RIBuild WP5 software tool

WP5 software tool has been developed within RIBuild Work Package 5 "*Development of cost/benefit and environmental impact assessment methodology based on building practice and intended use"*, whose aim was the development of a "probabilistic" approach for assessing the environmental impacts and global costs of internal insulation solutions for historic buildings based on a life cycle perspective. The Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) probabilistic methodologies developed in RIBuild WP5 are documented in deliverable reports 5.1 and 5.2. and available at this link: https://www.ribuild.eu/work-packages.

The LCC and LCA probabilistic approach, based on Monte-Carlo simulation, provides real-time estimates of the range and likelihood of the life-cycle costs and impacts, rather than single deterministic results, based on data inputs distributions, and can be used to support decision making. The tool for sensitivity analysis included in WP5 software offers an idea of the significance of input parameters' uncertainties and their impacts on the results.

The software allows performing the LCA and LCC "at component level", i.e. the assessments are performed for 1 m^2 of internally insulated walls ("case studies"), under several possible scenarios (energy scenarios, macro-economic scenarios and calculation periods). WP5 software tool already includes a database of case studies, based on RIBuild project research, and related LCA and LCC data inputs are set. As shown later, the user can start from them and modify related input data, if needed, or can add new cases he wants to assess.

This guide provides instructions for the use of WP5 software tool. Appendix 1 reports details on the LCA and LCC calculation assumptions, Appendix 2 presents the list of the national case studies included in the software database, Appendix 3 provides the software license.

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1.2 User guide

The tool web interface (Figure 1) contains the Main Menu with the following items: *Home*, *Pre-processing*, *Editing*, *LCC Run*, *LCA Run*, *Save results*.

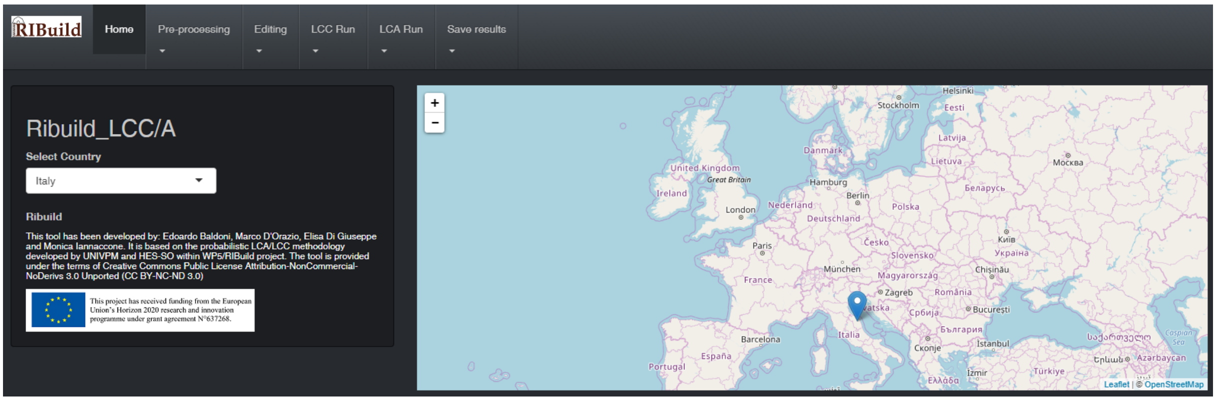


Figure 1 WP5 software tool homepage

Home

In the *Home* page (Figure 2), the user can select the Country where perform the LCC or the LCA assessment (or both). According to this selection, the internally insulated wall case studies included in the software database are filtered, and consequently specific national LCC and LCA data input are automatically selected. However, the user can always modify later (*Editing* menu) LCC and LCA data input, if he wants to assess new and different cases.

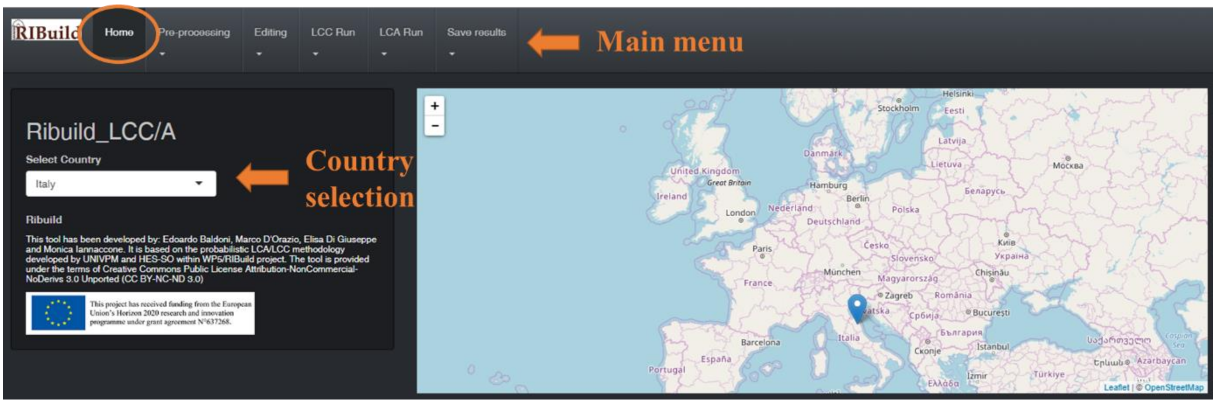


Figure 2 WP5 software tool homepage. Country selection.

Pre-processing

The *Pre-processing* menu contains the following items: *Visualize data*, *New system impact generation*, *Economic Scenario visualization*, *Qh calculation*.

Visualize data

In *Visualize data* (Figure 3), the user selects the insulation systems included into the database (for the previously selected country) and, by pushing on *visualize* button, he gets the Probability Distributions (PDFs) of the related LCA and LCC data inputs, i.e.: the system CI (investment cost), CM (maintenance cost), SL (service life), sI (environmental impact related to the production phase), smI (environmental impact related to the maintenance phase), EoLI (environmental impact related to the end of life phase).

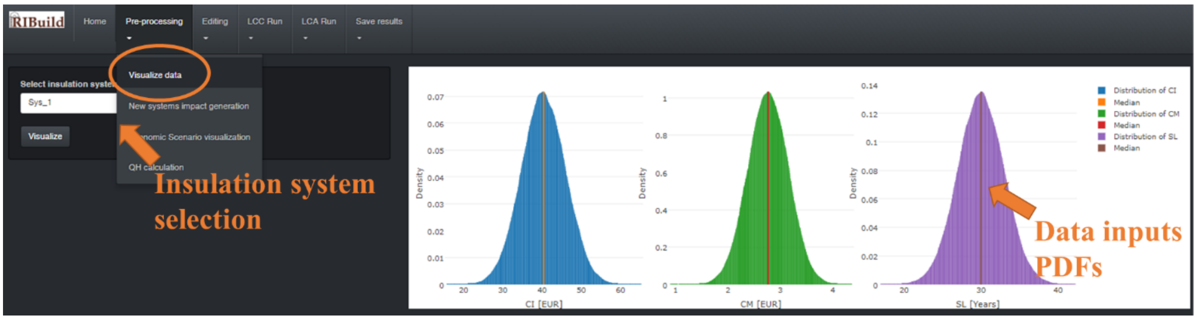


Figure 3 ***Pre-processing*** **menu → *Visualize data*, visualization of the PDFs of LCA and LCC data inputs**

New system impact generation

In *New system impact generation* (Figure 4), the user can create a new insulation system based on the materials available in the database, and calculate its environmental impact due to production, maintenance and end of life phases.

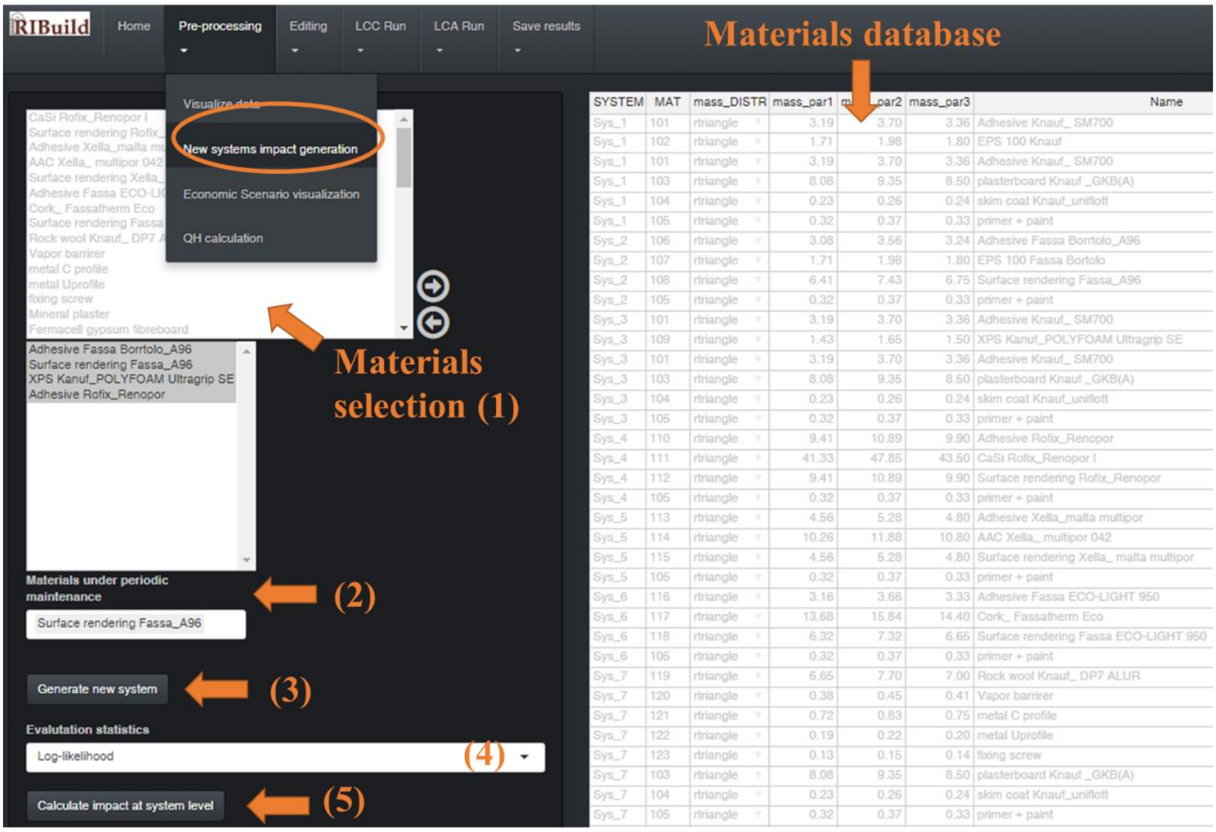


Figure 4 ***Pre-processing*** **menu → *New system impact generation*. Procedure for the creation of a new insulation system based on the materials available in the database and calculation of its environmental impact due to production, maintenance and end of life phases.**

At this aim, the user must (1) select the materials composing the new insulation system by highlighting their name on the table on the top left (multiple selection through CTRL or SHIFT is allowed) and pushing on the right arrow. Left arrow can be used to remove materials from the selection. The user can also directly edit materials data reported on the material database (table on the right) in order to personalize some materials' informations.

Then the user can (2) decide which materials of those selected will be subjected to periodic maintenance (if any), e.g. the internal painting (considering a maintenance frequency equal to the painting material service life reported in the table on the right).

Finally (3) the user must push the *generate new system* button. The new system generated is now included at the end of the table on the right (with a progressive numbering).

In order to calculate the environmental impact at insulation system level starting from the materials' impacts, it is necessary to (4) establish the evaluation statistics typology (Log-likelihood or Akaike criterion) and then (5) push the *Calculate impact at system level* button. The calculation is performed through basic random Monte-Carlo with 1000 iterations and distributions are estimated through a data-fitting test. Negative values for the impacts are not taken into account, so normal distributions are automatically converted into truncated normal distributions. The calculation may take a few dozen seconds (a time bar will appear on the right).

QH calculation

In *QH calculation* (Figure 5), the user can assess the heat transmission losses through the wall during the heating period [kWh/year] based on a simplified Heating Degree Days (HDD) methodology, as described in Appendix 1[1]. Qh can refer to the heat losses before (Qh_{pre}) or after (Qh_{post}) the insulation intervention.

For the case studies included into the software database, Qh_{pre} and Qh_{post} are already defined. However, the user can take this step to personalize his assessment.

In *QH calculation*, the user must:

1. select the insulation system;
2. select the EU region for the assessment[2];
3. select the existing wall surface-to-surface thermal resistance range [m^2K/W] (surfaces thermal resistances excluded).

If the user is evaluating a new system created under *New system impact generation*, he must also provide a value (*DU*) for the surface-to-surface thermal resistance of the insulation system (m^2K/W) (surfaces thermal resistances excluded).

Once pushed the *Run* button (4), summary data (5) and PDFs of Qh_{post} and Qh_{pre} for the case study will be represented on the right. These data can be copied (CTRL+c), to be used in the following editing menu, as shown later.

[1] See also deliverable reports D5.1 and 5.2 for further details.
[2] Countries climates are represented through HDD distributions, obtained from Eurostat data: cooling and heating degree days by NUTS 2 regions. Available from: http://ec.europa.eu/eurostat/web/products-datasets/-/nrg_chddr2_a

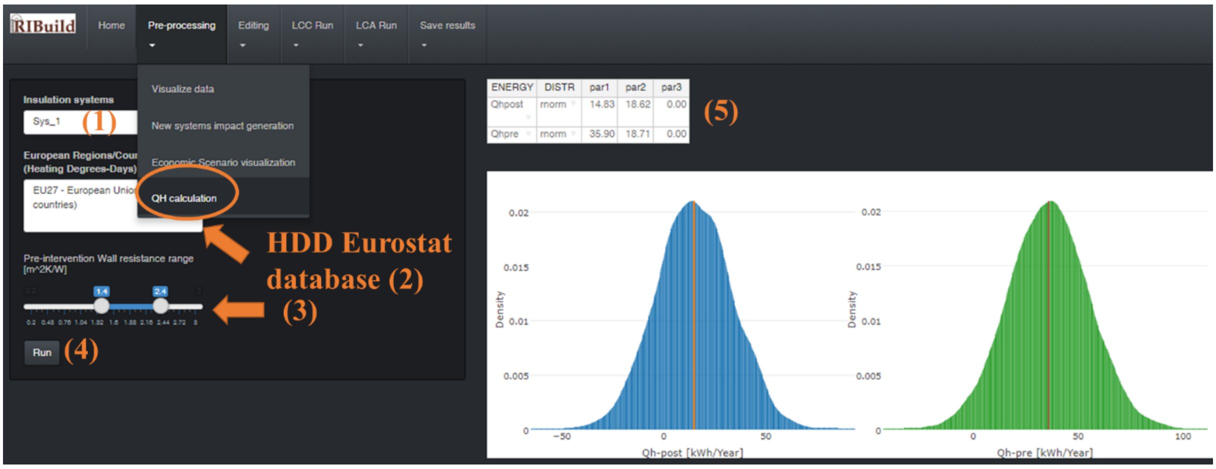


Figure 5 ***Pre-processing*** **menu → *QH calculation*. Assessment of the Qh$_{post}$ and Qh$_{pre}$ for a certain case study, based on the simplified HDD methodology (option 3).**

Editing

The *Editing* menu contains the following items: *Edit case study*, *Edit Energy Source*.

Edit case study

In *Edit case study*, the user can visualize all inputs data of the case studies included into the tool database or create a new case study, starting from the insulation system created in *New system impact generation*.

To visualize the summary data of a case study (Figure 6), the user (1) selects the case study name, to which an insulation system is associated (2). After pushing *Confirm* button (3), summary data inputs on tables will appear on the right (4).

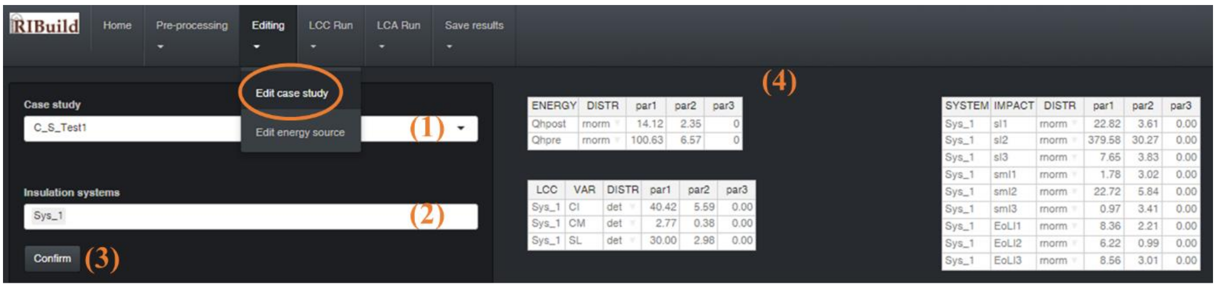


Figure 6 ***Editing*** **menu → *Edit case study*. Visualization of the summary data of a case study.**

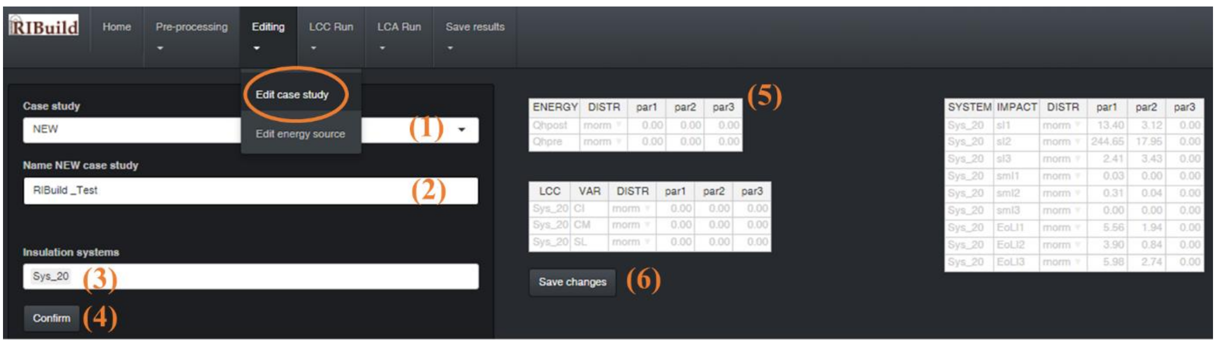


Figure 7 ***Editing*** **menu → *Edit case study*. Creation of a new case study.**

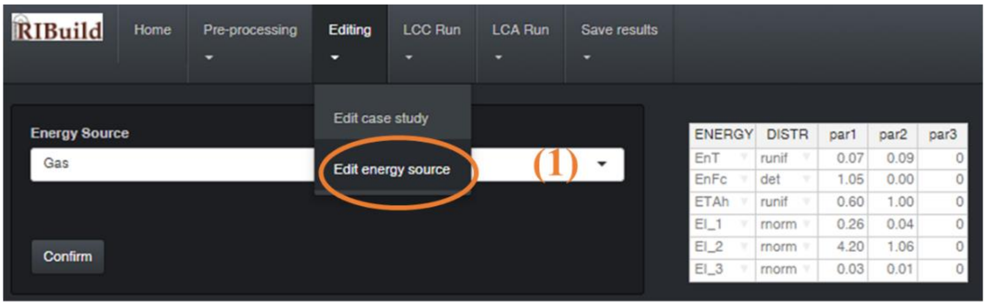
To create a new case study (Figure 7), the user selects the *NEW* option from the bar (1) and write a name for the case study (2). Then he selects the insulation system to be included in the case study from the bar (3) and push the *Confirm* button (4).

Summary input tables will appear on the right (5), only including data related to the insulation system.

Data on Qh_{post}, Qh_{pre}, investment cost (CI), maintenance cost (CM) and system service life (SL) must be provided and then *Save changes* button must be pushed to save the new case study. Notice that this procedure must be applied when the user assesses Qh_{post} and Qh_{pre} through the HDD method included in the tool (as previously described).

Edit energy source

Similarly, in *Edit energy source* (Figure 8), the user can visualize data of the national energy scenarios included into the tool database (filtered by Country) or create a new energy scenario, with similar procedure to that just described for a new case-study.
The energy scenario represents the heating source of the building where the wall case study is applied. The following inputs data are related to this choice: EnT (energy national tariff), EnFc (conversion factor to Primary Energy, to be set equal to 1 in LCC and established according to national laws for LCA), ETAh (overall heating equipment efficiency for heating), EI_1, EI_2, EI_3 (unitary impact of the energy vector according to impact indicators 1, 2, 3[3]).



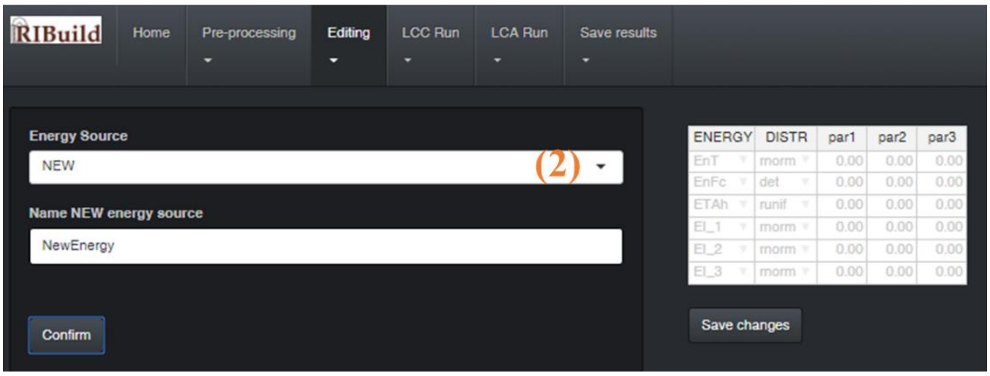


Figure 8 *Editing* menu → *Edit energy source*. Visualization of the summary data of an energy source (above) and creation of a new energy source (below).

LCC Run

The *LCC Run* menu contains *LCC analysis*, in order to perform the Monte-Carlo based LCC and *LCC - Sensitivity analysis*, to calculate the sensitivity indices[4].

[3] See Appendix 1 of the present guide for further details on the inputs data
[4] See section 2.7 of deliverable report D5.2 for further details on the sensitivity analysis method.

LCC Analysis

In *LCC* Analysis (Figure 9), the user (1) selects the case study to be assessed, among those in the tool database or among those created or edited during the work session. The user must also select the scenarios for the assessment: the energy scenario (2), the calculation period (4) - dragging the specific slider -, the macro-economic scenario (5). Finally, the user must choose the number of iterations[5] for the Monte Carlo calculation (3) and then push the *Compute* button (6). The calculation may take a few tens of seconds or some minutes depending on the simulations number (a time bar will appear on the right).

Once finished, the following results will appear on the right:

- the output probability and cumulative density functions for the Global Costs (GC) and Payback period (PB);
- Tables for each graph summarizing the simulations number, the mean value, the median value and the standard deviation of the PDF obtained.
- A table (down in the page) including an example of the yearly evolution of outputs from a single draw of input data.

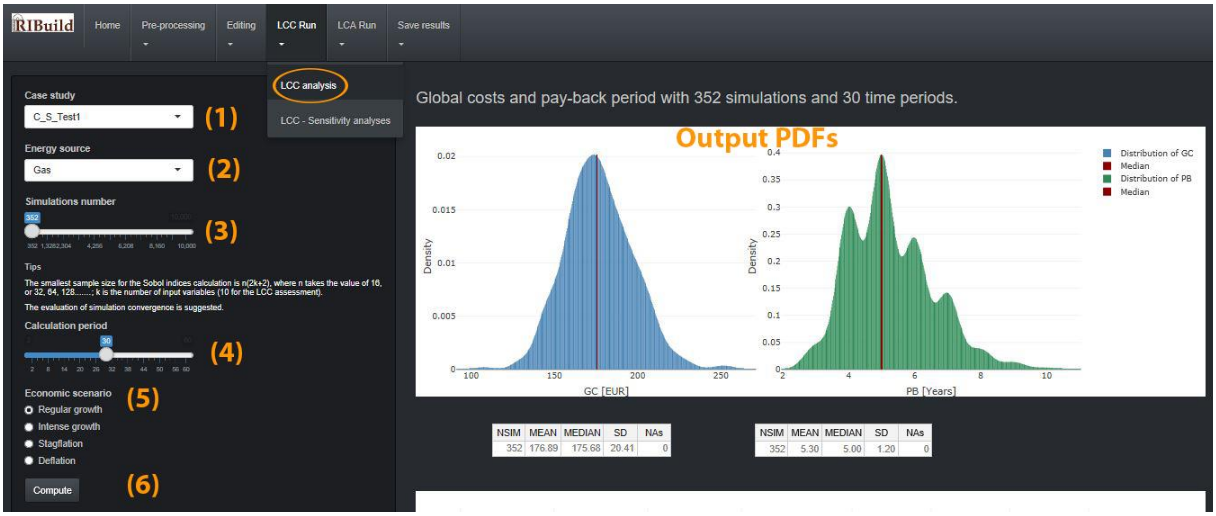


Figure 9 ***LCC Run*** **menu →** ***LCC analysis.*** **Assessment of the Global Cost and Payback period for a certain case study.**

LCC – Sensitivity Analysis

LCC – Sensitivity analysis can be performed after concluding the LCC assessment. Here the user can evaluate the Sobol's sensitivity indices according to the methods 1 and 2 documented in sections 2.6 and 3.5 of deliverable report 5.2.

Concerning the Sensitivity *Method 1* (Figure 10), the user directly gets the first and total order Sobol's indices by selecting the method (2) and pushing on *Run sensitivity analysis* button (3). The graph and table representing the first and total order indices for the LCC inputs obtained will appear on the right.

[5] The software suggests the minimum number of iterations required. It is let to the user to establish the proper number of iterations to obtain an accurate result, based on a result convergence analysis.

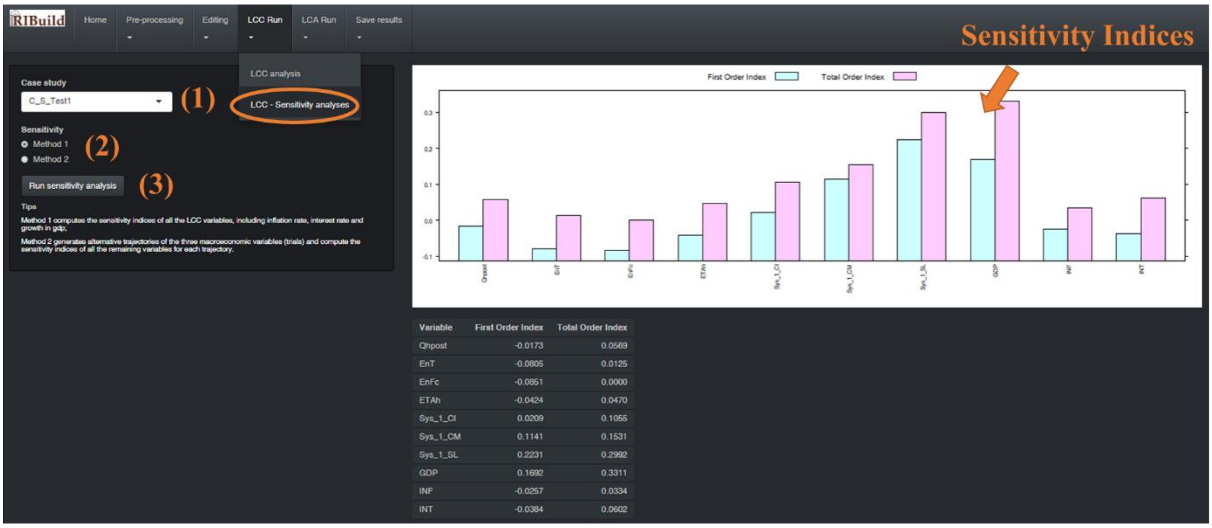


Figure 10 LCC Run menu → LCC – Sensitivity analysis. Calculation of the Sobol's first and total order indices for LCC inputs with Method 1

Concerning the Sensitivity *Method 2* (Figure 11), the user must also select the number of simulation trajectories of the economic parameters (3) and then obtain the distribution of first and total order Sobol's indices by pushing on *Run sensitivity analysis* button (4). The graph and table representing the obtained first and total order indices for LCC inputs will appear on the right.

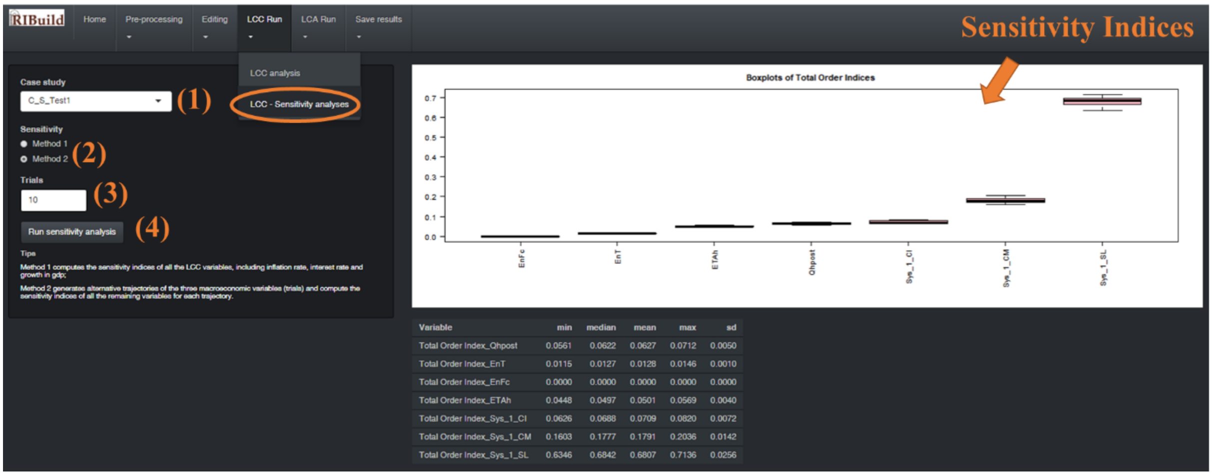


Figure 11 LCC Run menu → LCC – Sensitivity analysis. Calculation of the Sobol's first order and total order indices for LCC inputs with Method 2

LCA Run

The *LCA Run* menu contains the following items: *LCA*, *LCA – Sensitivity analysis*, in order to perform the Monte-Carlo based LCA and the calculation of sensitivity indices[6].

[6] See section 2.6 of deliverable report D5.1 for further details on the sensitivity analysis method.

Figure 12 ***LCA Run*** **menu → *LCA*. Assessment of the environmental impacts results for a certain case study.**

In *LCA* (Figure 12), the user (1) selects the case study to be assessed, among those in the tool database, or among those created or edited during the working session. He must also select the scenarios for the assessment: the energy scenario (2) and the calculation period (4) - dragging the specific slider. Finally, he must choose the number of iterations[7] for the Monte Carlo calculation (3) and then push the *Compute* button (5). The calculation may take a few dozen seconds or some minutes depending on the simulations number (a time bar will appear on the right).

Once finished, the following results will appear on the right:

- the output probability and cumulative density functions for the post-renovation and pre-renovation Global Impacts (GI) according to the specific environmental indicators (1,2,3);
- the output probability and cumulative density functions for the Global Impacts savings according to the specific environmental indicators;
- Tables for each graph summarizing the simulations number, the mean value, the median value and the standard deviation of the PDFs obtained.

LCA – Sensitivity analysis

LCA – Sensitivity analysis can be performed after concluding the LCA assessment (Figure 13). Here the user can evaluate the sensitivity first and total order Sobol's indices for each Impact indicator, to be selected in (2), by pushing on *Run sensitivity analysis* button (3). The graph and table representing the first and total order indices for the LCA inputs obtained will appear on the right.

[7] The software suggests the minimum number of iterations required. It is let to the user to establish the proper number of iterations to obtain an accurate result, based on a result convergence analysis.

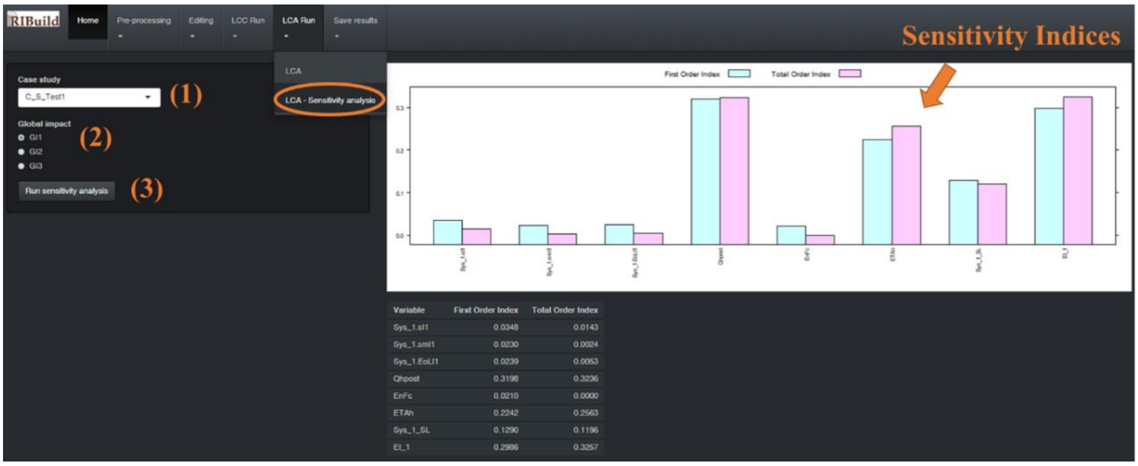


Figure 13 ***LCA Run*** **menu →** ***LCA – Sensitivity analysis*****. Calculation of the Sobol first order and total order indices for the LCA inputs.**

Save results

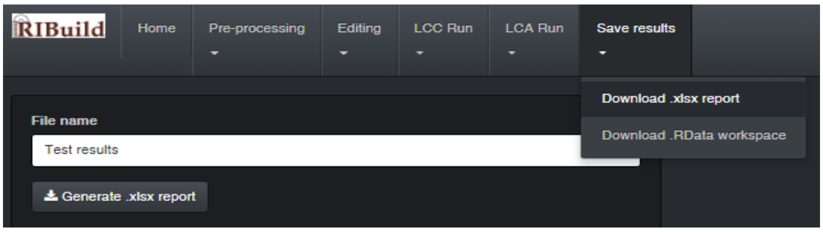


Figure 14 ***Save results*** **menu.**

Once the assessment is performed, results can be saved as *.xlsx* file (Figure 14). A file name must be filled and the generation button pushed. In separate sheets, the excel file contains:

- a summary of the input data PDFs;
- the whole input samples.

Then, for LCA:

- the whole output samples;
- The first and total order sensitivity indices for each environmental indicator.

And for LCC:

- the whole output samples;
- the cost shares defined as:
  SHARE_inv = (investment cost + replacement cost – residual value)/(global cost)
  SHARE_maint = (maintenance cost)/(global cost)
  SHARE_energ = (energy cost post renovation)/(global cost);
- The first and total order sensitivity indices related to the Method 1 and 2.

1.3 Appendix 1. Calculation Assumptions

Wall heat transmission losses

The LCA assessment requires input data on transmission heat losses before and after the renovation measure, in order to account for the use phase. As the LCA/LCC is performed at "component level", the operational energy use is considered the only heat transmission losses through the wall during the heating season.

A simplified calculation is included in WP5 tool based on an annual Heating Degree Days (HDD) method (Eq. 1):

$$Q_h = \frac{U}{1000}.HDD.HH\ [kWh/m^2]$$

Eq. 1

Where:
Q_h is the heat loss through the wall [kWh/m^2]
U is the wall U-value [W/m^2K]
HH is the heating hours a day [h] (set at 24 hours)
HDD are the annual heating degree-days [K]

The U-value of the wall is calculated with the following Eq. 2:

$$U = \frac{1}{R_{si}+R_{se}+R_w+R_{is}}\ [W/m^2K]$$

Eq. 2

Where:
R_{si} and R_{se} are the internal and external surface resistances: R_{si} = 0.13 [m^2K/W] and R_{se} = 0.04 [m^2K/W]
R_w is the original wall surface-to-surface thermal resistance [m^2K/W]
R_{is} is the applied insulation system surface-to-surface thermal resistance [m^2K/W] (insulation system comprising different layers of materials).

Next to this method, the user can provide Qh in the tool based on other more accurate methods, as coupled heat and mass (HAM) transfer numerical models based on hourly climate data[8].

LCA

The calculation of the environmental impacts of the insulation systems is based on the methodology developed in RIBuild Task 5.2 and described in deliverable report 5.1, which is here summarised.

Calculation assumptions

The probabilistic LCA is performed at "component level" and is based on the procedures defined in ISO 14040-14044 and EN 15804 and EN 15978 standards.

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[8] See also deliverable reports D5.1 and 5.2 for further details.

The goal of the study is to assess the environmental impacts of internal insulation measures installed on historic building facades. The functional unit (FU) is defined as *"the insulation intervention using several possible internal insulation systems and technologies needed to cover 1 m^2 of facade for a building reference study period*[9] *expressed in years*".

The scope of the study comprises the assessment of the environmental impacts of construction materials and the transmission heat losses assuming a given energy scenario, e.g. a heat source to convert the energy needs in final energy. The impacts of the new internal insulation systems after renovation cover next to the manufacturing and dismantling at the end-of-life, the use phase impacts related to the possible needs for maintenance and replacement of material layers or of the whole insulation system.

The maintenance measures can vary depending on the study context (country, location, type of wall and insulation system). At the aim of the probabilistic LCA of internal insulation on historic building, the *maintenance* is considered as the need of periodic replacement of the internal finishing material, i.e. the rendering or the painting, which depends on these specific materials' estimated service lives. Instead, *replacement* involves the whole insulation system, according to its estimated service life.

As a result, the following life cycle stages are included in the RIBuild LCA methodology: the production stage (modules A1-A3), the use stage (modules B2 maintenance, B4 replacement and B6 operational energy use) and the End of Life (EoL) stage (modules C1-C4), as summarized in Figure 15.

The LCA should be calculated for at least two environmental indicators, namely the Climate Change and the non-renewable Cumulative Energy Demand (CED_{NRE}). The WP5 software tool allows the user to use an additional third indicator at his choice.

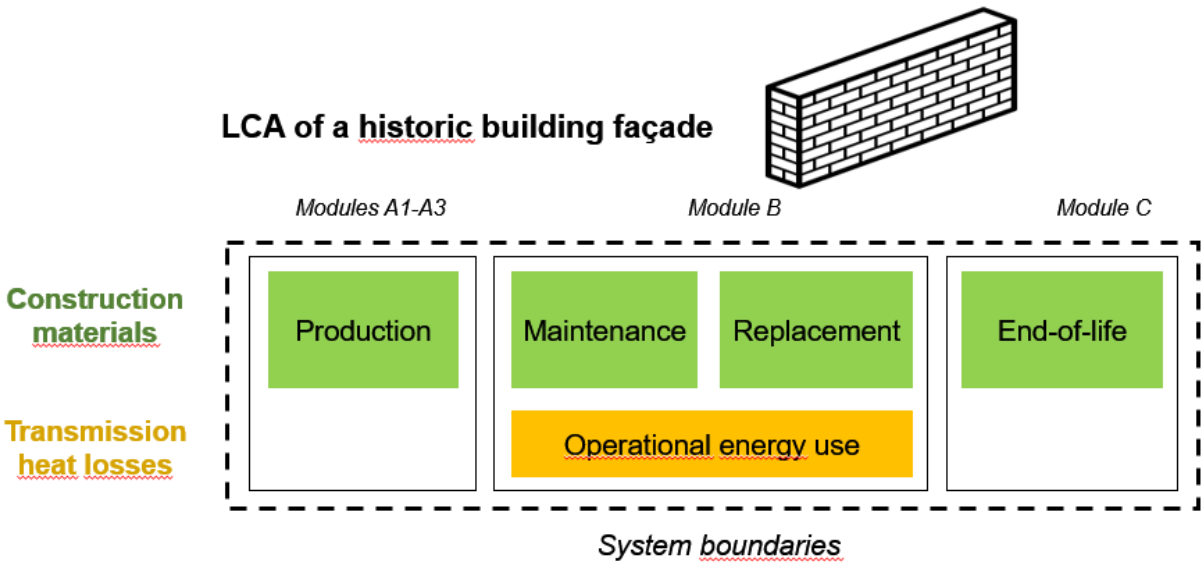


Figure 15 System boundaries for the LCA

Calculation equations included in the software model

The environmental impacts are obtained through the following equations (Eq. 3 and Eq. 4):

[9] Conventional term introduced in EN 15804 and EN 15978. Here this term is used in an equivalent manner to "calculation period".

$$IG1 = \left\{ \left(\sum_{j=1}^{n} sI1_j\right) + \left(\sum_{j=1}^{n} (sI1_j * s_j)\right) + \left(\sum_{j=1}^{n} EoLI1_j\right) + \left(\sum_{j=1}^{n} (EoLI1_j * s_j)\right) + \sum_{i=1}^{cp} \left(\frac{Q_h}{ETA_h} * EI1_i * EnFc\right) + \left(\sum_{j=1}^{n} smI1_j\right) \right\} \ [kgCO2eq]$$

Eq. 3

$$IG2 = \left\{ \left(\sum_{j=1}^{n} sI2_j\right) + \left(\sum_{j=1}^{n} sI2_j * s_j)\right) + \left(\sum_{j=1}^{n} EoLI2_j\right) + \left(\sum_{j=1}^{n} (EoLI2_j * s_j)\right) + \sum_{i=1}^{cp} \left(\frac{Q_h}{ETA_h} * EI2_i * EnFc\right) + \left(\sum_{j=1}^{n} smI2_j\right) \right\} \ [NRE - MJ]$$

Eq. 4

with the subscripts: i=year i-th; j= system j-th; k= material k-th; and 1 or 2 referred to the specific environmental indicators.

Where:

- *IG1* is the Global Impact expressed in terms of Climate Change-GWP [kgCO2eq];
- *IG2* is the Global Impact expressed in terms of non-renewable Cumulative Energy Demand [CED_{NRE} - MJ];
- sI_j is the j-System environmental impact related to production phase (Eq. 5);

$$sI_j = \begin{Bmatrix} \sum_{k=1}^{n} UI1_k * m_k \ [kgCO2eq] \\ \sum_{k=1}^{n} UI2_k * m_k \ [NRE - MJ] \end{Bmatrix}$$

Eq. 5

  and:
  - UI_k is the unitary production impact of the k-material composing the j-System [$kgCO_2eq/kg$] or [NRE - MJ/kg];
  - m_k is the mass of the k-material [kg];

- s_j is the number of replacements of the j-System within the calculation period *cp* [years], considering the j-System Service Life SL_j [years] (Eq. 6);

$$s_j = \mathrm{int}\left(\frac{cp - 1}{SL_j} \ [-]\right)$$

Eq. 6

- $EoLI_j$ is the j-System environmental impact related to the End of Life phase (Eq. 7);

$$EoLI_j = \begin{Bmatrix} \sum_{k=1}^{n} EOL1_k * m_k \ [kgCO2eq] \\ \sum_{k=1}^{n} EOL2_k * m_k \ [NRE - MJ] \end{Bmatrix}$$

Eq. 7

and:

- EOLk is the unitary End of Life impact of the k-material composing the j-System [kgCO2eq/kg] or [NRE - MJ/kg];

- EI_i is the unitary impact of the energy vector at year i-th;

- Q_h is the heat transmission losses through the wall during the heating period [kWh/year]; Q_h can refer to the heat losses before ($Q_h$pre) or after ($Q_h$post) the insulation intervention.

- ETA_h is the overall system efficiency for heating [-];

- EnFc is the conversion factor from delivered to primary energy [-];

- smI_j is the k-Material environmental impact related to the Material replacement (System periodic maintenance) (Eq. 8);

$$smI_j = \begin{Bmatrix} \sum_{k=1}^{n} UI1_k * m_k * s_k \text{ [kgCO2eq]} \\ \sum_{k=1}^{n} UI2_k * m_k * s_k \text{ [NRE - MJ]} \end{Bmatrix}$$

Eq. 8

and:

- s_k is the number of replacements of the k-material within the calculation period cp [years], considering the k-material Service Life slk [years] (Eq. 9)

$$s_k = \mathrm{int}\left(\frac{\mathrm{cp} - 1}{sl_\mathrm{k}} \; [-]\right)$$

Eq. 9

The parameters included from Eq. 3 to Eq. 9 are summarized in Table 1.

Table 1 Input parameters of the LCA included in the software tool

Input Parameter	Symbol	Unit
Replacement coefficient for System j-th	s_j	[-]
Replacement coefficient for Material k-th	s_k	[-]
Calculation period	cp	[year]
Service Life for System j-th	SL_j	[year]
Service Life for Material k-th	sl_k	[year]
Unitary production impact of the material k-th	UI_k	[kgCO_2eq/kg] or [CED_{NRE} - MJ/kg]
Unitary End of Life impact of the material k-th	EOL_k	[kgCO_2eq/kg] or [CED_{NRE} - MJ/kg]
Mass of the material k-th	m_k	[kg]
Heat transmission losses through the wall during the heating period	Q_h	[kWh/year]

Overall system efficiency for heating	ETA_h	[-]
Unitary impact of the energy vector at year i-th	EI_i	[kgCO$_2$eq/kWh] [CED$_{NRE}$ MJ/kWh]
Conversion factor from delivered to primary energy	EnFc	[-]

LCC

Calculation assumptions

The probabilistic LCC is performed at "component level" (component-level LCC analysis) and is based on the procedures of EN 15459-1:2017 and ISO 15686-5:2017, in order to calculate two possible economic indicators:

- The Global Cost (GC);
- The Payback Period (PB).

The functional unit (FU)[10] of the LCC is defined as "*the insulation intervention using a possible interior insulation system needed to cover 1 m^2 of façade for a calculation period expressed in years*".

Methodology developed and implemented allows the calculation in different study periods to compare the results on different time horizons, also taking into account the following references: the European Commission Delegated Regulation No 244/2012 and its Guidelines suggest a calculation period of 30 years for residential and public buildings and of 20 years for commercial buildings; IEA Annex 56 suggests to use a reference study period of 60 years; EN 15459-1:2017 suggests calculation periods of 50 years for residential buildings, 20 years for commercial buildings and 30 years for other typologies.

The scope of the methodology comprises the assessment of the economic impacts and the transmission heat losses of the insulation solution (assuming a given energy and economic scenario, and a calculation period). The LCC of the new interior insulation systems after renovation covers next to the investment costs, the use phase costs related to the possible needs for maintenance and replacement of material layers or whole insulation system and costs related to the energy consumptions.

The cost categories included in the calculation are the following (Figure 16)[11]: Initial investment cost; Energy cost; Maintenance cost; Replacement cost.

The initial investment cost (CI) represents the cost for the purchase and construction/installation of the design option (insulation system) considered. In general, the investment cost is composed by the cost of each material belonging to the design option and the labour cost of its installation, depending on the installation procedure and the necessary installation time.

[10] Even if in LCC the definition of a Functional Unit is not a mandatory requirement, it is defined here for consistency with the probabilistic LCA methodology.
[11] The cost of greenhouse gas emissions is neglected because LCC is performed in the perspective of a building designer or owner.

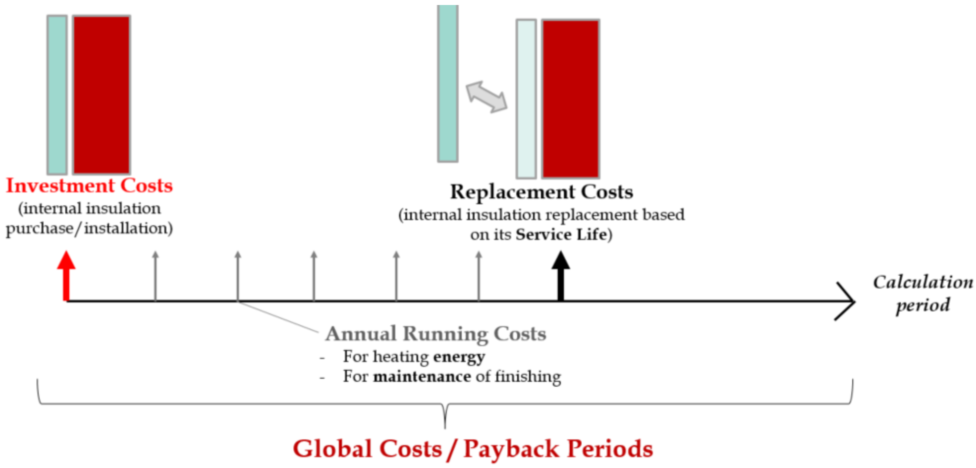


Figure 16 Schematic illustration of the cost categories included in the assessment

The energy cost (CE) is an annual cost for the energy use for heating, including national taxes. It is obtained multiplying the annual energy use by the tariff for the energy carrier considered (EnT). Since RIBuild focuses on the heating savings due to insulation options, the energy use concerned is that for *heating* (PE_H) that depends on energy needed for heating expressed by the heat transmission loss through the wall (Q_H) and the building overall efficiency for heating (ETA_H), as reported in the following Eq. 10.

$$PE_H = \left(\frac{Q_H}{ETA_H} \right)$$

Eq. 10

The building global efficiency for heating (ETA_H) and the energy tariff depend on the level knowledge of the building heating equipment and energy source typology. These parameters are related to specific national contexts.

The maintenance cost (CM) represents the cost for measures for preserving and restoring the desired quality of the building element (internal insulation). At the aim of the probabilistic LCC of interior insulations on historic buildings developed in RIBuild, the maintenance is considered as the need of periodic replacement of the internal finishing material, i.e. the rendering or the painting on the internal surface, which depends on these specific materials' estimated service life (or life span). Consistently with standard EN 15459, maintenance costs are then "yearly distributed" in order to obtain annual maintenance costs.

The replacement cost (CR) represents the substitute investment for the design option, according to the estimated economic lifecycle during the calculation period. It is a recurrent cost, with a frequency that depends on the Service Life (SL) of the insulation system concerned. The replacement cost is here considered equal to the investment cost necessary to replace the whole design option, discounted at the beginning of the calculation.

The LCC assessment can be performed in alternative future macro-economic scenarios[12]. Within each scenario, the variables entering the LCC calculation behave as stochastic variables and projections are generated as draws from appropriate probability distributions.

The quantitative expression of the scenarios is related to those (macro)economic variables affecting the life-cycle costs (either implicitly or explicitly). These variables are: Inflation rate; Interest rate;

[12] See section 3 of deliverable report D5.2 for further details.

GDP (Gross Domestic Product), Oil price (Crude oil, Brendt, nominal). Table 2 summarizes the macro-economic scenarios considered.

Table 2 Alternative macro-economic scenarios, where "Regular growth" can be considered the baseline scenario and the respective long-term expected values (and variances) are indicated with "=" as they serve as reference for the alternative scenarios; ↑ means higher than the baseline; ↓ means lower than the baseline

Variable: ***Scenario:***	**Inflation rate**	**Interest rate**	**GDP**	**Oil price**
Regular growth *(Baseline)*	=	=	=	=
Intense growth	↑	↑	↑	↑
Stagflation	↑	=	↓	↑
Deflation	↓	↓	↓	↓

Calculation equations included in the software model

The Global Cost (GC_{cp}) at the end of the calculation period (cp) referred to the starting year is calculated based on the method of standard EN 15459-1:2017 through the following Eq. 11:

$$GC_{cp} = \sum_{j=1}^{N} \left\{ CI_j + \sum_{t=1}^{CP} \left[\left(CM_{j,t} * R_t^{disc} * R_t^L \right) + \left(CE_{j,t} * R_t^{disc} * R_t^E \right) \right] + CR_{j,\mathrm{t_j}} - Val_{j,cp} \right\}$$

Eq. 11

where:
t is the number of the year;
j is the insulation system;
cp is the calculation period;
CI_j is the initial investment cost of the insulation system *j*;
$CM_{j,t}$ is the annual maintenance cost of the insulation system *j*;
$CE_{j,t}$ is the annual energy cost due to the insulation system *j* ;
R_t^{disc} is the discount rate;
R_t^L is the price development rate for human operation (labour cost);
R_t^E is the price development rate for energy;
$CR_{j,\mathrm{t_j}}$ is the replacement cost;
$Val_{j,cp}$ is the residual value of the insulation system at the end of the calculation period.

The frequency of the replacement cost $CR_{j,\mathrm{t_j}}$ depends on the service life SL_j of the insulation system concerned, as shown in Eq. 12

$$\left\{ \mathrm{CR}_{j,\mathrm{t_j}} = CI_j * R_{\mathrm{t_j}}^{disc} * R_{\mathrm{t_j}}^{L} \text{ , } \mathrm{t_j} = \mathrm{SL_j} + 1, 2\mathrm{SL_j} + 1, ..; \mathrm{SL_j} < \mathrm{cp} \right\}$$

Eq. 12

The residual value of the insulation system $Val_{j,cp}$ corresponds to the value of the system at the end of the calculation period. It is calculated based on a straight-line depreciation of the initial investment or replacement cost of the component until the end of the calculation, discounted at the beginning of the evaluation period, as shown in Eq. 13:

$$Val_{j,cp} = CI_j \left(\frac{r_j}{SL_j} \right) R_{cp}^{disc} \; R_{cp}^{L}$$

Eq. 13

where:

$$r_j = \left\{ SL_j \left[\text{int}\left(\frac{cp-1}{SL_j} \right) + 1 \right] \right\} - cp$$

Eq. 14

represents the remaining life span at the end of the calculation period of the last replacement of the system j, depending on the service life SL_j of the system concerned.

In the probabilistic methodology developed, the calculation of GC is "dynamic", i.e. annual variations of the discount rate as well as annual variations of the price development rates of the annual costs (i.e. energy costs, periodic or replacement costs, maintenance costs) are considered.

The discount rate R_t^{disc} is a definite value for comparison of the value of money at different times expressed in real terms. It depends on the discount factor, d_t, which is a multiplicative number used to convert a cash flow occurring at a given point in time (year *t*) to its equivalent value at the starting point [2]. The discount rate R_T^{disc} at any generic time period *T* is calculated as in Eq. 15:

$$R_T^{disc} = \prod_{t=1}^{T} \frac{1}{1+d_t} = \frac{1}{1+d_1} \; \frac{1}{1+d_2} \; \dots \; \frac{1}{1+d_T}$$

Eq. 15

The real discount factor, d_t, is a function of the inflation rate, π_t, and the nominal interest rate, i_t^N, according to Eq. 16.

$$d_t = \frac{i_t^N - \pi_t}{1+\pi_t}$$

Eq. 16

Furthermore, the methodology includes the possibility of development over time of prices for energy and labour that can be different from the inflation rate.

Accordingly, R_T^L and R_T^E are the price development rates that are applied to all cost components of the LCC equation (i.e. energy costs, periodic or replacement costs, maintenance costs), defined according to Eq. 17:

$$R_T^L = \prod_{t=1}^{T} (1+e_t^L) = (1+e_1^L) \; (1+e_2^L) \; \dots \; (1+e_T^L)$$

$$R_T^E = \prod_{t=1}^{T} (1+e_t^E) = (1+e_1^E) \; (1+e_2^E) \; \dots \; (1+e_T^E)$$

Eq. 17

where:

e_t^L is the escalation factor of the prices for human operation i.e. the growth rate of GDP (Gross Domestic Product) and it is computed in real terms as:

$$e_t^L = \frac{g_t^N - \pi_t}{1 + \pi_t}$$

Eq. 18

with g_t^N the nominal growth rate of GDP;

and e_t^E is the escalation factor of the prices for energy, i.e., the growth rate of crude oil price and it is computed in real terms as:

$$e_t^E = \frac{oilpg_t^N - \pi_t}{1 + \pi_t}$$

Eq. 19

where $oilpg_t^N$ is the nominal growth rate of crude oil price.

The payback period (PB) is calculated as the number of years, S, required to the cumulative energy savings (Eq. 20) to equalize the initial investment costs and its subsequent operating costs (maintenance and replacement costs) (Eq. 21). The present value of operating-related savings and the present value of all other costs are considered, according to the following equations:

$$Savings = \sum_{t=1}^{S} \left\{ \left[\left(\frac{Qh_{pre} - Qh_{post}}{ETA_H} \right) \right] EnT \right\} R_t^{disc} \; R_t^E$$

Eq. 20

$$Costs = \sum_{j=1}^{N} \left\{ CI_j + \sum_{t=1}^{S} \left[\left(CM_{j,t} + CR_{j,\mathrm{t_j}} \right) R_t^{disc} \, R_t^L \right] \right\}$$

Eq. 21

where:

Qh_{pre} is the pre-renovation energy need, namely the heat transmission losses through the not-insulated wall;

Qh_{post} is the post-renovation energy need, namely the heat transmission losses through the insulated wall.

The parameters included from Eq. 11 to Eq. 21 are summarized in Table 3.

Table 3 Input parameters of the LCC included in the software tool

Input Parameter	Symbol	Unit
Year	t	**[-]**
(Insulation) System	j	**[-]**
Calculation Period	cp	[year]
Initial investment cost of the system j (at time t_0)	CI_j	€/m^2 or €
Maintenance cost for system j at the year t	$CM_{j,t}$	€/m^2 or €
Energy cost due to the system j at the year t	$CE_{j,t}$	€
Discount Rate (at the year t)	R_t^{disc}	%
Inflation rate (at the year t)	π_t	%

Nominal interest rate (at the year t)	i_t^N	%
Price development rate for human operation (labour cost) (at the year t)	R_t^L	%
Price development rate for energy (for the year t)	R_t^E	%
Real discount factor	d_t	%
Nominal growth rate of GDP	g_t^N	%
Nominal growth rate of crude oil price	$oilpg_t^N$	%
Heat transmission losses through the wall during the heating period	Q_h	[kWh/year]
Overall building efficiency for heating	ETA_h	[-]
Energy tariff	$EnT_{(c,e)}$	$\left[\frac{€}{kWh}\right]$
Service Life for the System j	SL_j	[year]
Replacement cost for the System j in the replacement year t_j	CR_{j,t_j}	$€/m^2$ or €
Replacement year	t_j	[-]
Final value of component *j* at the calculation period *cp*	$Val_{j,cp}$	$€/m^2$ or €
Residual years of the component j	r_j	[year]
Global Cost (corresponding to the calculation period *cp*)	GC_{cp}	€

1.4 Appendix 2. List of case studies included into the tool database

The RIBuildWP5 software database already contains some LCC and LCA data on insulation systems typically adopted in Europe for building renovation. These data are based on the following main references:

- Source A: Di Giuseppe et al. A Stochastic Approach to LCA of Internal Insulation Solutions for Historic Buildings, Sustainability. 12 (2020) 1535. doi:10.3390/su12041535;
- Source B: RiBuild Deliverable D5.1;
- Source C: RiBuild Sustainability WebTool.

The insulation systems from these references are described in the following tables.

Stratigraphy of insulation systems from source A

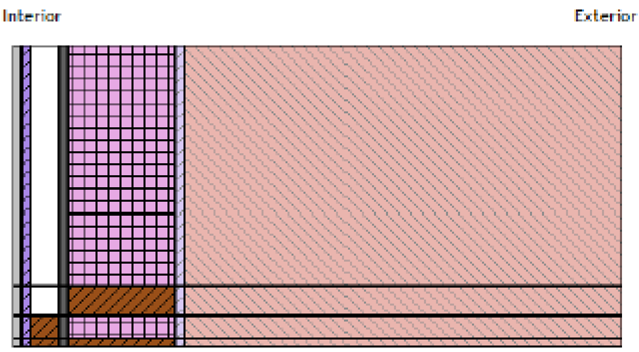
Table 4. Stratigraphy of the 5 Italian internal insulation layers from source A (outermost layer first), along with thermophysical properties of the most relevant materials and wall U-values obtained after the application of each insulation system on the considered masonry wall (including surface thermal resistances according to ISO 6946:2008).

Layer	Material ID	Standard Thickness [m]	Density $[kg/m^3]$	Mass [kg]	Thermal Conductivity [W/mK]
"EPS" insulation system (Wall U-value = 0.349 W/m^{2}K) EPS insulating board fixed to the wall through an adhesive mortar, externally finished by plasterboard					
Gypsum adhesive mortar	101	0.006	1400	3.50	0.400
EPS boards	102	0.080	15	1.26	0.035
Gypsum plasterboard	103	0.0125	680	8.93	0.200
Stucco	101	-	-	0.40	-
Gypsum finishing	104	0.002	950	1.90	0.400
"CaSi" insulation system (Wall U-value = 0.359 W/m^{2}K) CaSi insulation board fixed to the wall through an adhesive mortar, externally finished with a reinforced multilayer rendering system					
Adhesive mortar for CaSi	105	0.006	1450	8.70	0.600
CaSi	106	0.130	184	23.92	0.059
Glass fiber mesh	107	-	-	0.08	-
Surface rendering for CaSi	105	0.004	1450	5.80	0.0680
"AAC" insulation system (Wall U-value = 0.333 W/m^{2}K) AAC insulation board fixed to the wall through an adhesive mortar, externally finished with a reinforced multilayer rendering system					
Adhesive mortar for AAC	105	0.006	1450	8.70	0.180
AAC	109	0.100	90	9.00	0.042
Surface rendering for AAC	105	0.004	1450	5.80	0.180
"Cork" insulation system (Wall U-value = 0.339 W/m^{2}K) Cork insulation board fixed to the wall through an adhesive mortar, and plasterboard as an external layer					
Gypsum adhesive mortar	101	0.006	1400	3.50	0.400
Cork	110	0.090	150	10.80	0.039
Gypsum plasterboard	103	0.0125	680	8.93	0.200
Stucco	101	-	-	0.40	-
Gypsum finishing	104	0.002	950	1.90	0.400
"RW" insulation system (Wall U-value = 0.322 W/m^{2}K)					

	Rockwool insulating board fixed to the wall through a metallic frame with vapor barrier and two plasterboards as an external layer				
Rockwool	111	0.08	18	1.44	0.035
Air gap	-	0.02	1.23	-	5.423 [1]
Steel C-profiles	112	-	7800	0.84	-
Steel U-profiles	112	-	7800	1.97	-
Gypsum plasterboards	103	0.025	680	17.86	0.200
Aluminum vapor barrier	113	-	-	0.08	-
Steel screws	112	-	-	0.08	-
Stucco	101	-	-	0.40	-
Gypsum finishing	104	0.002	950	1.90	0.400

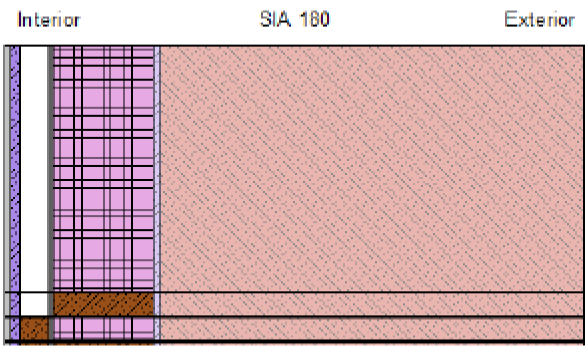
[1] Conductance value [W/m²K].

Stratigraphy of insulation systems from source B



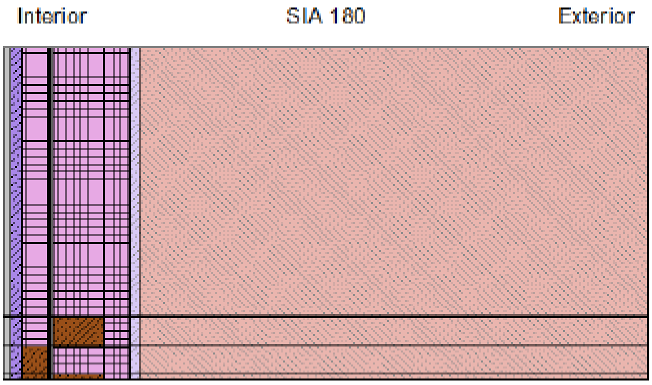
Material	Thickness [cm]	Conductivity [W/(m.K)]	Density [kg/m³]
Natural Stone	60	1.3	2000
Mineral coating	1	0.7	1400
Glasswool / Wood	8	0.035 / 0.14	38 / 480
Vapour barrier	0.024	0.2	875
Glasswool / Wood	5.8	0.035 / 0.14	38 / 480
Gypsum plasterboard	1.25	0.32	1150
Mineral cover coat	0.5	0.7	1200

Figure 17. Stratigraphy of insulation systems n.6 (Rockwool). From RibuildD5.1.



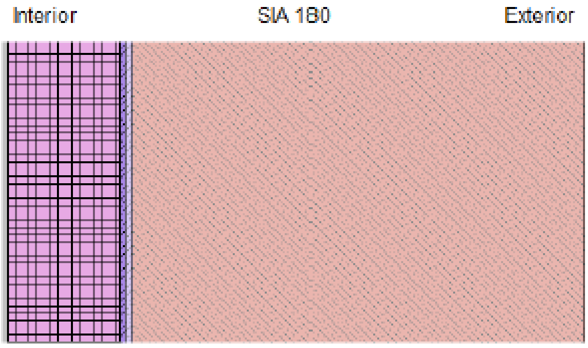
Material	Thickness [cm]	Conductivity [W/(m.K)]	Density [kg/m³]
Natural Stone	60	1.3	2000
Mineral coating	1	0.7	1400
Cellulose / Wood	14.7	0.038 / 0.14	50 / 480
Vapour barrier	0.024	0.2	875
Air / Wood	4	- / 0.14	- / 480
Gypsum plasterboard	1.25	0.32	1150
Mineral cover coat	0.5	0.7	1200

Figure 18. Stratigraphy of insulation systems n.7 (Cellulose). From RibuildD5.1.



Material	Thickness [cm]	Conductivity [W/(m.K)]	Density [kg/m³]
Natural Stone	60	1.3	2000
Mineral coating	1	0.7	1400
Glasswool	3	0.032	29
Glasswool / Wood	6	0.032 / 0.14	29 / 480
Vapour barrier	0.024	0.2	875
Glasswool / Wood	β.1	0.032 / 0.14	29 / 480
Gypsum plasterboard	1.25	0.32	1150
Mineral cover coat	0.5	0.7	1200

Figure 19. Stratigraphy of insulation systems n.8 (Glass Wool). From RibuildD5.1.



Material	Thickness [cm]	Conductivity [W/(mK)]	Density [kg/m³]
Natural Stone	60	1.3	2000
Mineral coating	1	0.7	1400
Light mortar	0.5	0.18	450
Multipor WI	15	0.045	115
Mineral cover coat	0.5	0.7	1200

Figure 20. Stratigraphy of insulation systems n.9 (AAC). From RibuildD5.1.

Table 19 Insulation systems B and C

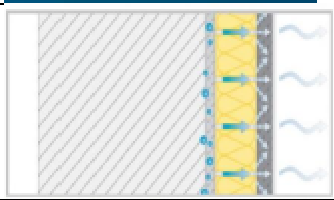
Insulation system	Material Layers	Thickness [m]	Density [kg/m³]	
B -MicroTherm insulation system	Microtherm climate panel	0.15	500	
	Inorganic adhesive plaster	0.005	1350	
	Putty	0.005	1400	
C -iQ-Therm insulation system	iQ-Therm board	0.08	45	
	iQ-Fix adhesive	0.005	1500	
	iQ-Top	0.005	630	
	iQ-Fill	0.003	1200	
	Pimer + Paint	0.003	1200	

Figure 21. Stratigraphy of insulation systems n.10 (B) and 11 (C). From RibuildD5.1.

Insulation systems from source C

Table 5. "CaSi" insulation system stratigraphies from source C.

Product name	Thickness [m]
Calsitherm KP inside lime plaster	0.01
ClimateBoard	0.025
Calsitherm KP Glue Mortar	0.005
Calsitherm KP inside lime plaster	0.01
ClimateBoard	0.03
Calsitherm KP Glue Mortar	0.005
Calsitherm KP inside lime plaster	0.01
ClimateBoard	0.05
Calsitherm KP Glue Mortar	0.005
Calsitherm KP inside lime plaster	0.01
ClimateBoard	0.08
Calsitherm KP Glue Mortar	0.005

Table 6. "Capillary-active PUR" insulation system stratigraphies from source C.

Product name	Thickness [m]
iQ-Top	0.01
iQ-Therm	0.03
iQ-Fix	0.008
iQ-Top	0.01
iQ-Therm	0.05
iQ-Fix	0.008
iQ-Top	0.01
iQ-Therm	0.08
iQ-Fix	0.008

Table 7. "Phenolic Foam" insulation system stratigraphies from source C.

Product name	Thickness [m]
PhenolicFoam	0.02
Gypsum Board Knauf Standard	0.0125
PhenolicFoam	0.045
Gypsum Board Knauf Standard	0.0125

PhenolicFoam	0.065
Gypsum Board Knauf Standard	0.0125
PhenolicFoam	0.08
Gypsum Board Knauf Standard	0.0125
PhenolicFoam	0.9
Gypsum Board Knauf Standard	0.0125
PhenolicFoam	0.11
Gypsum Board Knauf Standard	0.0125

Table 8. “AAC” insulation system stratigraphies from source C.

Product name	Thickness [m]
Climate plaster	0.01
MineralFoamMulltipor	0.06
Glue Mortar	0.005
Climate plaster	0.01
MineralFoamMulltipor	0.08
Glue Mortar	0.005
Climate plaster	0.01
MineralFoamMulltipor	0.1
Glue Mortar	0.005

Table 9. “Mineral Wool” insulation system stratigraphies from source C.

Product name	Thickness [m]
Vapour barrier Isover PBM 032	0.00022
Isover MineralWool32	0.7
Air	0.022
Gypsum Board Knauf Standard	0.0125
Vapour barrier Isover PBM 032	0.00022
Isover MineralWool32	0.95
Air	0.022
Gypsum Board Knauf Standard	0.0125
Vapour barrier Isover PBM 032	0.00022
Isover MineralWool32	1.2
Air	0.022
Gypsum Board Knauf Standard	0.0125

The materials, insulation systems, case study and energy sources contained in the database are summarized in the following.

Materials

Table 10. Summary table of materials included in the RiBuild software database.

Material ID	Name	Country	Source	LCA Method	Data type
101	Stucco ITA	Italy	A	CML	Stochastic
102	EPS boards ITA	Italy	A	CML	Stochastic
103	Gypsum Plasterboard ITA	Italy	A	CML	Stochastic
104	Gypsum finishing ITA	Italy	A	CML	Stochastic
105	Adhesive mortar ITA	Italy	A	CML	Stochastic
106	CaSi ITA	Italy	A	CML	Stochastic
107	Glass fiber mesh ITA	Italy	A	CML	Stochastic
108	Water-based paint ITA	Italy	A	CML	Stochastic
109	Aerate Autoclaved Concrete (AAC) ITA	Italy	A	CML	Stochastic
110	Cork ITA	Italy	A	CML	Stochastic
111	Rockwool ITA	Italy	A	CML	Stochastic
112	Metalic frame ITA	Italy	A	CML	Stochastic
113	Alluminum vapor barrier ITA	Italy	A	CML	Stochastic
201	Mineral plaster	Switzerland	B	RECIPE	Deterministic
202	Fermacell gypsum fibreboard	Switzerland	B	RECIPE	Deterministic
203	GYSO VS 80 R vapour barrier	Switzerland	B	RECIPE	Deterministic
204	Glasswool Isover PB M 032	Switzerland	B	RECIPE	Deterministic
205	Softwood	Switzerland	B	RECIPE	Deterministic
206	Rockwool Flumroc 1	Switzerland	B	RECIPE	Deterministic
207	Multipor WI insulation	Switzerland	B	RECIPE	Deterministic
208	Isofloc LM	Switzerland	B	RECIPE	Deterministic
209	Multipor light mortar	Switzerland	B	RECIPE	Deterministic
301	Isover glasswool rolls (lambda 37)	Denmark	B	RECIPE	Deterministic and stochastic
302	Isover Steel frame (stud)	Denmark	B	RECIPE	Deterministic and stochastic
303	Flexibatts 37 rockwool	Denmark	B	RECIPE	Deterministic and stochastic
304	OSB-3 board	Denmark	B	RECIPE	Deterministic and stochastic
305	Rockwool vapour barrier (plastic PE foil)	Denmark	B	RECIPE	Deterministic and stochastic
306	Gypsum plasterboard	Denmark	B	RECIPE	Deterministic and stochastic
307	PROMALUX-V calsium silicate boards	Denmark	B	RECIPE	Deterministic and stochastic
308	Micro dispers (acrylic primer+paint)	Denmark	B	RECIPE	Deterministic and stochastic
309	Sodium Silicate - Inorganic adhesive plaster	Denmark	B	RECIPE	Deterministic and stochastic

Material ID	Name	Country	Source	LCA Method	Data type
310	DalaPro Nova sandspartel (putty)	Denmark	B	RECIPE	Deterministic and stochastic
311	CalsiTherm climate board (replaced by promalux-v)	Denmark	B	RECIPE	Deterministic and stochastic
312	Adhesive mortar	Denmark	B	RECIPE	Deterministic and stochastic
313	Ytong multipor board	Denmark	B	RECIPE	Deterministic and stochastic
314	Ytong lightmortar	Denmark	B	RECIPE	Deterministic and stochastic
315	Kingspan KoolTherm K118 plaster board (replaced by foam board)	Denmark	B	RECIPE	Deterministic and stochastic
316	iQ-Therm board (replaced by foam board)	Denmark	B	RECIPE	Deterministic and stochastic
317	iQ-Fix adhesive (replaced by inorganic adhesives)	Denmark	B	RECIPE	Deterministic and stochastic
318	iQ-Top (replaced by gypsum plaster)	Denmark	B	RECIPE	Deterministic and stochastic
319	iQ-Fill (putty) (inorganic adhesive)	Denmark	B	RECIPE	Deterministic and stochastic
320	Pimer + Paint	Denmark	B	RECIPE	Deterministic and stochastic
401	Inside lime plaster for CaSi	Denmark	C	CML	Deterministic
402	CaSi	Denmark	C	CML	Deterministic
403	Glue Mortar for CaSi	Denmark	C	CML	Deterministic
404	Inside plaster for capillary-active PUR	Denmark	C	CML	Deterministic
405	Capillary-active PUR	Denmark	C	CML	Deterministic
406	Glue mortar for capillary-active PUR	Denmark	C	CML	Deterministic
407	Phenolic Foam	Denmark	C	CML	Deterministic
408	Gypsum Board	Denmark	C	CML	Deterministic
409	Aerate Autoclaved Concrete (AAC)	Denmark	C	CML	Deterministic
410	Polypropylene Vapour barrier	Denmark	C	CML	Deterministic
411	Glasswool	Denmark	C	CML	Deterministic
501	Inside lime plaster for CaSi	Sweden	C	CML	Deterministic
502	CaSi	Sweden	C	CML	Deterministic
503	Glue Mortar for CaSi	Sweden	C	CML	Deterministic
504	Inside plaster for capillary-active PUR	Sweden	C	CML	Deterministic
505	Capillary-active PUR	Sweden	C	CML	Deterministic
506	Glue mortar for capillary-active PUR	Sweden	C	CML	Deterministic
507	Phenolic Foam	Sweden	C	CML	Deterministic
508	Gypsum Board	Sweden	C	CML	Deterministic
509	Aerate Autoclaved Concrete (AAC)	Sweden	C	CML	Deterministic
510	Polypropylene Vapour barrier	Sweden	C	CML	Deterministic
511	Glasswool	Sweden	C	CML	Deterministic
601	Inside lime plaster for CaSi	Latvia	C	CML	Deterministic
602	CaSi	Latvia	C	CML	Deterministic
603	Glue Mortar for CaSi	Latvia	C	CML	Deterministic
604	Inside plaster for capillary-active PUR	Latvia	C	CML	Deterministic
605	Capillary-active PUR	Latvia	C	CML	Deterministic

Material ID	Name	Country	Source	LCA Method	Data type
606	Glue mortar for capillary-active PUR	Latvia	C	CML	Deterministic
607	Phenolic Foam	Latvia	C	CML	Deterministic
608	Gypsum Board	Latvia	C	CML	Deterministic
609	Aerate Autoclaved Concrete (AAC)	Latvia	C	CML	Deterministic
610	Polypropylene Vapour barrier	Latvia	C	CML	Deterministic
611	Glasswool	Latvia	C	CML	Deterministic
701	Inside lime plaster for CaSi	Switzerland	C	CML	Deterministic
702	CaSi	Switzerland	C	CML	Deterministic
703	Glue Mortar for CaSi	Switzerland	C	CML	Deterministic
704	Inside plaster for capillary-active PUR	Switzerland	C	CML	Deterministic
705	Capillary-active PUR	Switzerland	C	CML	Deterministic
706	Glue mortar for capillary-active PUR	Switzerland	C	CML	Deterministic
707	Phenolic Foam	Switzerland	C	CML	Deterministic
708	Gypsum Board	Switzerland	C	CML	Deterministic
709	Aerate Autoclaved Concrete (AAC)	Switzerland	C	CML	Deterministic
710	Polypropylene Vapour barrier	Switzerland	C	CML	Deterministic
711	Glasswool	Switzerland	C	CML	Deterministic
801	Inside lime plaster for CaSi	Germany	C	CML	Deterministic
802	CaSi	Germany	C	CML	Deterministic
803	Glue Mortar for CaSi	Germany	C	CML	Deterministic
804	Inside plaster for capillary-active PUR	Germany	C	CML	Deterministic
805	Capillary-active PUR	Germany	C	CML	Deterministic
806	Glue mortar for capillary-active PUR	Germany	C	CML	Deterministic
807	Phenolic Foam	Germany	C	CML	Deterministic
808	Gypsum Board	Germany	C	CML	Deterministic
809	Aerate Autoclaved Concrete (AAC)	Germany	C	CML	Deterministic
810	Polypropylene Vapour barrier	Germany	C	CML	Deterministic
811	Glasswool	Germany	C	CML	Deterministic
901	Inside lime plaster for CaSi	Belgium	C	CML	Deterministic
902	CaSi	Belgium	C	CML	Deterministic
903	Glue Mortar for CaSi	Belgium	C	CML	Deterministic
904	Inside plaster for capillary-active PUR	Belgium	C	CML	Deterministic
905	Capillary-active PUR	Belgium	C	CML	Deterministic
906	Glue mortar for capillary-active PUR	Belgium	C	CML	Deterministic
907	Phenolic Foam	Belgium	C	CML	Deterministic
908	Gypsum Board	Belgium	C	CML	Deterministic
909	Aerate Autoclaved Concrete (AAC)	Belgium	C	CML	Deterministic
910	Polypropylene Vapour barrier	Belgium	C	CML	Deterministic
911	Glasswool	Belgium	C	CML	Deterministic
1001	Inside lime plaster for CaSi	Italy	C	CML	Deterministic
1002	CaSi	Italy	C	CML	Deterministic
1003	Glue Mortar for CaSi	Italy	C	CML	Deterministic
1004	Inside plaster for capillary-active PUR	Italy	C	CML	Deterministic

Material ID	Name	Country	Source	LCA Method	Data type
1005	Capillary-active PUR	Italy	C	CML	Deterministic
1006	Glue mortar for capillary-active PUR	Italy	C	CML	Deterministic
1007	Phenolic Foam	Italy	C	CML	Deterministic
1008	Gypsum Board	Italy	C	CML	Deterministic
1009	Aerate Autoclaved Concrete (AAC)	Italy	C	CML	Deterministic
1010	Polypropylene Vapour barrier	Italy	C	CML	Deterministic
1011	Glasswool	Italy	C	CML	Deterministic

Insulation systems/Case studies

Table 11. Summary table of insulation systems and case studies included in the RiBuild software database. IS: Insulation system. CS: Case study. *LCC data estimated, to be verified in the national context and real application

IS / CS ID	Source	Country	IS	Materials included ID	Insulation thickness (m)	Existing wall thermal resistance (m^2K/W)	Insulation system thermal resistance (m^2K/W)	Climate	LCC data*	Data type
1	A	IT	EPS	101 102 103 104	0.08	0.4	2.297	Lombardia Region (IT)	X	Stochastic
2	A	IT	CaSi	105 106 107	0.13	0.4	2.218	Lombardia Region (IT)	X	Stochastic
3	A	IT	AAC	105 109	0.1	0.4	2.435	Lombardia Region (IT)	X	Stochastic
4	A	IT	Cork	101 110 103 104	0.09	0.4	2.382	Lombardia Region (IT)	X	Stochastic
5	A	IT	Rockwool	111 112 103 113 101 104	0.08	0.4	2.538	Lombardia Region (IT)	X	Stochastic
6	B	CH	Rockwool	201 202 206 205 203 206 205	0.14	0.77	3.509	CH	-	Deterministic
7	B	CH	Cellulose	201 202 205 203 208 205	0.15	0.77	3.472	CH	-	Deterministic
8	B	CH	Glass Wool	201 202 204 205 203 204 205 204	0.12	0.77	3.509	CH	-	Deterministic
9	B	CH	AAC	201 207 209	0.15	0.77	3.533	CH	-	Deterministic
10	B	DK	CaSi	307 309 310	0.15	0.261	2.31	Copenahagen	-	Deterministic and stochastic
11	B	DK	Capillary Active PUR	316 317 318 319 320	0.08	0.261	2.60	Copenahagen	-	Deterministic and stochastic
12	C	DK	CaSi	401 402 403	0.025	0.5	0.45	DK	X	Deterministic
13	C	DK	CaSi	401 402 403	0.03	0.5	0.53	DK	X	Deterministic
14	C	DK	CaSi	401 402 403	0.05	0.5	0.87	DK	X	Deterministic
15	C	DK	CaSi	401 402 403	0.08	0.5	1.38	DK	X	Deterministic
16	C	DK	Capillary Active PUR	404 405 406	0.03	0.5	1.07	DK	X	Deterministic

IS / CS ID	Source	Country	IS	Materials included ID	Insulation thickness (m)	Existing wall thermal resistance (m^2K/W)	Insulation system thermal resistance (m^2K/W)	Climate	LCC data*	Data type
17	C	DK	Capillary Active PUR	404 405 406	0.05	0.5	1.72	DK	X	Deterministic
18	C	DK	Capillary Active PUR	404 405 406	0.08	0.5	2.69	DK	X	Deterministic
19	C	DK	Phenolic Foam	407 408	0.02	0.5	1.16	DK	X	Deterministic
20	C	DK	Phenolic Foam	407 408	0.045	0.5	2.55	DK	-	Deterministic
21	C	DK	Phenolic Foam	407 408	0.065	0.5	3.66	DK	-	Deterministic
22	C	DK	Phenolic Foam	407 408	0.08	0.5	4.49	DK	-	Deterministic
23	C	DK	Phenolic Foam	407 408	0.09	0.5	5.05	DK	-	Deterministic
24	C	DK	Phenolic Foam	407 408	0.11	0.5	6.16	DK	-	Deterministic
25	C	DK	AAC	401 409 403	0.06	0.5	1.36	DK	X	Deterministic
26	C	DK	AAC	401 409 403	0.08	0.5	1.8	DK	X	Deterministic
27	C	DK	AAC	401 409 403	0.1	0.5	2.25	DK	X	Deterministic
28	C	DK	Glass Wool	410 411 408	0.07	0.5	2.24	DK	-	Deterministic
29	C	DK	Glass Wool	410 411 408	0.095	0.5	3.02	DK	-	Deterministic
30	C	DK	Glass Wool	410 411 408	0.12	0.5	3.8	DK	-	Deterministic
31	C	SE	CaSi	501 502 503	0.025	0.5	0.45	SE	X	Deterministic
32	C	SE	CaSi	501 502 503	0.03	0.5	0.53	SE	X	Deterministic
33	C	SE	CaSi	501 502 503	0.05	0.5	0.87	SE	X	Deterministic
34	C	SE	CaSi	501 502 503	0.08	0.5	1.38	SE	X	Deterministic
35	C	SE	Capillary Active PUR	504 505 506	0.03	0.5	1.07	SE	X	Deterministic
36	C	SE	Capillary Active PUR	504 505 506	0.05	0.5	1.72	SE	X	Deterministic
37	C	SE	Capillary Active PUR	504 505 506	0.08	0.5	2.69	SE	X	Deterministic
38	C	SE	Phenolic Foam	507 508	0.02	0.5	1.16	SE	X	Deterministic
39	C	SE	Phenolic Foam	507 508	0.045	0.5	2.55	SE	-	Deterministic
40	C	SE	Phenolic Foam	507 508	0.065	0.5	3.66	SE	-	Deterministic
41	C	SE	Phenolic Foam	507 508	0.08	0.5	4.49	SE	-	Deterministic
42	C	SE	Phenolic Foam	507 508	0.09	0.5	5.05	SE	-	Deterministic
43	C	SE	Phenolic Foam	507 508	0.11	0.5	6.16	SE	-	Deterministic
44	C	SE	AAC	501 509 503	0.06	0.5	1.36	SE	X	Deterministic
45	C	SE	AAC	501 509 503	0.08	0.5	1.8	SE	X	Deterministic
46	C	SE	AAC	501 509 503	0.1	0.5	2.25	SE	X	Deterministic

IS / CS ID	Source	Country	IS	Materials included ID	Insulation thickness (m)	Existing wall thermal resistance (m^2K/W)	Insulation system thermal resistance (m^2K/W)	Climate	LCC data*	Data type
47	C	SE	Glass Wool	510 511 508	0.07	0.5	2.24	SE	-	Deterministic
48	C	SE	Glass Wool	510 511 508	0.095	0.5	3.02	SE	-	Deterministic
49	C	SE	Glass Wool	510 511 508	0.12	0.5	3.8	SE	-	Deterministic
50	C	LT	CaSi	601 602 603	0.025	0.5	0.45	LT	X	Deterministic
51	C	LT	CaSi	601 602 603	0.03	0.5	0.53	LT	X	Deterministic
52	C	LT	CaSi	601 602 603	0.05	0.5	0.87	LT	X	Deterministic
53	C	LT	CaSi	601 602 603	0.08	0.5	1.38	LT	X	Deterministic
54	C	LT	Capillary Active PUR	604 605 606	0.03	0.5	1.07	LT	X	Deterministic
55	C	LT	Capillary Active PUR	604 605 606	0.05	0.5	1.72	LT	X	Deterministic
56	C	LT	Capillary Active PUR	604 605 606	0.08	0.5	2.69	LT	X	Deterministic
57	C	LT	Phenolic Foam	607 608	0.02	0.5	1.16	LT	X	Deterministic
58	C	LT	Phenolic Foam	607 608	0.045	0.5	2.55	LT	-	Deterministic
59	C	LT	Phenolic Foam	607 608	0.065	0.5	3.66	LT	-	Deterministic
60	C	LT	Phenolic Foam	607 608	0.08	0.5	4.49	LT	-	Deterministic
61	C	LT	Phenolic Foam	607 608	0.09	0.5	5.05	LT	-	Deterministic
62	C	LT	Phenolic Foam	607 608	0.11	0.5	6.16	LT	-	Deterministic
63	C	LT	AAC	601 609 603	0.06	0.5	1.36	LT	X	Deterministic
64	C	LT	AAC	601 609 603	0.08	0.5	1.8	LT	X	Deterministic
65	C	LT	AAC	601 609 603	0.1	0.5	2.25	LT	X	Deterministic
66	C	LT	Glass Wool	610 611 608	0.07	0.5	2.24	LT	-	Deterministic
67	C	LT	Glass Wool	610 611 608	0.095	0.5	3.02	LT	-	Deterministic
68	C	LT	Glass Wool	610 611 608	0.12	0.5	3.8	LT	-	Deterministic
69	C	CH	CaSi	701 702 703	0.025	0.5	0.45	CH	X	Deterministic
70	C	CH	CaSi	701 702 703	0.03	0.5	0.53	CH	X	Deterministic
71	C	CH	CaSi	701 702 703	0.05	0.5	0.87	CH	X	Deterministic
72	C	CH	CaSi	701 702 703	0.08	0.5	1.38	CH	X	Deterministic
73	C	CH	Capillary Active PUR	704 705 706	0.03	0.5	1.07	CH	X	Deterministic
74	C	CH	Capillary Active PUR	704 705 706	0.05	0.5	1.72	CH	X	Deterministic
75	C	CH	Capillary Active PUR	704 705 706	0.08	0.5	2.69	CH	X	Deterministic

IS / CS ID	Source	Country	IS	Materials included ID	Insulation thickness (m)	Existing wall thermal resistance (m^2K/W)	Insulation system thermal resistance (m^2K/W)	Climate	LCC data*	Data type
76	C	CH	Phenolic Foam	707 708	0.02	0.5	1.16	CH	-	Deterministic
77	C	CH	Phenolic Foam	707 708	0.045	0.5	2.55	CH	-	Deterministic
78	C	CH	Phenolic Foam	707 708	0.065	0.5	3.66	CH	-	Deterministic
79	C	CH	Phenolic Foam	707 708	0.08	0.5	4.49	CH	-	Deterministic
80	C	CH	Phenolic Foam	707 708	0.09	0.5	5.05	CH	-	Deterministic
81	C	CH	Phenolic Foam	707 708	0.11	0.5	6.16	CH	-	Deterministic
82	C	CH	AAC	701 709 703	0.06	0.5	1.36	CH	X	Deterministic
83	C	CH	AAC	701 709 703	0.08	0.5	1.8	CH	X	Deterministic
84	C	CH	AAC	701 709 703	0.1	0.5	2.25	CH	X	Deterministic
85	C	CH	Glass Wool	710 711 708	0.07	0.5	2.24	CH	-	Deterministic
86	C	CH	Glass Wool	710 711 708	0.095	0.5	3.02	CH	-	Deterministic
87	C	CH	Glass Wool	710 711 708	0.12	0.5	3.8	CH	-	Deterministic
88	C	DE	CaSi	801 802 803	0.025	0.5	0.45	DE	X	Deterministic
89	C	DE	CaSi	801 802 803	0.03	0.5	0.53	DE	X	Deterministic
90	C	DE	CaSi	801 802 803	0.05	0.5	0.87	DE	X	Deterministic
91	C	DE	CaSi	801 802 803	0.08	0.5	1.38	DE	X	Deterministic
92	C	DE	Capillary Active PUR	804 805 806	0.03	0.5	1.07	DE	X	Deterministic
93	C	DE	Capillary Active PUR	804 805 806	0.05	0.5	1.72	DE	X	Deterministic
94	C	DE	Capillary Active PUR	804 805 806	0.08	0.5	2.69	DE	X	Deterministic
95	C	DE	Phenolic Foam	807 808	0.02	0.5	1.16	DE	-	Deterministic
96	C	DE	Phenolic Foam	807 808	0.045	0.5	2.55	DE	-	Deterministic
97	C	DE	Phenolic Foam	807 808	0.065	0.5	3.66	DE	-	Deterministic
98	C	DE	Phenolic Foam	807 808	0.08	0.5	4.49	DE	-	Deterministic
99	C	DE	Phenolic Foam	807 808	0.09	0.5	5.05	DE	-	Deterministic
100	C	DE	Phenolic Foam	807 808	0.11	0.5	6.16	DE	-	Deterministic
101	C	DE	AAC	801 809 803	0.06	0.5	1.36	DE	X	Deterministic
102	C	DE	AAC	801 809 803	0.08	0.5	1.8	DE	X	Deterministic
103	C	DE	AAC	801 809 803	0.1	0.5	2.25	DE	X	Deterministic
104	C	DE	Glass Wool	810 811 808	0.07	0.5	2.24	DE	-	Deterministic
105	C	DE	Glass Wool	810 811 808	0.095	0.5	3.02	DE	-	Deterministic
106	C	DE	Glass Wool	810 811 808	0.12	0.5	3.8	DE	-	Deterministic

IS / CS ID	Source	Country	IS	Materials included ID	Insulation thickness (m)	Existing wall thermal resistance (m^2K/W)	Insulation system thermal resistance (m^2K/W)	Climate	LCC data*	Data type
107	C	BE	CaSi	901 902 903	0.025	0.5	0.45	BE	X	Deterministic
108	C	BE	CaSi	901 902 903	0.03	0.5	0.53	BE	X	Deterministic
109	C	BE	CaSi	901 902 903	0.05	0.5	0.87	BE	X	Deterministic
110	C	BE	CaSi	901 902 903	0.08	0.5	1.38	BE	X	Deterministic
111	C	BE	Capillary Active PUR	904 905 906	0.03	0.5	1.07	BE	X	Deterministic
112	C	BE	Capillary Active PUR	904 905 906	0.05	0.5	1.72	BE	X	Deterministic
113	C	BE	Capillary Active PUR	904 905 906	0.08	0.5	2.69	BE	X	Deterministic
114	C	BE	Phenolic Foam	907 908	0.02	0.5	1.16	BE	-	Deterministic
115	C	BE	Phenolic Foam	907 908	0.045	0.5	2.55	BE	-	Deterministic
116	C	BE	Phenolic Foam	907 908	0.065	0.5	3.66	BE	-	Deterministic
117	C	BE	Phenolic Foam	907 908	0.08	0.5	4.49	BE	-	Deterministic
118	C	BE	Phenolic Foam	907 908	0.09	0.5	5.05	BE	-	Deterministic
119	C	BE	Phenolic Foam	907 908	0.11	0.5	6.16	BE	-	Deterministic
120	C	BE	AAC	901 909 903	0.06	0.5	1.36	BE	X	Deterministic
121	C	BE	AAC	901 909 903	0.08	0.5	1.8	BE	X	Deterministic
122	C	BE	AAC	901 909 903	0.1	0.5	2.25	BE	X	Deterministic
123	C	BE	Glass Wool	910 911 908	0.07	0.5	2.24	BE	-	Deterministic
124	C	BE	Glass Wool	910 911 908	0.095	0.5	3.02	BE	-	Deterministic
125	C	BE	Glass Wool	910 911 908	0.12	0.5	3.8	BE	-	Deterministic
126	C	IT	CaSi	1001 1002 1003	0.025	0.5	0.45	Lombardia Region (IT)	X	Deterministic
127	C	IT	CaSi	1001 1002 1003	0.03	0.5	0.53	Lombardia Region (IT)	X	Deterministic
128	C	IT	CaSi	1001 1002 1003	0.05	0.5	0.87	Lombardia Region (IT)	X	Deterministic
129	C	IT	CaSi	1001 1002 1003	0.08	0.5	1.38	Lombardia Region (IT)	X	Deterministic
130	C	IT	Capillary Active PUR	1004 1005 1006	0.03	0.5	1.07	Lombardia Region (IT)	-	Deterministic
131	C	IT	Capillary Active PUR	1004 1005 1006	0.05	0.5	1.72	Lombardia Region (IT)	-	Deterministic
132	C	IT	Capillary Active PUR	1004 1005 1006	0.08	0.5	2.69	Lombardia Region (IT)	-	Deterministic
133	C	IT	Phenolic Foam	1007 1008	0.02	0.5	1.16	Lombardia Region (IT)	-	Deterministic

IS / CS ID	Source	Country	IS	Materials included ID	Insulation thickness (m)	Existing wall thermal resistance (m^2K/W)	Insulation system thermal resistance (m^2K/W)	Climate	LCC data*	Data type
134	C	IT	Phenolic Foam	1007 1008	0.045	0.5	2.55	Lombardia Region (IT)	-	Deterministic
135	C	IT	Phenolic Foam	1007 1008	0.065	0.5	3.66	Lombardia Region (IT)	-	Deterministic
136	C	IT	Phenolic Foam	1007 1008	0.08	0.5	4.49	Lombardia Region (IT)	-	Deterministic
137	C	IT	Phenolic Foam	1007 1008	0.09	0.5	5.05	Lombardia Region (IT)	-	Deterministic
138	C	IT	Phenolic Foam	1007 1008	0.11	0.5	6.16	Lombardia Region (IT)	-	Deterministic
139	C	IT	AAC	1001 1009 1003	0.06	0.5	1.36	Lombardia Region (IT)	X	Deterministic
140	C	IT	AAC	1001 1009 1003	0.08	0.5	1.8	Lombardia Region (IT)	X	Deterministic
141	C	IT	AAC	1001 1009 1003	0.1	0.5	2.25	Lombardia Region (IT)	X	Deterministic
142	C	IT	Glass Wool	1010 1011 1008	0.07	0.5	2.24	Lombardia Region (IT)	-	Deterministic
143	C	IT	Glass Wool	1010 1011 1008	0.095	0.5	3.02	Lombardia Region (IT)	-	Deterministic
144	C	IT	Glass Wool	1010 1011 1008	0.12	0.5	3.8	Lombardia Region (IT)	-	Deterministic

Energy sources

Table 12 Summary table of energy sources included in the RiBuild software database. *LCC data retrieved from: https://ec.europa.eu/eurostat/web/energy/data/database

Energy source	LCA Source	Country	Insulation system	LCC data*	LCA data	LCA Method	Data type
1	A	IT	Gas	X	X	CML	Stochastic
2	A	IT	electricity	X	X	CML	Stochastic
3	B	CH	Gas	X	X	CML	Deterministic
4	B	CH	electricity	X	X	CML	Deterministic
5	B	CH	oil	X	X	CML	Deterministic
6	B	DK	oil	X	X	RECIPE	Deterministic
7	B	DK	Gas	X	X	RECIPE	Deterministic
8	B	DK	Renewable energy	-	X	RECIPE	Deterministic
9	B	DK	electricity	X	X	RECIPE	Deterministic
10	B	DK	District heating	X	X	RECIPE	Deterministic
11	C	BE	Biomass furnace	-	X	RECIPE	Deterministic
12	C	BE	Natural gas boiler	X	X	RECIPE	Deterministic
13	C	BE	Oil boiler condensing	-	X	RECIPE	Deterministic
14	C	BE	Oil boiler non-condensing	-	X	RECIPE	Deterministic
15	C	DK	Biomass furnace	-	X	RECIPE	Deterministic
16	C	DK	District Heating	X	X	RECIPE	Deterministic
17	C	DK	Natural gas boiler	X	X	RECIPE	Deterministic

18	C	DE	Biomass furnace	-	X	CML	Deterministic
19	C	DE	Natural gas boiler	X	X	CML	Deterministic
20	C	DE	Oil boiler condensing	-	X	CML	Deterministic
21	C	DE	Oil boiler non-condensing	-	X	CML	Deterministic
22	C	IT	Biomass furnace	-	X	CML	Deterministic
23	C	IT	Electricity	X	X	CML	Deterministic
24	C	IT	Natural Gas Boiler	X	X	CML	Deterministic
25	C	LT	Biomass furnace	-	X	CML	Deterministic
26	C	LT	District Heating	-	X	CML	Deterministic
27	C	LT	Natural gas boiler	X	X	CML	Deterministic
28	C	SE	Biomass furnace	-	X	CML	Deterministic
29	C	SE	District Heating	-	X	CML	Deterministic
30	C	SE	Electricity	X	X	CML	Deterministic
31	C	CH	Biomass furnace	-	X	CML	Deterministic
32	C	CH	Natural gas boiler	-	X	CML	Deterministic
33	C	CH	Oil boiler condensing	-	X	CML	Deterministic
34	C	CH	Oil boiler non-condensing	-	X	CML	Deterministic

Energy source ID	Country	Energy source	Data type
1	IT	Gas	Stochastic
2	IT	electricity	Stochastic
3	CH	Gas	Deterministic
4	CH	electricity	Deterministic
5	CH	oil	Deterministic
6	DK	oil	Deterministic
7	DK	Gas	Deterministic
8	DK	Renewable energy	Deterministic
9	DK	electricity	Deterministic
10	DK	District heating	Deterministic
11	BE	Biomass furnace	Deterministic
12	BE	Natural gas boiler	Deterministic
13	BE	Oil boiler condensing	Deterministic
14	BE	Oil boiler non-condensing	Deterministic
15	DK	Biomass furnace	Deterministic
16	DK	District Heating	Deterministic
17	DK	Natural gas boiler	Deterministic
18	DE	Biomass furnace	Deterministic
19	DE	Natural gas boiler	Deterministic
20	DE	Oil boiler condensing	Deterministic
21	DE	Oil boiler non-condensing	Deterministic
22	IT	Biomass furnace	Deterministic
23	IT	Electricity	Deterministic
24	IT	Natural Gas Boiler	Deterministic
25	LT	Biomass furnace	Deterministic
26	LT	District Heating	Deterministic
27	LT	Natural gas boiler	Deterministic

28	SE	Biomass furnace	Deterministic
29	SE	District Heating	Deterministic
30	SE	Electricity	Deterministic
31	CH	Biomass furnace	Deterministic
32	CH	Natural gas boiler	Deterministic
33	CH	Oil boiler condensing	Deterministic
34	CH	Oil boiler non-condensing	Deterministic

1.5 Appendix 3. Software License

This tool has been developed by: Edoardo Baldoni, Marco D'Orazio, Elisa Di Giuseppe and Monica Iannaccone. It is based on the probabilistic LCA/LCC methodology developed by UNIVPM and HES-SO within WP5/RIBuild project.

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