Sustainability of modular lightweight steel building from design to deconstruction

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Abstract

The increasing concerns over population growth, depletion of natural resources and global warming as well as catastrophic natural events is leading the international scientific community to envisage sustainability as a crucial goal. The built environment plays a key role on the triple bottom line of the sustainable development - Planet, People, Profit - because of several environmental, social and economic impacts produced by the construction sector. The acknowledged need to promote a sustainable building market is an international high-priority issue as underlined by the 2030 Agenda for Sustainable Development. Indeed one of its strategic objectives highlights to make cities and human settlement inclusive, safe, resilient and sustainable. In line with the 2020 Europe Strategy and the European 2050 Roadmap, energy efficiency and CO_2 savings towards a low-carbon economy are regarded as ambitious objectives to be achieved for both new and existing buildings. Thus, controlling and reducing the environmental impacts of new constructions is fundamental.

In line with this, the “Energy efficient LIghtweight Sustainable SAfe steel construction” (ELISSA) research project financed under the European FP7 aimed to develop a modular Cold – formed steel system that is energy efficient and robust. This paper presents the life cycle analysis of the building developed as case demonstrator. It analyses the environmental impacts during both the construction and the deconstruction phase. This works provides a benchmark of

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the current possibilities offered by lightweight steel structures in the framework of sustainable constructions.

Introduction

The International Energy Agency points out that residential and commercial buildings account for roughly 32% of global energy use and almost 10% of the total direct energy-related CO_2 emissions. It also highlights the importance of implementing stringent energy-saving requirements for new buildings and retrofitting, and the need to use high-efficient technologies in building envelopes and heating/cooling systems. In this context, the reduction of the environmental impacts of the built environment and the improvement of the energy efficiency of buildings during their entire life cycle is a worldwide prime objective for energy policy. As a result, the demanding legislation concerning the reduction of the energy consumption of buildings has been challenging both the construction sector and the research community to develop new high-efficient products and construction techniques, to set up new methodologies for assessing the energy demand of buildings during each stage of their life cycle (Shares et al. 2017), and to develop new technologies to improve the use of renewable energy sources, such as solar thermal energy.

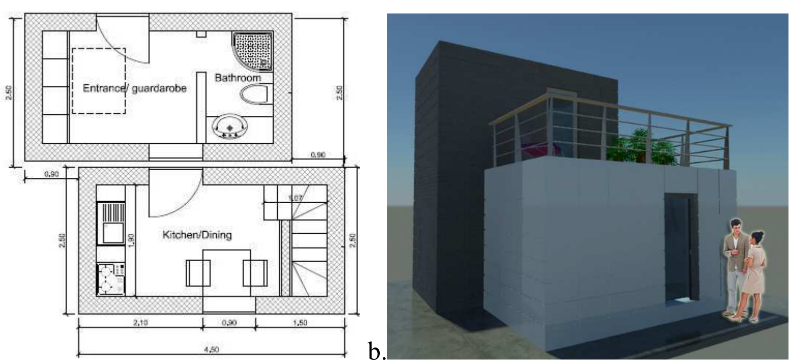
The project ELISSA is a collaborative work of three universities (National Technical University of Athens, University of Federico II in Naples, University of ULSTER in United Kingdom), one research centre (STRESS SCARL from Italy), and seven industrial partners (Farbe SPA (Italy), Woelfel Beratende Ingenieure GmbH & Co KG (Germany), Ayerisches Zentrum fur Angewandteenergieforschung ZAE EV (Germany), Knauf Gips GK (Germany), Haring Nepple AG (Switzerland), Knauf of Lothar Knauf SAS (Italy), VA-Q-TEC AG (Germany)). It aimed at the development and demonstration of nano-enhanced prefabricated lightweight steel skeleton/dry wall systems with improved thermal, vibration/seismic and fire performance, resulting from the inherent thermal, damping and fire spread prevention properties of carefully preselected inorganic nanomaterials (aerogels, VIPs, MMTs, CNT) and NEMS as well as the development of industrially friendly methods for their application. The structural design of the ELISSA house and testing of the Mock-up have been largely presented and discussed in previous Authors papers (Landolfo et al 2018, Fiorino et al 2018, 2017 a, b, 2016).

This paper, building on previous work by the Authors about environmental impact of lightweight steel structures (Iuorio et al 2011), discusses the environmental impacts of the construction and deconstruction process of the ELISSA Mock-up realized in Naples at the end of the research project.

The ELISSA construction system

Central to the research project was the conceptual design of the "ELISSA House" (Figure 1), a two-storey building. The concept has been developed based on two main constraints: the house aimed to represent a real-life condition, able to show case and contain all the required equipment for a single person dwelling; and, the dimensions in plan and elevation were defined in order to allow the production of a full-scale prototype to be tested in the laboratory of the Department of Structures for Engineering and Architecture at the University of Naples Federico II.

The ELISSA house was made of three modules that were horizontally and vertically jointed. In a single floor module, the entrance with wardrobe and the bathroom are located, while in a two-storey floor module, the kitchen / living area is located on the ground floor and a single bedroom is arranged on the second floor. Each module has a 2.5 x 4.5m plan. The total usable area is of 34m^2 plus a terrace accessible from the bedroom and located on the roof of the single storey module. The maximum height is 5.4m. Light and fresh air are guaranteed through the main door and ceiling window in the single storey module and through windows and balcony in the two- storey building.



a b.

Fig 1. ELISSA house: a) first floor, b) perspective view

Mock - up

A mock-up of the ELISSA house was realized at the University of Naples as proof of concept and for seismic testing. The load bearing structure of the ELISSA mock-up has Cold Formed Steel (CFS) walls and floors sheathed with gypsum based board panels. In particular high impact Knauf Diamant Boards are used for walls and Knauf GIFAfloor boards for floors, where Knauf Diamant boards are gypsum based panels with high mechanical and fire resistance and sound insulation, and Knauf GIFAFloor is a high quality, interlocking tongue and grooved floor board system, engineered using gypsum fibreboard technology. The connections between sheathing and CFS profiles are realized with 2.2 mm ballistic nails for the walls and 2.8mm nails for the floors. The finishing has been defined to improve thermal performance and provide specific high thermal performance solutions. The main products used for finishing are: Aquapanel outdoor, mineral wool, Knauf Diamant boards, Knauf GIFA floor boards and Vacuum insulation panels. Aquapanel outdoor are cement boards that can withstand the extreme weathering effects of wind, rain and snow. Figure 2, 3 and 4 describe the external wall, intermediate floor and roof compositions, respectively. The construction of the mock-up last approximately 15 days, of which 5 days were spent for the assembly of the structural part and the finishing, while 10 days were needed for mounting and demounting the scaffolding. Eight days were instead needed for disassembly the ELISSA mock-up after the seismic tests were performed.

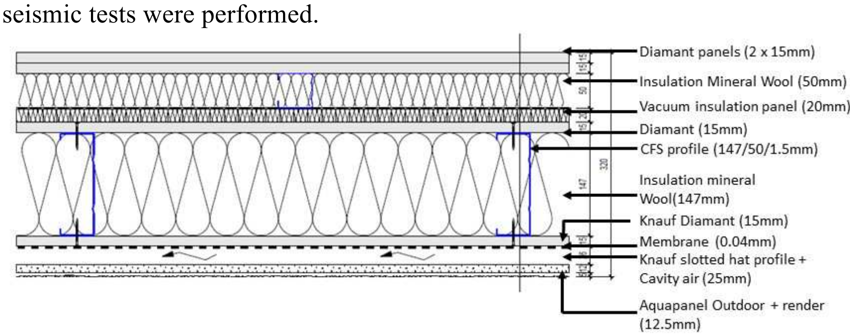


Fig.2. Mock-up External wall.

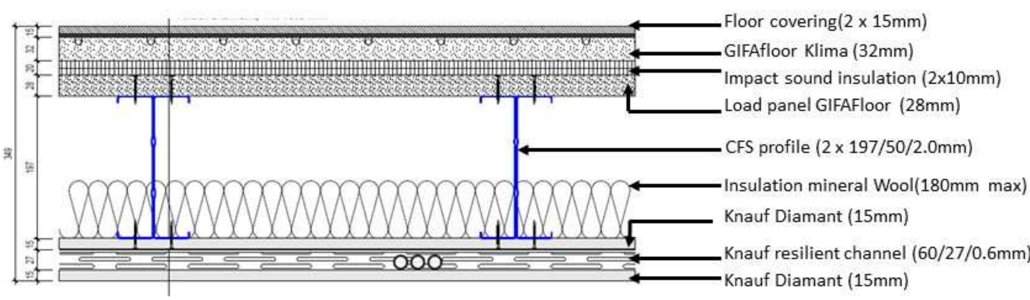


Fig 3. Mock-up intermediate floor

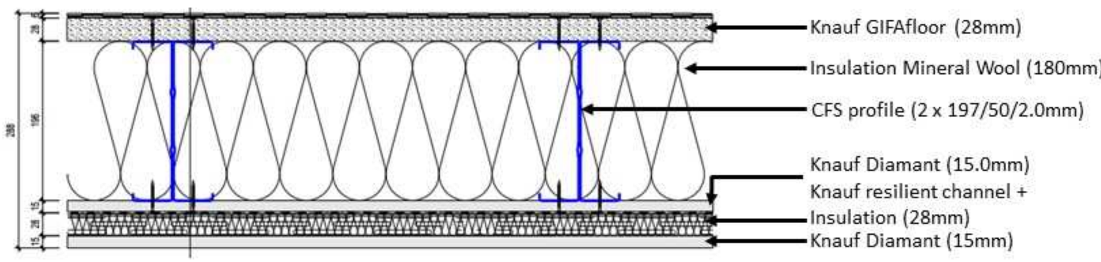


Fig.4. Mock-up roof system.

Life cycle analysis

The work proposes to use Life Cycle Assessment (LCA) as an environmental assessment methodology to investigate the sustainability of lightweight steel systems. In particular, in agreement with current research outcome, the Authors recognizes the fact that with reduction of operational energy thanks to the adoption of technical solutions towards Net Zero buildings, the evaluation of the embodied carbon associated with the construction and the end of life phase becomes of primary importance (Iuorio et al 2013, De Wolf et al. 2014). To this end, this paper investigates the environmental impact of the ELISSA house looking at the construction phase and the end of life phase. The LCA is developed according to the ISO 14040 (2006) and ISO 14044 (2006) and it is articulated in four steps: Goal and Scope, Life cycle inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation and results phases. SimaPro 7.3 software in combination with several LCA databases (e.g. Ecoinvent 3) and materials Environmental Product Declaration (EPDs) are used to analyse the environmental footprint of the ELISSA house.

Goal and scope definition

The ELISSA house has been detailed in section 2. The scope of this section is to analyse the environmental impact of the ELISSA mock up through LCA methodology.

The LCA analysis includes the following phases: 1. Construction (cradle – to - gate); 2. End of Life (EoL). The construction phase includes the manufacturing and transportation of building materials (Modules A1-A3, EN 15804:2012+A1:2013), intended as structural materials, insulation, and finishing, as well as the assembly of all the structural and non-structural components of the ELISSA Mock up (Module A5, EN 15804:2012+A1:2013). Instead in the End of life phase the deconstruction of the mock-up (Module C1, EN 15804:2012+A1:2013) as well as the disposal (Module C4, UNI EN

15804:2012) and/or the recycling of the materials is considered (Module D, UNI EN 15804:2012)

Inventory analysis

Inventory analysis involves data collection and calculation procedures to quantify relevant input and output data of the ELISSA mock-up (ISO 14044 2006). Table 1 summarizes the amount of materials used for the overall mock-up. The transportation of the materials from the production site to the site where the Mock-up has been assembled is not part of this analysis, because the ELISSA mock up could have been realized anywhere.

1. Construction phase

For the construction stage, only the equipment adopted for the assembly of the mock-up in the laboratory has been considered. It is worth noticing that the construction process of the ELISSA house is a dry construction process, where all materials and components are fabricated in factories and transported on site where they are assembled. All the connections between structural parts are realized with mechanical connections and the connection between structures and finishing is either glue based or with mechanical connections. The data and duration of use of all the equipment, having environmental impacts, are summarized in table 2.

Table 1. Material amount and data source

Material	Quantity	Discarded parts in construction	Unit	Source
Galvanized CFS profiles*	2006	30	[kg]	Ecoinvent 3
Knauf Diamant (15 mm)	300	44	[m^2]	Primary data
Knauf GIFAfloor (28 mm)	36	6	[m^2]	Primary data
Floor heating/ cooling GIFAfloor Klima (32mm)	24	4	[m^2]	Primary data
Aquapanel Outdoor + Render (12.5 mm)	57	9	[m^2]	Primary data
Exterior Basecoat	530	94	[kg]	Ecoinvent 3
VIP	227	≈0	[kg]	Ecoinvent 3
Mineral wool	350	45	[kg]	Ecoinvent 3
Membrane LDS 0.04**	8,5	≈0	[kg]	Primary data

*Galvanized CFS profiles includes: C (147/50/1.5) + C(197/50/2.0) + Resilient channel (60/27/0.6) + slotted hat profiles
** Vapour permeable and waterproof foil
http://www.knaufinsulation.gr/en/content/homeseal-lds-004

Table 2. Equipment data for construction phase

Equipment	**Time [hr]**	**Power [kW]**	**Energy [kWh]**	**Fuel [l]**	**Use**
Building equipment: staple gun	11.5	0.085	0.98		Connecting GIFA floor to CFS profiles
Grinding machine	1.5	0.64	44.85		To cut GIFa floor on site
Screwdriver	3	0.327	0.98		Screws
Tow truck	2.99	15	44.85		Handling of components
Lift truck	5.33			37.31	Handling of components
Forklift	0.5			3.5	Handling components

2. End of life phase

The designed life-cycle for the ELISSA house is 50 years. For the definition of the end of the life scenarios, data were derived by the real deconstruction process of the ELISSA Mock-up. Table 3 summarized the quantities of materials that have been recycled (i.e. CFS profiles), reused (i.e. VIP panels) and landfill (i.e all the other materials). Table 4 synthetize the equipment having environmental impacts used in the deconstruction phase.

Table 3. Waste scenarios

Material	**Recycling**	**Reuse**	**Landfill**
Galvanized CFS profiles*	100%	-	-
Knauf Diamant (15 mm)	-	-	100%
Knauf GIFAfloor (28 mm)	-	-	100%
Floor heating/ cooling GIFAfloor Klima (32mm)	-	-	100%
Aquapanel Outdoor + Render (12.5 mm)	-		100%
Exterior Basecoat	-	-	100%
VIP		100%	-
Mineral wool	-	-	100%
Membrane LDS 0.04	-	-	100%

Table 4. Equipment data for deconstruction phase

Equipment	**Time [hr]**	**Power [kW]**	**Energy [kWh]**	**Fuel [l]**
Tow truck	6	15	90.0	
Lift truck	2.5			17.5
Forklift	1			7

Impact assessment

The results of the environmental analysis are presented according to the data format of the Environmental Product Declaration (EPD) standard (UNI EN 15804:2012). Indeed, the environmental outcomes are expressed through six impact categories: Global Warming Potential (GWP), Ozone Depletion Potential (OPD), Photochemical Ozone Creation Potential (POCP), Eutrophication Potential (EP), Acidification, Potential (AP), and Non Renewable Energy (NRE).

1. **Life cycle of ELISSA mock-up**

The LCA of the mock-up, synthetized in figure 5, demonstrates that main impacts are given by the material production phase (Modules A1-A3), while the impacts of A5 and C1 modules can be considered negligible; furthermore, the EoL processing provides several benefits mainly due to the recycling of steel and reuse of VIP (Modules C4; D).

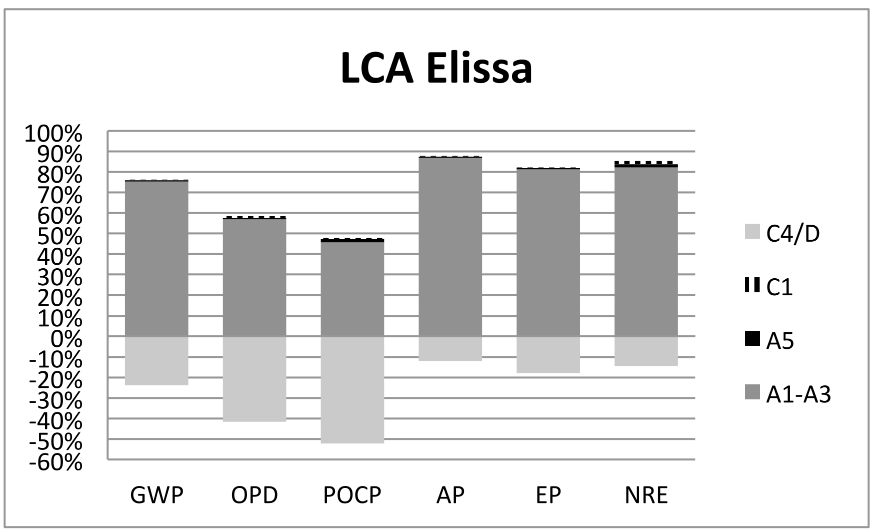


Fig 5. LCA of the overall Mock-up (A1-A3; A5; C1; C4; D modules).

In the following sections, the interpretation of the environmental results related to the construction phase and the EoL of Elissa mock-up is presented.

2. Construction phase

Looking in detail to the material production phase, (i.e. A1- A3 modules), it is worth analyse the impacts of the materials used for walls and floors realization. Instead, with regards to the impacts related to the construction process phase (A5 module) only the analysis of the waste produced in this stage is presented. As depicted in figure 5, the impact of A5 module is neglected. Excepted for the steel material that is recycled, all the others are sent to landfill (Table 1). Figure 6 and 7 show the impacts of the materials used for walls and floors respectively. It appears clear that in both cases CFS profiles plays a major role, followed by the Diamant boards for the GWP indicator. This demonstrates that the impact of the structural components is largely higher that the impact of all the other finishing materials. In terms of waste (A5 module), several credits are obtained for the recycling of steel material. Landfilling of Diamant, GIFAfloor and Aquapanel, instead, contributes to the higher environmental impact as reported in the Figure 8.

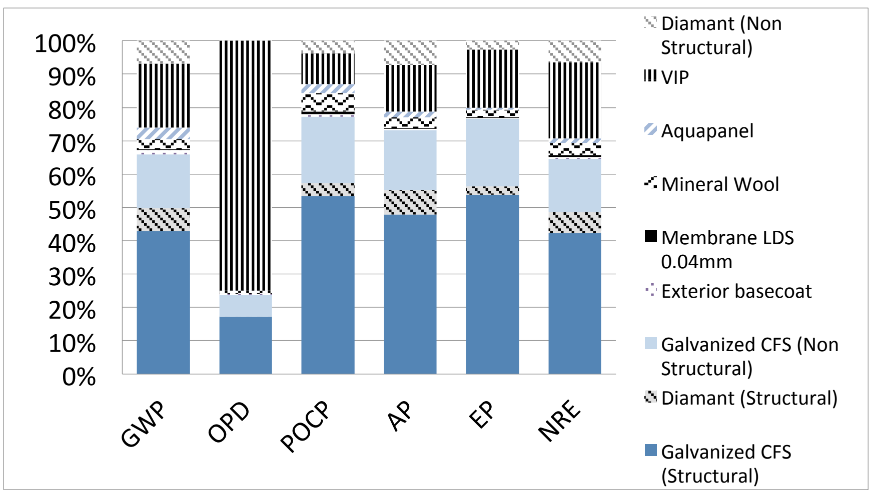


Fig 6. LCA of walls production

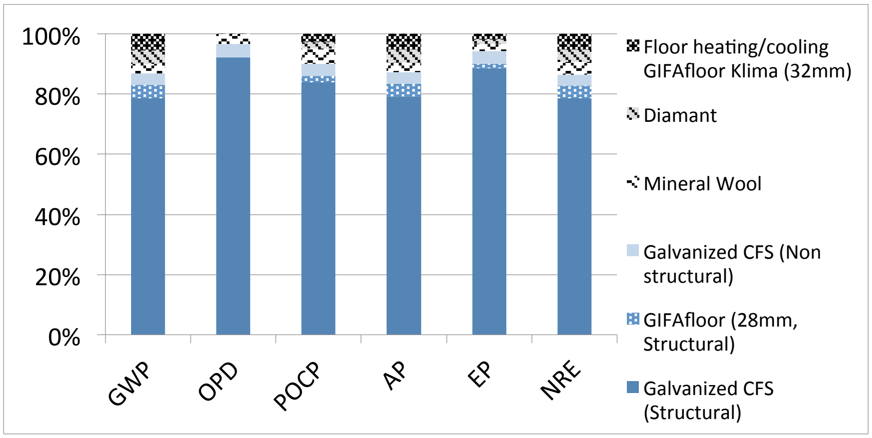


Fig 7. LCA of Floors production

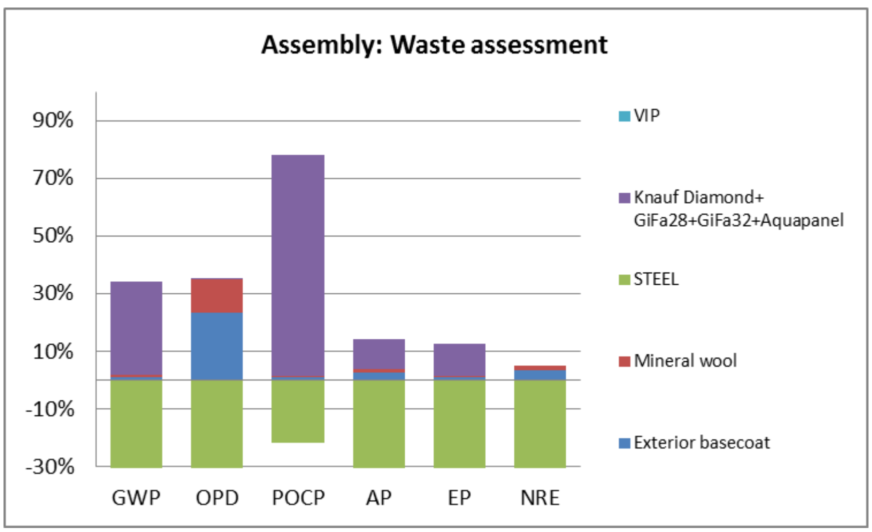


Fig. 8. Waste production in the construction phase (A5 modules).

3. End of life phase

Looking at the end of life and leaving aside the C1 phase, which impact can be neglected, figure 9 demonstrates that the recycle of steel materials and the reuse of VIP panels (C4-D modules) provide environmental beneficial effects.

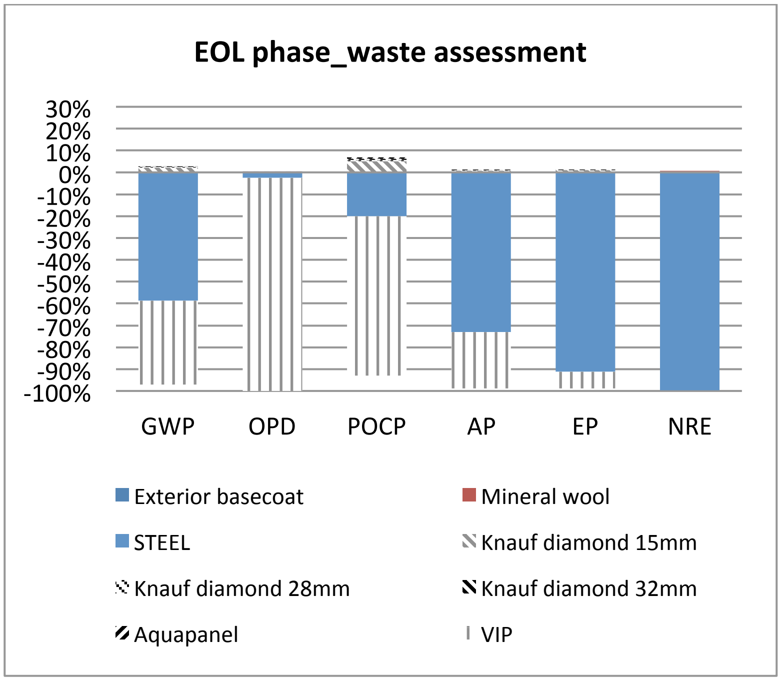


Figure 9. Waste production in the EOL phase (C4-D Modules)

Conclusions

Quantifying the sustainability of any structural systems is a current critical point towards the reduction of the impacts of the construction sector. In particular providing reliable benchmarking of real structural typology is a challenge, which this paper aims to address with the analysis of a real construction. The ELISSA mock up realized in Naples at the end of an FP7 program, devoted to the development of a CFS system characterized by high seismic and thermal performance, allowed the Authors to critically look at the construction and deconstruction phases of a prototype. The analysis according to an LCA methodology of the materials quantities and equipment used for the construction and deconstruction of the housing prototype, allows evaluating the environmental impacts of structural and non-structural components in the construction phase, as well as the impacts of the construction and deconstruction process. The paper shows, that for a system where the finishing have been carefully selected for maximize the thermal performance and minimize the environmental impacts, the structural components (i.e. galvanized CFS profiles and Diamond boards) play a key role in terms of environmental impacts. The study also demonstrates that those impacts are partially counterbalanced by the recycling of components (in this specific case of steel and VIP) in the end of life phase.

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