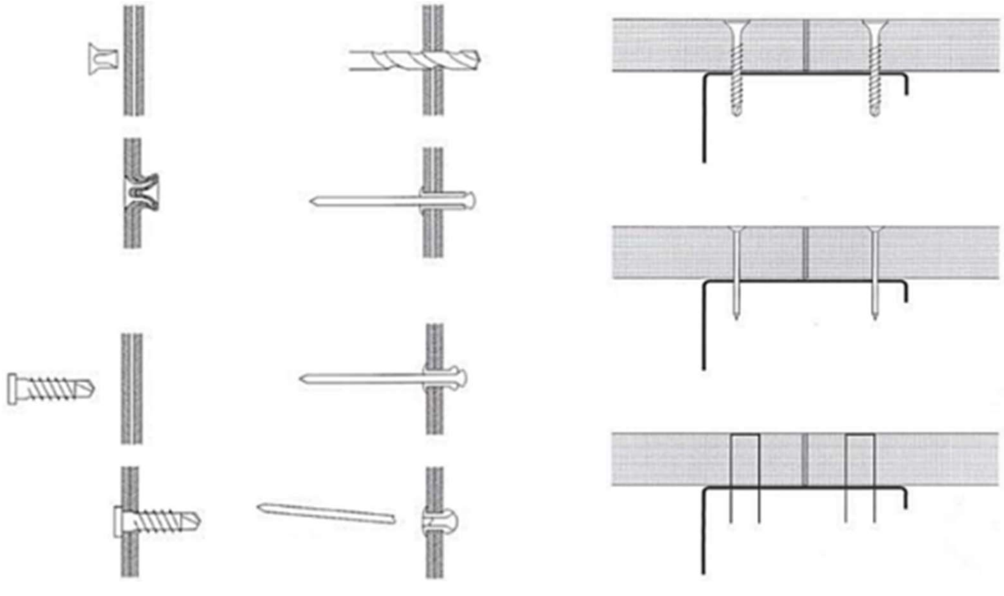


Figure 6 – Fixing methods (LSK, 2005).

2.3.5 Thermal insulation materials

In LSF construction, given its lightness and the presence of high thermal conductivity materials (e.g., steel), the appropriate use of thermal insulation materials is essential to improve the thermal behaviour of the construction. The thermal insulation materials most frequently used in LSF buildings are mineral wool and expanded polystyrene (EPS) (Figure 7) (Soares *et al*., 2017). Mineral wool is an inorganic and fibrous material (Karamanos *et al*., 2008) applied, generally, in the cavity between the inner and outer sheathing panels, being interrupted in the zones occupied by the steel profiles. In addition to its function as thermal insulation, this material also acts as acoustic insulation and as fire-resistant barrier. Normally, the thermal conductivity of mineral wool ranges between 33 and 40 mW/(m·K) (Schiavoni *et al*., 2016). In turn, EPS is a rigid thermal insulation material, often commercialized in the form of panels, being produced from small polystyrene spheres that undergo a process of volume increase through the addition of a blowing agent (Calbureanu *et al*., 2010). This material has a thermal conductivity that varies between 31 and 38 mW/(m·K) (Schiavoni *et al*., 2016) and it is applied in LSF buildings, generally, integrated into the *External Thermal Insulation Composite System* (ETICS). This thermal insulation system minimises the thermal bridges caused by steel profiles, as it is applied continuously to the exterior surface of the building.

a) b)

Figure 7 – Thermal insulation materials: a) mineral wool (Termolan, 2021); b) expanded polystyrene (Thermal-engineering, 2021).

Additionally, the application of thermal break (TB) strips along stud flanges is one of the most used strategies to reduce heat losses caused by the high thermal conductivity of the steel profiles and therefore increase the global thermal resistance of the wall. Usually, the TB strips are composed of thermal insulation materials, such as, recycled rubber, extruded polystyrene and aerogel (Figure 8) (Ribeiro *et al*., 2021).

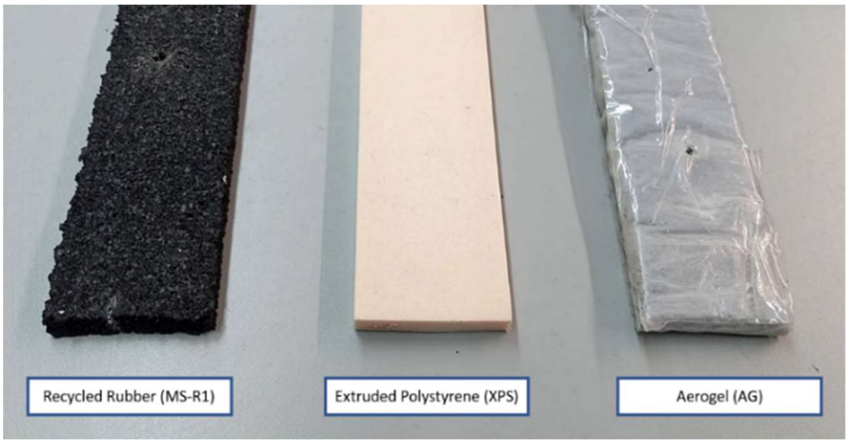


Figure 8 – Thermal break strips materials (Ribeiro *et al.*, 2021)

2.3.6 Wind and air tightness membranes

In cold climates, the appropriate use of air tightness membranes contributes to minimise heat losses through the building envelope by reducing air infiltrations. An effective reduction of air infiltration and interstitial condensation involves the application of two membranes along the external envelope. A wind-tight membrane should be used along the inner side of external coatings if there is no waterproof membrane or, if there is one, it is not capable of preventing air infiltration. Furthermore, this membrane should be permeable to vapour in order to allow the removal of possible humidity existing inside the LSF construction elements, avoiding its accumulation. Another membrane, generally denominated as vapour barrier, should be applied on the inner surface of the envelope, in order to prevent the escape of warm air from inside of the building. This membrane should be able to prevent the passage of moisture into the interior of the LSF construction elements, thus avoiding possible interstitial condensations (Figure 9) (Soares *et al.*, 2017).

Figure 9 – Air tightness membrane (Soares *et al.*, 2017).

2.3.7 Finishing options

Regarding finishing options for LSF construction system, it is possible to adopt solutions which are very similar to those used in traditional constructions (Figure 10). Gypsum plasterboard is the most commonly used material for finishing the inner surface of walls and ceilings. In turn, ETICS is generally used as finishing material on the outer side of the walls. Concerning floors, it is possible to apply several traditional finishing materials, such as, ceramic tiles, hardwood, floating floors, carpets, mortar, cork and linoleum. Regarding roofs, according to their type and geometry, ceramic tiles, shingle type, membrane roofing, sheet metal roofing or other traditional systems can be adopted (Soares *et al.*, 2017).

Figure 10 – LSF building exterior appearance (Bloken, 2021c).

3. TYRE4BUILDINS CALCULATION TOOL

3.1 Framework

Tyre4BuildIns Calculation Tool was developed within the Tyre4BuildIns research project (Tyre4BuidlIns, 2022). The Tyre4BuildIns – *Recycled tyre rubber resin-bonded for building insulation systems towards energy efficiency* – research project has as main focus the use of recycled tyre rubber for the development of an innovative and sustainable thermal insulation material that promotes the increase of energy efficiency in 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.

Tyre4BuildIns Calculation Tool evaluates the performance of Lightweight Steel Framed (LSF) walls, regarding thermal behaviour, energy efficiency, environmental impacts and monetary cost-benefit balance. This tool comparatively evaluates the performance of two LSF walls: i) a reference wall (Solution A), and; ii) a thermally improved wall (Solution B). The assessment of these two LSF walls is performed considering four features: i) thermal transmittance coefficient (Module 1); ii) energy benefits (Module 2); iii) life-cycle assessment (Module 3), and; iv) cost-benefit analysis (Module 4). Furthermore, a fifth module (Module 5) performs a multicriteria analysis that provides information about on what the best solution is.

This chapter performs a detailed description of the Tyre4BuildIns Calculation Tool. First, a general framework of the tool is performed, where its general structure, its format and layout, and the various tabs that compose it are presented. Then, the inputs necessary for the operation of the tool, as well as the calculation methodologies and their respective outputs are described in detail.

3.2 General features

3.2.1 Structure

The general structure of this tool, namely the identification and location of the main inputs and outputs, is illustrated in Figure 11.

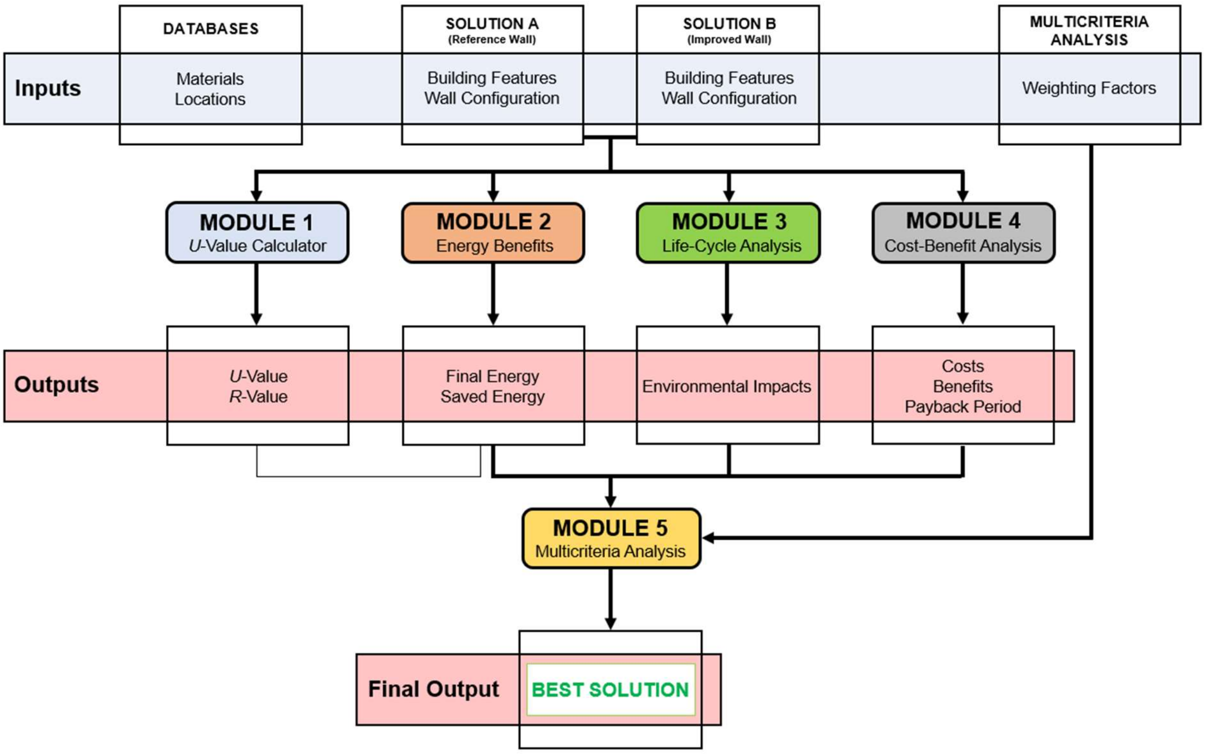
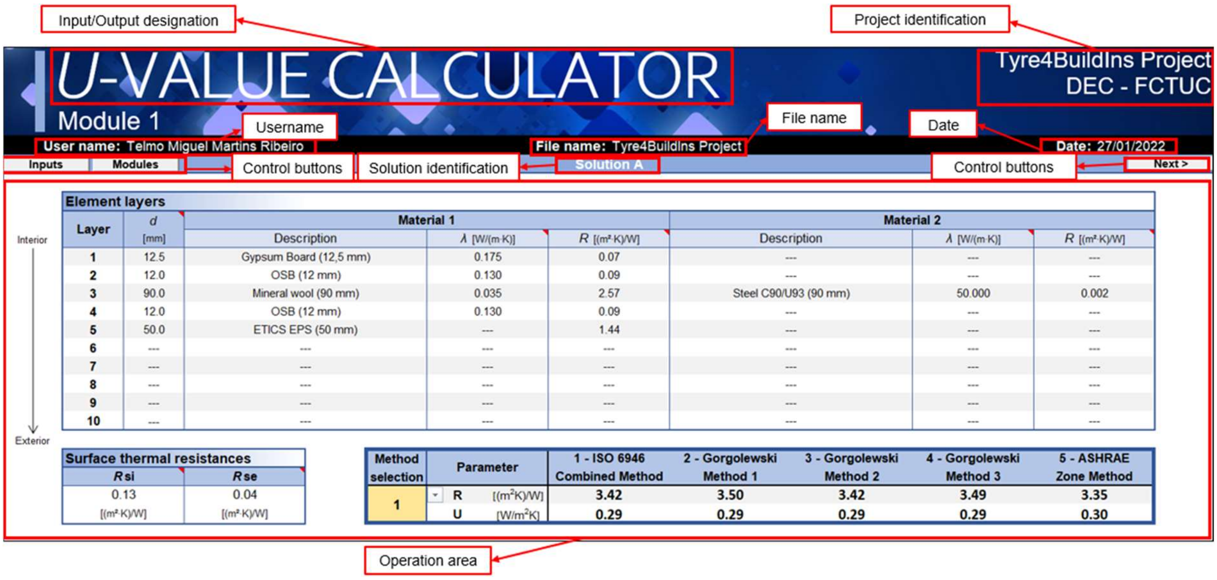


Figure 11 – General structure of the calculation tool.

The first step for the operation of the tool is the definition of the inputs. 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 also be inserted. Moreover, the weighting factor values for the multicriteria analysis should also be 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, 3 and 4, and; ii) weighting factors for the environmental indicators of Module 3. The outputs of this calculation tool are organised into five calculation modules. The Module 1 – *U-value Calculator* computes the thermal transmittance coefficient (and the thermal resistance value) of the LSF walls using five analytical 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.

3.2.2 Format and layout

Tyre4BuildIns Calculation Tool was developed in *Microsoft Excel* format and the general layout of the tool is presented in Figure 12.



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Element layers

Layer	*d* [mm]	Material 1			Material 2		
		Description	*λ* [W/(m·K)]	*R* [(m²·K)/W]	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	90.0	Mineral wool (90 mm)	0.035	2.57	Steel C90/U93 (90 mm)	50.000	0.002
4	12.0	OSB (12 mm)	0.130	0.09	---	---	---
5	50.0	ETICS EPS (50 mm)	---	1.44	---	---	---
6	---	---	---	---	---	---	---
7	---	---	---	---	---	---	---
8	---	---	---	---	---	---	---
9	---	---	---	---	---	---	---
10	---	---	---	---	---	---	---

Surface thermal resistances

*R*si	*R*se
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]	**3.42**	**3.50**	**3.42**	**3.49**	**3.35**
	U	[W/m²K]	**0.29**	**0.29**	**0.29**	**0.29**	**0.30**

Figure 12 – 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 “movement” within the tabs of the tool. The control buttons of the tool and their respective functions are shown in Table 2.

Table 2 – Control buttons and respective functions.

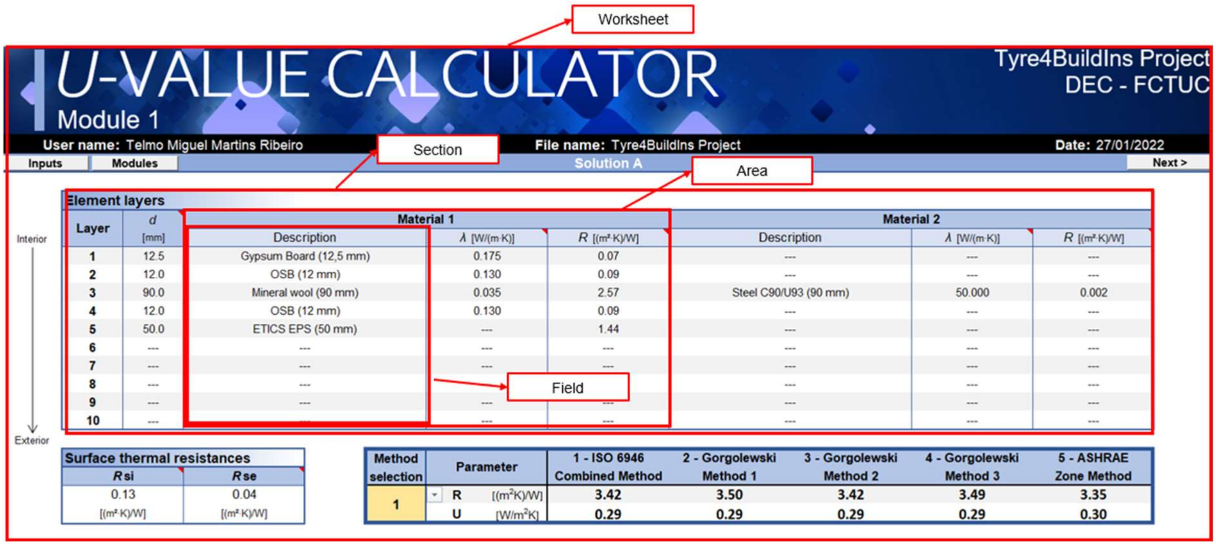
Control Button	Function
Add Location	Move to *Location Database* tab to add a new location
Add Material	Move to *Materials Database* tab to add new material
Back	Move to the previous tab
Inputs	Move to the *Inputs* first tab
Modules	Move to Modules tab
Next	Move to the next tab
Start Menu	Move to *Start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

Moreover, this tool uses a colour coding to facilitate the interpretation of input or output cells. The colour coding adopted is described in Table 3.

Table 3 – Colour coding.

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

Regarding the organisation of the information within the tool, four levels can be considered, as illustrated in Figure 13: i) worksheet; ii) section; iii) area, and; iv) field.



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Element layers

Layer	d [mm]	Material 1			Material 2		
		Description	λ [W/(m·K)]	R [(m²·K)/W]	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	90.0	Mineral wool (90 mm)	0.035	2.57	Steel C90/U93 (90 mm)	50.000	0.002
4	12.0	OSB (12 mm)	0.130	0.09	---	---	---
5	50.0	ETICS EPS (50 mm)	---	1.44	---	---	---
6	---	---	---	---	---	---	---
7	---	---	---	---	---	---	---
8	---	---			---	---	---
9	---	---	---	---	---	---	---
10	---	---	---	---	---	---	---

Surface thermal resistances

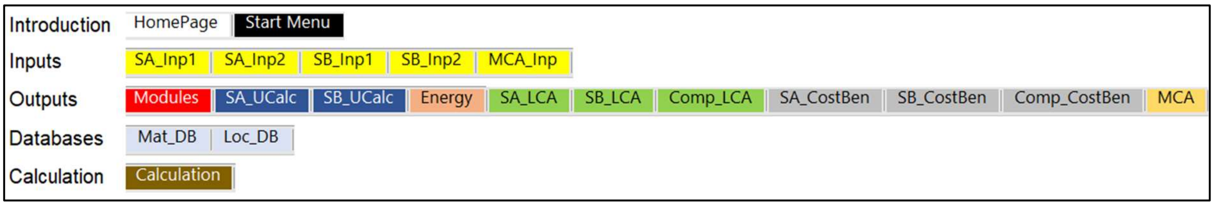
Rsi	Rse
0.13 [(m²·K)/W]	0.04 [(m²·K)/W]

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]	3.42	3.50	3.42	3.49	3.35
	U	[W/m²K]	0.29	0.29	0.29	0.29	0.30

Figure 13 – Organization levels of the tool information: worksheet, section, area and field.

3.2.3 Worksheets

The Tyre4BuildIns Calculation Tool workbook is composed by 21 worksheets organized into five categories, depending on their type of function: i) Introduction; ii) Inputs; iii) Outputs; iv) Databases, and; v) Calculation. In Figure 14, the groups of tabs existing in the tool are displayed. The identification and the function of each tab of the Tyre4BuildIns Calculation Tool worksheet are shown in Table 4.



Introduction: HomePage, Start Menu
Inputs: SA_Inp1, SA_Inp2, SB_Inp1, SB_Inp2, MCA_Inp
Outputs: Modules, SA_UCalc, SB_UCalc, Energy, SA_LCA, SB_LCA, Comp_LCA, SA_CostBen, SB_CostBen, Comp_CostBen, MCA
Databases: Mat_DB, Loc_DB
Calculation: Calculation

Figure 14 – Excel tabs of the tool.

Table 4 – Identification and function of the worksheets.

Category	Worksheet identification	Function
Introduction	HomePage	Tool logo; 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

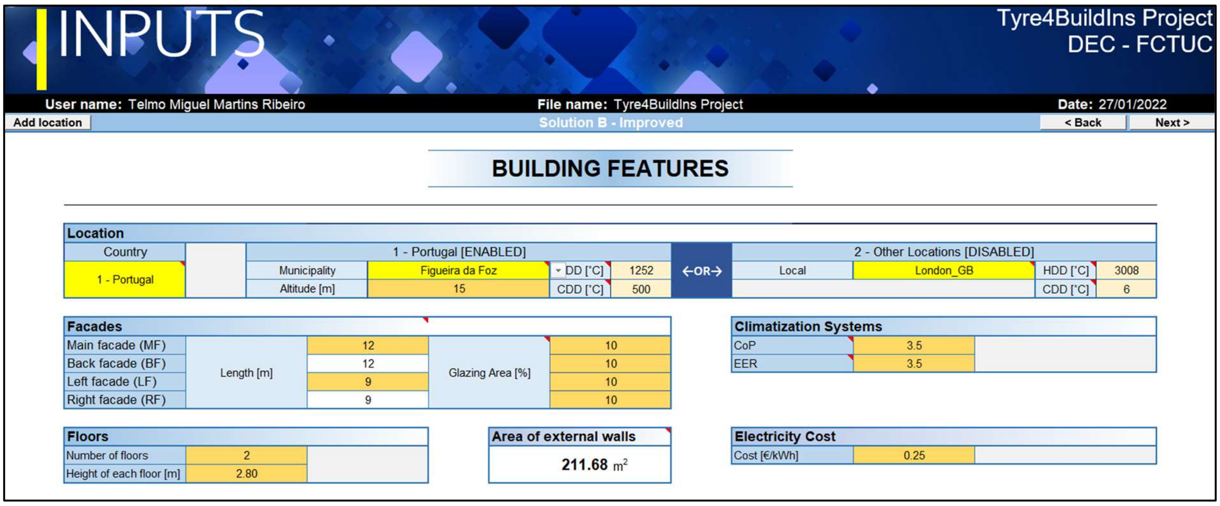
3.3 Inputs Description

3.3.1 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 introduction of a solution is carried out through the definition of two sets of parameters: i) *Building Features*, and; ii) *Wall Configuration*, as detailed next.

Building Features

The building features of Solution A and Solution B are defined in the [*SA_Inp1*] (Figure 15) 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*] area, 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*" (REH, 2013).



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Solution B - Improved

BUILDING FEATURES

Location

Country	1 - Portugal [ENABLED]				2 - Other Locations [DISABLED]			
1 - Portugal	Municipality	Figueira da Foz	DD [°C]	1252	Local	London_GB	HDD [°C]	3008
	Altitude [m]	15	CDD [°C]	500			CDD [°C]	6

Facades

Main facade (MF)	Length [m]	12	Glazing Area [%]	10
Back facade (BF)		12		10
Left facade (LF)		9		10
Right facade (RF)		9		10

Climatization Systems

CoP	3.5
EER	3.5

Floors

Number of floors	2
Height of each floor [m]	2.80

Area of external walls

211.68 m²

Electricity Cost

Cost [€/kWh]	0.25

Figure 15 – Print-screen of the [*SA_Inp1*] worksheet: Inputs of building features of Solution B (Improved LSF wall).

In the [*2 - Other Locations*] area, 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 (Spinoli *et al.*, 2018). The equations adopted for the calculation of HDD and CDD, are shown in Table 5 and Table 6, respectively. In this tool, the HDD were calculated using a reference temperature (T_{ref}) of 18 °C and the daily CDD were calculated using a T_{ref} of 25 °C, 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.

The calculation tool already has a weather database for 15 worldwide cities, as will be later presented in sub-chapter 3.3.4 (Locations Database).

Table 5 – UK Met Office equations to calculate the Heating Degree Days (Spinoli *et al.*, 2018).

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 6 – UK Met Office equations for calculating the Cooling Degree Days (Spinoli *et al.*, 2018).

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*] section (Figure 15) 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*] section. Using the values introduced in these fields, the tool calculates and displays the area of external walls (A_w), through the expression:

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

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*] section (Figure 15) 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*] field (Figure 15), the cost of the electricity per kilowatt-hour should be defined.

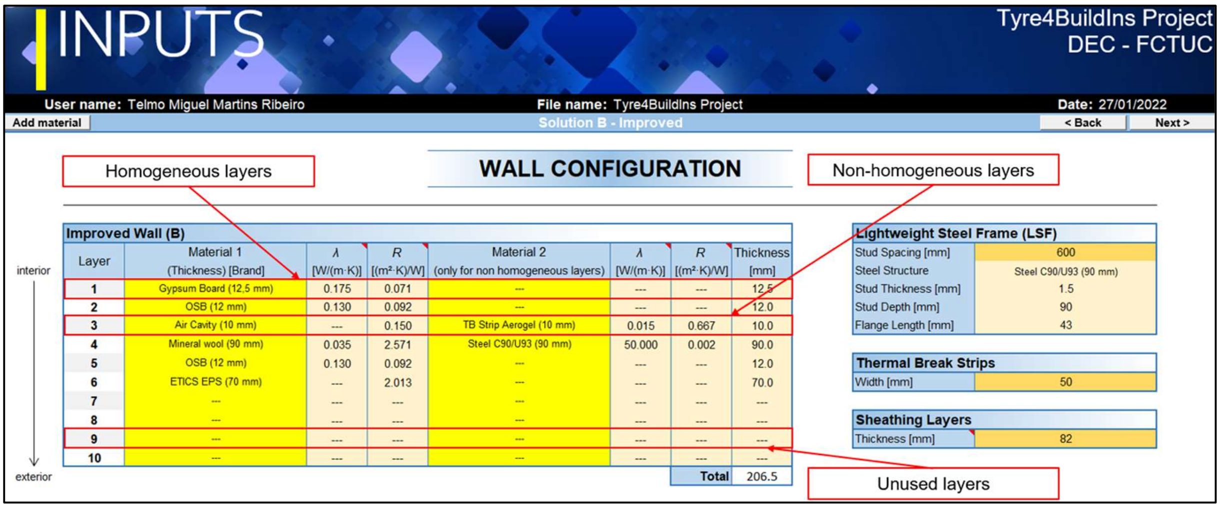
A summary of the parameters that need to be defined in the [*SA_Inp1*] or [*SB_Inp1*] worksheets is presented in Table 7.

Table 7 – 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

Wall Configuration

The wall configurations of Solution A and Solution B are defined in the [*SA_Inp2*] (Figure 16) 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.



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Solution B - Improved

WALL CONFIGURATION

Improved Wall (B)

Layer	Material 1 (Thickness) [Brand]	λ [W/(m·K)]	R [(m²·K)/W]	Material 2 (only for non homogeneous layers)	λ [W/(m·K)]	R [(m²·K)/W]	Thickness [mm]
1	Gypsum Board (12,5 mm)	0.175	0.071	---	---	---	12.5
2	OSB (12 mm)	0.130	0.092	---	---	---	12.0
3	Air Cavity (10 mm)	---	0.150	TB Strip Aerogel (10 mm)	0.015	0.667	10.0
4	Mineral wool (90 mm)	0.035	2.571	Steel C90/U93 (90 mm)	50.000	0.002	90.0
5	OSB (12 mm)	0.130	0.092	---	---	---	12.0
6	ETICS EPS (70 mm)	---	2.013	---	---	---	70.0
7	---	---	---	---	---	---	---
8	---	---	---	---	---	---	---
9	---	---	---	---	---	---	---
10	---	---	---	---	---	---	---
						Total	206.5

Lightweight Steel Frame (LSF)	
Stud Spacing [mm]	600
Steel Structure	Steel C90/U93 (90 mm)
Stud Thickness [mm]	1.5
Stud Depth [mm]	90
Flange Length [mm]	43

Thermal Break Strips	
Width [mm]	50

Sheathing Layers	
Thickness [mm]	82

Figure 16 – Layout of the [*Wall Configuration*] inputs.

In the [Reference Wall (A)] section (Figure 16), 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 sub-chapter 3.3.3, contains a set of branded materials, with a predefined thickness and the respective characteristic parameters. This tool allows to define two types of layers: i) homogeneous layers (1 material), or; ii) non-homogeneous layers (2 materials). The assembly of each layer must be carried out as explained in Table 8.

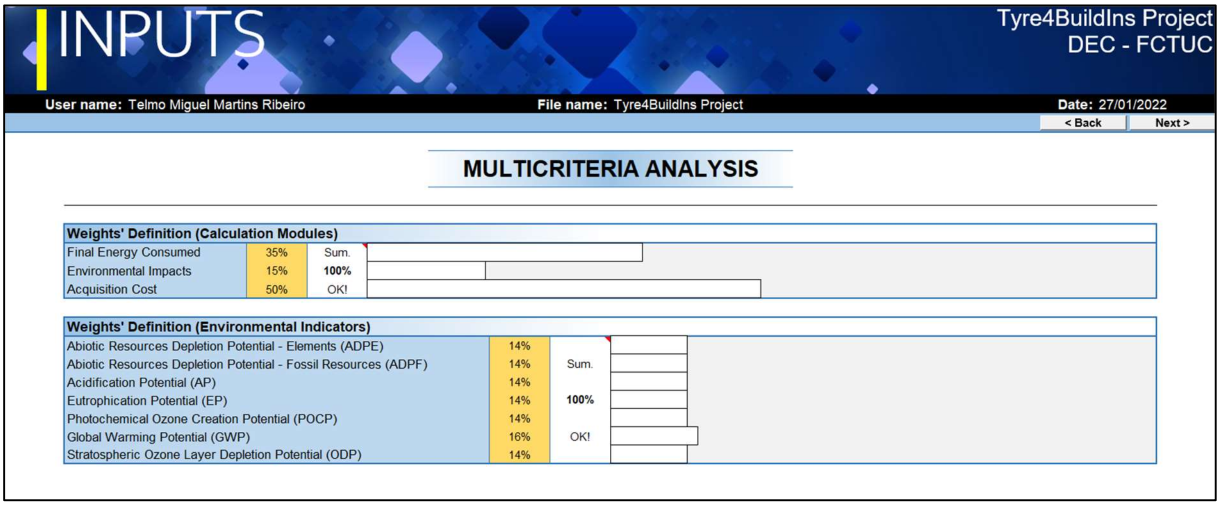
Table 8 – Instructions for the LSF wall layer assembly.

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 "---".
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 "---".

The [*Lightweight Steel Frame (LSF)*] section (Figure 16) 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*] section (Figure 16). Finally, in the [*Sheathing Layers*] 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 (ASHRAE, 2017).

3.3.2 Multicriteria Analysis

The weighting factors used in the multicriteria analysis are defined in the [*MCA_Inp*] worksheet (Figure 17). 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.



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MULTICRITERIA ANALYSIS

Weights' Definition (Calculation Modules)		
Final Energy Consumed	35%	Sum.
Environmental Impacts	15%	**100%**
Acquisition Cost	50%	OK!

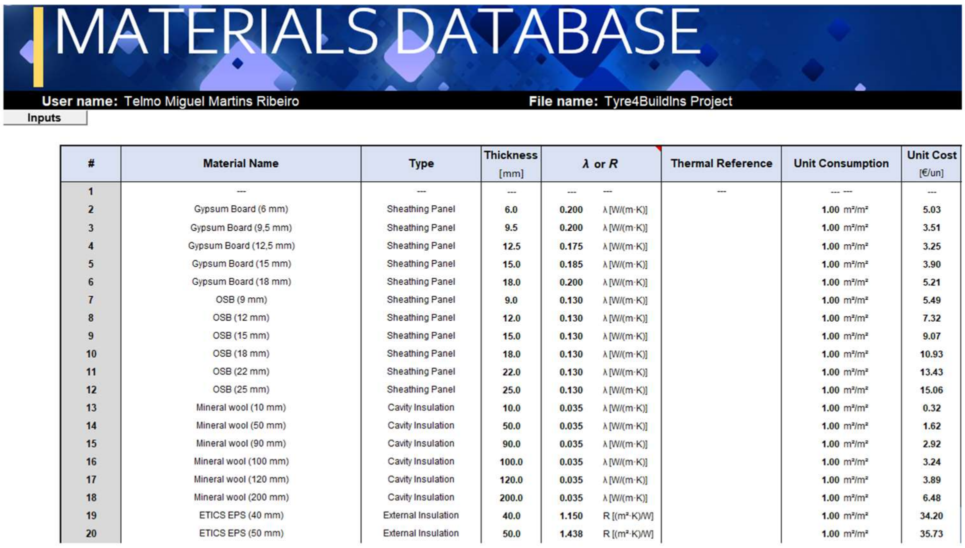
Weights' Definition (Environmental Indicators)		
Abiotic Resources Depletion Potential - Elements (ADPE)	14%	
Abiotic Resources Depletion Potential - Fossil Resources (ADPF)	14%	Sum.
Acidification Potential (AP)	14%	
Eutrophication Potential (EP)	14%	**100%**
Photochemical Ozone Creation Potential (POCP)	14%	
Global Warming Potential (GWP)	16%	OK!
Stratospheric Ozone Layer Depletion Potential (ODP)	14%	

Figure 17 – Layout of the [*MCA_Inp*] worksheet.

The weights referring to the modules should be defined in the [*Weight's Definition (Modules)*] section (Figure 17) 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)*] section. The weight values must be expressed in percentage and, for each category, the sum of the weights must be equal to 100%.

3.3.3 Materials Database

The Materials Database contains the materials that can be used in the walls and it is based in [*Mat_DB*] worksheet (Figure 18). 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 9.

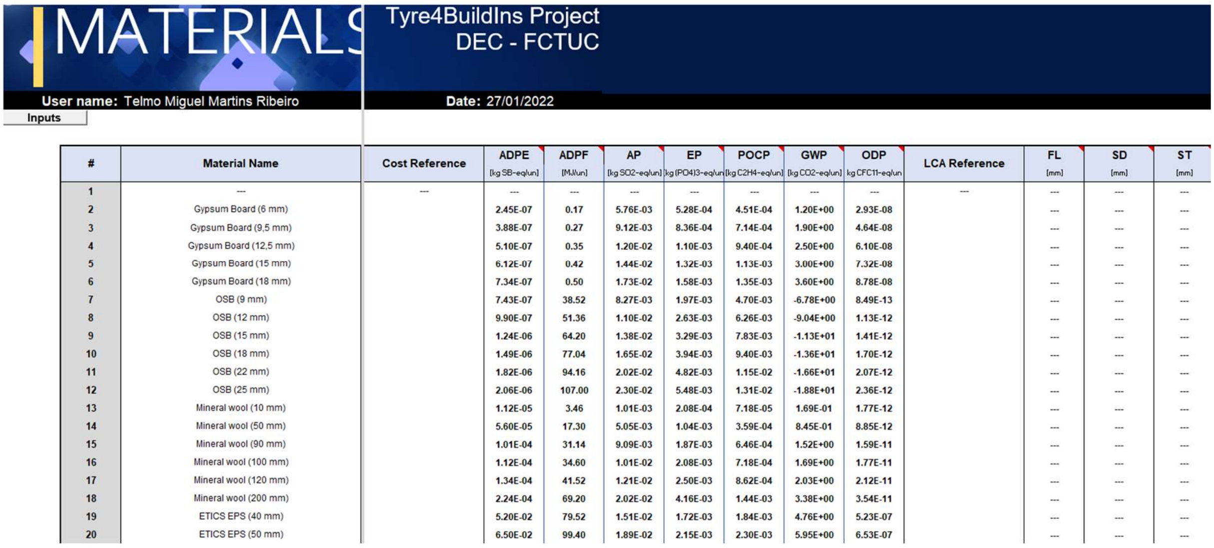


MATERIALS DATABASE

User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project

Inputs

#	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



MATERIALS

Tyre4BuildIns Project
DEC - FCTUC

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Inputs

#	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		---	---	---

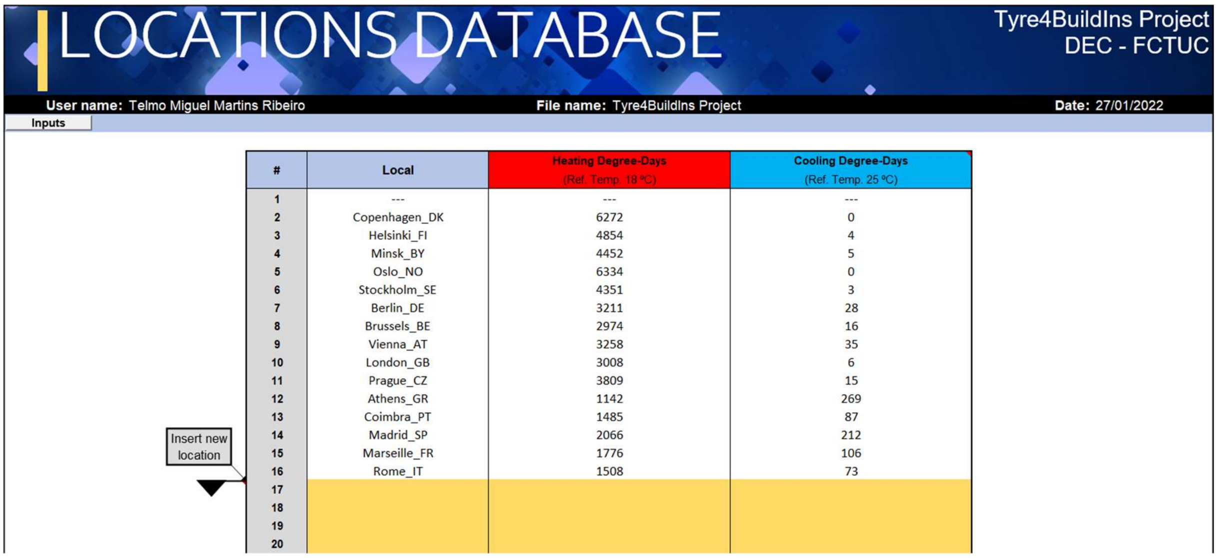
Figure 18 – Materials database layout.

Table 9 – 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/m^2 or m^2/m^2
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)

3.3.4 Locations Database

The Locations Database contains the locations (beyond Portugal) available in the tool and it is based in [*Loc_DB*] worksheet (Figure 19). 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 (Spinoli *et al.*, 2018). 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.



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#	Local	Heating Degree-Days (Ref. Temp. 18 ºC)	Cooling Degree-Days (Ref. Temp. 25 ºC)
1	---	---	---
2	Copenhagen_DK	6272	0
3	Helsinki_FI	4854	4
4	Minsk_BY	4452	5
5	Oslo_NO	6334	0
6	Stockholm_SE	4351	3
7	Berlin_DE	3211	28
8	Brussels_BE	2974	16
9	Vienna_AT	3258	35
10	London_GB	3008	6
11	Prague_CZ	3809	15
12	Athens_GR	1142	269
13	Coimbra_PT	1485	87
14	Madrid_SP	2066	212
15	Marseille_FR	1776	106
16	Rome_IT	1508	73
17			
18			
19			
20			

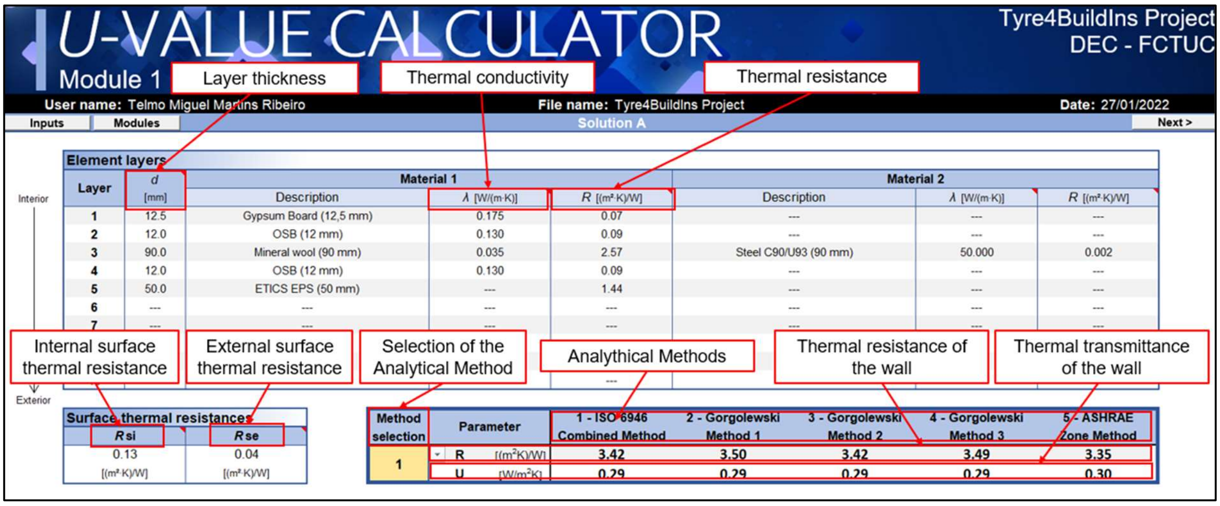
Figure 19 – Locations Database layout.

3.4 Calculation methodology and outputs

3.4.1 Module 1 – *U*-value Calculator

Module 1 – *U-value Calculator* (Figure 20) determines the thermal transmittance coefficient (and thermal resistance value) 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 (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 coefficient (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, and it is expressed in $W/(m^2 \cdot K)$. In turn, the thermal resistance (R-value) can be determined from the inverse of the U-value, being expressed in $m^2 \cdot K/W$.



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File name: Tyre4BuildIns Project
Date: 27/01/2022

Element layers

Layer	d [mm]	Material 1 Description	Material 1 λ [W/(m·K)]	Material 1 R [(m²·K)/W]	Material 2 Description	Material 2 λ [W/(m·K)]	Material 2 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	90.0	Mineral wool (90 mm)	0.035	2.57	Steel C90/U93 (90 mm)	50.000	0.002
4	12.0	OSB (12 mm)	0.130	0.09	---	---	---
5	50.0	ETICS EPS (50 mm)	---	1.44	---	---	---
6	---	---	---	---	---	---	---
7	---	---	---	---	---	---	---

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]	3.42	3.50	3.42	3.49	3.35
	U	[W/m²K]	0.29	0.29	0.29	0.29	0.30

Figure 20 –Layout of Module 1: U-value Calculator (Solution A – Reference LSF wall).

When the construction element is composed by layers of homogeneous materials arranged in parallel, and the heat flux is unidirectional, the parameter U can be determined by Equation 10:

$$U = \frac{1}{R} = \frac{1}{R_{si} + \sum_j R_j + R_{se}} \tag{10}$$

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 Equation 11:

$$R_j = \frac{d_j}{\lambda_j} \tag{11}$$

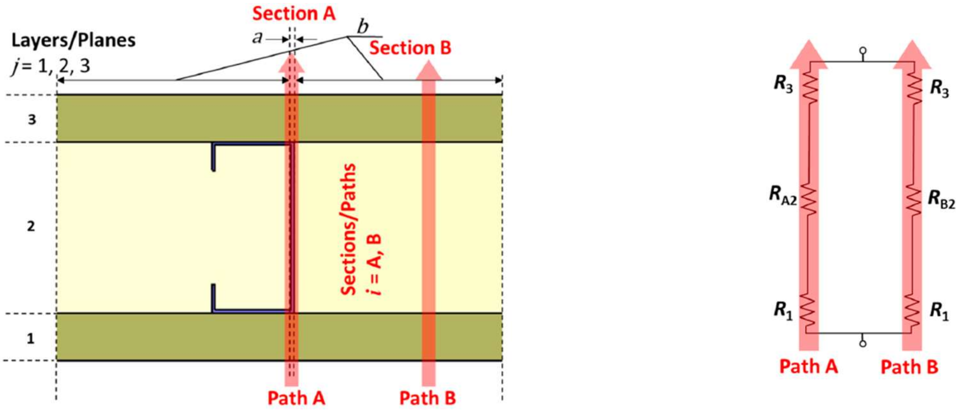
where d_j [m] is the layer j thickness and λ [W·m^{-1}·K^{-1}] is the material thermal conductivity of the layer j.

In the case of LSF walls, the construction element is composed by a mix of homogeneous and heterogeneous layers, being the calculation of 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 (ISO 6946, 2017); ii) Gorgolewski Method 1 (Gorgolewski, 2007); iii) Gorgolewski Method 2 (Gorgolewski, 2007); iv) Gorgolewski Method 3 (Gorgolewski, 2007) and; v) ASHRAE Zone Method (ASHRAE, 2017). The calculation procedure for each of the five methods is presented below. A detailed description of these analytical methods can be found in a previous publication (Santos *et al.*, 2020) of the Tyre4BuildIns research project (Tyre4BuildIns, 2022).

ISO 6946 Combined Method

ISO 6946 Combined Method is a simplified analytical method described in the International Standard ISO 6946 (ISO 6946, 2017) computed by two sub-methods: i) Parallel Path Method, and; ii) Isothermal Path Method. Although it is one of the most used analytical methods, ISO 6946 Combined Method is only valid for cases in which the quotient between the upper and lower limits of thermal resistance is less than 1.5. Furthermore, in construction elements where the thermal insulation is interrupted by metal, the ISO 6946 Combined Method should not be applied.

The Parallel Path Method provides the upper limit of the total thermal resistance ($R_{tot;upper}$), considering that the heat transfer is one-dimensional and perpendicular to the surfaces of the building element. In the computation of this method two paths are considered, as illustrated in Figure 21: i) Path A, passing through the steel stud web, and; ii) Path B, passing in the cavity zone between the steel studs.



a) b)

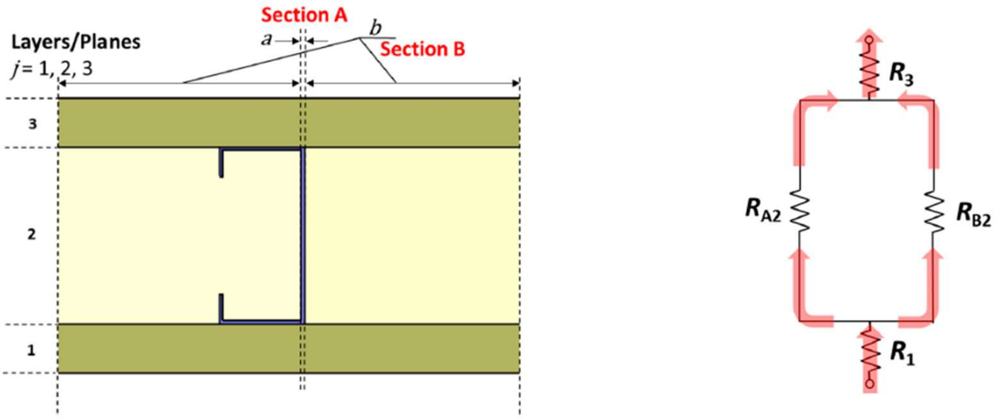
Figure 21 – Parallel Path Method: a) LSF wall cross-section; b) Equivalent parallel path circuit (Santos *et al.*, 2020).

Section A, related to Path A, has a width equal to the steel stud thickness, and Section B, related to Path B, has a width equal to the difference between stud spacing and stud thickness. Thus, the upper limit of the total thermal resistance, $R_{tot;upper}$ [m^2·K·W^{-1}], is determined by:

$$\frac{1}{R_{tot;upper}} = \frac{f_A}{R_{tot;A}} + \frac{f_B}{R_{tot;B}} \tag{12}$$

where, f_A is the fractional area of section A, f_B is the fractional area of section B, $R_{tot;A}$ is the total thermal resistance of section/path A, and $R_{tot;B}$ is the total thermal resistance of section/path B. The total thermal resistances of path A and B are determined by the summation of the thermal resistances inherent to each path, including the internal and external surface thermal resistances.

The Isothermal Planes Method allows to determine the lower limit of the total thermal resistance ($R_{tot;lower}$), considering that the thermal resistances of inhomogeneous layers are combined in parallel. The schematic illustration of the Isothermal Planes Method applied to an LSF wall is presented in Figure 22.



a) b)

Figure 22 – Isothermal Planes Method: (a) LSF wall cross-section; (b) equivalent series-parallel circuit (Santos *et al.*, 2020).

First, for each inhomogeneous layer, the equivalent thermal resistance is determined according to Equation 13 for general cases, or Equation 14 for the case illustrated in Figure 22.

$$\frac{1}{R_j} = \frac{f_A}{R_{Aj}} + \frac{f_B}{R_{Bj}} + \cdots + \frac{f_Q}{R_{Qj}} \tag{13}$$

$$\frac{1}{R_2} = \frac{f_A}{R_{A2}} + \frac{f_B}{R_{B2}} \tag{14}$$

In a second phase, according to Equation 15 (general cases) and Equation 16 (Figure 22 case), the series resistances, including the equivalent thermal resistance of the inhomogeneous layers and the internal and external surface thermal resistances, are summed up to obtain the lower limit of the total thermal resistance, $R_{tot;lower}$ [m^2·K·W^{-1}].

$$R_{tot;lower} = R_{si} + \sum_{j} R_j + R_{se} \tag{15}$$

$$R_{tot;lower} = R_{si} + R_1 + R_2 + R_3 + R_{se} \tag{16}$$

The total thermal resistance prescribed by this method is calculated through an arithmetic average of the total upper ($R_{tot;upper}$) and lower ($R_{tot;lower}$) thermal resistances (Equation 17).

$$R_{tot;ISO} = \frac{R_{tot;upper} + R_{tot;lower}}{2} \tag{17}$$

Gorgolewski Methods

The Gorgolewski methods (Gorgolewski, 2007) use the upper and lower limits of thermal resistances calculated by ISO 6946 methodology but apply different weights to these limits. Considering a factor p that can assume values between 0 and 1, the total thermal resistance is calculated using Equation 18.

$$R_{tot;gorg} = p \cdot R_{tot;upper} + (1 - p) \cdot R_{tot;lower} \tag{18}$$

The calculation procedure of each Gorgolewski Method for the determination of factor p is presented in Table 10.

Table 10 – Definition of factor p for Gorgolewski Methods.

<table>
<tr><td>Gorgolewski Method 1</td><td>$$p = 0.8\left(\frac{R_{tot;upper}}{R_{tot;lower}}\right) + 0.1 \tag{19}$$
$R_{tot;upper}$ – Upper limit of the total thermal resistance;
$R_{tot;lower}$- Lower limit of the total thermal resistance.</td></tr>
<tr><td>Gorgolewski Method 2</td><td><table>
<tr><th rowspan="2">p-Values</th><th colspan="2">Frame Type</th></tr>
<tr><th>Hybrid</th><th>Cold</th></tr>
<tr><td>Stud spacing ≥ 500</td><td>0.50</td><td>0.30</td></tr>
<tr><td>Stud spacing < 500</td><td>0.40</td><td>0.25</td></tr>
</table></td></tr>
<tr><td>Gorgolewski Method 3</td><td>$$p = 0.8\left(\frac{R_{tot;upper}}{R_{tot;lower}}\right) + 0.44 - 0.1\left(\frac{fl}{0.04}\right) - 0.2\left(\frac{0.6}{ss}\right) - 0.44\left(\frac{sd}{0.1}\right) \tag{20}$$
$R_{tot;upper}$ - Upper limit of the total thermal resistance; fl – flange length;
$R_{tot;lower}$- Lower limit of the total thermal resistance; ss - the stud spacing;
sd - stud depth;
All dimensions in metres [m].</td></tr>
</table>

ASHRAE Zone Method

The ASHRAE Zone Method (ASHRAE, 2017) is a simplified analytical method proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) that is computed considering two sections in the wall (Figure 23): i) section W, representing the section influenced by the steel stud thermal bridge, and; ii) section CAV, corresponding to the section that is not influenced by the steel stud thermal bridge.

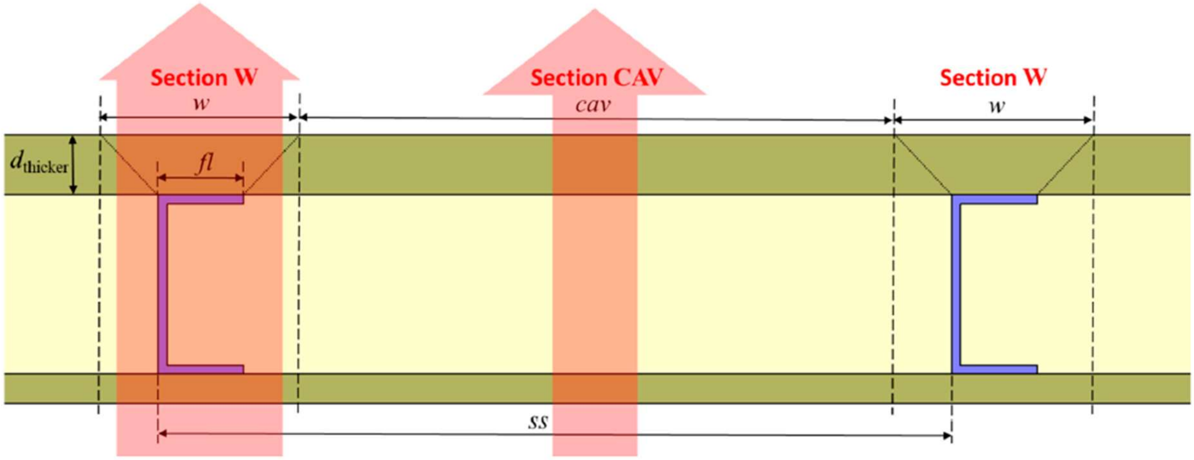


Figure 23 – ASHRAE Zone Method: illustration of the Section W and Section CAV (Santos *et al.*, 2020).

The length w [m] of section W is calculated by Equation 21,

$$w = fl + 2d_{thicker} \tag{21}$$

where, fl [m] is the flange length, and d_{thick} [m] represents the thickness, in meters, of the thicker sheathing side. In turn, the length cav of Section CAV is determined by the difference between the stud spacing and the length w.

The detailed composition of Section W, as well as the series-parallel circuit that illustrates the calculation scheme for the thermal resistances used in ASHRAE Zone Method are presented in Figure 24.

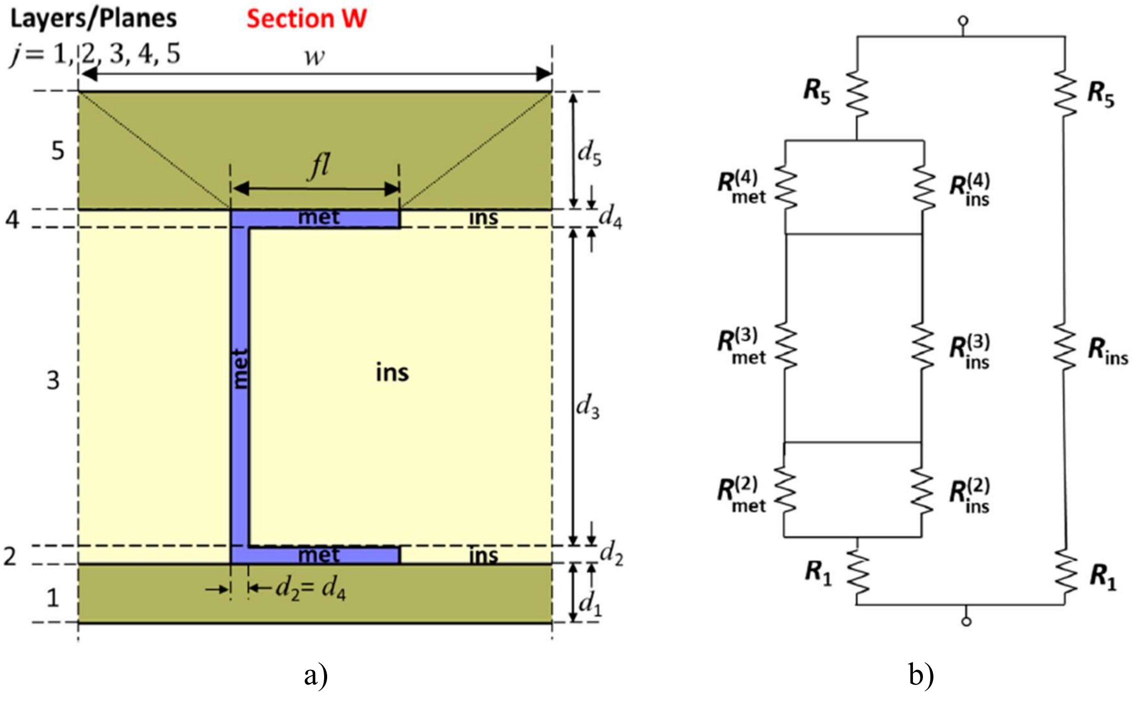


Figure 24 – ASHRAE Zone Method: a) dimensions of Section W; b) series-parallel circuit calculation scheme for the thermal resistances (Santos *et al.*, 2020).

The total thermal resistance of Section CAV, $R_{tot,cav}$ [m^2·K·W^{-1}], is determined by the summation of the thermal resistances of all the layers that compose this section, as well as the internal and external surface thermal resistances, by the expression,

$$R_{tot;cav} = R_{si} + R_1 + R_{ins} + R_5 + R_{se} \tag{22}$$

where R_{si} [m^2·K·W^{-1}] is the internal surface thermal resistance, R_1 [m^2·K·W^{-1}] is the thermal resistance of layer 1, R_{ins} [m^2·K·W^{-1}] is the thermal resistance of the insulation layer [m^2·K·W^{-1}], R_5 [m^2·K·W^{-1}] is the thermal resistance of layer 5, and R_{se} [m^2·K·W^{-1}] is the external surface thermal resistance.

Concerning the total thermal resistance of the Section W, $R_{tot,w}$, in a first phase, for each thermally inhomogeneous layer (j = 2, 3, 4), the equivalent thermal resistance combining metal (met) and insulation (ins) materials is calculated by Equations 23, 24 and 25.

$$\frac{1}{R_2} = \sum_{i=1}^{2} \frac{f_i^{(2)}}{R_i^{(2)}} = \frac{fl/w}{R_{met}^{(2)}} + \frac{(w - fl)/w}{R_{ins}^{(2)}} \tag{23}$$

$$\frac{1}{R_3} = \sum_{i=1}^{2} \frac{f_i^{(3)}}{R_i^{(3)}} = \frac{d_2/w}{R_{met}^{(3)}} + \frac{(w - d_2)/w}{R_{ins}^{(3)}} \tag{24}$$

$$\frac{1}{R_4} = \sum_{i=1}^{2} \frac{f_i^{(4)}}{R_i^{(4)}} = \frac{fl/w}{R_{met}^{(4)}} + \frac{(w - fl)/w}{R_{ins}^{(4)}} \tag{25}$$

Next, the total thermal resistance of Section W, $R_{tot,w}$ [m^2·K·W^{-1}], is determined by the summation of the three equivalent thermal resistances (R_2, R_3 and R_4) and the thermal resistances of the homogeneous layers (R_1 and R_5), including the internal R_{si} [m^2·K·W^{-1}] and external R_{se} [m^2·K·W^{-1}] surface thermal resistances (Equation 26).

$$R_{tot;w} = R_{si} + R_1 + R_2 + R_3 + R_4 + R_5 + R_{se} \tag{26}$$

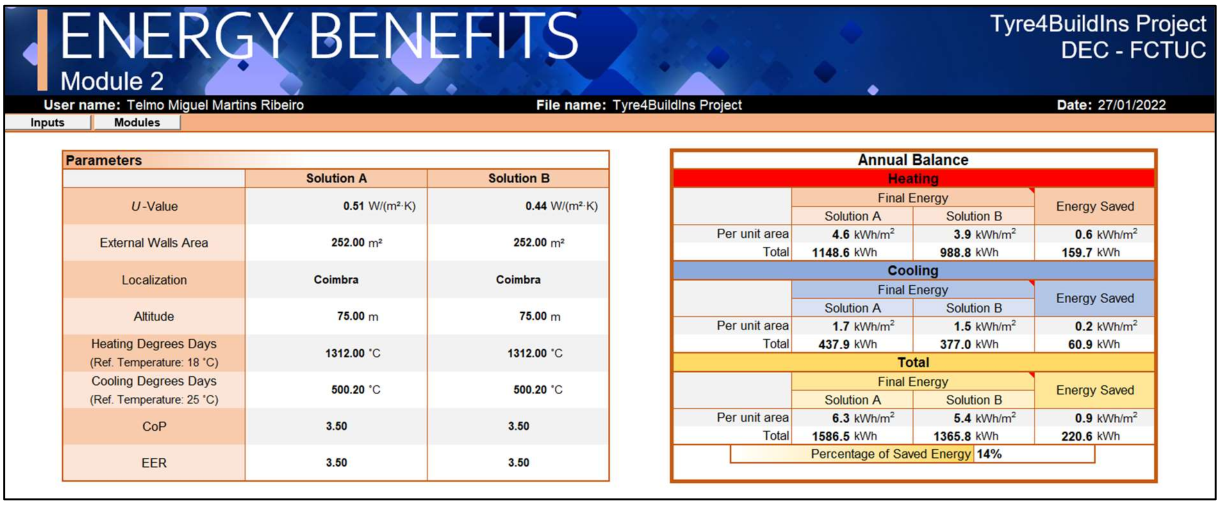
The calculation of the total thermal resistance by ASHRAE Zone Method, $R_{tot;ASHRAE}$ [m^2·K·W^{-1}], is performed using Equation 27,

$$\frac{1}{R_{tot;ASHRAE}} = \sum_{i=1}^{2} \frac{f_i}{R_i} = \frac{w/ss}{R_{tot,w}} + \frac{cav/ss}{R_{tot,cav}} \tag{27}$$

where w [m] and cav [m] are the lengths of sections W and CAV, respectively, $R_{tot,w}$ [m^2·K·W^{-1}] and $R_{tot,cav}$ [m^2·K·W^{-1}] are the total thermal resistances of sections W and CAV, respectively, and ss [m] is the studs spacing.

3.4.2 Module 2 – Energy Benefits

Module 2 – *Energy Benefits* (layout illustrated in Figure 25) 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).



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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		Energy Saved
Heating			
	Solution A	Solution B	
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			
	Solution A	Solution B	
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			
	Solution A	Solution B	
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 25 – Layout of Module 2 – *Energy Benefits*.

The saved energy is quantified in terms of final energy (e.g., electricity) consumed by the climatization systems and the results are presented per year, and per heating and cooling season. The quantification of the annual saved energy can be calculated according to Equation 28,

$$E_{saved} = E_{final}^{ref} - E_{final}^{imp} \tag{28}$$

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,

$$E_{final} = \frac{Q_{tr}^{heating}}{CoP} + \frac{Q_{tr}^{cooling}}{EER} \tag{29}$$

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.

Portugal locations

For situations in which the wall under analysis is inserted in a building located in Portugal, the heat transfer by transmission through the construction element is determined using the Portuguese legal requirement for the energy performance of housing buildings "*REH – Regulamento de Desempenho Energético dos Edifícios de Habitação*" (REH, 2013). Thus, the determination of the heat transfer by transmission, for the heating season, $Q_{tr}^{heating}$ [kWh], is obtained by Equation 30,

$$Q_{tr}^{heating} = Q_{tr,i} = \frac{H_{tr,i} \cdot HDD \cdot 24}{1000} \tag{30}$$

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, $Q_{tr}^{cooling}$ [kWh], is given by Equation 31,

$$Q_{tr}^{cooling} = Q_{tr,v} = \frac{H_{tr,v} \cdot (\theta_{v,ref} - \theta_{v,ext}) \cdot L_v}{1000} \tag{31}$$

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).

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, is determined by Equations 32 and 33, respectively:

$$Q_{tr}^{heating} = \frac{H_{tr,h} \cdot HDD \cdot 24}{1000} \tag{32}$$

$$Q_{tr}^{cooling} = \frac{H_{tr,c} \cdot CDD \cdot 24}{1000} \tag{33}$$

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 25): i) U-value; ii) external walls area; iii) localization; 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.

3.4.3 Module 3 – Life-Cycle Analysis

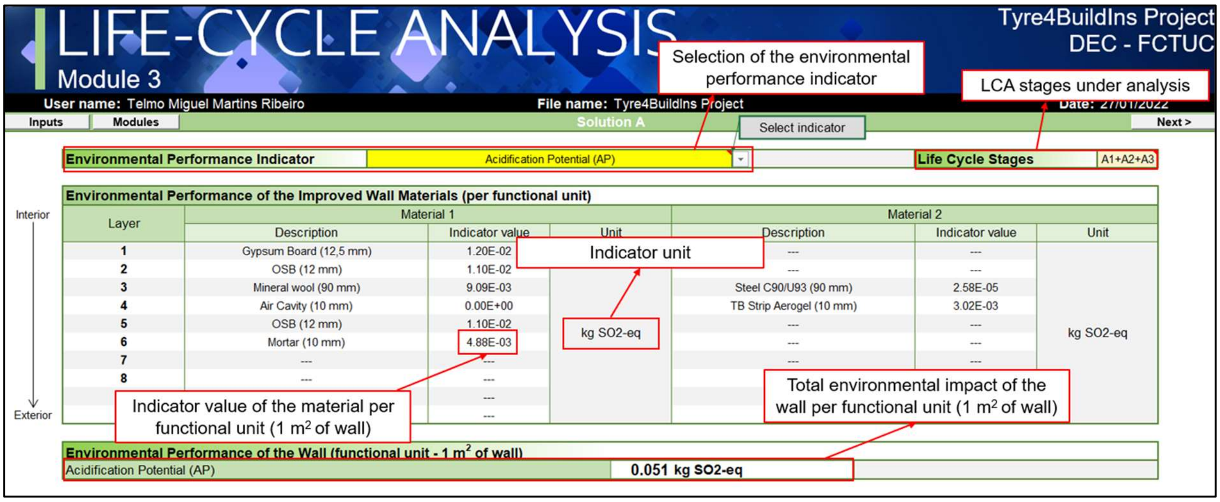
Module 3 – *Life-Cycle Analysis* assesses the environmental impacts associated with the evaluated LSF walls. The quantification of the environmental impacts is carried out considering a functional unit of 1 m^2 of LSF wall and the results are displayed for each constituent material and for the global configuration of the wall. The seven indicators considered to assess the environmental impacts are presented in Table 11.

Table 11 – Indicators of environmental impacts considered in Module 3.

Environmental impact indicator	Unit
Abiotic Resources Depletion Potential – Elements (ADPE)	kg Sb eq
Abiotic Resources Depletion Potential – Fossil Resources (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 (ISO 14040, 2006). 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.

Module 3 – *Life-Cycle Analysis* comprises three worksheets: [*LCA_SA*], [*LCA_SB*] and [*LCA_Total*]. The [*LCA_SA*] (Figure 26) and [*LCA_SB*] (Figure 27) worksheets display the environmental impacts related to Solution A and Solution B, respectively. In turn, the [*LCA_Total*] (Figure 28) presents an overview and comparison of the two solutions.



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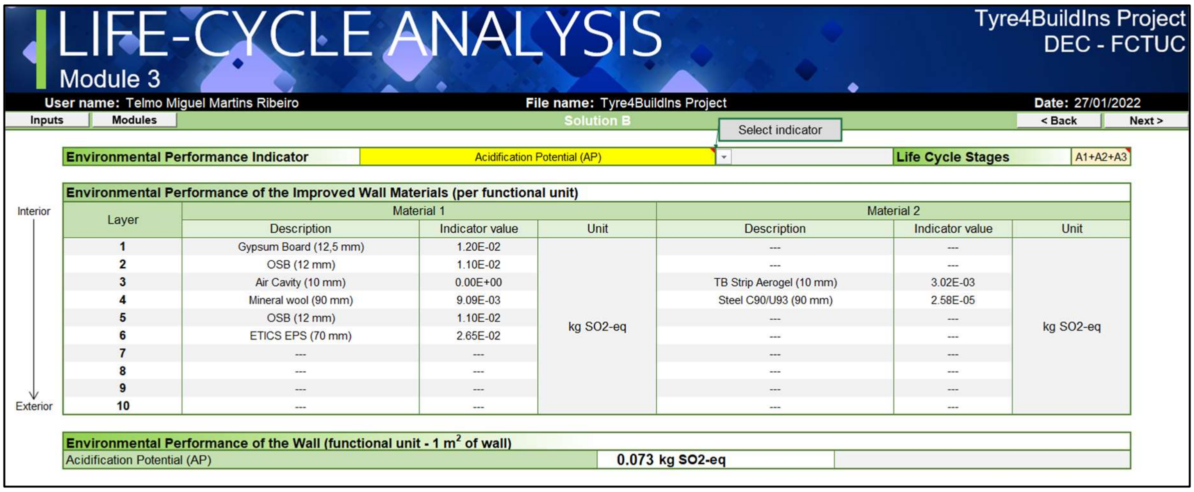
Environmental Performance Indicator: Acidification Potential (AP)
Life Cycle Stages: A1+A2+A3

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

Layer	Material 1			Material 2		
	Description	Indicator value	Unit	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	Air Cavity (10 mm)	0.00E+00		TB Strip Aerogel (10 mm)	3.02E-03	
5	OSB (12 mm)	1.10E-02		---	---	
6	Mortar (10 mm)	4.88E-03		---	---	
7	---	---		---	---	
8	---	---				

Environmental Performance of the Wall (functional unit - 1 m² of wall)
Acidification Potential (AP) **0.051 kg SO2-eq**

Figure 26 – Layout of Module 3 – *Life-Cycle Analysis* (Solution A – Reference LSF wall).



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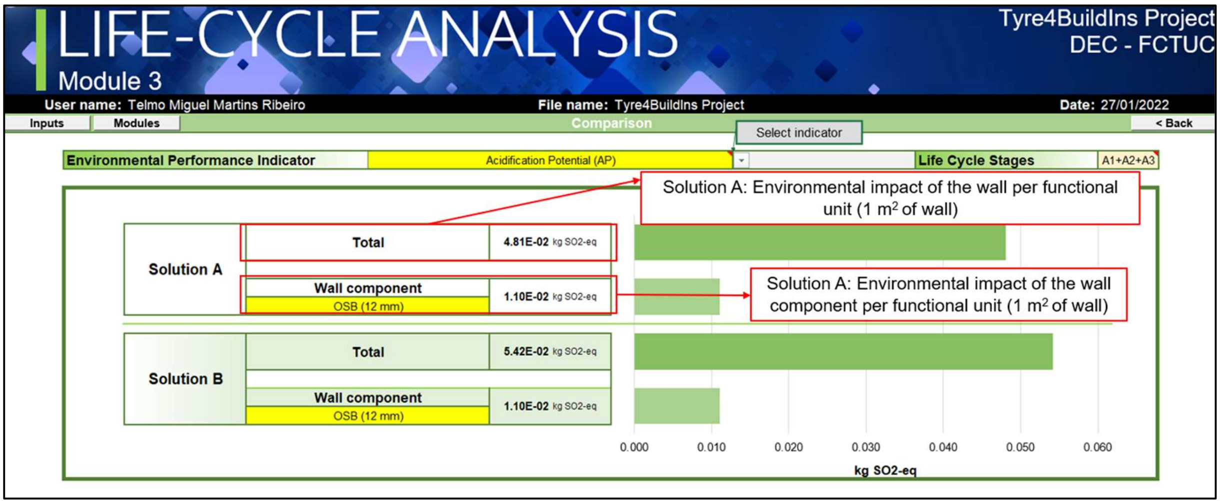
Environmental Performance Indicator: Acidification Potential (AP)
Life Cycle Stages: A1+A2+A3

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

Layer	Material 1			Material 2		
	Description	Indicator value	Unit	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	Air Cavity (10 mm)	0.00E+00		TB Strip Aerogel (10 mm)	3.02E-03	
4	Mineral wool (90 mm)	9.09E-03		Steel C90/U93 (90 mm)	2.58E-05	
5	OSB (12 mm)	1.10E-02		---	---	
6	ETICS EPS (70 mm)	2.65E-02		---	---	
7	---	---		---	---	
8	---	---		---	---	
9	---	---		---	---	
10	---	---		---	---	

Environmental Performance of the Wall (functional unit - 1 m² of wall)
Acidification Potential (AP) **0.073 kg SO2-eq**

Figure 27 – Layout of Module 3 – *Life-Cycle Analysis* (Solution B – Improved LSF wall).



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

Solution A	**Total**	**4.81E-02** kg SO2-eq
	Wall component OSB (12 mm)	**1.10E-02** kg SO2-eq
Solution B	**Total**	**5.42E-02** kg SO2-eq
	Wall component OSB (12 mm)	**1.10E-02** kg SO2-eq

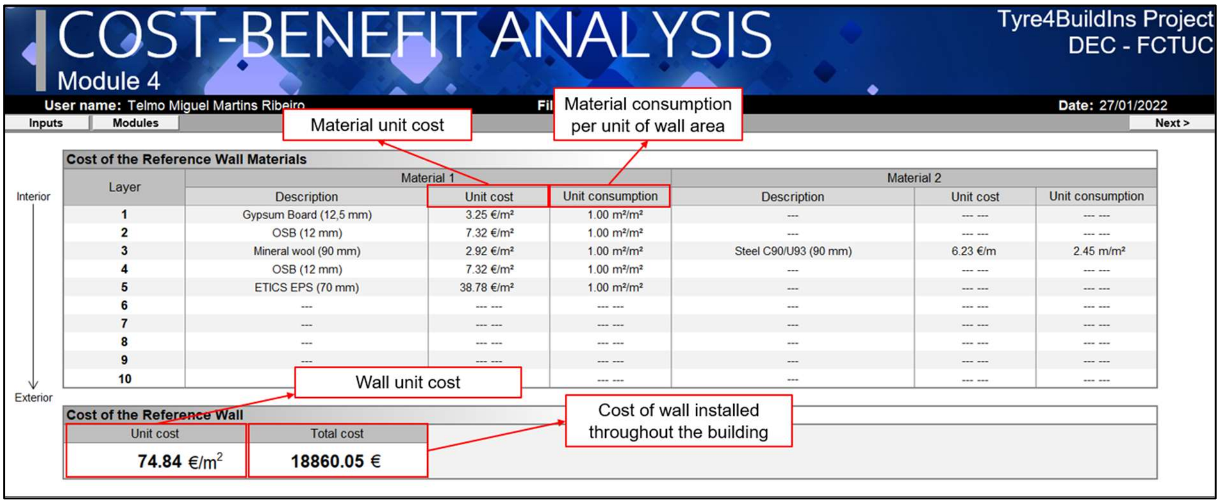
Solution A: Environmental impact of the wall per functional unit (1 m² of wall)

Solution A: Environmental impact of the wall component per functional unit (1 m² of wall)

Figure 28 – Layout of Module 3 – *Life-Cycle Analysis* (Total).

3.4.4 Module 4 – Cost-Benefit Analysis

Module 4 – *Cost-Benefit Analysis* aims to evaluate the monetary balance that arises from 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 29) and [*CostBen_SB*] worksheet (Figure 30) 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 31) 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.



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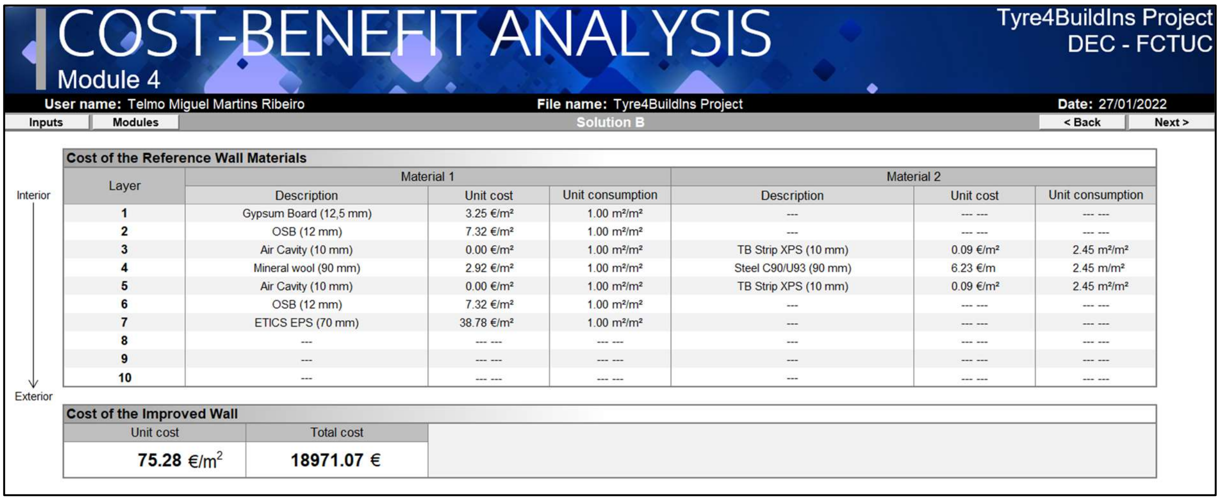
Cost of the Reference Wall Materials

Layer	Material 1			Material 2		
	Description	Unit cost	Unit consumption	Description	Unit cost	Unit consumption
1	Gypsum Board (12,5 mm)	3.25 €/m^2	1.00 m^2/m^2	---	--- ---	--- ---
2	OSB (12 mm)	7.32 €/m^2	1.00 m^2/m^2	---	--- ---	--- ---
3	Mineral wool (90 mm)	2.92 €/m^2	1.00 m^2/m^2	Steel C90/U93 (90 mm)	6.23 €/m	2.45 m/m^2
4	OSB (12 mm)	7.32 €/m^2	1.00 m^2/m^2	---	--- ---	--- ---
5	ETICS EPS (70 mm)	38.78 €/m^2	1.00 m^2/m^2	---	--- ---	--- ---
6	---	--- ---	--- ---	---	--- ---	--- ---
7	---	--- ---	--- ---	---	--- ---	--- ---
8	---	--- ---	--- ---	---	--- ---	--- ---
9	---	--- ---	--- ---	---	--- ---	--- ---
10			--- ---	---	--- ---	--- ---

Cost of the Reference Wall

Unit cost	Total cost
74.84 €/m^2	**18860.05 €**

Figure 29 – Layout of Module 4 – *Cost-Benefit Analysis* (Solution A – Reference LSF wall).



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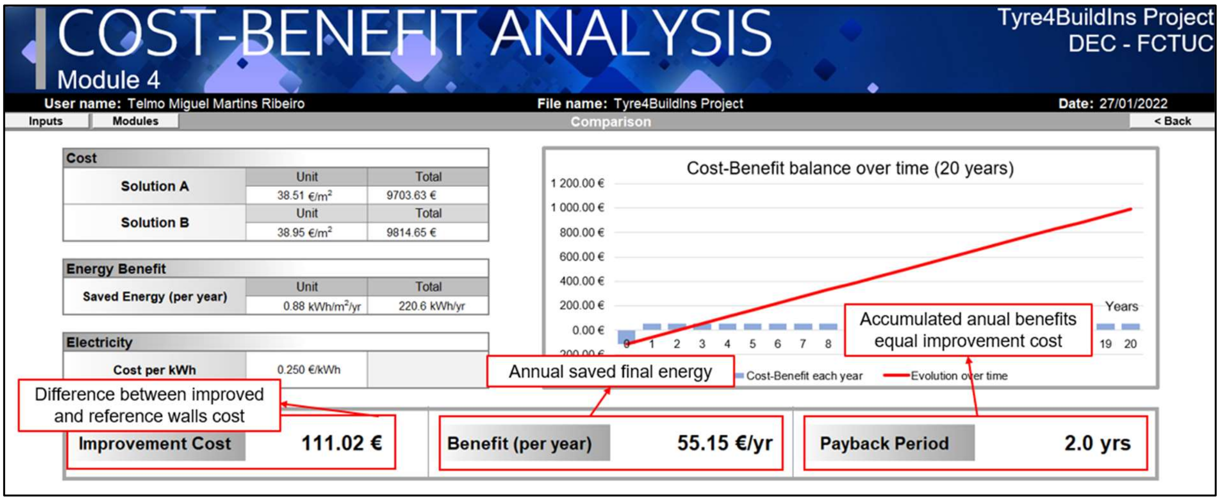
Cost of the Reference Wall Materials

Layer	Material 1			Material 2		
	Description	Unit cost	Unit consumption	Description	Unit cost	Unit consumption
1	Gypsum Board (12,5 mm)	3.25 €/m^2	1.00 m^2/m^2	---	--- ---	--- ---
2	OSB (12 mm)	7.32 €/m^2	1.00 m^2/m^2	---	--- ---	--- ---
3	Air Cavity (10 mm)	0.00 €/m^2	1.00 m^2/m^2	TB Strip XPS (10 mm)	0.09 €/m^2	2.45 m^2/m^2
4	Mineral wool (90 mm)	2.92 €/m^2	1.00 m^2/m^2	Steel C90/U93 (90 mm)	6.23 €/m	2.45 m/m^2
5	Air Cavity (10 mm)	0.00 €/m^2	1.00 m^2/m^2	TB Strip XPS (10 mm)	0.09 €/m^2	2.45 m^2/m^2
6	OSB (12 mm)	7.32 €/m^2	1.00 m^2/m^2	---	--- ---	--- ---
7	ETICS EPS (70 mm)	38.78 €/m^2	1.00 m^2/m^2	---	--- ---	--- ---
8	---	--- ---	--- ---	---	--- ---	--- ---
9	---	--- ---	--- ---	---	--- ---	--- ---
10	---	--- ---	--- ---	---	--- ---	--- ---

Cost of the Improved Wall

Unit cost	Total cost
75.28 €/m^2	**18971.07 €**

Figure 30 – Layout of Module 4 – *Cost-Benefit Analysis* (Solution B – Improved LSF wall).



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Cost		
	Unit	Total
Solution A	38.51 €/m²	9703.63 €
	Unit	Total
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

Difference between improved and reference walls cost

Annual saved final energy

Accumulated anual benefits equal improvement cost

Figure 31 – Layout of Module 4 – *Cost-Benefit Analysis* (Total).

3.4.5 Module 5 – Multicriteria Analysis

Module 5 – Multicriteria Analysis (Figure 32) determines the most favourable LSF wall configuration (Solution A or B) considering three criteria: i) energy consumption; ii) environmental impacts, and; iii) acquisition cost. The values of each criterion, for solutions A and B, are displayed in two matrixes (Figure 32): i) Decision Matrix, and; ii) 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 32). In the Standardized Decision Matrix, the values of each criterion are adjusted on a scale 0 to 1 (Figure 32), where higher values mean greater benefits. The quantification of the criteria on a scale of 0 to 1 is carried out through a linear normalisation, using Equation 34,

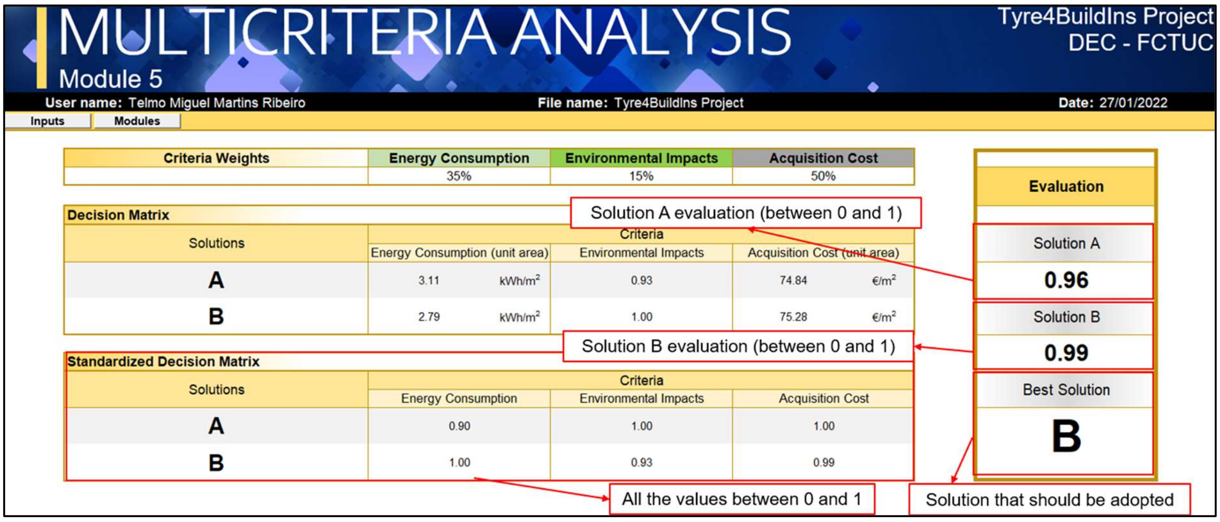
$$r_{ij} = \frac{min_i x_{ij}}{x_{ij}} \tag{34}$$

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. Thus, the final evaluation (FE) of each solution is determined by Equation 35:

$$FE = EC \times W_{EC} + EI \times W_{EI} + AC \times W_{AC} \quad (35)$$

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



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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	3.11	kWh/m²	0.93	74.84	€/m²
B	2.79	kWh/m²	1.00	75.28	€/m²

Standardized Decision Matrix

Solutions	Criteria		
	Energy Consumption	Environmental Impacts	Acquisition Cost
A	0.90	1.00	1.00
B	1.00	0.93	0.99

Evaluation
Solution A
0.96
Solution B
0.99
Best Solution
B

Solution A evaluation (between 0 and 1)

Solution B evaluation (between 0 and 1)

All the values between 0 and 1

Solution that should be adopted

Figure 32 – Layout of Module 5: Multicriteria Analysis.

4. COMPUTATIONAL VERIFICATIONS

4.1 Framework

In this chapter, the 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 12, the references of the parameter values associated with each material used in this dissertation are presented.

Table 12 – References of the parameter values of the materials.

Material	Thermal reference	Cost reference	LCA reference
Gypsum Plasterboard (12.5 mm)	(Gyptec, 2021)	(Gyptec, 2021)	(Gyproc, 2021)
OSB (12 mm)	(Sonae Arauco, 2021)	(Sonae Arauco, 2021)	(Egger, 2021)
Mineral Wool (90 mm)	(Volcalis, 2021)	(Volcalis, 2021)	(Knauf, 2021)
Steel Stud (C90 x 43 x 15 x 1.5 mm)	(Pertecno, 2021)	(Pertecno, 2021)	(Pertecno)
ETICS EPS (50 mm)	(Cype, 2021)	(Cype, 2021)	(Atlas, 2021)
Finishing Option (5 mm)	(Cype, 2021)	(Cype, 2021)	---
Mortar (5 mm)	(Santos, C., Matias, L., 2006)	---	---
XPS TB Strip (10 mm)	(IFoam, 2021)	(IFoam, 2021)	(Danosa, 2021)
EPS (50 mm)	(Isovit, 2021)	(Isovit, 2021)	---

4.2 Module 1 – *U*-value Calculator

The composition of the LSF wall considered in Module 1 verification is presented in Table 13.

Table 13 – 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 (C90 x 43 x 15 x 1.5 mm; 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 for the calculation of the thermal resistance values (R-values) using the five simplified analytical methods programmed in the tool is performed.

Combined Method

[$R_{tot;upper}$ | from Equation 12]

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

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

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

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

[$R_{inhomogeneous\ layer}$ | from Equation 13]

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

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

[$R_{tot;lower}$ | from Equation 15]

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

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

[$R_{tot;ISO}$ | from Equation 17]

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

<u>Gorgolewski Method 1</u>

[p factor | from Equation 19]

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

[$R_{tot;gorg1}$ | from Equation 18]

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

<u>Gorgolewski Method 2</u>

[p factor | from Table 10]

$$p = 0.50$$

[$R_{tot;gorg2}$ | from Equation 18]

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

<u>Gorgolewski Method 3</u>

[p factor | from Equation 20]

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

[$R_{tot;gorg3}$ | from Equation 18]

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

ASHRAE Zone Method

[$R_{tot;cav}$ | from Equation 20]

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

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

[w | from Equation 19]

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

[$R_{innerflange;MW}$ | from Equation 21]

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

[$R_{web;MW}$ | from Equation 22]

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

[$R_{outerflange;MW}$ | from Equation 23]

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

[$R_{tot;w}$ | from Equation 24]

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

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

[$R_{tot;ASHRAE}$ | from Equation 25]

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

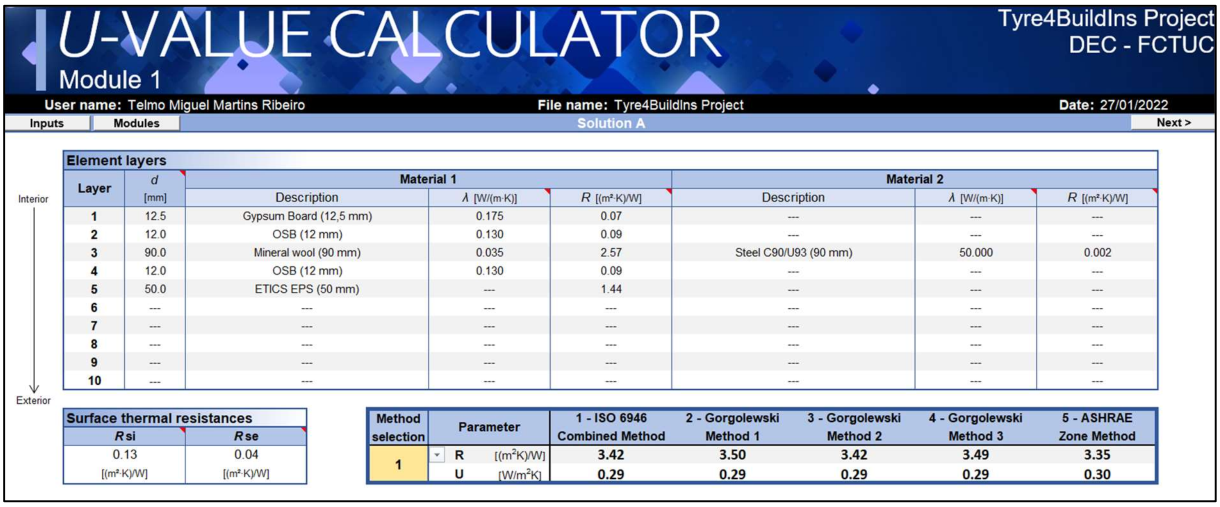
$$R_{tot;ASHRAE} = 3.35\ m^2 \cdot K \cdot W^{-1}$$

The summary of the results obtained above is presented in Table 14.

Table 14 – 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 33. 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.



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Element layers

Layer	d [mm]	Material 1			Material 2		
		Description	λ [W/(m·K)]	R [(m²·K)/W]	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	90.0	Mineral wool (90 mm)	0.035	2.57	Steel C90/U93 (90 mm)	50.000	0.002
4	12.0	OSB (12 mm)	0.130	0.09	---	---	---
5	50.0	ETICS EPS (50 mm)	---	1.44	---	---	---
6	---	---	---	---	---	---	---
7	---	---	---	---	---	---	---
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	[(m^{2}K)/W]	3.42	3.50	3.42	3.49	3.35
	U	[W/m^{2}K]	0.29	0.29	0.29	0.29	0.30

Figure 33 – 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 15 and Figure 34); ii) warm frame construction (Table 16 and Figure 35), and; iii) hybrid construction (Table 17 and Figure 36).

Table 15 – 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	---

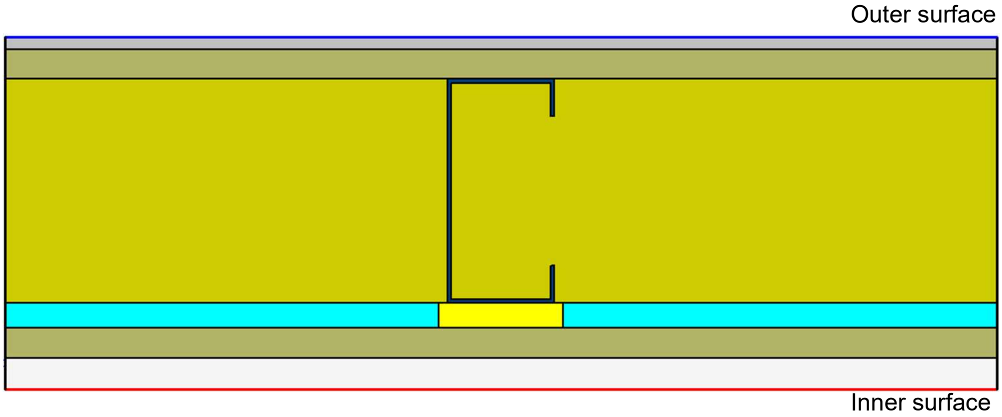


Figure 34 – LSF wall cross-section (cold frame construction).

Table 16 – 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 mm; ss: 400 mm)	90	--- | 50.000
OSB	12	0.100
EPS	50	0.036
Finishing	5	0.045
Total Thickness	191.5	---

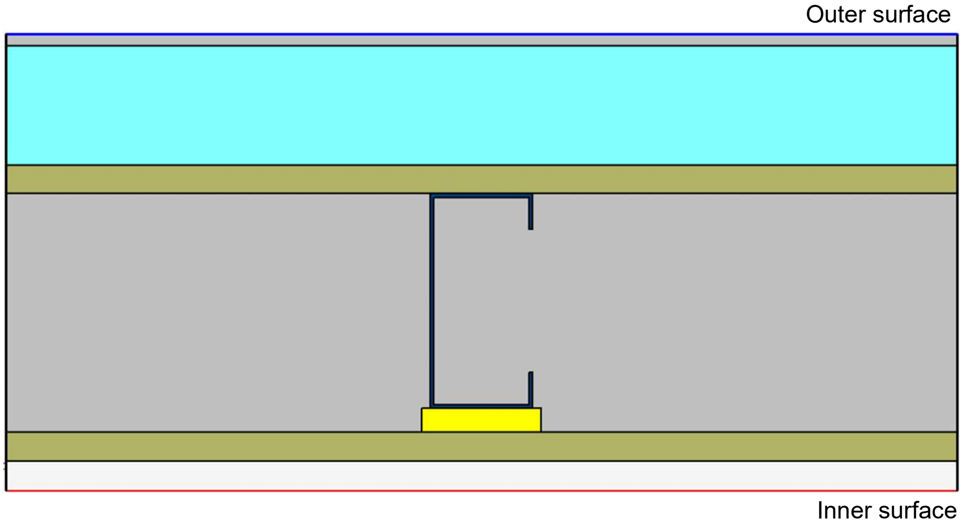


Figure 35 – LSF wall cross-section (warm frame construction).

Table 17 – 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	---

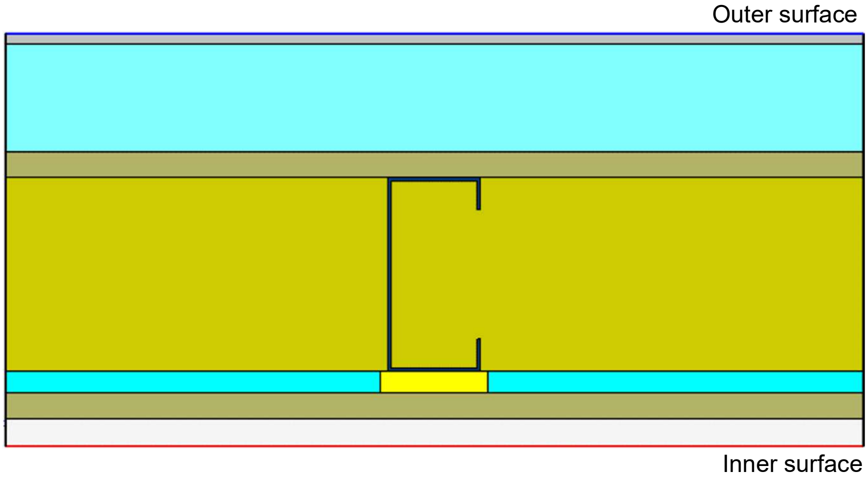


Figure 36 – LSF wall cross-section (hybrid construction).

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 18. In addition, for a better visualization of the differences obtained, the percentage differences are displayed graphically in Figure 37.

Table 18 – Thermal transmittance values, U: numerical simulations (THERM) vs analytical methods computed within the Tyre4BuildIns Tool.

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

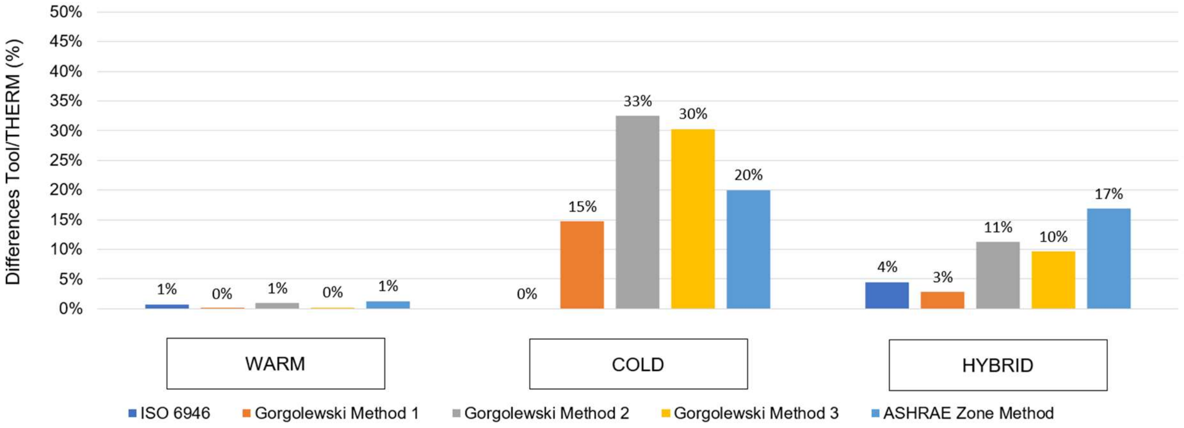


Figure 37 – Percentage differences between tool and THERM *U*-values.

The results obtained (Figure 37) allow to verify that, for all the cases evaluated, the *U*-values provided by the tool are higher than the *U*-values calculated 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 (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.

4.3 Module 2 – Energy Benefits

The verification of Module 2 was performed considering two LSF walls solutions, whose parameters are presented in Table 19.

Table 19 – 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 ºC	1508 ºC
Cooling Degree Days	212 ºC	73 ºC
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 below.

Solution A

[$Q_{tr}^{heating}$ | from Equation 29]

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

[$Q_{tr}^{cooling}$ | from Equation 29]

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

[E_{final} | from Equation 29]

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

Solution B

[Q_{tr}^{heati} | from Equation 29]

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

[$Q_{tr}^{cooling}$ | from Equation 29]

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

[E_{final} | from Equation 29]

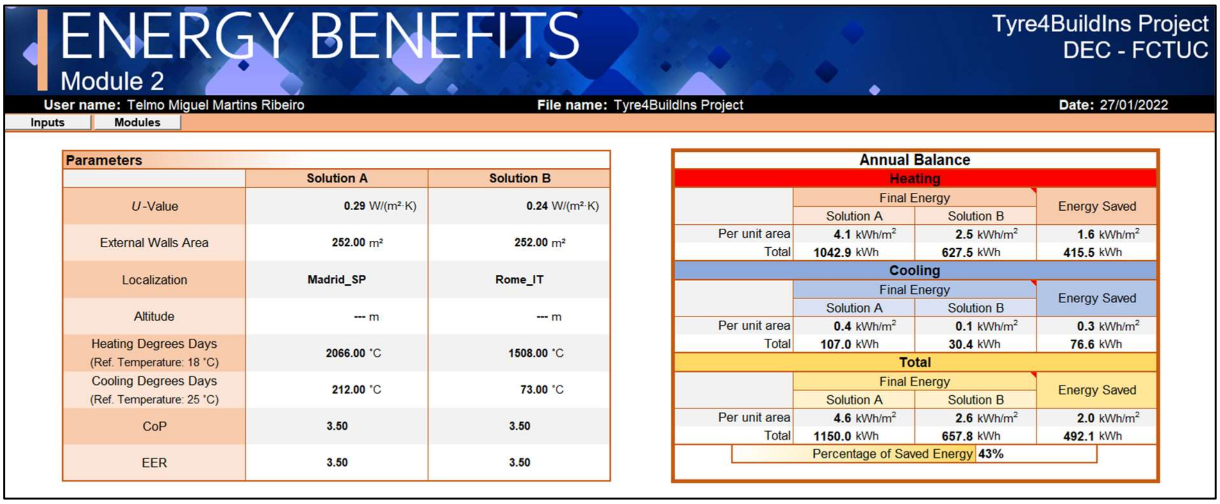
$$E_{final} = \frac{2196.188}{3.5} + \frac{106.314}{3.5} = 658\ kWh$$

<u>Saved Energy</u>

[E_{saved} | from Equation 29]

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

In Figure 38, 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.



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Parameters	Solution A	Solution B
U-Value	0.29 W/(m²·K)	0.24 W/(m²·K)
External Walls Area	252.00 m²	252.00 m²
Localization	Madrid_SP	Rome_IT
Altitude	--- m	--- m
Heating Degrees Days (Ref. Temperature: 18 °C)	2066.00 °C	1508.00 °C
Cooling Degrees Days (Ref. Temperature: 25 °C)	212.00 °C	73.00 °C
CoP	3.50	3.50
EER	3.50	3.50

Annual Balance			
Heating			
	Final Energy		Energy Saved
	Solution A	Solution B	
Per unit area	4.1 kWh/m²	2.5 kWh/m²	1.6 kWh/m²
Total	1042.9 kWh	627.5 kWh	415.5 kWh
Cooling			
	Final Energy		Energy Saved
	Solution A	Solution B	
Per unit area	0.4 kWh/m²	0.1 kWh/m²	0.3 kWh/m²
Total	107.0 kWh	30.4 kWh	76.6 kWh
Total			
	Final Energy		Energy Saved
	Solution A	Solution B	
Per unit area	4.6 kWh/m²	2.6 kWh/m²	2.0 kWh/m²
Total	1150.0 kWh	657.8 kWh	492.1 kWh
Percentage of Saved Energy	43%		

Figure 38 – Module 2 verification: Tyre4BuildIns Calculation Tool results.

4.4 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 20.

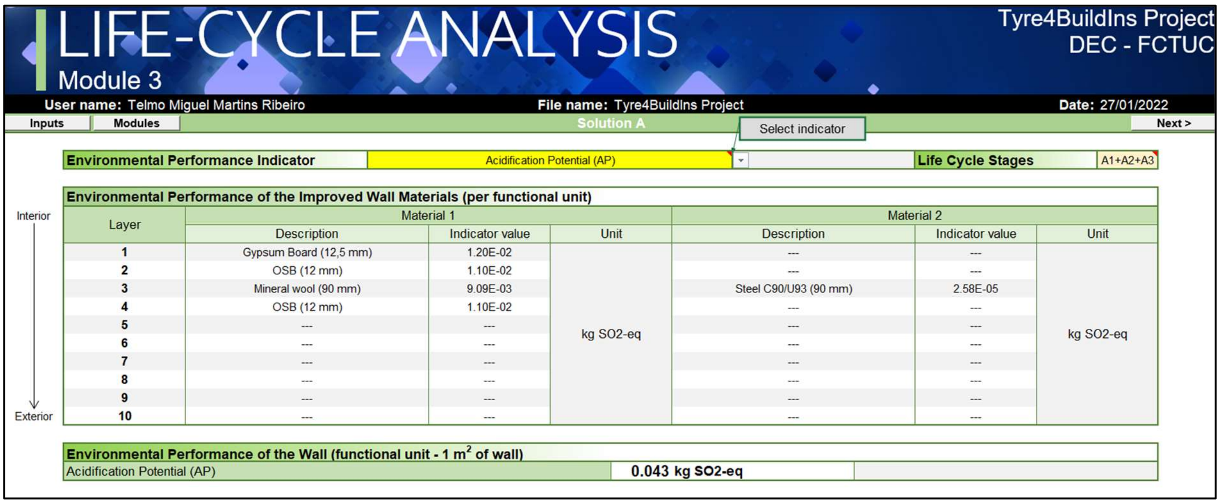
Table 20 – Composition and acidification potential value of the LSF wall.

Material (Inner to outer layer)	*d* [mm]	Acidification Potential [$kg \cdot SO_{2\text{-eq}}$]
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 values of each constituent material, the Acidification Potential (AP) of the LSF wall, per functional unit, is obtained by:

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

In Figure 39, 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.



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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			Material 2		
	Description	Indicator value	Unit	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	---	---		---	---	
6	---	---		---	---	
7	---	---		---	---	
8	---	---		---	---	
9	---	---		---	---	
10	---	---		---	---	

Environmental Performance of the Wall (functional unit - 1 m^2 of wall)

Acidification Potential (AP) **0.043 kg SO2-eq**

Figure 39 – Module 3 verification: print-screen of Solution A results.

4.5 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 taking into account: 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 21 and Table 22 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 21 – 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 22 – 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	---

Taking into account 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:

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

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

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

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

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

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

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

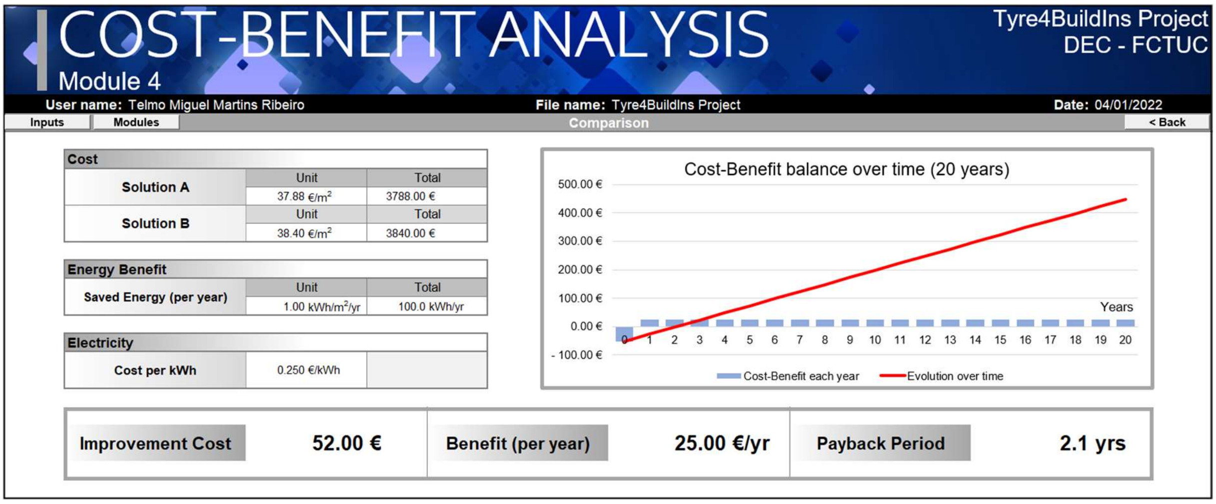
Regarding benefits, the annual benefit (AB) from using the thermally improved wall instead of the reference wall is calculated through,

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

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

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

In Figure 40, 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.



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Cost		
Solution A	Unit	Total
	37.88 €/m²	3788.00 €
Solution B	Unit	Total
	38.40 €/m²	3840.00 €

Energy Benefit		
Saved Energy (per year)	Unit	Total
	1.00 kWh/m²/yr	100.0 kWh/yr

Electricity		
Cost per kWh	0.250 €/kWh	

Improvement Cost	**52.00 €**	**Benefit (per year)**	**25.00 €/yr**	**Payback Period**	**2.1 yrs**

Figure 40 – Module 4 verification: print screen of the comparison worksheet.

4.6 Module 5 – Multicriteria Analysis

The verification of Module 5 – Multicriteria Analysis was carried out by comparing the results provided by the tool with the results obtained by performing the calculation procedure of the multicriteria analysis.

The data considered in this verification are presented in Table 23 (criteria weights) and Table 24 (decision matrix).

Table 23 – Module 5 verification: criteria weights.

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

Table 24 – Module 5 verification: decision matrix.

Decision Matrix			
Solutions	Criteria		
	Energy consumption	Environmental impacts	Acquisition costs
A	6.30 kWh/m^2	0.88	36.07 €/m^2
B	5.25 kWh/m^2	1.00	36.51 €/m^2

Using Equation 34, the standardized decision matrix presented in Table 25 was obtained.

Table 25 – Module 5 verification: standardized decision matrix.

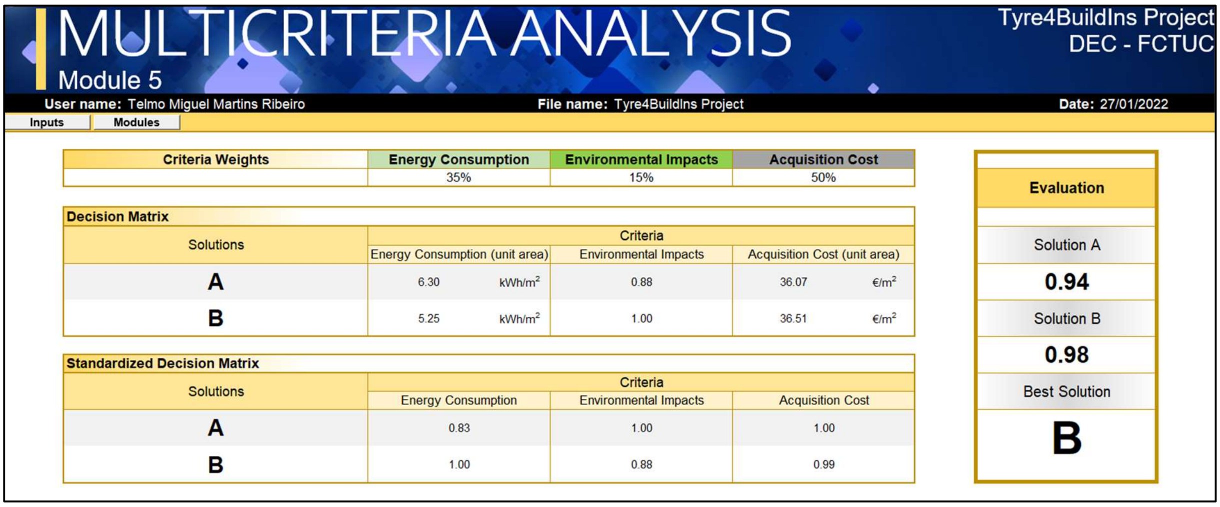
Standardized Decision Matrix			
Solutions	Criteria		
	Energy consumption	Environmental impacts	Acquisition costs
A	$^{5.25}/_{6.30} = 0.83$	$^{0.88}/_{0.88} = 1.00$	$^{36.07}/_{36.07} = 1.00$
B	$^{5.25}/_{5.25} = 1.00$	$^{0.88}/_{1.00} = 0.88$	$^{36.07}/_{36.51} = 0.99$

The final evaluation (FE) of solutions A and B is determined using Equation 35, 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 41. 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.



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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 41 – Module 5 verification: Tyre4BuildIns Calculation Tool results.

5. DESIGN EXAMPLE

5.1 Framework

In this chapter, in order to demonstrate the full operation of the calculation tool, a design example is performed. Firstly, the inputs used in this example are presented, 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.

5.2 Input data

The input data considered in this design example for Solution A (reference) and Solution B (improved) are presented in Table 26 and Table 27, respectively. In turn, Table 28 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 42 along the inner and outer flanges of the metal profiles in the improved solution (Solution B).

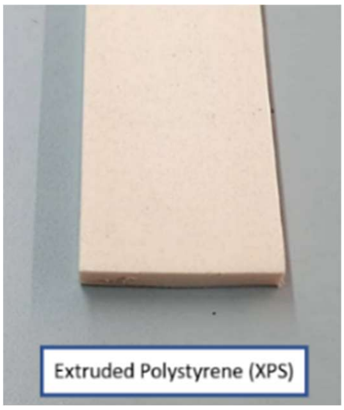


Figure 42 – Extruded polystyrene (XPS) thermal break strip.

Solution A – Reference Solution

Table 26 – Input data of Solution A – Reference Solution.

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)

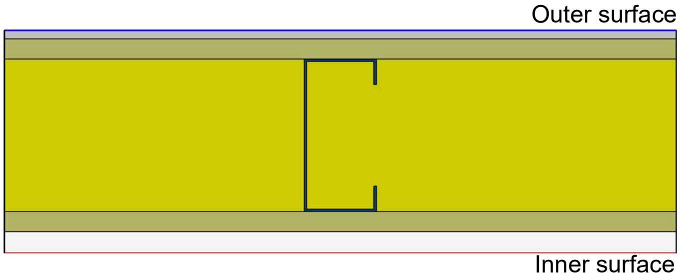
Length	10 m
Glazing Area	10%

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 27 – Input data of Solution B – Improved Solution.

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)

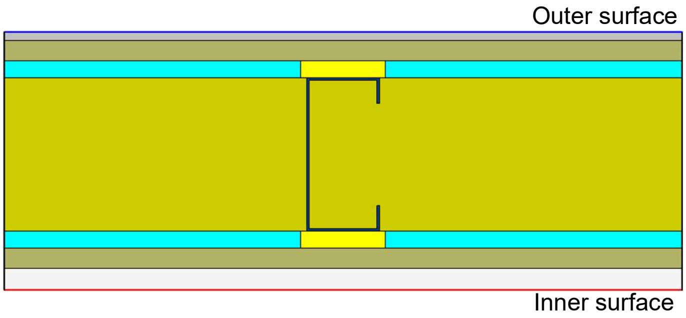
Length	10 m
Glazing Area	10%

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)

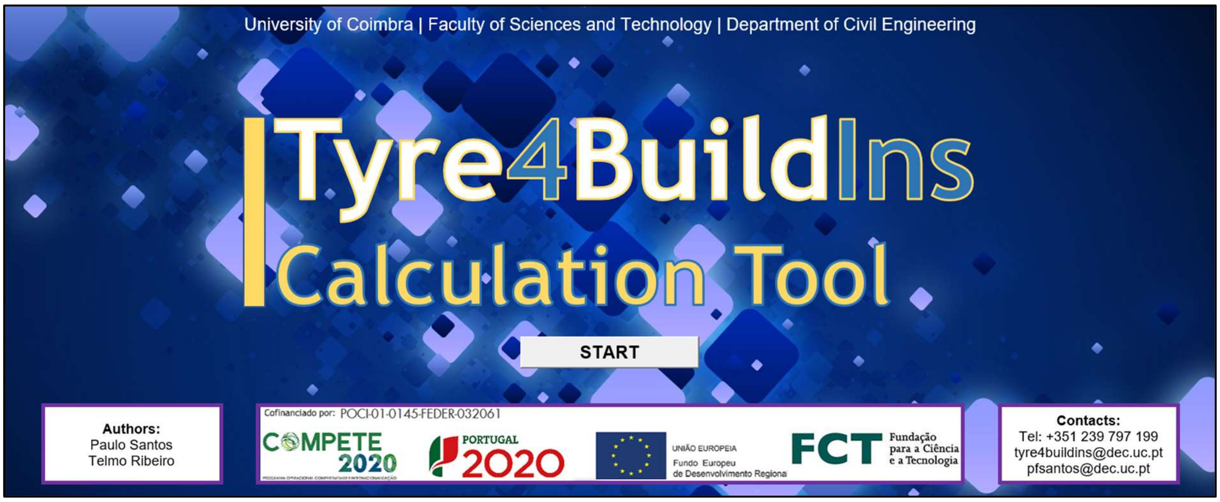
Table 28 – Input data of Multicriteria Analysis.

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 Resources (ADPF)	14%
Acidification potential (AP)	14%
Eutrophication potential (EP)	14%
Photochemical Ozone Creation Potential (POCP)	14%
Global warming potential (GWP)	16%
Stratospheric Ozone Layer Depletion Potential (ODP)	14%

5.3 Tool operation

The operation of the tool for this example is illustrated in Figures 43 to 60, 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.



University of Coimbra | Faculty of Sciences and Technology | Department of Civil Engineering

Tyre4BuildIns
Calculation Tool

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tyre4buildins@dec.uc.pt
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Figure 43 – Design example: Tab 1 of Tyre4BuildIns Calculation Tool.

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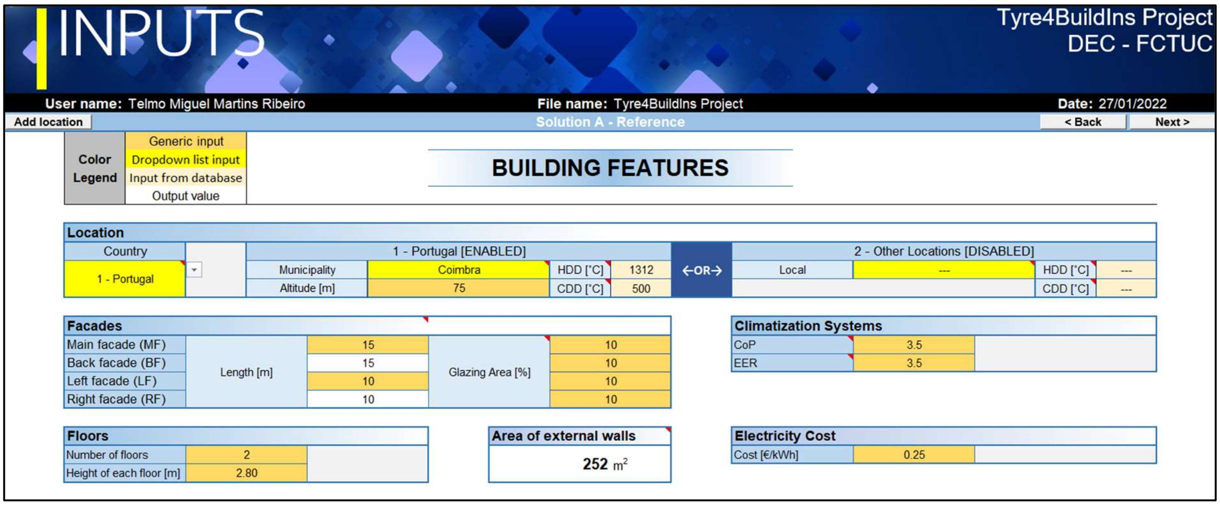
File name: Tyre4BuildIns Project

Date: 27/01/2022

Figure 44 – Design example: Tab 2 of Tyre4BuildIns Calculation Tool.



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Solution A - Reference

Color Legend: Generic input | Dropdown list input | Input from database | Output value

BUILDING FEATURES

Location

Country		1 - Portugal [ENABLED]				2 - Other Locations [DISABLED]			
1 - Portugal		Municipality	Coimbra	HDD [°C]	1312	Local	---	HDD [°C]	---
		Altitude [m]	75	CDD [°C]	500			CDD [°C]	---

Facades

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

Climatization Systems

CoP	3.5
EER	3.5

Floors

Number of floors	2
Height of each floor [m]	2.80

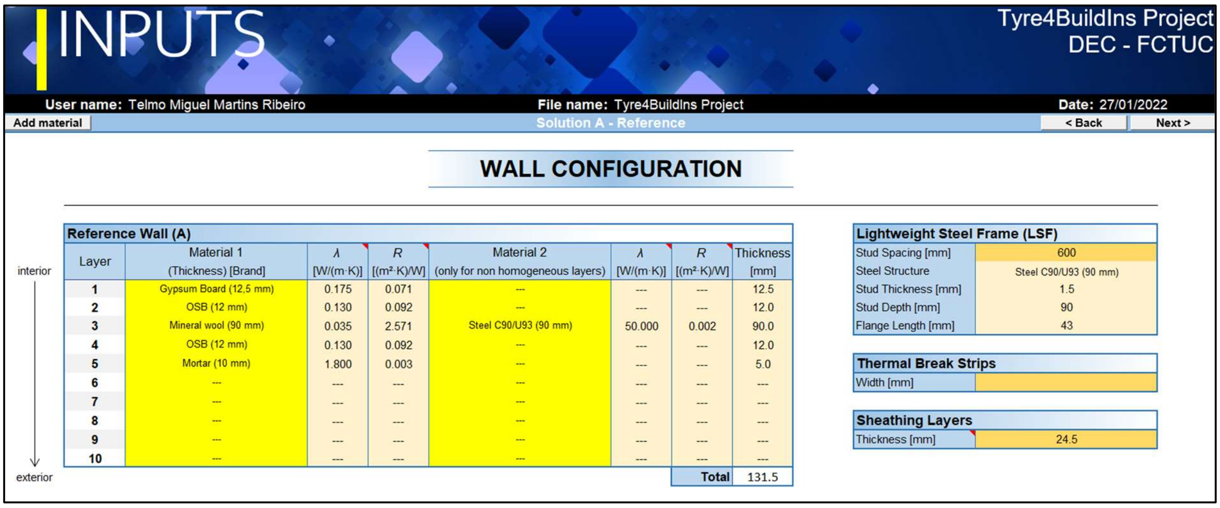
Area of external walls

252 m²

Electricity Cost

Cost [€/kWh]	0.25

Figure 45 – Design example: Tab 3 of Tyre4BuildIns Calculation Tool.



User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

Solution A - Reference

WALL CONFIGURATION

Reference Wall (A)

Layer	Material 1 (Thickness) [Brand]	λ [W/(m·K)]	R [(m²·K)/W]	Material 2 (only for non homogeneous layers)	λ [W/(m·K)]	R [(m²·K)/W]	Thickness [mm]
1	Gypsum Board (12,5 mm)	0.175	0.071	---	---	---	12.5
2	OSB (12 mm)	0.130	0.092	---	---	---	12.0
3	Mineral wool (90 mm)	0.035	2.571	Steel C90/U93 (90 mm)	50.000	0.002	90.0
4	OSB (12 mm)	0.130	0.092	---	---	---	12.0
5	Mortar (10 mm)	1.800	0.003	---	---	---	5.0
6	---	---	---	---	---	---	---
7	---	---	---	---	---	---	---
8	---	---	---	---	---	---	---
9	---	---	---	---	---	---	---
10	---	---	---	---	---	---	---
						Total	131.5

Lightweight Steel Frame (LSF)

Stud Spacing [mm]	600
Steel Structure	Steel C90/U93 (90 mm)
Stud Thickness [mm]	1.5
Stud Depth [mm]	90
Flange Length [mm]	43

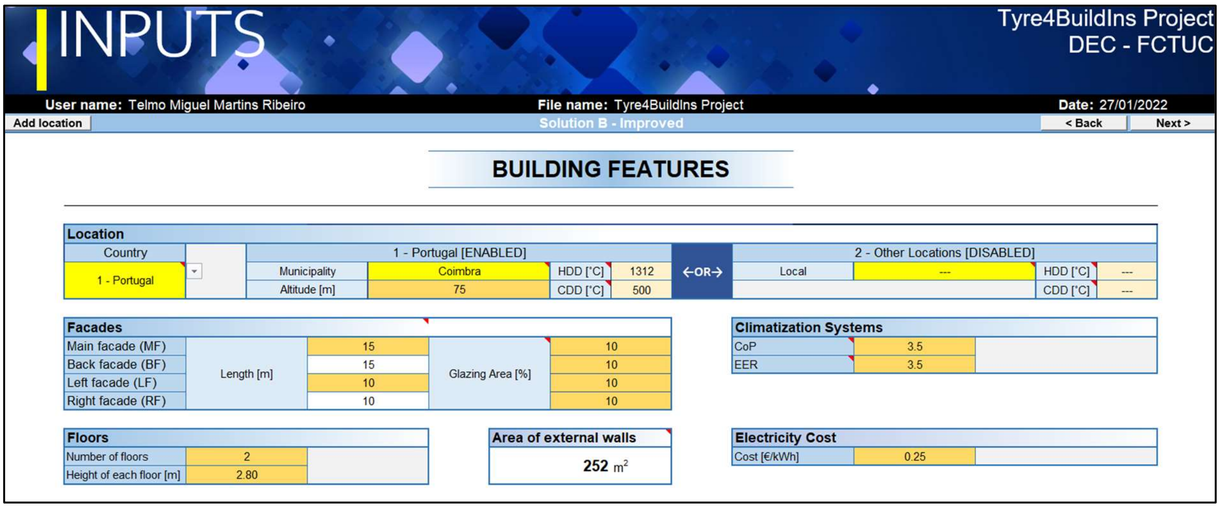
Thermal Break Strips

Width [mm]	

Sheathing Layers

Thickness [mm]	24.5

Figure 46 – Design example: Tab 4 of Tyre4BuildIns Calculation Tool.



User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

Solution B - Improved

BUILDING FEATURES

Location

Country	1 - Portugal [ENABLED]				2 - Other Locations [DISABLED]			
1 - Portugal	Municipality	Coimbra	HDD [°C]	1312	Local	---	HDD [°C]	---
	Altitude [m]	75	CDD [°C]	500			CDD [°C]	---

Facades

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

Climatization Systems

CoP	3.5
EER	3.5

Floors

Number of floors	2
Height of each floor [m]	2.80

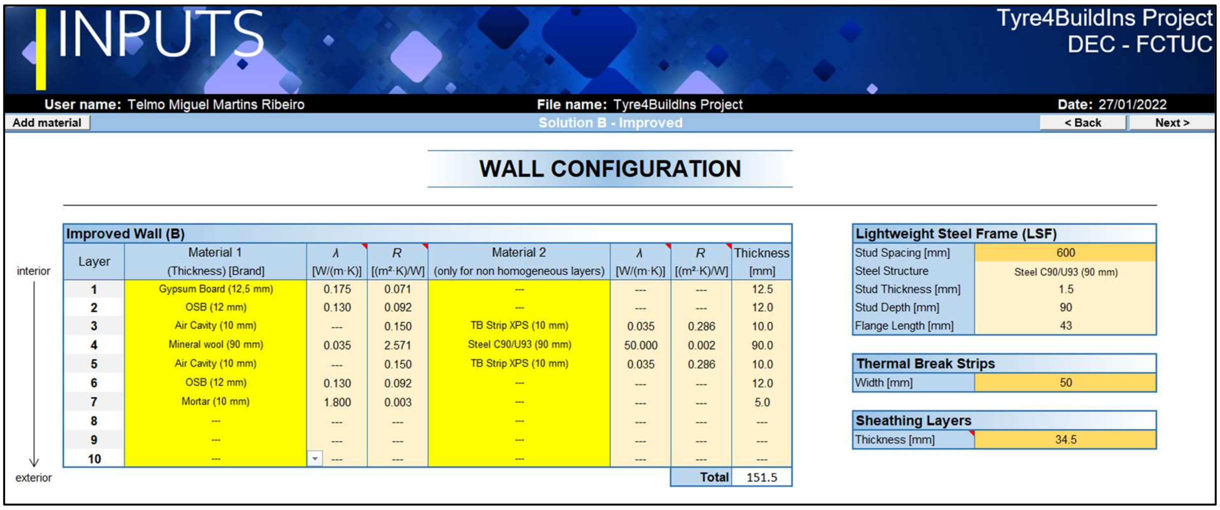
Area of external walls

252 m²

Electricity Cost

Cost [€/kWh]	0.25

Figure 47 – Design example: Tab 5 of Tyre4BuildIns Calculation Tool.



User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

Solution B - Improved

WALL CONFIGURATION

Improved Wall (B)

Layer	Material 1 (Thickness) [Brand]	λ [W/(m·K)]	R [(m²·K)/W]	Material 2 (only for non homogeneous layers)	λ [W/(m·K)]	R [(m²·K)/W]	Thickness [mm]
1	Gypsum Board (12,5 mm)	0.175	0.071	---	---	---	12.5
2	OSB (12 mm)	0.130	0.092	---	---	---	12.0
3	Air Cavity (10 mm)	---	0.150	TB Strip XPS (10 mm)	0.035	0.286	10.0
4	Mineral wool (90 mm)	0.035	2.571	Steel C90/U93 (90 mm)	50.000	0.002	90.0
5	Air Cavity (10 mm)	---	0.150	TB Strip XPS (10 mm)	0.035	0.286	10.0
6	OSB (12 mm)	0.130	0.092	---	---	---	12.0
7	Mortar (10 mm)	1.800	0.003	---	---	---	5.0
8	---	---	---	---	---	---	---
9	---	---	---	---	---	---	---
10	---	---	---	---	---	---	---
						Total	151.5

Lightweight Steel Frame (LSF)

Stud Spacing [mm]	600
Steel Structure	Steel C90/U93 (90 mm)
Stud Thickness [mm]	1.5
Stud Depth [mm]	90
Flange Length [mm]	43

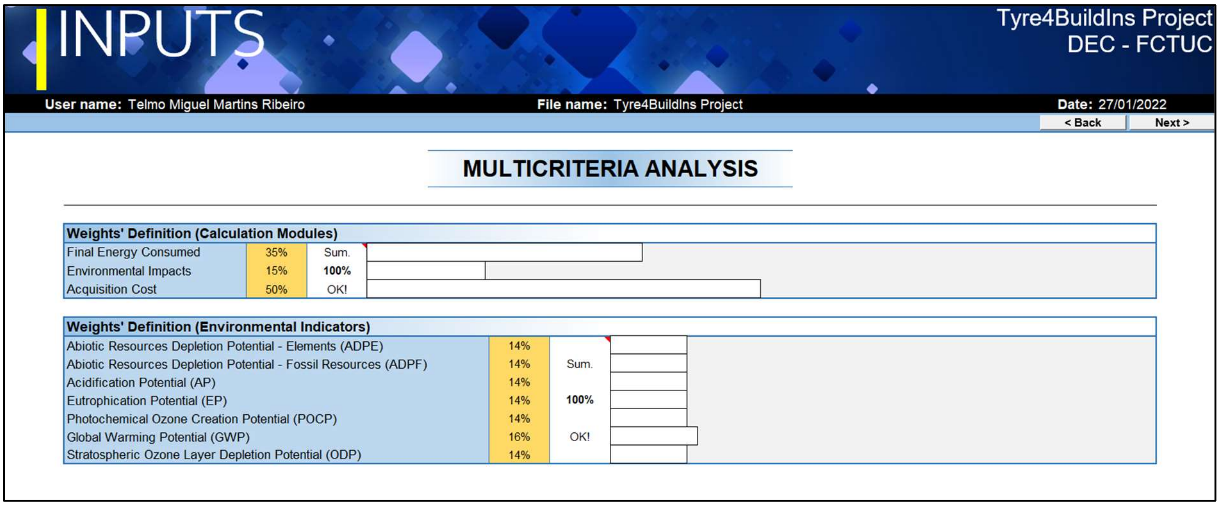
Thermal Break Strips

Width [mm]	50

Sheathing Layers

Thickness [mm]	34.5

Figure 48 – Design example: Tab 6 of Tyre4BuildIns Calculation Tool.



User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

MULTICRITERIA ANALYSIS

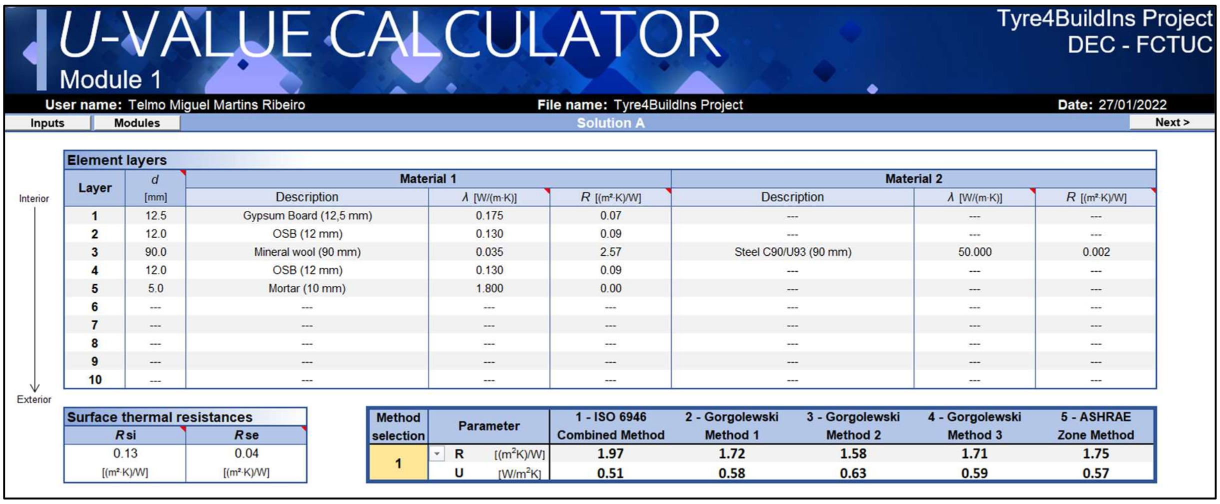
Weights' Definition (Calculation Modules)		
Final Energy Consumed	35%	Sum.
Environmental Impacts	15%	**100%**
Acquisition Cost	50%	OK!

Weights' Definition (Environmental Indicators)		
Abiotic Resources Depletion Potential - Elements (ADPE)	14%	
Abiotic Resources Depletion Potential - Fossil Resources (ADPF)	14%	Sum.
Acidification Potential (AP)	14%	
Eutrophication Potential (EP)	14%	**100%**
Photochemical Ozone Creation Potential (POCP)	14%	
Global Warming Potential (GWP)	16%	OK!
Stratospheric Ozone Layer Depletion Potential (ODP)	14%	

Figure 49 – Design example: Tab 7 of Tyre4BuildIns Calculation Tool.

User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

Figure 50 – Design example: Tab 8 of Tyre4BuildIns Calculation Tool.



User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

Element layers

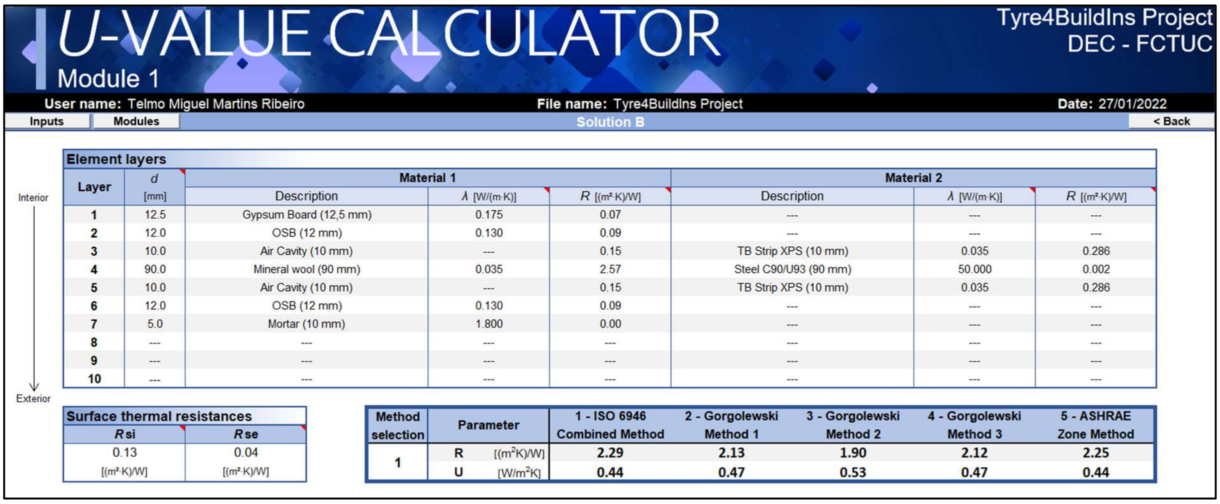
Layer	*d* [mm]	Material 1			Material 2		
		Description	*λ* [W/(m·K)]	*R* [(m²·K)/W]	Description	*λ* [W/(m·K)]	*R* [(m²·K)/W]
1	12.5	Gypsum Board (12,5 mm)	0.175	0.07	---	---	---
2	12.0	OSB (12 mm)	0.130	0.09	---	---	---
3	90.0	Mineral wool (90 mm)	0.035	2.57	Steel C90/U93 (90 mm)	50.000	0.002
4	12.0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

Surface thermal resistances

*R*si	*R*se
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]	**1.97**	**1.72**	**1.58**	**1.71**	**1.75**
	U	[W/m²K]	**0.51**	**0.58**	**0.63**	**0.59**	**0.57**

Figure 51 – Design example: Tab 9 of Tyre4BuildIns Calculation Tool.



User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

Solution B

Element layers

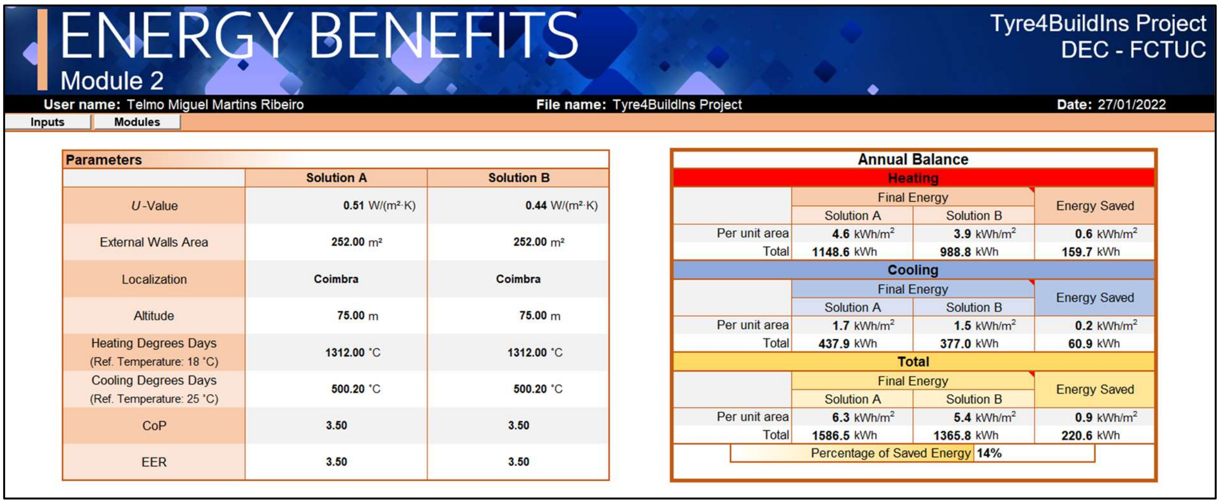
Layer	d [mm]	Material 1 Description	λ [W/(m·K)]	R [(m²·K)/W]	Material 2 Description	λ [W/(m·K)]	R [(m²·K)/W]
1	12.5	Gypsum Board (12,5 mm)	0.175	0.07	---	---	---
2	12.0	OSB (12 mm)	0.130	0.09	---	---	---
3	10.0	Air Cavity (10 mm)	---	0.15	TB Strip XPS (10 mm)	0.035	0.286
4	90.0	Mineral wool (90 mm)	0.035	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	0.04
[(m²·K)/W]	[(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 52 – Design example: Tab 10 of Tyre4BuildIns Calculation Tool.



User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

Parameters

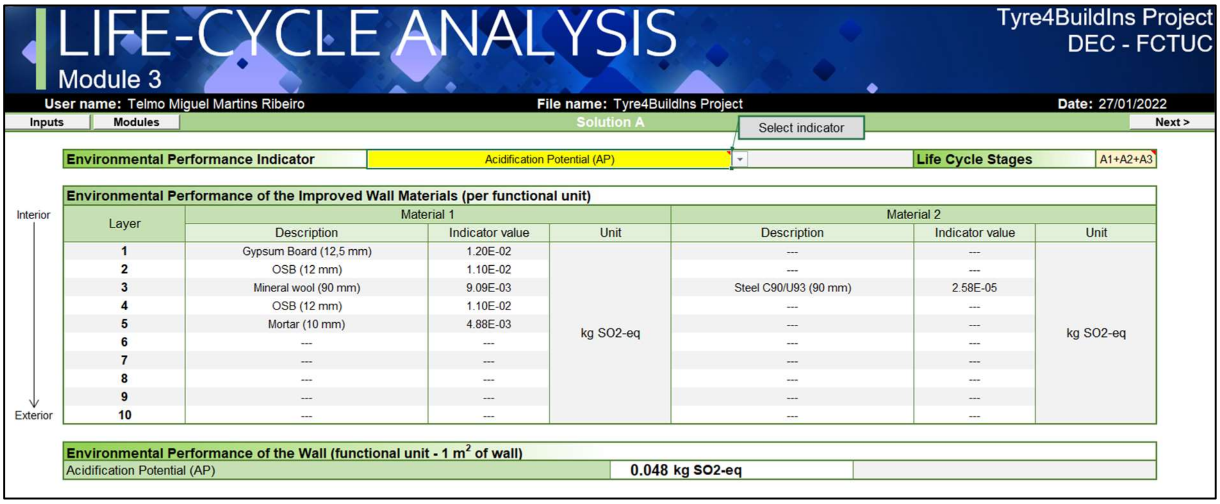
	Solution A	Solution B
U-Value	0.51 W/(m²·K)	0.44 W/(m²·K)
External Walls Area	252.00 m²	252.00 m²
Localization	Coimbra	Coimbra
Altitude	75.00 m	75.00 m
Heating Degrees Days (Ref. Temperature: 18 °C)	1312.00 °C	1312.00 °C
Cooling Degrees Days (Ref. Temperature: 25 °C)	500.20 °C	500.20 °C
CoP	3.50	3.50
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 53 – Design example: Tab 11 of Tyre4BuildIns Calculation Tool.



User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

Solution A

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

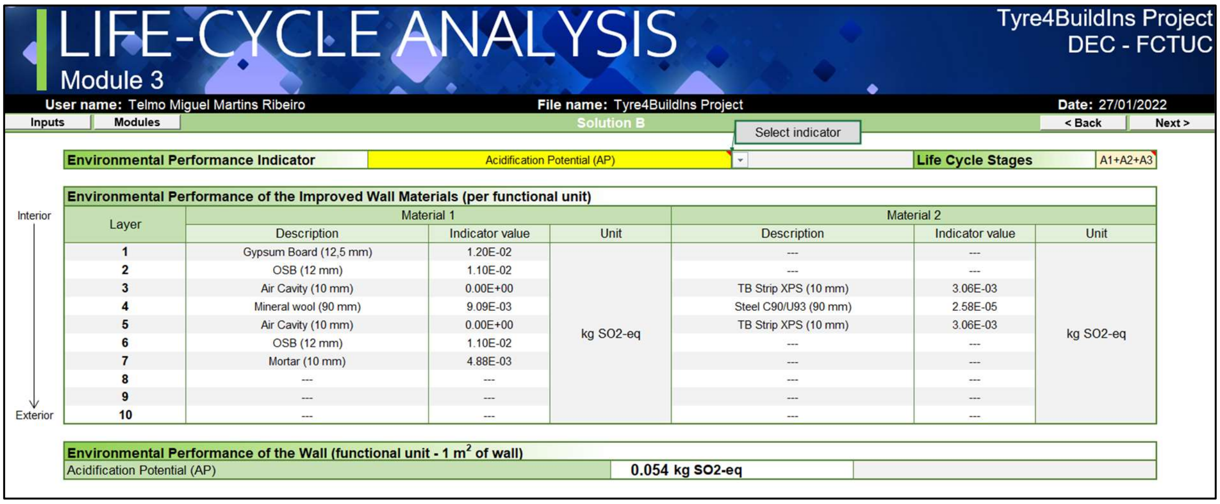
Environmental Performance of the Improved Wall Materials (per functional unit)

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 m^2 of wall)

Acidification Potential (AP) 0.048 kg SO2-eq

Figure 54 – Design example: Tab 12 of Tyre4BuildIns Calculation Tool.



User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

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

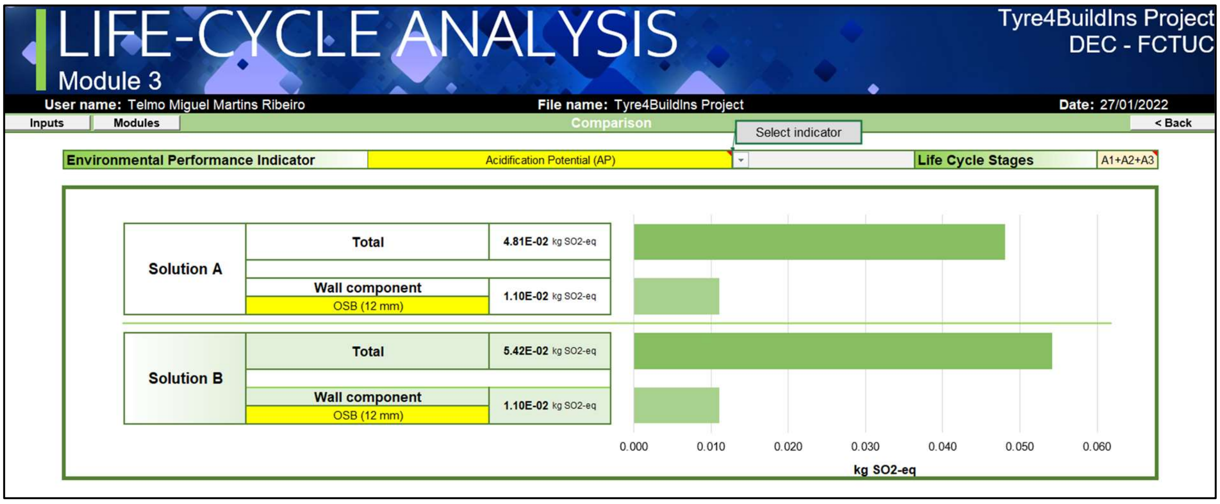
Environmental Performance of the Improved Wall Materials (per functional unit)

Layer	Material 1			Material 2		
	Description	Indicator value	Unit	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	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 55 – Design example: Tab 13 of Tyre4BuildIns Calculation Tool.

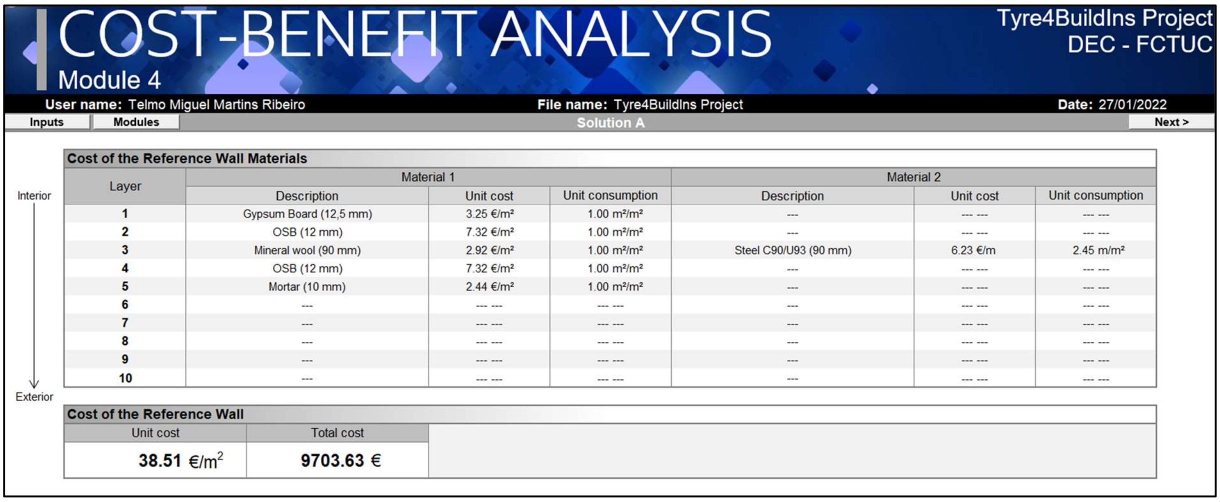


User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

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

Solution A	**Total**	**4.81E-02** kg SO2-eq
	Wall component OSB (12 mm)	**1.10E-02** kg SO2-eq
Solution B	**Total**	**5.42E-02** kg SO2-eq
	Wall component OSB (12 mm)	**1.10E-02** kg SO2-eq

Figure 56 – Design example: Tab 14 of Tyre4BuildIns Calculation Tool.



User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

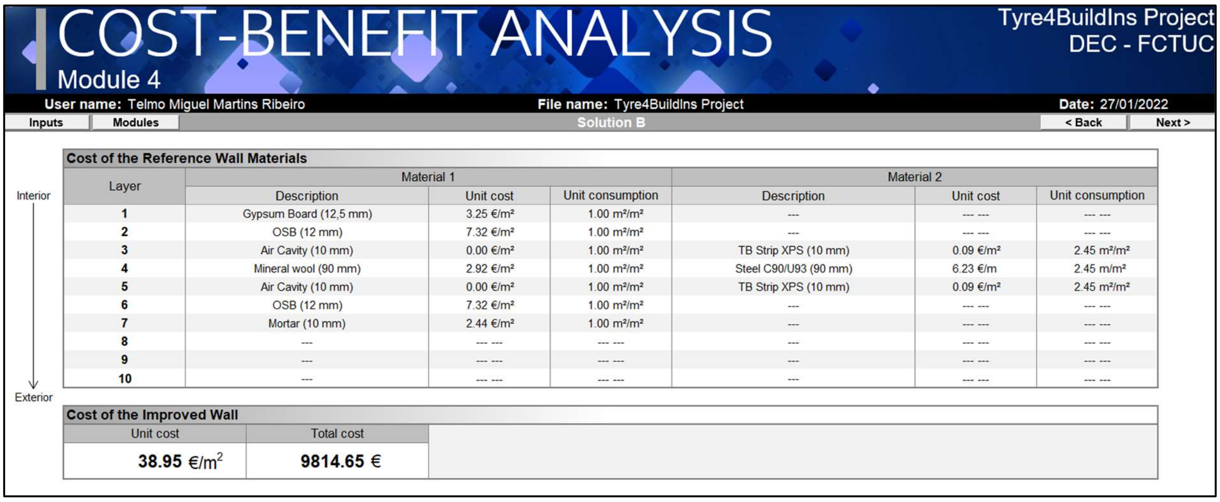
Cost of the Reference Wall Materials

Layer	Material 1			Material 2		
	Description	Unit cost	Unit consumption	Description	Unit cost	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 57 – Design example: Tab 15 of Tyre4BuildIns Calculation Tool.



User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

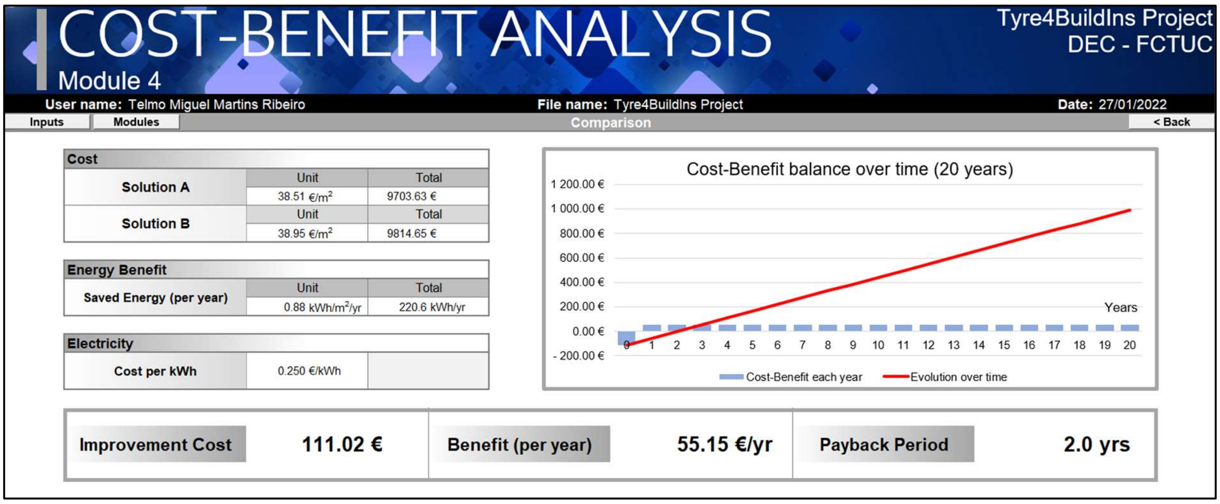
Cost of the Reference Wall Materials

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

Cost of the Improved Wall

Unit cost	Total cost
38.95 €/m^2	**9814.65 €**

Figure 58 – Design example: Tab 16 of Tyre4BuildIns Calculation Tool.



User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

Cost

	Unit	Total
Solution A	38.51 €/m^2	9703.63 €
Solution B	38.95 €/m^2	9814.65 €

Energy Benefit

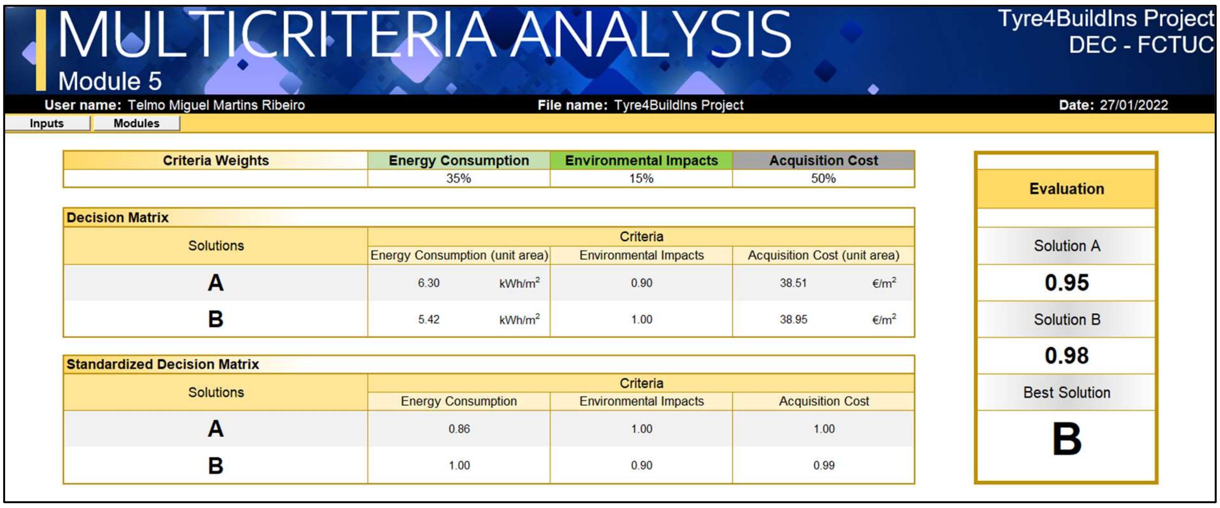
	Unit	Total
Saved Energy (per year)	0.88 kWh/m^2/yr	220.6 kWh/yr

Electricity

Cost per kWh	0.250 €/kWh	

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

Figure 59 – Design example: Tab 17 of Tyre4BuildIns Calculation Tool.



User name: Telmo Miguel Martins Ribeiro **File name:** Tyre4BuildIns Project **Date:** 27/01/2022

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/m^2	0.90	38.51 €/m^2
B	5.42 kWh/m^2	1.00	38.95 €/m^2

Standardized Decision Matrix

Solutions	Criteria		
	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 60 – Design example: Tab 18 of Tyre4BuildIns Calculation Tool.

6. CONCLUSIONS AND FUTURE WORK

In this dissertation, an automatic calculation tool to evaluate the performance of LSF walls was developed. The Tyre4BuildIns Calculation Tool was developed in *Microsoft Excel* format and performs a comparative analysis between two LSF walls considering four aspects: i) thermal transmittance coefficient (Module 1), ii) energy benefits (Module 2), iii) life cycle analysis (Module 3) and iv) cost-benefit analysis (Module 4). Additionally, Module 5 performs a multicriteria analysis based on the four aspects mentioned, and indicates which solution is the most favourable.

Tyre4BuildIns Calculation Tool provides a set of functionalities for the performance evaluation of LSF walls, through the operation of five calculation modules. Module 1 – *U-value Calculator* determines the thermal transmittance coefficient (and the thermal resistance values) of LSF walls, using five analytical methods: i) ISO 6946 Combined Method; ii) Gorgolewski Method 1; iii) Gorgolewski Method 2; iv) Gorgolewski Method 3, and; v) ASHRAE Zone Method. In turn, Module 2 – *Energy Benefits* calculates the energy benefits provided by the adoption of a thermally improved wall (Solution B), instead of a reference wall (Solution B) with lower thermal resistance. In addition of the constitution of the wall, the location and features of the building where the wall will be inserted are also considered. Next, Module 3 – *Life-Cycle Analysis* performs a quantification of the environmental impacts associated to the LSF walls considered, through a life cycle analysis. The assessment of the environmental impacts is carried out considering seven environmental indicators: i) Abiotic Resources Depletion Potential – Elements (ADPE); ii) Abiotic Resources Depletion Potential – Fossil Resources (ADPF); iii) Acidification Potential (AP); iv) Eutrophication Potential (EP); v) Photochemical Ozone Creation Potential (POCP); vi) Global Warming Potential (GWP), and; vii) Stratospheric Ozone Layer Depletion Potential (ODP). In Module 4 – *Cost-Benefit Analysis* the costs (in terms of materials) associated with the walls under analysis, and the benefits provided by the energy savings determined in Module 2 are evaluated. Furthermore, 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, is also indicated by this module. Finally, Module 5 – Multicriteria Analysis performs a multicriteria analysis based on the results provided by the previous modules, considering the criteria weights defined in the inputs stage. This module performs a final evaluation of the two solutions, and indicates the most favourable solution.

The computational verifications performed in Chapter 4 demonstrated that the Tyre4BuildIns Calculation Tool presents a correct programming of the calculation methodologies used and provides reliable results in all calculation modules. Furthermore, regarding Module 1 – U-value Calculator the comparison of U-values provided by the calculation tool through analytical methods with those calculated using numerical simulations, revealed that the results given by the tool are accurate, especially in warm frame LSF walls.

The greatest value of the Tyre4BuildIns Calculation Tool is the possibility of carrying out a global and integrated analysis of the LSF walls, evaluating the main aspects that characterise them. Furthermore, the possibility of assigning different weights for the evaluation of the various criteria under analysis is an important functionality, since it allows the analysis to be carried out by giving the importance to each criterion desired by the user. A global and integrated analysis in the definition of the construction element makes it possible to find the solution that offers the best combination considering acquisition costs, thermal behaviour and environmental impacts. This type of analysis becomes even more important with the growing environmental concerns and the need to implement more sustainable constructions.

Tyre4BuildIns Calculation Tool can be an important tool in the area of LSF construction, helping in the definition of the most favourable LSF wall solution. Regarding future works, the development of a tool that allows the analysis of the performance of other constructive elements may also be useful. Walls made of other materials, roofing or glazing are some constructive elements of the building outer envelope that could be included in another calculation tool. Another possible future work would be the adaptation of the Tyre4BuildIns Calculation Tool to other formats. The use of this tool through a website or an application for computers and mobile phones would be a way to make it more easily accessible.

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