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Modeling the energy and environmental life cycle of buildings: A co-simulation approach

Maurizio Cellura[a], Francesco Guarino[a,*], Sonia Longo[a], Marina Mistretta[b]

[a] DEIM Department – University of Palermo, Viale delle Scienze, Building 9, 90128 Palermo, Italy
[b] PAU Department – University of Reggio Calabria, Via Salita Melissari Feo di Vito, I 89124 Reggio Calabria, Italy

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ABSTRACT

Building simulation is currently looking towards interdisciplinary experiences, aiming to the integration of simulation tools in different technical domains. At the same time, the interest of the building community to high performance buildings has also strengthened the interest on Life Cycle performances of such buildings, due to the reduction in their operational stage impacts. In this context, the paper proposes an integration of building simulation and Life Cycle Assessment through the programming of a TRNSYS component. It can perform Life Cycle Assessment studies, while having as output as well energy balances and energy and environmental payback times. Currently, the tool is tailored to calculate the indicators Global energy requirement and Global warming potential, but its flexibility allows to calculate any kind of indicator, if given the right inputs.

Validation results report percentage deviations variable between 10E-3% and 10E-8% if compared to a standard Life Cycle Assessment study, thus it is possible to state that the Type is a reliable tool for such applications.

1. Introduction

In many regions throughout the world, clean and sustainable energy solutions are being driven by legislation e.g. the European Performance of Buildings Directive [1] and ASHRAE Standard 189 [2] aiming to bring about high performance buildings through a holistic approach to design. In addition, the collaboration activities of the International Energy Agency have accelerated developments in key areas such as energy technologies and solar cooling and heating [3–5]. Other organizations, such as CIBSE in the UK [6] and the Department of Energy in the US [7], recognizing that the design of the built environment is a complex task due to the presence of interacting technical domains, different performance expectations and pervasive uncertainties, are supporting building simulation take-up through the development of application manuals and educational materials.

Predicting the effect of all the interacting technical aspects in building simulation at the same time is not simple and involves achieving integration among different domains, uncertainties and modeling choices. Building simulation tools provide means to approach such complexity and the need to improve the energy efficiency of the building sector, whilst allowing exploration of the impact of design parameters on solutions that provide the required life cycle performance at acceptable cost. Over the last decades building simulation has grown always more integrated among different mathematical models and approaches: from the load calculations, to the simulation of heat and mass transfer, to airflow and daylighting modeling, to comfort and occupants behavior, control models, exergy, life cycle, micro-grids etc. Thus, the most relevant research target of the last decade has become the enhancement of the potential to couple different domain models in order to describe effectively the interaction between different sections and parts of the building.

1.1. State of the art: methodological needs of LCA of buildings

Among the other domains, it is increasingly more important to extend the perspective to the life cycle [8] modeling of buildings in order to include the hidden impacts required to achieve good building performances.

The sector has seen a growing interest in the past years, as discussed in [9]. The study examined the literature related to the building life cycle assessment published from 2014 to 2014 through bibliometric methods, highlighting a continuous increase in the last decades in publications in the sector.

Life Cycle Assessment is a powerful tool to compare different systems that provide the same service and optimize processes and components in complex systems during several phases of their life cycle

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[*] Corresponding author.
E-mail address: francesco.guarino@unipa.it (F. Guarino).

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Nomenclature

LCA	Life Cycle Assessment
GWP	Global warming potential
GER	Global energy requirements
NZEB	Net Zero Energy Buildings
G	Energy generation
C	Energy consumption
E	Exported energy
I	Imported energy
w	Characterization factors
j	Energy carriers
t_1, t_2	Time frame of the analysis
GER_M	Primary energy consumption necessary to create a product or a service
GER_U	Primary energy consumption necessary to use a product or a service
GER_{RD}	Primary energy consumption necessary to recycle or dispose a product or a service
m_i	Mass of the substance i emitted
CF_i	Characterization factor that reflects the relative contribution of the substance i to the impact on GWP
EPT	Energy Payback Time
GWP_PT	GWP Payback time
Ey	Yearly primary energy generated from renewable sources
G_y	Net avoided GWP associated to the energy generation from renewable sources
$I_{A1\text{-}3}$	Modules A1-A3 total impact
q_j	Quantity of the jth material/component as volume, area/thickness, mass or component number
$i_{A1\text{-}3,j}$	Specific impact for stages A1-A3, due to the production of the jth material
I_{A4}	Module A4 total impact
$D_{A4,j}$	Transportation distance of the jth material/component to the construction site
$i_{T,k}$	Specific impact of the kth means of transport, referred to 1 t * km
I_{A5}	Module A5 total impact
$p_{A5,x}$	Energy or water used during building construction
$i_{A5,x}$	Specific impact for energy or water used during the building construction
$q_{j,s}$	Quantity of swarf per each j_{th} material
$i_{j,s}$	Specific impact of the end-of-life of swarf per each j_{th} material
$I_{B1\text{-}5}$	Overall impact of the B1-B5 stages
s_j	Ratio between the quantity of the jth material/component replaced during the whole operational stage and the whole quantity of the jth material/component available in the building at the beginning of the operational stage
$i_{C3\text{-}4,j}$	Specific impact of the j-th material/component in the C3-4 end-of-life stage
I_b	Further impacts related to the B_{1-5} stages
I_{B6}	Overall impact of the B6 stage
i_{Ij}	Characterization factors chosen for the analysis related to the j_{th} energy carrier for energy imported and generated
v	Expected useful life
I_{B7}	Overall impacts for the B7 stage
W	Yearly water use volume during the B7 stage
i_w	Specific impact due to water use
I_{C1}	Overall impact due to the demolition of the building
$p_{C1,x}$	Water or energy use during Module C_1
I_{C2}	Impact due to the transportation of the materials/components to the end-of-life site
$D_{C2,j}$	Transportation distance of the jth material/component to the end-of-life site
$I_{C3\text{-}4}$	Overall impacts of the C3-C4 stages
$i_{C3\text{-}4,\ j}$	Specific end-of-life impact of the jth material/component
I_D	Total Benefits and loads beyond the system boundary
$i_{e,x}$	Avoided specific impact for exported energy
$i_{D,j}$	Net specific benefits achievable by the recycling of the j_{th} material

[10]. Modern building simulation practice tends to focus much more on the operational phase neglecting the other life cycle steps. For lightweight and low performances buildings the operation stage has the highest impact while construction and end-of-life are cause of usually negligible impacts. In these buildings, the use phase usually accounts for 70–90% of the total life cycle primary energy use [11,12]. But this concept is usually not valid in the case of Net Zero Energy Buildings (NZEBs) [13], or more in general, passive and low energy buildings. In these buildings, the higher complexity of the design and of the HVAC systems, and the overall higher energy embodied (EE) in materials and systems, causes a decrease of the impact of the operational phase and the increase of embodied impacts in all the other life cycle steps [14].

This issue calls for a higher integration between building simulation and LCA from the early stages of the design. In the following paragraphs, the most relevant and up to date original papers and reviews on the topic are briefly discussed.

In [15], Pomponi and Moncaster describe, from an LCA perspective, the approach to the methodology towards the reduction in embodied carbon in buildings. After a wide analysis of more than 100 journal articles, it is revealed the need for a pluralistic approach in LCA. Most previous approaches to the problem have in fact often overlook the use stage and the buildings' end of life.

In [16], Fouquet et al. discuss a review of methodological challenges and developments in LCA of low energy buildings. The paper highlights the need for accounting of biogenic carbon in LCA as well as dynamic LCA computation, including year by year variations in the calculations. The element of dynamic simulation is hereby strengthened as well as the need to include more variability and uncertainty analysis in the LCA methodology.

Kaur Anand et al. in [17] presents a review of the LCA research field applied to buildings. They state that the areas of embodied energy and building certification systems have seen the maximum growth in the most recent years, concluding that challenges and research opportunities from these areas require further research. The review also points towards the need for indicators and tools introducing the life cycle perspective in the building early design phase.

Eleftheriadis et al. [18] highlight some challenges for future research. In particular the LCA method in the building sector is seen as time consuming and as requiring a high level of knowledge of the field for the analyst; data quality is seen as a challenge as well, since the early availability of data is critical for the final assessment. Lastly, another limit to the methodology is its usual use in a later phase of a project for certification purposes and not as decision-making, early in the design development.

The importance of including life cycle oriented choices in the design process is applied in [19] for a specific case study. The paper presents a cradle-to-grave Life Cycle Assessment of energy conservation measures for a designed office building in central London. The original design compiled with the UK building regulations. Several LCA-oriented modification are discussed as well as operational energy saving techniques. Globally, over a 60-years building lifetime, operational energy was 10 times higher than embodied energy, while operational carbon was 8 times higher than embodied carbon. Once more, the need for balancing and obtaining tradeoffs between embodied energy/

carbon and use phase energy use/carbon emissions is mentioned as well as the significance of LCA for early stage building design decisions.

1.2. State of the art: previous co-simulation experiences

Since the need for introducing LCA into design tools is an established research need in the field, it is therefore needed to innovate current simulation tools by developing integrated simulation approaches able to model all the life cycle steps of a building's life.

This concept was approached in existing papers in the last decade, but in most cases, they described simplified applications with no real validation or connections to LCA most up-to-date references and standards.

As described in [20] nearly no building simulation tool has taken the needed step towards the integration of Life Cycle Assessment into building simulation tools. Some examples are available and are briefly discussed in the following paragraphs.

In the last years, the IMPACT compliant assessments method including BREEAM calculations was included in the commercial building simulation IES VE tool [21]. The tool covers the whole life cycle of buildings but has some issues in the available database quality and diversification and in the lack of necessary detail in the modeling.

In [22] a LCA database manager has been developed for the ESP-r suite. The study, developed more than a decade ago, although had some flaws in data quality and lack of a validation, was a promising start on the way to holistic assessment of building performance.

A simplified LCA module was introduced in the UMI – Urban modeling interface developed at Massachusetts Institute of Technology. Life Cycle module in UMI takes as inputs embodied energy/embodied carbon data and performs a simplified Life Cycle Inventory calculation. Its website [23] states that the LCA component in UMI “is not a complete LCA tool, such as other commercial more complex software suites focused on LCA modeling for products and materials, and it does not include a validated dataset for environmental properties of building components”.

In [24], authors describe how the LCA method is integrated into the thermal simulation tool BSIM. The materials used in the building simulation database were linked to the Building Environmental Assessment Tool (BEAT) [25]. The tool was only used to calculate the environmental impact of the construction phase of the building. In [26] a review of several Building Integrated Modeling (BIM) applications directly incorporating life cycle impacts calculations or visualization is proposed, examining more than one hundred studies in the field. Results clarify that at the moment only limited research efforts are spent in the modeling of building maintenance, retrofitting and demolition and that a relevant lack of ‘cradle-to-grave’ modeling tools is felt in the BIM landscape.

In the context of the co-simulation of different tools, an integration between a building information modeling tool (BIM) and a simplified LCA tool [27] is proposed in [28]. A simple model of a wall and a door is proposed in the analysis, no validation or whole-building analysis is presented in the paper.

Although not directly proposing an integration among tools and modeling, some studies [29,30] discuss the necessity to integrate the building simulation practice with LCA studies to see the larger picture while performing design choices but in most cases they are used as two distinct methodological approaches, that do not include co-simulation of different tools or development of innovative instruments. In particular, [29] proposes a comprehensive energy and environmental life-cycle assessment of the roof retrofit of a Portuguese single-family house integrating thermal dynamic simulation. Results show that the use phase accounted for 60–70% of all the life cycle impacts in all categories. The paper shows the importance of the co-existence of dynamic simulation and LCA, by quantifying the marginal life cycle benefit of additional insulation levels while providing recommendations for optimal insulation levels in the Mediterranean area.

In [30] a similar approach is proposed, by linking life cycle assessment and thermal building simulation. A sensitivity analysis application is performed, in order to account for the variability in real occupancy scenarios to both the building simulation and the LCA.

In [31], authors propose a dynamic parametric analysis tool (PAT) for the comprehensive assessment of operational energy use, embodied energy and embodied material emissions during the production and operation phases of a building. The results show that the tool developed in this study can be used to define optimal solutions of building envelopes for the different parameters of the analysis. In conclusion, this study facilitates the first steps of development and testing for a PAT that evaluate optimised solutions that minimise operational energy use, embodied CO2eq emissions and embodied energy. However, as authors state, the tool “is not meant to give precise results, given its limitation in the calculation method, (but) can be used for performing a comparative pre-assessment of various design solutions”.

Lastly, Cubi et al. [32], discusses the necessity of having integrated LCA and building simulation tools. The integration of life cycle assessment databases into building energy simulation tools would allow design teams to accurately assess environmental performance of building design alternatives. They conclude that a single tool capable of providing accurate LCA results of buildings would very much facilitate design choices based on environmental performances.

However, in the case of the most relevant and worldwide used tools of building simulation [33,34] and of Life Cycle Assessment (LCA) modeling [35], there is no integration available of these two aspects.

The first objective of the paper was to analyze the state of the art on the integration of building simulation and LCA, identifying any research needs in the field. From this first step, it was clear that the need of coupling building simulation to LCA is becoming increasingly more needed with the development of Net Zero Energy Buildings. This connection needs to be established earlier in the design process than it usually is, otherwise life cycle thinking would not be able to influence the final design. To do so, it is also identified a lack of specific tools to be adopted as early design and modeling tools able to use both the building simulation and life cycle thinking perspective.

In this context, the next sections describe in detail the second objective of the paper: the development of an innovative modular tool, defined “Type”, that is able to perform Life Cycle Assessment studies while working in TRNSYS simulation environment. The Type allows to analyze, in the same working environment, the energy-environmental impacts connected to both the use stage and the life cycle of the building, aiming to a higher systemic integration among two domains – building simulation and life cycle modeling – particularly needed for high performance buildings. The Type has been applied to a case-study of NZEB located in Italy and a validation of its code is done by performing the LCA study in both the Type and an existing study [8–36] under the same assumptions and by comparing the results.

The paper includes the following sections: in the Section 2 the LCA modeling is described as well as the graphical interface, the main outputs of the Type and the mathematical background, Section 3 briefly describes the case study and shows the results of the comparison between the results obtained by the Type and the existing LCA study of the same building as well as all the outputs of the Type, the discussion (Section 4) and conclusions (Section 5) includes all the final and generalized remarks on the study.

2. Methods

One of the objectives of the research is the programming of a LCA Type to be integrated in the library of the TRNSYS software [33] in order to create a tool able to target both the use phase modeling and the other phases of the life cycle of a building in the same simulation environment. Moreover, since in available literature data quality is usually an issue for LCA tools [37] implemented in building performance simulation software, a validation of the algorithms results is performed.

TRNSYS environment can be basically described as being made up two different cores. The first one is based on an engine that reads and processes input files and iteratively solves the system of equations used: it is basically the software architecture, that calls routines and is the 'brain' of the graphic interface of the tool. The second one is a library of components (Types), each of which models the performances of one part of the building and of the HVAC system (pipes, pumps etc.). The engine works routinely calling the library when a specific component is chosen by the user to work in the project. The proposed LCA Type is included in the TRNSYS library of components.

In detail, the Type allows LCA modeling of buildings according to a "from cradle to cradle" approach, in accordance to the International standard of organization 14040 [38,39] series and to the UNI EN 15978 [40]. The modeling is based on a set of linear equations modeling each step of the building life cycle. It is moreover structured in accordance to the modularity principle of the UNI EN 15978 regulation, according to which all processes influencing the environmental performance of the building in its useful life must be assigned to the module of the life cycle in which they occur.

The LCA Type is described in Fig. 1. All "modules" reported in Fig. 1 refer to a specific life cycle stage, as described in the UNI EN15978 regulation. The Type requires external data provided by the user and outputs of the building performance simulation.

The Type performs the calculation of the following outputs:

- Yearly primary and final energy balances (load-generation L-G and import-export I-E) for prosumer buildings, according to Eqs. (1) and (2) respectively:

$$LGBalance = \sum_{t=t_1}^{t_2} \sum_{j=1}^{j_n} G_j(t) \cdot w_{g,j} - \sum_j C_j(t) \cdot w_{c,j} \tag{1}$$

$$IEBalance = \sum_{t=t_1}^{t_2} \sum_{j=1}^{j_n} I_j(t) \cdot w_{g,j} - \sum_j E_j(t) \cdot w_{c,j} \tag{2}$$

  where G and C are respectively the instantaneous energy generation and the consumption, E and I are respectively instantaneous energy exported and imported, w are the characterization factors chosen for the analysis, $_j$ are the energy carriers considered for generation and consumption, t_1 and t_2 are the time boundaries for the analysis. All balances can be arranged as instantaneous and cumulated output as well;
- Global Energy Requirement (GER), expressed in MJ. Its impact factors have been calculated with the Cumulative Energy Demand method [29]. GER is calculated as in Eq. (3):

$$GER = GER_M + GER_U + GER_{RD} \tag{3}$$

  where:

  GER_M is the primary energy consumption necessary to create a product or a service;
  GER_U is the primary energy consumption necessary to use a product or a service;
  GER_{RD} is the primary energy consumption necessary to recycle or dispose a product or a service;

- Global Warming Potential (GWP), calculated as kg of CO_{2eq}, which impact factors have been calculated with the IPCC 2007 method [42]. GWP is calculated as in Eq. (4):

$$GWP = \sum m_i * CF_i \tag{4}$$

  where:

  m_i is the mass of the substance i emitted;
  CF_i is the characterization factor that reflects the relative contribution of the substance i to the impact on GWP;

- Energy payback time (EPT), calculated as the years necessary for energy generation on site to be equal to the overall primary energy consumed during the whole life cycle of the building (Eq. (5)):

$$EPT = \frac{GER}{Ey} \tag{5}$$

  where:

  E_y represents the yearly primary energy generated from renewable sources;

- GWP payback time (GWP-PT) defined as the years needed for the avoided GWP – thanks to the on-site renewable energy generation during the use phase – to be equal to the overall GWP generated during the life cycle of the building (Eq. (6)):

$$GWPPT = \frac{GWP}{Gy} \tag{6}$$

  where:

  G_y represents the net avoided GWP associated to the energy generation from renewable sources.

The Type relies on an external database to provide most of the information required for the LCA modeling. The database (Figs. 2–4 show screenshots of different sections of the database) includes the specific impacts due to GER and GWP of building materials, energy carriers, transports and end-of-life processes. These data are from [41].

The very simple and easily modifiable structure (basically a matrix with rows equal to the number of elements included in the database) allows to implement any other environmental impact calculations (e.g.

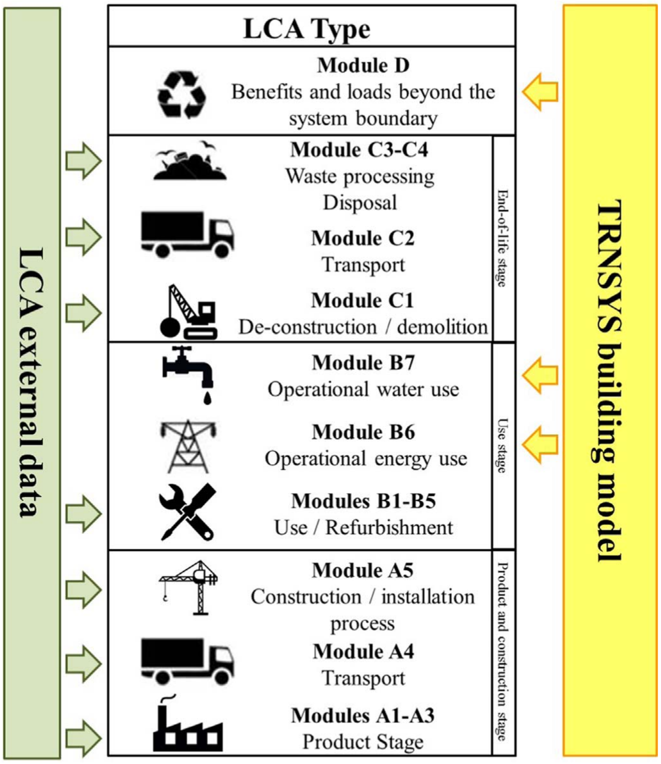
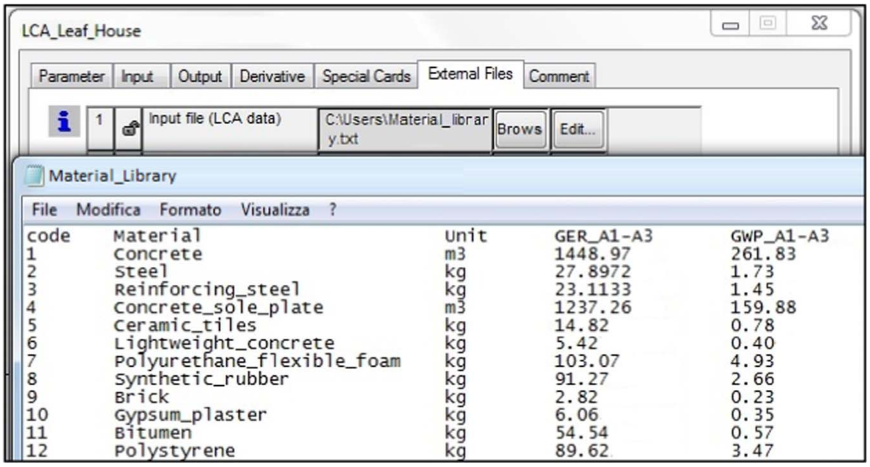


Fig. 1. Schematic description of the LCA Type.



1 Input file (LCA data) C:\Users\Material_library.txt

```
code     Material                      Unit     GER_A1-A3     GWP_A1-A3
1        Concrete                      m3       1448.97       261.83
2        Steel                         kg       27.8972       1.73
3        Reinforcing_steel             kg       23.1133       1.45
4        Concrete_sole_plate           m3       1237.26       159.88
5        Ceramic_tiles                 kg       14.82         0.78
6        Lightweight_concrete          kg       5.42          0.40
7        Polyurethane_flexible_foam    kg       103.07        4.93
8        Synthetic_rubber              kg       91.27         2.66
9        Brick                         kg       2.82          0.23
10       Gypsum_plaster                kg       6.06          0.35
11       Bitumen                       kg       54.54         0.57
12       Polystyrene                   kg       89.62         3.47
```

Fig. 2. Structure of the LCA database – Materials.

Ozone depletion potential, Abiotic potential) or new elements required by the LCA modeling (e.g. specific HVAC components, additional materials included in the envelope).

2.1. Methods: assumptions and life cycle modeling

For each of the life cycle step, the most relevant modeling assumptions and data needed are included in the following list. It is worth mentioning however that since the GWP and GER calculations performed are rather similar, a general notation system is used in the following equations, that is valid for both cases.

2.1.1. Product stage (A1-A3 modules)

The impacts for this stage are calculated as:

$$I_{A1-3} = \sum_j (q_j \cdot i_{A1-3,j}) \tag{7}$$

where:

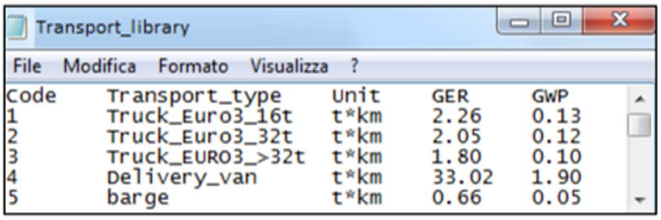
$I_{A1\text{-}3}$ = Total A1-A3 impact;
$i_{A1\text{-}3,j}$ = Specific impact for stages A1-A3, due to the production of the j^{th} material;
q_j = Quantity of the jth material/component as volume, area/thickness, mass or component number (e.g. one split air conditioner).

Two solutions are available to input q_j to the type:

1. Manual input of all features of the building envelope (mass and materials);
2. Connection of the output from Type 56 (TRNSYS building modeling tool) directly with the LCA Type, in order to acquire information on the geometry and on the features of the envelope, as shown in Fig. 5. Users would still need to add some more information in the Type (e.g. thickness of the layers).

2.1.2. Construction process – transport (Module A4)

This step includes the transportation of materials and products from the manufacturing firms to the construction site. Users should select the type of transport used and the distance (in km) covered by transports for each material/component already included in the product stage.



```
Code     Transport_type     Unit    GER     GWP
1        Truck_Euro3_16t    t*km    2.26    0.13
2        Truck_Euro3_32t    t*km    2.05    0.12
3        Truck_EURO3_>32t   t*km    1.80    0.10
4        Delivery_van       t*km    33.02   1.90
5        barge              t*km    0.66    0.05
```

Fig. 4. Structure of the LCA database – Transports.

The impacts of this stage are calculated as in Eq. (8):

$$I_{A4} = \sum_j (q_j \cdot D_{A4,j} \cdot i_{T,k}) \tag{8}$$

where:

I_{A4} = Impact due to the transportation of the materials to the construction site;
q_j = Quantity of the jth material/component [kg];
$D_{A4,j}$ = Transportation distance of the jth material/component to the construction site [km];
$i_{T,k}$ = specific impact of the kth means of transport, referred to 1 t * km.

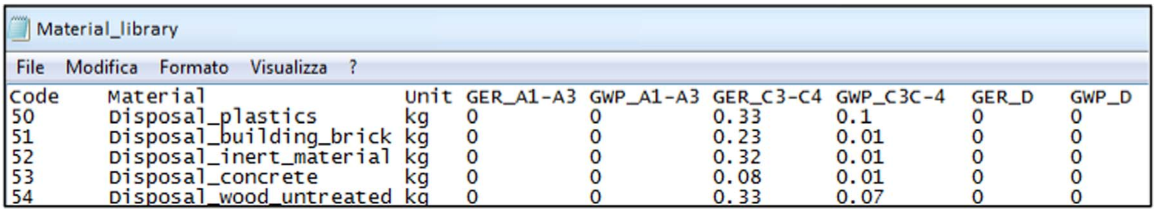
2.1.3. Construction process – construction – installation process (Module A5)

The modeling of this stage requires data for water and energy use during the building construction and other inputs. It is also required to indicate the energy carrier chosen. This stage includes also the end-of-life of swarf.

The impact of this stage is calculated as in Eq. (9).

$$I_{A5} = \sum_x (p_{A5,x} \cdot i_{A5,x}) + \sum_j (q_{j,s} \cdot i_{j,s}) \tag{9}$$

where:



```
Code    Material                   Unit  GER_A1-A3  GWP_A1-A3  GER_C3-C4  GWP_C3C-4  GER_D   GWP_D
50      Disposal_plastics          kg    0          0          0.33       0.1        0       0
51      Disposal_building_brick    kg    0          0          0.23       0.01       0       0
52      Disposal_inert_material    kg    0          0          0.32       0.01       0       0
53      Disposal_concrete          kg    0          0          0.08       0.01       0       0
54      Disposal_wood_untreated    kg    0          0          0.33       0.07       0       0
```

Fig. 3. Structure of the LCA database – End-of-life.

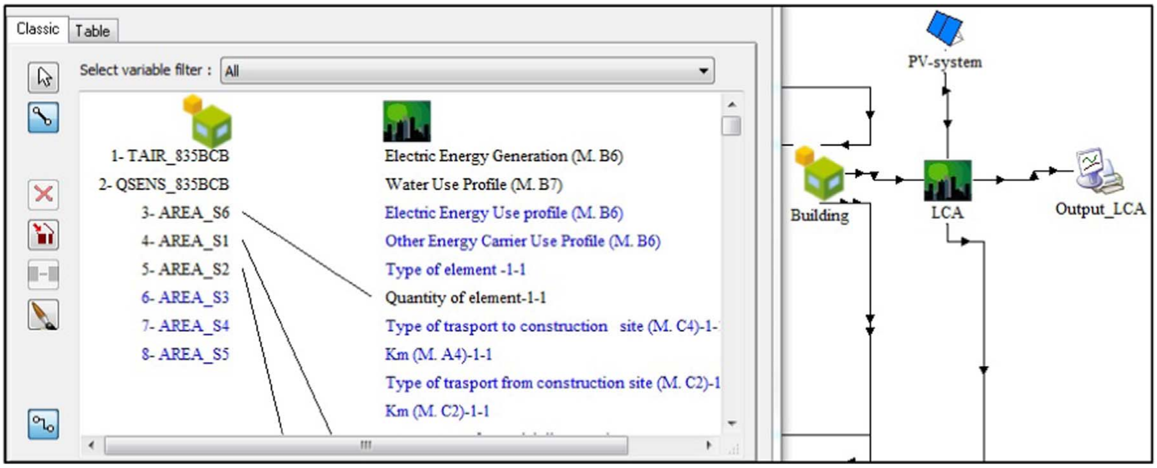

Select variable filter : All

Fig. 5. Connection of Type 56 (on the left) to the LCA Type (on the right) in TRNSYS – Simulation Studio.

$\mathrm{I_{A5}}$: Total impact due to the building construction;
$\mathrm{p_{A5,x}}$: Energy or water used during building construction;
$\mathrm{i_{A5,x}}$: Specific impact for energy or water used during the building construction;
$\mathrm{q_{j,s}}$: Quantity of swarf per each $\mathrm{j_{th}}$ material [kg];
$\mathrm{i_{j,s}}$: Specific impact of the end-of-life of swarf per each $\mathrm{j_{th}}$ material.

2.1.4. *Use stage – use, maintenance, repair, replacement and refurbishment (B1-B5)*

The modeling of these stages requires data on energy uses with detail of the energy carrier chosen and information on the materials and components that are replaced during the useful life. Module – B1 encompasses the impacts and aspects arising from the normal conditions of use of components of the building, such as the release of substances from the façade, roof, floor covering and other surfaces. In the case of replaced materials and component, their production, transports and end-of-life impacts are allocated in this stage. The overall impact is calculated through Eq. (10). This formulation includes mostly the replacement impact, that is usually the most relevant for these stages, however the others can be added if needed through the $\mathrm{I_b}$ term.

$$I_{B1-5} = \sum_j (q_j\cdot i_{A1-3,j}\cdot s_j) + \sum_j (q_j\cdot i_{C3-4,j}\cdot s_j) + \mathrm{I_B} \qquad (10)$$

where:

$\mathrm{I_{B1\text{-}5}}$ = Overall impact of the B1-B5 stages;
$\mathrm{s_j}$ = Ratio between the quantity of the jth material/component replaced during the whole operational stage and the whole quantity of the jth material/component available in the building at the beginning of the operational stage;
$\mathrm{i_{A1\text{-}3,j}}$ = Specific impact of the j-th material/component in the A1-A3 production stage;
$\mathrm{i_{C3\text{-}4,j}}$ = Specific impact of the j-th material/component in the C3-4 end-of-life stage;
$\mathrm{q_j}$ = Quantity of the jth material/component used in the building. This value is read from the original input for the production stage;
$\mathrm{I_b}$ = Further impacts related to the $\mathrm{B_{1\text{-}5}}$ stages.

2.1.5. *Use stage – operational energy use (Module B6)*

The Type requires as inputs energy use profiles from the building simulation in order to calculate the energy-environmental impacts of the Module B6, as shown in Eq. (11).

$$IB6 = \sum_{j=1}^{j_n} [I_j(t)\cdot i_{I,j} + G_j(t)\cdot i_{G,j}]\cdot v \qquad (11)$$

where:

I = Instantaneous imported energy;
G = Instantaneous energy generated on site and auto-consumed by the building;
i_{Ij} = Characterization factors chosen for the analysis related to the $\mathrm{j_{th}}$ energy carrier for energy imported and generated;
t = Time frame of a year;
v = expected useful life;
$\mathrm{t_1}$, $\mathrm{t_2}$ = boundaries of the period chosen.

2.1.6. *Use stage – operational water use (Module B7)*

To calculate the impacts for this stage, it is required to connect the Type to water use profiles in TRNSYS environment. The overall impacts for this stage are calculated in Eq. (12):

$$I_{B7} = (W\cdot i_W)\cdot v \qquad (12)$$

where:

$\mathrm{I_{B7}}$ = Overall impacts for the B7 stage;
W = Yearly water use volume;
$\mathrm{i_w}$ = Specific impact due to water use;
v = Useful life of the building, in years.

2.1.7. *End of life stage – de-construction, demolition, transport, waste processing, disposal (Modules C1-4)*

The following information are needed to assess the energy and environmental impacts arisen from the End-of-life stage: use of water, electricity and other energy carriers required for demolition, identification of recycling/disposal treatments, transport distances. More details are available in Eqs. (13)–(15). Benefits of recycling are not included.

In detail, the C1 stage overall impacts are modeled as in Eq. (13):

$$I_{C1} = \sum_j (p_{C1,x}\cdot i_{e,x}) \qquad (13)$$

where:

$\mathrm{I_{C1}}$ = Overall impact due to the demolition of the building;
$\mathrm{p_{C1,x}}$ = Water or energy use (with details on the energy carrier);
$\mathrm{i_{e,x}}$ = Specific impact of the $\mathrm{x_{\text{-}th}}$ energy carrier or water;

The C2 stage is modeled as in Eq. (14). The modeling follows strictly what already discussed for stage A4 (Eq. (8)):

$$I_{C2} = \sum_j (q_j\cdot D_{C2,j}\cdot i_{T,k}) \qquad (14)$$

where:

$\mathrm{I_{C2}}$ = Impact due to the transportation of the materials/components to the end-of-life site;

q_j = Quantity of the jth material/component reaching the end-of-life site [kg];
$D_{C2,j}$ = Transportation distance of the jth material/component to the end-of-life site [km];
$i_{T,k}$ = Specific impact of the jth means of transport, referred to 1 t * km.

Stages C3-C4 are modeled as in Eq. (15):

$$I_{C3-4} = \sum_j (q_j \cdot i_{C3-4,j}) \tag{15}$$

where:

$I_{C3\text{-}4}$ = Overall impacts of the C3-C4 stages;
q_j = Quantity of the kth material/component at the end-of-life [kg];
$i_{C3\text{-}4,\ j}$ = Specific end-of-life impact of the jth material/component.

2.1.8. Benefits and loads beyond the system boundary – reuse, recovery, recycling potential (Module D)

The scenarios for reuse, recovery and recycling potentials are included in Module D, as well as the net avoided environmental burdens resulting from the mass and energy flows exiting the system, minus those entering the system. Eq. (16) describes the calculations performed in this stage.

$$I_D = \sum_{x=1}^{n} [E(t) \cdot i_{e,x}] \cdot v + \sum_j (q_j \cdot i_{D,j}) \tag{16}$$

where:

E (t) = Instantaneous exported energy;
$i_{e,x}$ = Avoided specific impact for exported energy;
v = Useful life of the building, in years;
q_j = Quantity of the jth material/component used in the building to be reused/recovered or recycled [kg];
$i_{D,j}$ = Net specific benefits achievable by the recycling of the j_{th} material.

3. Validation case study

The tool described so far has been used to perform an integrated Life Cycle simulation of the “Leaf House” building. Located in Angeli di Rosora, Italy, the Leaf House [8–36] is a residential building (Shown in Fig. 6) including 6 units in which renewable energy technologies are implemented (photovoltaics, 20 kWp south oriented, solar thermal acting as shading to the big southern windows) and characterized by a low transmittance envelope (U=0.15 W/(m^2 K)) 30 cm of poroton block on the internal side, 18 cm of EPS insulation on the external side.

Windows are double glazed with an argon gap, window to wall ratio reaches 20% of the total south façade and it is around 10% on the others. Monitored by more than 1000 sensors, the building has been analyzed in detail in terms of energy flows during the use phase, being assimilated to a Net Zero Energy Building through the use of non-steady state building simulation, and in terms of life cycle performances through the use of the LCA methodology.

3.1. Results

In this section a comparative validation of the results of the LCA of the Leaf House performed with the Type are shown together with the results obtained on the same case-study in [8–36].

In [8] and [36] authors discuss the results of a LCA study on the aforementioned case study. The LCA was performed in compliance with the ISO 14040 series [38,39]. In particular, the functional unit is the whole building; system boundaries include upstream and downstream processes needed to establish and maintain the function of the building. The reference study period and the required service life of the building are assumed the same and equal to 70 years. Energy and environmental impacts arisen from the following stages of the building life cycle are taken into account:

- production of the building (including production processes of all building materials and components, the construction step including raw material acquisition and resource supply),
- operation (including all the processes occurring during the building service, such as heating, cooling, water supply, electrical appliance usage, renewable energy generation),
- material and component replacement,
- end-of-life of the building (including all the processes from the demolition/dismantling to disposal/recycling),
- transports, including all the transport steps occurring during the whole life cycle of the buildings.

The impact caused by the infrastructures are neglected, e.g. the impacts of the construction of roads, trucks used to carry the construction materials.

About the data quality, site-specific data are integrated with literature data. In particular, inventory datasets on energy supply and transportation are from [41].

The analysis is based on the same assumptions, functional unit, cut-off rules and input data, thus comparing only the two calculation methodologies. Table 1 and Fig. 7 show respectively the results of the LCA study performed by the Type in TRNSYS environment and the deviations of the results obtained by the Type in comparison to the results achieved by [8–36].

As shown in Fig. 7, the deviations with the results of [8–36] are very limited for all the stages of the life cycle and are only due to truncation of decimals in the input data. The maximum and minimum error for the GER are respectively 2.9 E-5% and 6.21 E-10%, while for the GWP they are 3.35 E-5% and 3.8 E-9% respectively.

It is possible to state that by comparative validation with well accepted modeling tool, the new TRNSYS component hereby described achieves errors acceptable to be used in LCA modeling. The main outputs and results obtainable from the TRNSYS Type (Eqs. (1)–(6)) will now be briefly described with reference to the case study to give an overview of the main features of the tool.

The outputs of the Type can be both tables and graphs. Fig. 8 shows, as an example, the results reported for Eq. (1): a load-generation balance. The results are both instantaneous (the lighter blue curve) and cumulative (the thicker curve).

Fig. 8 shows an example of a table output, as formatted by the Type itself. In detail, the table shows: the energy balance, GWP, EPT and

Fig. 6. Different views of the Leaf House.

Table 1
Results for the two indicators GWP and GER.

Module	LCA type	
	GWP [kg CO_{2eq}]	GER [MJ]
A1-A2-A3	583,556.87	10,067,373.99
A4	16,638.74	286,988.19
A5	605.01	9181.30
B1-B5	439,294.14	8,696,859.28
B6	806,881.2	15,701,071.54
B7	1675.66	25,928.64
C1	0	0
C2	7489.84	126,644.03
C3-C4	111,582.26	1,575,256.57
D	−1,046,264.45	−11,794,544.29
Total	921,459.27	24,694,759.25

GWP_PT. In order to perform a dominance analysis the Type reports GER and GWP for each life cycle stage and their relative share in comparison to the total. It is worth mentioning that the highest share on the total reported by the analysis is due to the use of energy for heating and cooling, reported in the B6 column (about 43% for the GER indicator and about 41% for the GWP). The material harvesting and building components production phase has an impact on the results close to 30% for both the GWP (29.66%) and GER (27.59%) indicator, reported under the A1-A2-A3 column.

The outputs of Fig. 10 include EPT and GWP-PT calculated as the ratio between the overall life cycle impacts and the yearly energy generation or benefits achievable by renewable energy generation. Table 2 includes two different results.

The two cases differ mostly on the assumptions performed: the first case does not include the electricity exported in the analysis (usually not included in LCA boundaries), that is included instead in the second one.

One of the most useful applications of the new Type is the Eco-Design approach to improve the eco-profile of the building along the life cycle. In particular, a comparison between energy and environmental impacts of the operational phase, generally considered the most impactful, and other phases of the life cycle of the building could help developers to select the most effective environmental design options. An application reported in Fig. 9 as example, shows the selection of the thickness of the envelope of vertical walls of the building.

The vertical walls are composed of 100 mm insulation facing the external side and 200 mm of brick facing the conditioned environment. The problem is the determination of the thickness of the layers of brick and insulation. This opens up a conflicting domain problem: if using additional layers of materials to the envelope can improve its performances but it also means that these materials need to be extracted, processed and used in the construction itself. This process has non-negligible energy and environmental impacts.

Fig. 9 compares the variation of electricity use in the B6 use phase and the overall GWP and GER, for a set of parametric analyses scenarios determined by variating the thickness of the brick layer between 200 cm and 450 cm (thermal lag hours variable between 5 and 13 h).

The results identify a generic increase of GWP among all cases up to 57,000 kg of CO_{2eq} in the 450 mm scenario of GER up to 990 GJ and a reduction of energy uses during the B6 step variable up to 60 MW h energy use in the useful life in the same scenario. While the energy building performances improve, among all the scenarios of Fig. 9, the Life Cycle GWP and GER grow largely. Environmental payback times of the single retrofit action are also reported in Fig. 9. Calculated as the ratio of GWP avoided per year during the B6 phase and increase in GWP due to the remaining life cycle of the materials introduced in the retrofit, results are close to those reported in Table 2 for the 250 mm scenario. When the size of the brick grows, payback times grow slightly.

In the second example a similar study is performed for the insulation thickness.

In all the design cases in Fig. 10 the GWP increases as well as the GER in all scenarios.

However, since only a limited increase in GWP (2.20%) and GER (0.70%) is available in the 150 mm scenario if compared to the existing one, corresponding to a relevant reduction in the Electricity use in the B6 stage (3.50%), this scenario is worth considering.

A trend similar to the previous figure can be traced also for the payback time in Fig. 10, that is lowest for the 150 mm scenario and grows the thicker the insulation adopted.

4. Discussion

Net Zero Energy Buildings and – more in general – “prosumers” buildings are complex objects that cannot be studied mono-dimensionally. Efforts are required to try and approach them in a multi-disciplinary way. The Type proposed is inscribed in these efforts and aims to partially fill the gap in the integrated life cycle building simulation.

The main results of the Type validation showed that the tool proposed in the paper is able to reach a level of accuracy comparable to that of detailed LCA studies Its most important feature is however the possibility of working in a building simulation environment among the most used worldwide, ensuring integration between further operational stage calculations (e.g. exported and imported energy, load generation, dynamic weighting) and the LCA methodology. The tool allows for the calculation of several indexes of immediate impact on the interdisciplinary design: imported and exported energy calculations dig in the load matching behavior of the building, LCA results split in stages allow to understand which is the most impactful phase of the building life cycle and, most importantly, it is possible to accept tradeoffs between the use phase performances and the overall life

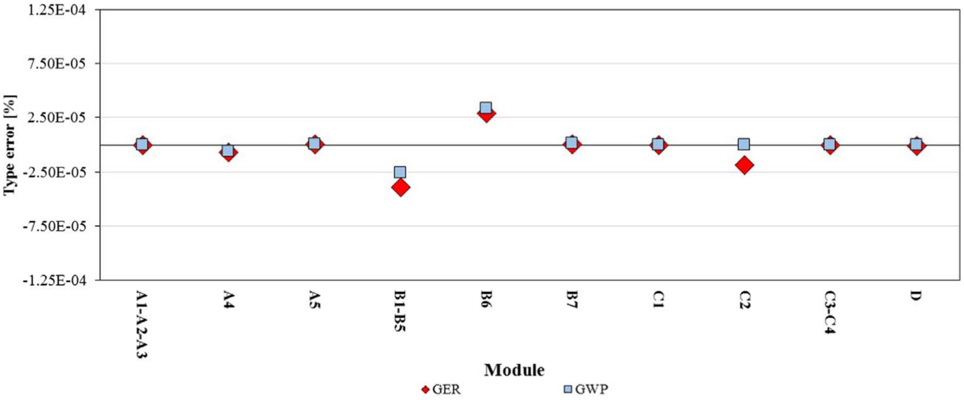
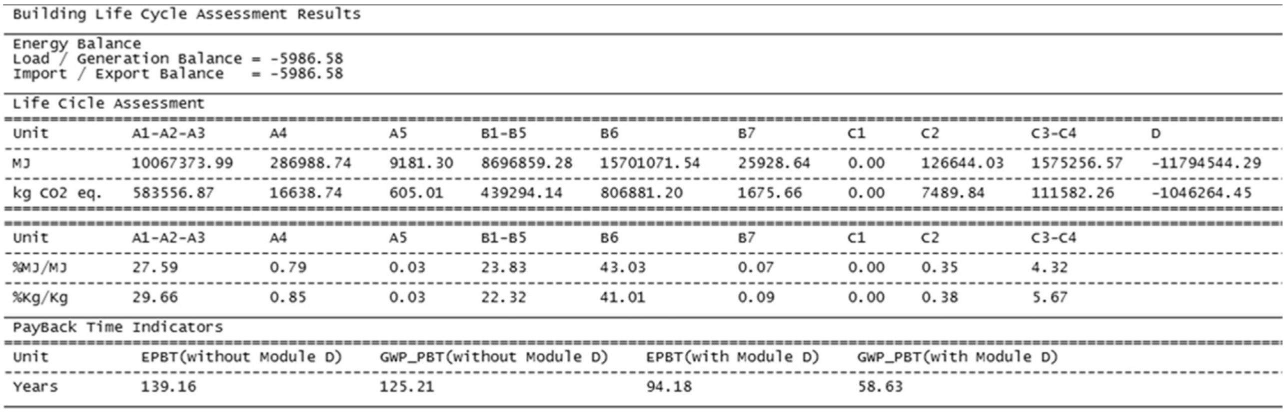


Fig. 7. Comparison of the Type outputs with [8–36] – GER and GWP.



```
Building Life Cycle Assessment Results

Energy Balance
Load / Generation Balance = -5986.58
Import / Export Balance   = -5986.58

Life Cicle Assessment
=====================================================================================================================================
Unit         A1-A2-A3      A4          A5        B1-B5        B6            B7         C1      C2          C3-C4         D
-------------------------------------------------------------------------------------------------------------------------------------
MJ           10067373.99   286988.74   9181.30   8696859.28   15701071.54   25928.64   0.00    126644.03   1575256.57    -11794544.29
-------------------------------------------------------------------------------------------------------------------------------------
kg CO2 eq.   583556.87     16638.74    605.01    439294.14    806881.20     1675.66    0.00    7489.84     111582.26     -1046264.45
=====================================================================================================================================
=====================================================================================================================================
Unit         A1-A2-A3      A4          A5        B1-B5        B6            B7         C1      C2          C3-C4
-------------------------------------------------------------------------------------------------------------------------------------
%MJ/MJ       27.59         0.79        0.03      23.83        43.03         0.07       0.00    0.35        4.32
-------------------------------------------------------------------------------------------------------------------------------------
%Kg/Kg       29.66         0.85        0.03      22.32        41.01         0.09       0.00    0.38        5.67

PayBack Time Indicators
=====================================================================================================================================
Unit          EPBT(without Module D)      GWP_PBT(without Module D)      EPBT(with Module D)      GWP_PBT(with Module D)
-------------------------------------------------------------------------------------------------------------------------------------
Years         139.16                      125.21                         94.18                    58.63
```

Fig. 8. Example of table outputs.

Table 2
Payback Times results.

	EPT [years]	GWP_PT [years]
Not Including Exported Energy	139.16	125.65
Including Exported Energy	109.50	79.24

cycle performances or improve the design by having a combined view on the matter. The topic of conflicting needs for sustainable design is of particular interest to modern sustainable development, since the risk to perform design decisions without considering their effects on the broader consumption and production systems is becoming always more relevant. The Type is a tool that can help practitioners to approach the complexity behind the building as a system that has impacts on several domains affecting the sphere of sustainability. It is also one of the most important research needs in modern building performance simulations, as in order to represent interactions and conflicts occurring between problem parts and model performance trade-offs, the coupling of different domain models is fundamental.

In order to allow practitioners and building analysts to perform even simplified analysis with solid data, the new Type will be correlated with an organized database of freely available LCI datasets, in order to make the Type usable without any pre-processing of data.

Still, it is possible to use the LCA database embedded in the Type to adapt and customize the building model, while for specific and detailed applications it is also currently possible to integrate manually the database with data from e.g. EPDs and/or other LCA studies.

5. Conclusions

The paper has elaborated the state of the art on the integration between LCA and building simulation, highlighting the research needs in the field mainly related to the integration of building simulation and LCA. As potential advancement to the state of the art, the paper presented a LCA tool applied to buildings integrated in the TRNSYS environment that is able to perform “from cradle to cradle” LCA studies. A validation of the tool was performed by comparison of the results of a detailed LCA to those of the Type, obtaining negligible differences. The research aims to identify possible areas of overlapping between building simulation practice and LCA in an attempt to target the limited availability of such integrated simulation tools: the work described in the paper is actually one of the first applications of detailed integrated modeling of these two aspects in literature.

The Type is a solid tool able to support the design of buildings: it aims towards the integration of the Life Cycle point of view in the design choices to allow a sustainability oriented design, that would take into account the repercussions of design choices to the whole life cycle of the building, not only to the operational phase performances. This can have several potential positive repercussions: a diffusion of the LCA methodology among building simulation practitioners, it can allow a deeper connection between building performances and life cycle energy and environmental performances from the design stage, making sensitivity analyses and early design modifications easier, and it would allow to approach the new complexity of Net Zero Energy Buildings from the more fitting life cycle perspective.

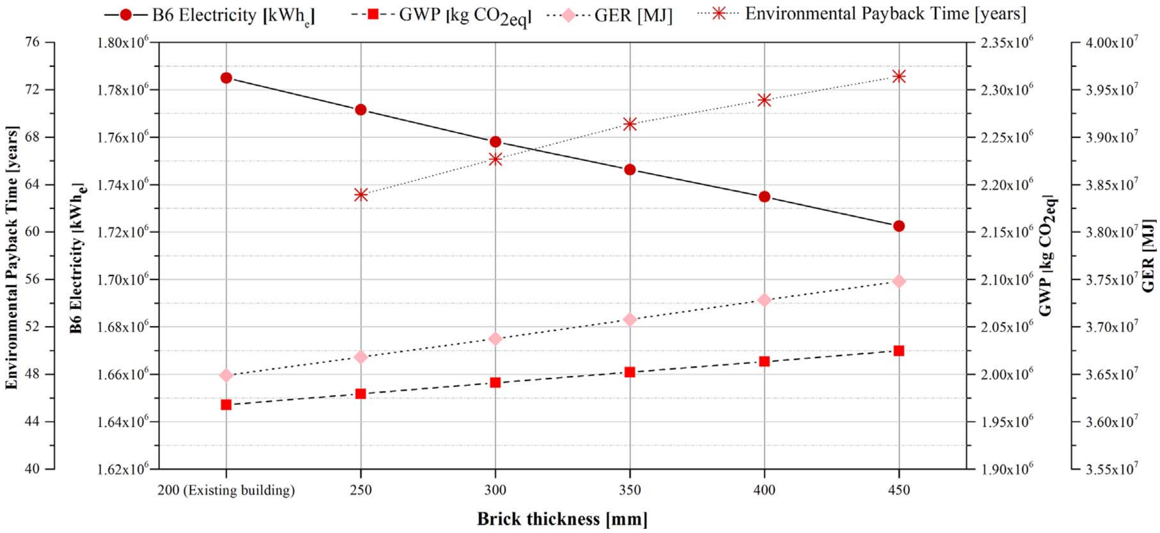


Fig. 9. Example of eco-design scenarios, brick thickness.

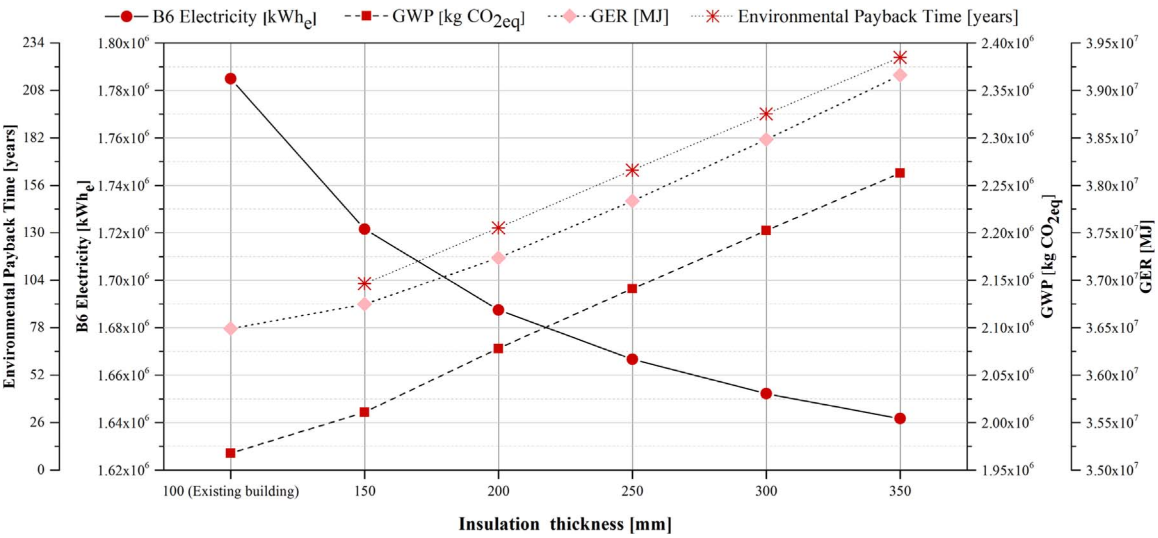


Fig. 10. Example of eco-design scenarios, insulation thickness.

The flexibility of the Type would allow further development and a wide set of potential applications: it is possible to integrate and modify the contents of the database adding more components and materials, to integrate new energy-environmental impact indicators together with GER and GWP and to easily perform dominance and sensitivity analyses.

References

[1] Directive 2010/31/EU of the European Parliament and of the Council (Recast), in Official Journal of the European Union 19 May 2010.
[2] ANSI/ASHRAE/IES/USGBC Standard 189.1-2014, Standard for the design of high-performance green buildings; 2014.
[3] EA-SHC, IEA Solar heating & cooling programme; 2016. 〈http://www.iea-shc.org/〉. [Accessed 20 June 2016].
[4] Finocchiaro P, Beccali M, Cellura M, Guarino F, Longo S. Life Cycle Assessment of a compact desiccant evaporative cooling system: the case study of the “Freescoo”. Sol Energy Mater Sol Cells 2015;156:83–91.
[5] Beccali M, Cellura M, Finocchiaro P, Guarino F, Longo S, Nocke B. Life cycle performance assessment of small solar thermal cooling systems and conventional plants assisted with photovoltaics. Sol Energy 2014;104:93–102.
[6] CIBSE, Chartered institution of building services engineers; 2016. 〈http://www.cibse.org/〉. [Accessed 20 June 2016].
[7] DOE, United States Department of Energy; 2016. 〈http://www.energy.gov〉. [Accessed 20 June 2016].
[8] Cellura M, Guarino F, Longo S, Mistretta M. Energy life-cycle approach in Net zero energy buildings balance: operation and embodied energy of an Italian case study. Energy Build 2014;72(371):81.
[9] Geng S, Wang Y, Zuo J, Zhou Z, Du H, Mao G. Building life cycle assessment research: a review by bibliometric analysis. Renew Sustain Energy Rev 2017;76:176–84.
[10] Beccali M, Cellura M, Finocchiaro P, Guarino F, Longo S, Nocke B. Life Cycle Assessment performance comparison of small solar thermal cooling systems with conventional plants assisted with photovoltaics. Energy Procedia 2012;30:893–903.
[11] Adalberth K, Almgren A, Petersen EH. Life cycle assessment of four multi-family buildings. Int J Low Energy Sustain Build 2001;2:1–21.
[12] Beccali M, Cellura M, Fontana M, Longo S, Mistretta M. Energy retrofit of a single-family house: life cycle net energy saving and environmental benefits. Renew Sustain Energy Rev 2013;27:283–93.
[13] Cellura M, Guarino F, Longo S, Mistretta M. Different energy balances for the redesign of nearly net zero energy buildings: an Italian case study. Renew Sustain Energy Rev 2015;45:100–12.
[14] Cellura M, Di Gangi A, Longo S, Orioli A. An Italian input-output model for the assessment of energy and environmental benefits arising from retrofit actions of buildings. Energy Build 2013;62(97):106.
[15] Pomponi F, Moncaster A. Embodied carbon mitigation and reduction in the built environment – what does the evidence say?. J Environ Manag 2016;181:687–700.
[16] Fouquet M, Levasseur A, Margni M, Lebert A, Lasvaux S, Souyri B, et al. Methodological challenges and developments in LCA of low energy buildings: application to biogenic carbon and global warming assessment. Build Environ 2015;90:51–9.
[17] Kaur Anand C, Amor B. Recent developments, future challenges and new research directions in LCA of buildings: a critical review. Renew Sustain Energy Rev 2017;67(408):416.
[18] Eleftheriadis S, Mumovic D, Greening P. Life Cycle Energy efficiency in building structures: a review of current developments and future outlooks based on BIM capabilities. Renew Sustain Energy Rev 2017;67:811–25.
[19] Azzouz A, Borchers M, Moreira J, Mavrogianni A. Life Cycle Assessment of energy conservation measures during early stage office building design: a case study in London, UK. Energy Build 2017;139:547–68.
[20] Ostergard T, Jensen RI, Maagaard SE. Building simulations supporting decision making in early design – a review. Renew Sustain Energy Rev 2016;61:187–201.
[21] 〈https://www.iesve.com/〉. [Last Accessed 25 April 2017].
[22] Citherlet S. Towards the holistic assessment of building performance based on an integrated simulation approach [Doctoral thesis]. Swiss Federal Institute of Technology; 2001.
[23] 〈http://urbanmodellinginterface.ning.com/〉. [Last Accessed 25 April 2017].
[24] Pedersen F, Hansen K, Wittchen KB, Grau KE, Johnsen K. Combining building thermal simulation methods and LCA methods. In: Proceedings of the NSB2008, 8th symposium on building physics in the Nordic countries. Copenhagen, Denmark, 16–18 June. 200; 2008. p. 605-11.
[25] Petersen EH. LCA tool for use in the building industry. Int J Low Energy Sustain Build 1999;1:1–11.
[26] Wong JKW, Zhou J. Enhancing environmental sustainability over building life cycles through green BIM: a review. Autom Constr 2015;57:156–65.
[27] Athena Sustainable Material Institute. Athena EcoCalculator; 2016. Retrieved May 2012, from 〈http://www.athenasmi.org/our-software-data/ecocalculator/〉. [Accessed 20 June 2016].
[28] Jrade A, Jalaei F. Integrating building information modelling and life cycle assessment tools to design sustainable building. In: Proceedings of the CIB W78 2012: 29th international conference. Beirut, Lebanon. 17–19 October 2012. p. 173-82.
[29] Rodrigues C, Freire F. Integrated life-cycle assessment and thermal dynamic simulation of alternative scenarios for the roof retrofit of a house. Build Environ 2014;81:204–15.
[30] Peuportier B, Thiers S, Guiavarch A. Eco-design of buildings using thermal simulation and life cycle assessment. J Clean Prod 2013;39(7):3–78.
[31] Lolli N, Mamo Fufa S, Inman M. A parametric tool for the assessment of operational energy use, embodied energy and embodied material emissions in building. Energy Procedia 2017;111:21–30.
[32] Cubi E, Bergerson J. Should building energy simulation tools integrate life cycle assessment? A discussion of the potential benefits and challenges. In: eSIM conference proceedings. Ottawa, Canada; 8–9 May 2014.
[33] University of Wisconsin. TRNSYS 17: a transient system simulation program. Solar Energy Laboratory 2010.
[34] LBNL. EnergyPlus, Version 8.4, Berkely, CA: Lawrence Berkeley National Laboratory 2010.
[35] PE International. Gabi 6.5 Software. Leinfelden-echterdingen, Germany 2015.
[36] Mistretta M, Arcoleo M, Cellura M, Nardi Cesarini D, Guarino F, Longo S. Refurbishment scenario to shift nearly net ZEBs towards net ZEB target: an Italian Case Study. Book Chapter in nearly zero energy building refurbishment; 2013. p. 233–52.
[37] Cellura M, Longo S, Mistretta M. Sensitivity analysis to quantify uncertainty in Life Cycle Assessment: the case study of an Italian tile. Renew Sustain Energy Rev 2011;15(9):4697–705.
[38] ISO 14040. Environmental management e life cycle assessment e principles and framework; 2006.
[39] ISO 14044. Environmental management – life cycle assessment – requirements and guidelines; 2006.
[40] UNI EN 15978. Sustainability of construction works – assessment of environmental performance of buildings – calculation method; 2011.
[41] Frischknecht R, Jungbluth N, Althaus HJ, Bauer C, Doka G, Dones R, et al. Implementation of life cycle impact assessment methods. Final report Ecoinvent. Swiss Centre for Life Cycle Inventories, Dübendorf, CH; 2007.
[42] IPCC. Climate Change 2013: the physical science basis. PCC Working Group I Contribution to AR5 (2013). 〈http://www.ipcc.ch/report/ar5/wg1/〉.