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Integration of building simulation and life cycle assessment: a TRNSYS application

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Abstract

The study proposes a tool developed within the TRNSYS environment aimed at integrating its building simulation features during the use phase with a Life Cycle Assessment approach. The tool can be used to investigate the relevance of each life-cycle step of the building on the primary energy consumption and global warming potential.
The Life Cycle stages can be modelled with different approaches: direct input of the embodied energy and global warming potential values for each life cycle step as defined in the EN 15978, use of an internal database of embodied energy and global warming potential of construction materials and energy systems, direct connections of building simulation outputs to the tool for the use phase. The proposed component is able to model correctly the LCA of a case study, obtaining negligible deviations from the results of a LCA study performed with a state of the art LCA software (lower than 0.05% for all impacts).

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Keywords: Life Cycle Assessment, Building simulation, Tool integration, TRNSYS

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1. Introduction

The necessity to achieve a sustainable built environment is usually expressed in the widespread need to reduce energy uses while integrating clean and affordable generation solutions in the building systems and mitigating environmental impacts.

Predicting the effect of all these aspects at the same time is not simple and involves achieving integration among different domains, uncertainties and modeling choices. 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 [1], 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.

Among the others domain models, it is increasingly more important to extend the perspective to the life cycle [2] modeling of buildings. Modern building simulation practice tends to focus much more on the operational phase instead of focusing on the bigger picture including as well the other life cycle steps. It is true indeed that for lightweight and low performances buildings the use phase has the highest impact and the construction and end-of-life steps are usually negligible. The use phase usually accounts for 70-90% of the building total life cycle primary energy use [3].

This statement is usually contradicted in the case of Net Zero Energy Buildings (NZEBs) [4, 5], or more in general, passive and low energy buildings [6]. 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. Approaching the modeling by including all the life cycle stages of the building would be beneficial to the design in achieving higher scientific clarity.

The integrated modeling of the whole life cycle of buildings has been in some cases described in literature [7], but in both the most relevant and used tools of building simulation [8, 9] and of Life Cycle Assessment modeling [10, 11], there is no integration available of these two aspects.

The importance to integrate these two domains in modern sustainable building design is particularly relevant, in particular following the acceleration on legislation and building research on the topic of NZEBs [12].

In this context, the paper shows an innovative modular tool, defined “Type”, that is able to perform Life Cycle Assessment studies while working in one of the most used building simulation tool environments in the world (TRNSYS). The Type, based on the UNI EN 15978 regulation [13], allows analyzing, in the same working environment, the energy-environmental impacts connected to both the use phase and the other life cycle steps, aiming to a higher systemic integration among two domains – building simulation and life cycle modeling – particularly needed for NZEBs. The Type has been applied to a case-study of NZEB located in Italy, a validation of its code is done by performing the LCA study in both the Type and a specific state of the art LCA software under the same assumptions and comparing the results.

2. Methods

The objective of the research is the programming of a LCA type to be integrated in the library of the TRNSYS software [8] 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.

TRNSYS environment can be basically described by 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. 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, envelope etc). The LCA Type, programmed in FORTRAN, is based on these features and is easily integrated in the building simulation library of components.

In detail, the Type allows LCA modeling of buildings according to a “from cradle to cradle” approach, in accordance to the ISO 14040 [14, 15] series and to the UNI EN 15978 [13] regulation. The calculations are based on a set of linear equations modelling each step of the life cycle of a building and is structured in accordance to the modularity principle of the regulations, 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 description of the LCA Type working process is described in Fig.1.

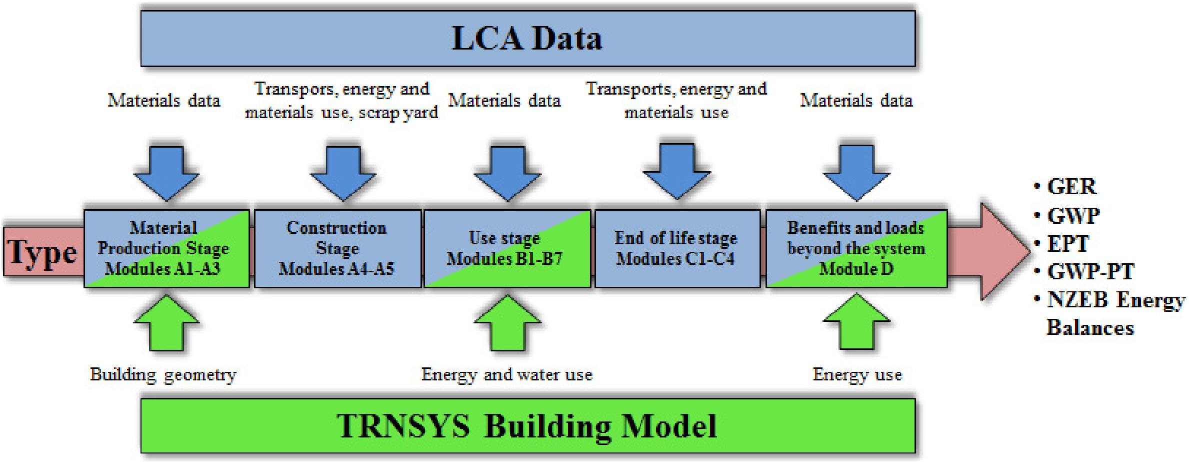


Fig. 1. Schematic description of the TRNSYS Type.

The Type acquires data from both the LCA and from the building simulation aiming to the calculation of the following outputs:

- Yearly energy balance (load-generation and import-export) for Net Zero Energy Buildings, according to equation 1 and 2 respectively:

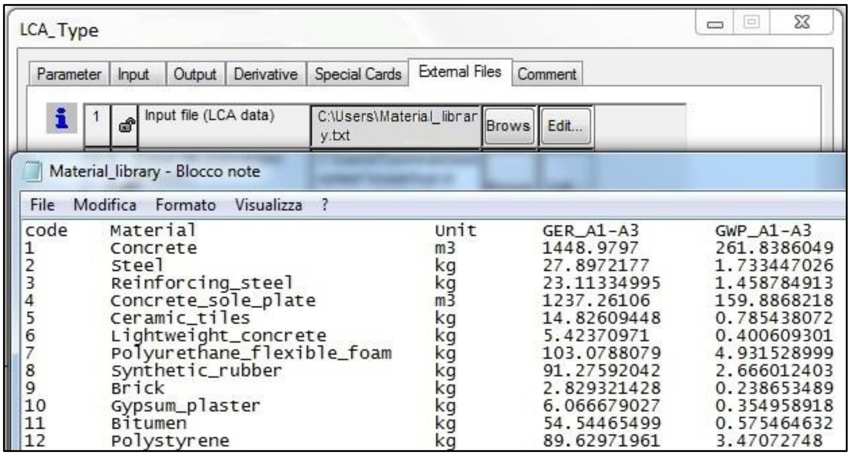
$$LG - Balance = \sum_{t=t_1}^{t_2} \sum_{j=1}^{j_n} g_j(t) \cdot w_{g,j} - \sum_j c_j(t) \cdot w_{c,j} \quad (1)$$

$$IE - Balance = \sum_{t=t_1}^{t_2} \sum_{j=1}^{j_n} i_j(t) \cdot w_{g,j} - \sum_j e_j(t) \cdot w_{c,j} \quad (2)$$

  where *g* and *c* are respectively the energy generation and the consumption, *e* and *i* are respectively energy exported and imported, *w* are the conversion/weighting 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 [16];
- Global Warming Potential (GWP), calculated as kg of $CO_{2eq.}$ whose impact factors have been calculated with the IPCC 2007 method [17];
- 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,
- 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 produced during the life cycle of the building.

The Type relies on an external database to provide most of the information required for the LCA modelling, in particular the upper part of the scheme, coloured in blue. The database (Fig.2) includes the specific impacts due to primary energy consumption and Global Warming Potential of building materials, energy carriers, transports and end-of-life processes.

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. Ozone depletion potential, Abiotic potential) or new elements required by the LCA modelling (e.g. specific HVAC components, additional materials included in the envelope). New materials, construction elements, HVAC components, transport processes can easily be introduced in the database by modifying the data included in the cells or adding new rows.



code	Material	Unit	GER_A1-A3	GWP_A1-A3
1	Concrete	m3	1448.9797	261.8386049
2	Steel	kg	27.8972177	1.733447026
3	Reinforcing_steel	kg	23.11334995	1.458784913
4	Concrete_sole_plate	m3	1237.26106	159.8868218
5	Ceramic_tiles	kg	14.82609448	0.785438072
6	Lightweight_concrete	kg	5.42370971	0.400609301
7	Polyurethane_flexible_foam	kg	103.0788079	4.931528999
8	Synthetic_rubber	kg	91.27592042	2.666012403
9	Brick	kg	2.829321428	0.238653489
10	Gypsum_plaster	kg	6.066679027	0.354958918
11	Bitumen	kg	54.54465499	0.575464632
12	Polystyrene	kg	89.62971961	3.47072748

Fig. 2. Structure of the LCA Database.

In particular, for each of the Life Cycle steps the most relevant modeling assumptions and data needed are included in the following bullet points list:

- Product stage (A1-A3 modules). Two solutions are available:
  - Manual Input of all features of the envelope of the building (mass and materials);
  - Connect 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. 3;

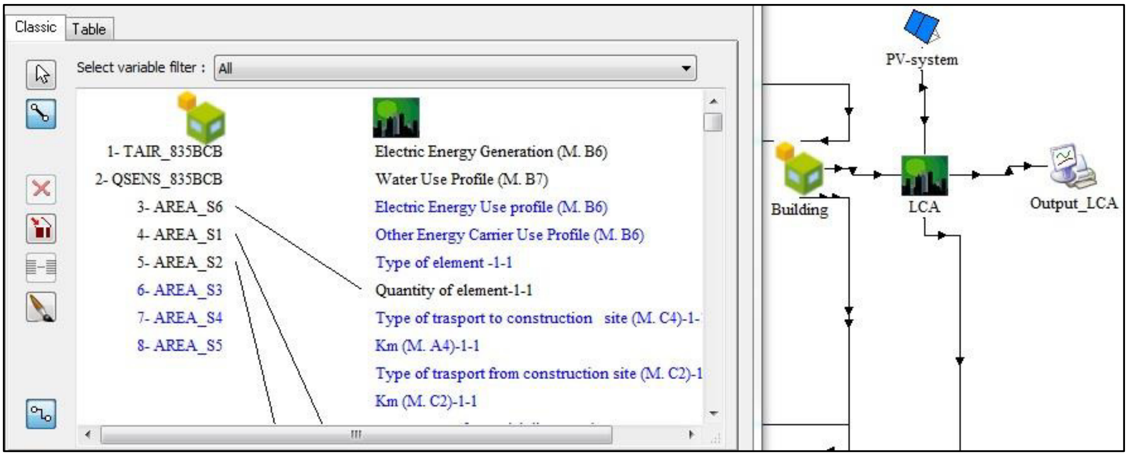


Fig. 3. Connection of Type 56 (on the left) to the LCA Type (on the right) in TRNSYS – Simulation Studio.

- 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 already included in the Product stage;

- Construction Process – Construction – Installation Process (Module A5). The modeling of this stage requires data for water and energy use. It is also required to indicate the energy carrier chosen;
- 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 use;
- 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 equation 3

$$B6 = \sum_{t=t_1}^{t_2} \sum_{j=1}^{j_n} \left[I_j(t) \cdot i_{I,j} + G_j(t) \cdot i_{G,j} \right] \cdot v \tag{3}$$

where *I* is the imported energy, *G* the energy generated on site and auto-consumed by the building, i_j are the weighting factors chosen for the analysis (e.g. converting from final to primary energy, kWh_p/kWh_f), j are the energy carrier for energy imported and generated, t is a time frame of a year, v is the useful life (years) expected while t_1 and t_2 are the boundaries of the time frame chosen.

- Use stage – Operational water use (Module B7). To calculate impacts for this stage, it is required to connect the Type to water use profiles in TRNSYS environment;
- End of Life Stage – De-construction, demolition, Transport, Waste processing, Disposal (Modules C1-4). For these stages, it is necessary to include in the Type the uses of water, electricity and other energy carriers required for the demolition, to identify the processes of recycle/disposal, the transport distances in km and the typology of transport used;
- Benefits and loads beyond the system boundary – Reuse, Recovery, Recycling potential (Module D). The scenarios for reuse, recovery and recycling potentials are included in this module, as well as the net avoided environmental burdens resulting from the flows exiting the system, minus the flows entering the system.

The outputs of the Type can be both tables and graphs. Fig.4 shows, as an example, the results reported for Equation (1): a load-generation Net Zero Energy Building Balance. The results are both instantaneous (the lighter blue curve) and cumulative (the thicker curve). The conversion factors of final energy into primary energy adopted in this example are symmetrical between electrical generation and load [18, 19, 20] with $w_g = w_c = 2.5$ MJ_p/MJ_f. The outputs allow to understand effectively some immediate information about the building studied: the example building reported in the figure shows a relative degree of balance of generation and consumption during the colder months as the cumulative energy balance is nearly flat, but the hottest months mark a strong variation in the results and a nearly linear increase in the cumulate trend of the energy balance.

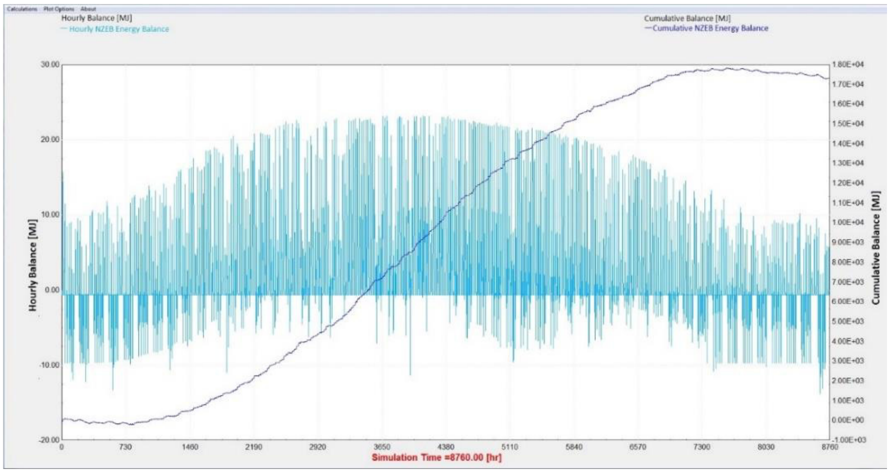


Fig. 4. Net Zero Energy Balance results output.

Fig.5 shows an example of a table output, as formatted by the Type itself. In order to perform a dominance analysis the Type reports in the outputs also the relative share of each life cycle stage impacts in comparison to the total.

Fig. 5. Example of table output.

Building Life Cycle Assessment Results

Energy Balance
Load / Generation Balance = 17344.86 MJ
Import / Export Balance = 8839.71 MJ

Life Cicle Assessment

Unit	A1-A2-A3	A4	A5	B1-B5	B6	B7	C1	C2	C3-C4	D
MJ	680047.01	20269.87	1787.31	2329.67	376462.67	0.00	445.38	16870.96	39311.80	-472049.49
kg CO2 eq.	40770.45	1211.88	83.31	111.21	11226.75	0.00	26.69	1011.91	2097.58	-42840.05

Unit	A1-A2-A3	A4	A5	B1-B5	B6	B7	C1	C2	C3-C4
%MJ/MJ	59.78	1.78	0.16	0.21	33.10	0.00	0.04	1.48	3.46
%Kg/Kg	72.11	2.14	0.15	0.20	19.86	0.00	0.05	1.79	3.71

PayBack Time Indicators

Unit	EPBT(without Module D)	GWP_PBT(without Module D)	EPBT(with Module D)	GWP_PBT(with Module D)
Years	22.08	19.14	13.50	4.63

3. Results: validation

In order to perform a validation of the proposed tool, the results obtained by the Type were compared with the results of a detailed LCA analysis [21], by using the same literature databases and the same modelling assumptions in the two cases.

The analysis is based on a LCA of a prefabricated module developed in the research of the National research council – Nicola Giordano (Messina), in Italy. [22]

Table 1 shows for all the life cycle stages a comparison between the results of the detailed LCA reported in [21] and of the LCA Type hereby presented.

Table 1 – Validation results and error analysis.

Module	GER [MJ]		GWP [kg $CO_{2\,eq}$]	
	Type LCA	Percentage variation	Type LCA	Percentage variation
A1-A3	680,047.01	-0.02485%	41,809.9	-0.01195%
A4	20,269.87	+0.00001%	1,213.5	-0.000,16%
A5	1,787.31	-0.00665%	82.7	-0.012,36%
B1-B5	2,329.67	-0.00008%	111.1	-0.00287%
B6	376,462.67	-0.00738%	11,450.2	-0.02294%
B7	0.00	-	0.00	-
C1	445.38	-0.00091%	26.6	-0.012,49%
C2	16,870.96	+0.00002%	1,008.6	-0.000,08%
C3-C4	39,311.80	+0.00012%	2,075.0	+0.00634%
D	-472,049.49	-0.02037%	-42,932.5	-0.00688%

The percentage difference among the results of the detailed LCA and of the LCA Type is below 0.05% in all the LCA stages showed: it is thus possible to state that the Type allows to perform LCA studies in accordance to the EN UNI 15978 regulation and that is a reliable tool for such applications.

4. Discussion and conclusions

The paper has 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 aim of 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.

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 and to perform easily dominance and sensitivity analyses.

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