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THE ENVIRONMENTAL IMPACTS OF AN INNOVATIVE MODULAR LIGHTWEIGHT STEEL SYSTEM: THE ELISSA CASE

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Abstract

A responsible use of resources is necessary to achieve a drastic reduction of environmental impact of the construction sector. This paper investigates the environmental impacts of a new dry construction based on the adoption of cold formed steel (CFS) members as main structural components, which was developed during the ELISSA European FP7 project. The peculiarity of the system is to achieve both high seismic and thermal performance. The first prototype, cited in this paper as ELISSA mock-up, was realized in the laboratory of University of Naples Federico II. The development of the prototype was a fundamental source for a precise evaluation of the environmental impacts. The quality of data in Life Cycle analysis (LCA) is indeed critical for the validity of any study. This paper presents the first LCA of a CFS house, which is based on a real case. The LCA is carried out according to a "Cradle to gate approach, with options EN 15804:2012+A1: Production and Construction; End of Life". The study demonstrates that when materials are carefully selected to reduce operational energy as well as embodied carbon, then the structural system is highly responsible for the LCA impacts. However, when one square meter of the ELISSA mock-up wall is compared to a conventional reinforced masonry wall, than the environmental impacts are much lower than those of the conventional system. This study demonstrates that the ELISSA wall with a thickness, which is one fifth of a comparable conventional system, presents Global Warming Potential that are drastically lower.

Keywords: cold-formed steel; embodied carbon; end of life; life-cycle analysis; modular housing; waste assessment.

1. Introduction

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 (Giesekam J. et al. 2018). Current policies (IPCC 2014, Singh and Kishore 2018) for energy efficiency in buildings are pushing both Europe and America to a drastic reduction of energy requirements for buildings. As a result, we are witnessing a reduction in the energy required to operate buildings without taking into account that the reduction of greenhouse gas emissions should also consider the building materials and structures. The life cycle energy of a building, in fact, includes "embodied carbon energy" and "operational energy". Recent research (Manish et al. 2012, Ochsendorf et al. 2011, Pomponi et al. 2017) shows that embodied energy constitutes a growing proportion of the whole-life energy requirements and carbon emissions. The term ‘embodied carbon’ (Monahan and Powell 2011, Gan et al 2019) refers to the lifecycle greenhouse gas emissions, that occurs during the manufacture and transportation of construction materials and components, as well as the construction process itself and end-of-life aspects of the building including demolition, reuse and recycling. The term embodied carbon can also include the “in use” phase, accounting the greenhouse gases emissions associated to the maintenance, repair, and replacement of building components, but this phase is not considered in this work.

For low-energy buildings, embodied carbon energy is an important parameter, since although less energy is used during their operation, they often requires additional materials to achieve lower operating energy. Awareness of these parameters is essential to avoid shifting problems from one part of the life cycle to another.

This paper aims to investigate the environmental impacts of an innovative modular lightweight system developed during an industrial and academic collaboration. The new investigated modular system is based on lightweight steel skeleton coupled with gypsum and cement –based boards and other materials to provide a safe, fast, energy efficient and long lasting, high quality solution to housing, particularly in high seismic risk areas. This study also aims to build confidence in innovative prefabricated systems, by describing in detail the production, construction and demolition process of a new modular system, with clearly indication of its environmental burdens and by indicating future avenues to further reduce the environmental life-cycle impacts. Analysis and discussion of innovative prefabricated systems is an essential step for the transformation of the construction sector (Tam et al, 2007, Iuorio et al. 2019).

The system was developed through the collaborative work of three universities (National Technical University of Athens, University of Federico II in Naples, University of ULSTER in United Kingdom), one research center (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, vacuum insulation panes (VIPs), MMTs, CNT) and NEMS as well as the development of industrially friendly methods for their application. This paper, after presenting the ELISSA construction system in Section 2, analyses the construction process of a prototype built in Naples with the aim to assess the structural performances (Section 3) and in Section 4 presents a full life cycle analysis of the built prototype. Finally, Section 4.5 presents a comparison between 1 square meter of the ELISSA wall prototype with a square meter of a more conventional wall, made up of reinforced masonry, having the same thermal transmittance.

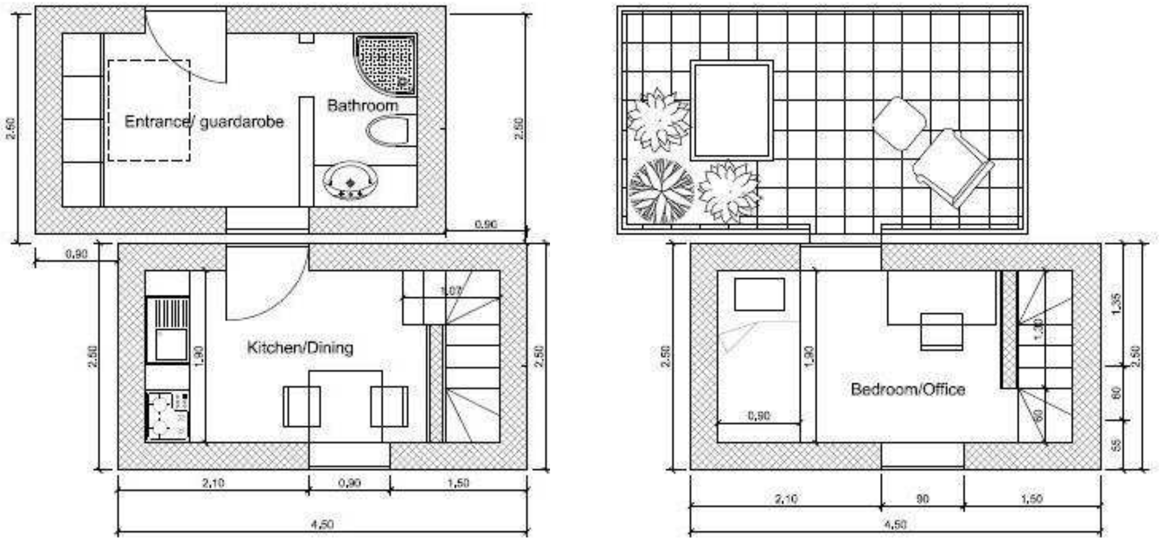
2. The ELISSA construction system

2.1. The architectural concept

Central to the research project was the conceptual design of the “ELISSA House” (figure 1), a two-storey building. The concept was developed based on two main constraints: the house aimed to represent a real-life condition, able to showcase 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 (figure 2). 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.

In the following sections, the structural and technological system is discussed in detail.



a)

b)

Figure 1. Elissa house plans: a) first floor, b) second floor

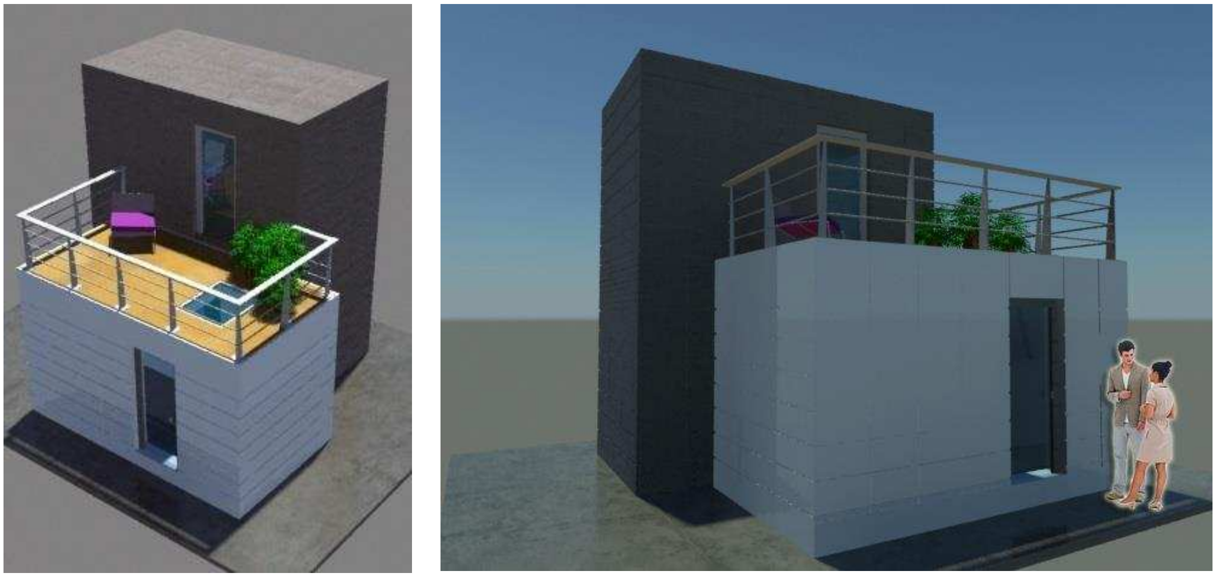


Figure 2. “ELISSA house” axonometric views.

2.2. Structural and technological system

2.2.1 Wall system

ELISSA wall panel is a nano-enhanced lightweight steel skeleton/dry wall system with improved thermal, seismic and fire performance. It consists of multifunctional prefabricated elements with improved thermal properties to achieve low energy consumption during the operational phase of the building. It provides less waste disposal due to the prefabrication and the use of re-usable/recyclable building materials.

The skeleton of the wall is called ‘’Transformer’’. It is a prefabricated load-bearing steel system consisted of thin-walled, cold-formed steel (CFS) U- and C sections. In particular, studs are made of 147x50x1.5 mm (outside-to-outside web depth x outside-to-outside flange size x thickness) C (lipped channel) sections, which are connected at the ends to 150x40x1.5 mm (outside-to-outside web depth x outside-to-outside flange size x thickness) U (unlipped channel) section wall tracks. Both studs and tracks are CFS profiles, made of steel grade S320GD+Z, and zinc coated and dip - hot galvanized. One of the main feature is that CFS profiles can be manufactured to precise specifications, resulting in minimal job site scrap, all of which can be easily and economically recycled. This also entails reduced job site waste, and minimization of site disturbance, which makes the system particularly suitable for the sustainable management of construction sites. The wall steel frame was sheathed with 15 mm thick Knauf Diamant boards (impact resistant gypsum panels) on both sides. Knauf Diamant boards couple a high density (i.e. density of 1024 kg/m^3) and high strength gypsum core with a purpose designed liner paper to provide impact performance higher than standard gypsum boards.

Fastening is a critical issue in CFS systems for two main reasons: market competitiveness and structural performance. From the market perspective, the cost of the wall unit and the required time for installation are the main determinants. From the structural performance perspective, the fastening between CFS steel profiles as well as between steel profiles and sheathing panels are determinant of the overall structural performance of the CFS system. It is worth mentioning that the structural design of CFS systems can be carried out according to two methodologies, named: “all – steel design” and “sheathing braced design”. The “all steel design” considers only the steel members as part of the structural systems, while the “sheathing braced design” considers the interaction between steel profiles and sheathing panels. Under this hypothesis, walls and floor decks act as diaphragms (Dubina et al. 2012). The global structural response of the wall diaphragms depends on the local response of the wall components (steel studs, anchors, sheathing panels and steel – to – sheathing panel connections), and previous studies demonstrates (Iuorio et al. 2014, Fiorino et al. 2014) that, under seismic actions, a good seismic performance can be achieved. In addition, the selection of sheathing – to –steel connections and their spacing (i.e. their number and distribution) is critical where the structure is designed according to a seismic dissipative approach. The most common fastening method is based on self-drilling, self- tapping screws, that when compared with more traditional nails are stronger and more durable. Hence, for the ELISSA house, the connections among the steel profiles were made by 4.8 mm diameter clinching connection, while, for the connections between sheathing and steel profiles, 2.2 mm diameter ballistic nails spaced at 150 mm were used at the field and at the perimeter of the panels. In particular, clinching are often used in automotive manufacturing process, because of their improved fabrication efficiency. They are well known for their advantages in terms of: simplicity and cleanness of the process, low run time, reduced energy used, possibility to automate the process, the easy quality checks and the lacking of fasteners or other consumables in the process (Lambiase, 2013). As such, clinching is used in the Transformer system to simplify and automate the connection between steel profiles.

The wall systems were designed in order to allow the ELISSA house to withstand high seismic loads. Therefore, in order to withstand any wall overturning phenomena, that can be caused by either seismic or wind loads, special devices, called hold-downs, were placed at the ends of wall segments. The hold downs are high strength L-shaped devices, connected to studs by four M22 bolts (8.8 grade). Hold downs connect first floor walls to the foundation, as well as they connect together first and second floor walls through the intermediate floor. In both cases, the connections are realized with M20 bolt threaded rods. To resist any shear deformation and transfer shear loads, shear connections made by 5.5 mm diameter self-drilling screws spaced every 200 mm were used between second floor wall tracks and intermediate floor, while M10 bolts (8.8 grade steel) spaced every 300 mm were used between first floor walls and ground floor.

2.2.1.1 *Finishing & insulation*

As stated in the introduction, finishing and insulation were selected in order to advance the use of nano insulation materials, and provide high thermal transmittance (U) values, in order to reduce the operational costs and associated operational energy during the life time of the ELISSA construction. As shown in figure 3, the wall system is made of a stratified dry construction, where the insulation is provided by mineral wool (FCB 035) placed between the studs and Vacuum Insulation Panels (VIP) glued to the Knauf Diamant Boards, which are connected to the flange of the studs on the interior side of the wall. The VIP panels are produced by VA-Q-TEC and they are built of fumed silica core, which are sealed into a high gas barrier film under vacuum. They have a thickness of 14 mm, a density less than 200kg/m^3 and a transmittance value (λ) of about 0,007 W/mK. The VA-Q-VIP elements stand out because of their smooth edges and corners due to a special edge fold technique, that allow individual elements to be joined almost seamlessly, with consequent avoidance of thermal bridges. The interior side of VIP surface is attached to a non-load-bearing steel structure made by galvanized cold-rolled runners and studs, that incorporates a 50 mm layer of Rockwool and two layers of 15 mm Knauf Diamant. On the outside, an air gap of 25 mm is achieved by slotted hat profiles, to which 12.5 mm Aquapanel Outdoor Plasterboards are connected. The Aquapanel plasterboards are cement – bound, mineral panels with planar lattice structure of longitudinally and transversally arranged glass fiber mats. Table 1 and figure 3 illustrates the configuration of the ELISSA wall panel, the types of materials used, their thickness, densities and thermal transmittance values. For the calculation of the wall thermal performance, the convection heat transfer coefficients for the inside (h_i) and the outside (h_e) environment have been considered, according to ISO 6946, as follows: h_i equal to 7.69 W/m^{2}K and h_e equal to 25 W/m^{2}K.

Table 1. List of material for the wall stratification with indication of density and thermal transmittance values.

Material	**Thickness (mm)**	**Density (kg/m^3)**	**λ (W/mK)**
External render	15	1800	
AquaPanel Outdoor(AP)	12,5		0,35
Air Cavity (cav)	26		0,14
Knauf Diamant	15	1030	0.27
Mineral Wool	147		0,035
Knauf Diamant (D)	15	1030	0,27
VIP	14	200	0,007
Mineral Wool	50		0,035
Knauf Diamant	15	1030	0.27
Knauf Diamant	15	1030	0.27
U-value of the wall	**0,12(W/m^{2}K)**		

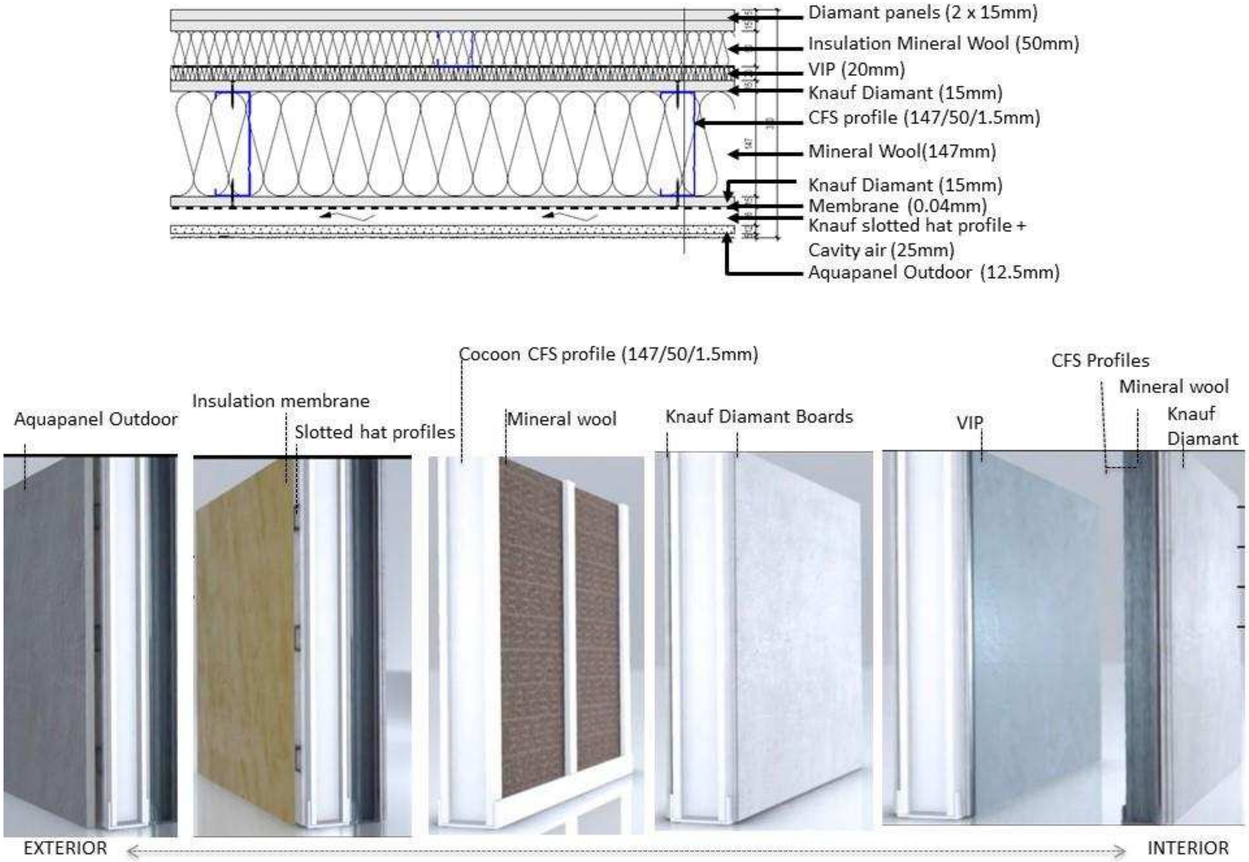


Figure 3. Wall section in detail on the top and 3D view of all the wall layers on the bottom.

2.2.2 Floor system

Floors and roof (figure 4) were also based on complete dry technologies. Floors structure is made of back-to-back coupled 197x50x2.0 mm C section joists spaced at about 500 mm on the center. The joists are connected at the ends to 200x40x1.5 mm U section floor tracks. The connections among the steel profiles were made by 4.8 mm diameter self-drilling screws. The diaphragm behavior is achieved by adopting 28 mm thick gypsum fiber panels named Knauf GIFAfloor boards. The Knauf GIFAfloor systems use engineered flooring panels with a recycled material content of 50%. Fibres from wholly recycled paper are blended with a mix of natural and flue gas desulphurised gypsum to create non-combustible gypsum fibreboard panels with A1 fire rating. They have an excellent loadbearing capability and their high thermal conductivity (λ_r = 0.44 W/mK) makes the panels ideal in underfloor heating systems. The GIFAfloor boards were glued together with a polyurethanic adhesive (Knauf klebstoff) and connected to the floor steel frame by means 3.4 mm diameter ballistic nails spaced at 100 mm.

2.2.2.1 *Finishing and insulation*

Figure 4 shows the stratigraphy of floors and roof. For the first and intermediate floor, the Knauf GIFAFloor Klima systems have been installed for the heating and cooling of the interior spaces. The GIFAfloor system is characterized by having heating pipes for hot water installed directly below the surface, allowing the heat to be transmitted to the room directly through the floor covering. Moreover, the systems can also be used for cooling in summer. Insulation is provided by mineral wool with thickness ranging between 180mm (for intermediate floor) to 196 mm for roof. The hygrothermal performance of the thermal bridges of the building envelope was evaluated according to ISO 10211, by means of the temperature factor method. The temperature factor values of all critical regions are higher than the critical value of 0.7, at which there is a risk for mold growth, according to the DIN 4108 standard. Further details are available in Mandilaras et al. 2015, and Atsonios et al. 2019.

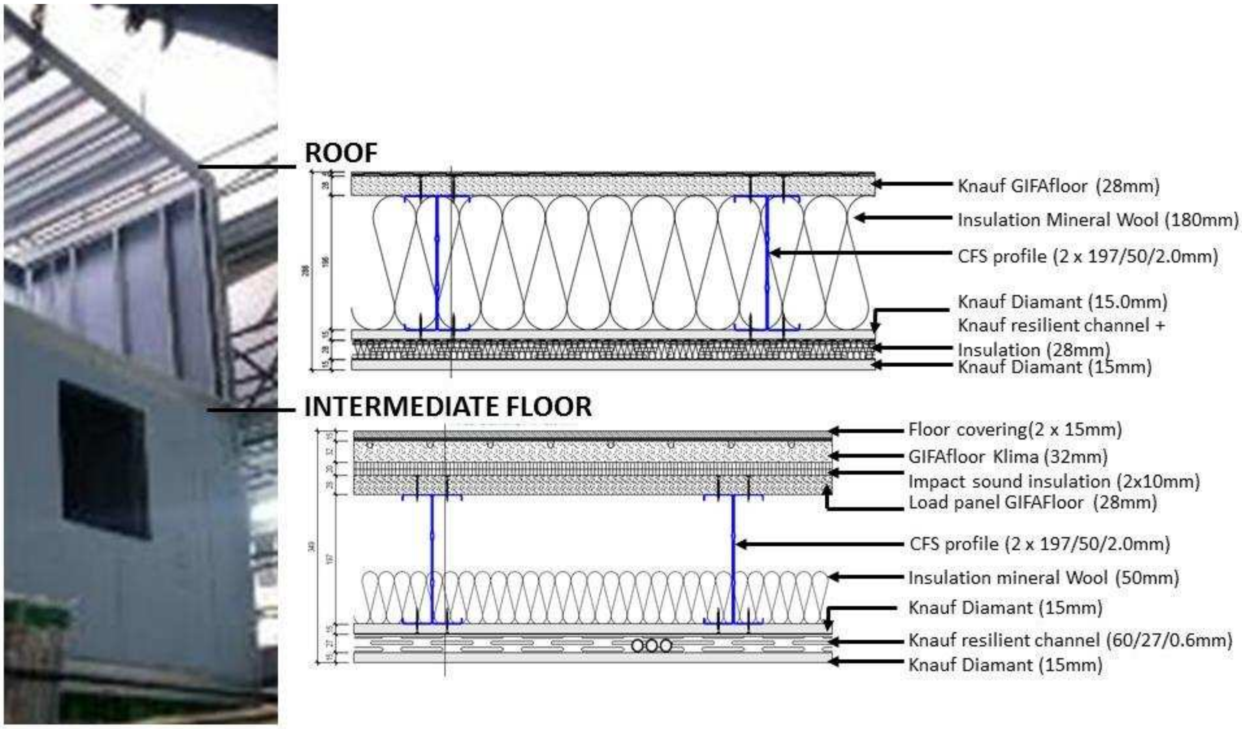


Figure 4. ELISSA house section, with indication of floors and roof stratigraphy.

3. Construction and deconstruction process

The construction of the ELISSA mock up took about fifteen days (table 2). The first four days were used for preparing the installation of the ground floor to the shaking table. This part was delicate for this specific cases, since the ELISSA mock up needed to be tested on shaking table (Landolfo et al. 2018) under seismic loading. The mock up, as indicated in Section 2 has plan dimensions of 4.5 x 2.5m, while the shaking table had dimensions of 3x3m. Therefore, an ad hoc stiff steel reticular structure was designed and realized to install the mock up on the shaking table, and great care was given to the installation of hold downs and stiffeners before placing the ground floor. The mounting of the mockup itself took 5 days, of which 2 for the structural parts and 3 for the finishing. The construction involved four specialized companies, of which one took care of scaffolding, one was expert in steel construction, Knauf was responsible for the finishing and one company dealt with waste management. In terms of workmen, five workers and two supervisors were involved every day. Images of the construction process are reported in figure 5 and 6.

Table 2. Gantt chart of the construction process.

	Phases	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	Mounting of hold down and web stiffeners to install the ground floor	▨	▨	▨	▨								
2	Mounting of the scaffolding					▨	▨						
3	Mounting of the structural elements							▨	▨				
4	Mounting of the finishing									▨	▨	▨	
5	Scaffold disassembling												▨

Figure 5. Mounting of structural elements of the mock-up.

Figure 6. Mounting of finishing products of mock-up

The disassembly took about 8 days (see table 3) and involved 3 companies, one responsible for the scaffolding, one responsible of demolition and one for the waste management. For the demolition four workers and two supervisors were involved every day. The demolition sequence is shown in figure 7.

Table 3. Gantt chart of the deconstruction process.

	Phases	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	Mounting of the scaffolding	▨							
2	Disassembly of the roof		▨						
3	Disassembly of the finishing part of the 2nd floor		▨	▨					
4	Removing of all walls and waste				▨				
5	Scaffold disassembling					▨			
6	Disassembly of the ground floor module and waste management						▨	▨	▨

Figure 7. Deconstruction process

4. Life cycle analysis

This paper 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 the reduction of operational energy due 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 2018, 2013, De Wolf et al. 2014). To this end, this paper investigates the environmental impacts of the ELISSA house looking at the construction phase and the End of Life (EoL) phase. This study describes an attributional, process-based, comparative LCA aimed at quantifying the environmental performances of the ELISSA mock-up house, and compare ELISSA wall components to a traditional masonry wall. Since an attributional LCA is used in this paper, then all the environmentally relevant physical flows that characterize the life cycle of the ELISSA mock up are described (Ekvall et al 2016).

The LCA is developed according to the ISO 14040 (2006) and ISO 14044 (2006) and it is articulated in four steps: Goal and Scope definition, 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 mock-up.

4.1. Goal and scope definition

The ELISSA house has been detailed in section 2. The goal of this work is twofold:

i. Analyse the environmental impact of the ELISSA mock up through LCA methodology;
ii. Compare one square meter of the ELISSA wall with those of a traditional reinforced masonry building, considering the hypothesis that those buildings have the same thermal profile (for LCA comparative purposes).

Figure 8 shows the system boundaries and indicates the approach adopted in this work, for which the LCA analysis includes the following phases (i.e. "Cradle to gate, with options" EN 15804:2012+A1:2013: 1. Production and Construction; 2. End of Life (EoL)). The first phase includes the raw material supply, and manufacturing of the building components (Production phase: 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 for walls and floors of the ELISSA Mock up and the energy consumption associated with operating machines (Construction phase: Module A5, EN 15804:2012+A1:2013). The End of life phase includes the deconstruction of the mock-up (Module C1, EN 15804:2012+A1:2013) and the activities of waste processing and disposal (Module C4, UNI EN 15804:2012) including the recycling of the materials (Module D, UNI EN 15804:2012). In particular, this phase considers the benefits associate with reuse, recovery and potential recycling of steel and VIPs. The functional unit for the ELISSA mock-up is 25 m^2 while the functional unit for the comparison of the ELISSA wall with a traditional masonry house having same thermal profile is 1 m^2.

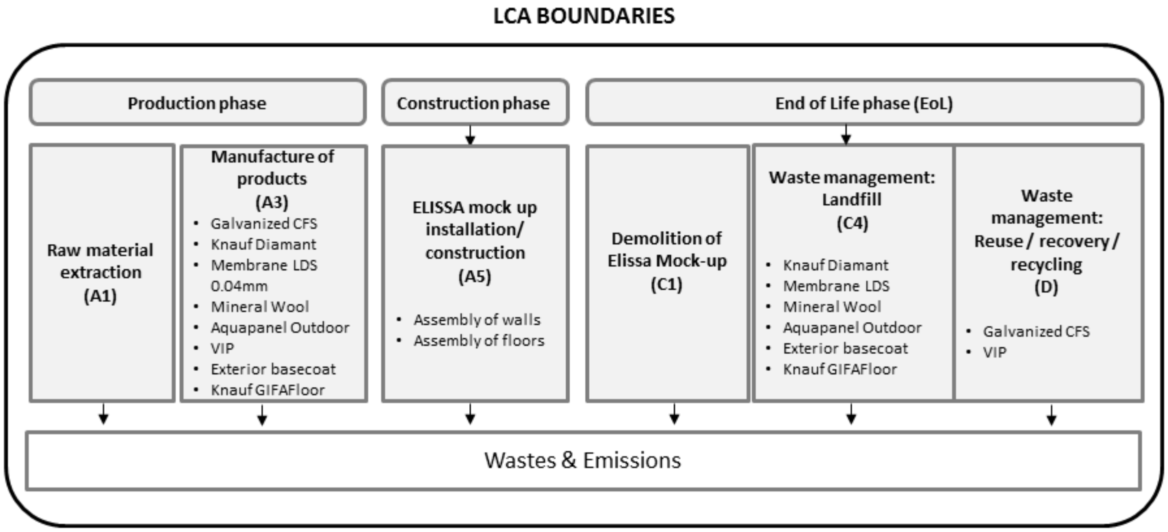


Figure 8. LCA system boundary

4.2 Inventory analysis of the ELISSA mock-up

Inventory analysis involves data collection and calculation procedures to quantify relevant input and output data of the ELISSA mock-up (ISO 14044 2006). Primary data concerning the production of several construction materials such as Diamant, Aquapanel boards etc. were directly collected from the manufacturers (e.g. KNAUF, 2016). Where the data were missing, the study was completed on the basis of information obtained from databases available in the SimaPro 7.3 LCA software package. These secondary data were retrieved from the Ecoinvent 3.0.1 database (Ecoinvent, 2014) and the datasets are indicated in table 4.

Table 4 summarizes the amount of materials used for the overall mock- up, and the data source. It is very important to note that a careful acquisition of high-quality primary data is essential to reduce the uncertainties of LCA results (Vitale et al. 2018, Moncaster et al. 2018). This is extremely important when the intent is to capture the environmental impact of a construction system like the CFS that is not as spread as more traditional construction systems such reinforced concrete or masonry buildings that are familiar to a large part of people across Italy and Europe (Shares et al. 2017). The uniqueness of this paper is that most of the data were collected by the Authors during the construction and demolition of the mock-up in the laboratory. Therefore, the amount of material used in the construction as well as the waste in the construction and deconstruction phase are of high quality.

4.2.1. Production phase [A1 – A3]

Table 4 shows the materials quantities and data source for the calculation of the environmental impacts. It can be noticed that several primary data are used, and only for few materials Ecoinvent 3.0.1 is used.

In this specific case, in order to guarantee data quality requirements, including time-related, geographical and technological representativeness, LCI Ecoinvent data have been suitably modified on the basis of the information and practices of the involved manufacturers. For example, for the production of galvanized CFS, data retrieved from Ecoinvent 3.0.1 related to "hot dipped galvanized steel, BOF route at plant/RER U" are modified in order to include the zinc coating and deep drawing that are not present in the Ecoinvent selected data.

Table 4. Material amount and data source

Material	Quantity	Unit	Source	Dataset
Galvanized CFS profiles*	2006	[kg]	Ecoinvent 3	hot dipped galvanized steel, BOF route at plant/RER U, Zinc coating, coils/RER U
Knauf Diamant (15 mm)	300	[m^2]	Primary data	-
Knauf GIFAfloor (28 mm)	36	[m^2]	Primary data	-
Floor heating/ cooling GIFAfloor Klima (32mm)	24	[m^2]	Primary data	-
Aquapanel Outdoor + Render (12.5 mm)	57	[m^2]	Primary data	-

Exterior Basecoat	530	[kg]	Ecoinvent 3	Cement mortar, at plant/CH U
VIP	227	[kg]	Primary data	
Mineral wool	350	[kg]	Ecoinvent 3	Rock wool, packed, at plant/CH U
Membrane LDS 0.04**	8,5	[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

4.2.2. Transport phase [A4]

For the ELISSA mock-up, all the materials and components where transported from the original manufacturer to the lab. However, since the ELISSA mock-up is a prototype, that in the future could be realized anywhere, a sensitivity analysis has been developed considering five different transport scenarios, as follows:

- Scenario 1. The transportation is not considered
- Scenario 2. Considers the real transportation for the assembly of the mock-up
- Scenario 3. Considers the case when all components are bought in South Italy and transported to the laboratory in Naples
- Scenario 4. Considers the transportation in the case that all components are bought in North Italy and transported in the laboratory in Naples
- Scenario 5. Investigates the environmental impacts in the case of transportation distance 30% bigger than in the real investigated case.

Note, for each scenario, the transport of materials and components from/to construction site has been done by lorry of 3.5 to 7.5 t Euro 5, and in each case empty return trips have been accounted for. Table 5 indicates the distances in terms of km considered in each scenario.

Table 5. Material amount and transportation distances

Material	**Quantity [t]**	**Transport [km]**				
		Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**

Galvanized CFS profiles	2.01	0	1200	100	700	1600
Knauf Diamant (15 mm)	4.65	0	1400	20	500	1900
Knauf GIFAfloor (28 mm)	1.51	0	1400	20	500	1900
Floor heating/ cooling GIFAfloor Klima (32mm)	1.15	0	1400	20	500	1900
Aquapanel Outdoor + Render (12.5 mm)	0.91	0	1400	20	500	1900
Exterior Basecoat	0.53	0	1400	20	500	1900
VIP	0.23	0	1400	100	900	1900
Mineral wool	0.35	0	1400	20	500	1900
Membrane LDS 0.04	0.01	0	1400	20	500	1900

4.2.3. Construction phase [A5]

For the construction stage, only the equipment adopted for the assembly of the mock-up in the laboratory is 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. As such, while many operations are conducted with hand tools (such as hummer) only few require electrical energy or fuel. The data and duration of use of the equipment, as well as the energy and data sources are summarized in table 6. For the energy, the European mix has been adopted. Table 7 shows, instead, the amount of materials that were discarded during the construction stage.

Table 6. Equipment data for the construction phase

Equipment	Time [hr]	Power [kW]	Energy [kWh]	Fuel [l]	Dataset	Use
Building equipment: staple gun	11.5	0.085	0.98		Electricity, medium voltage, production RER, at grid/RER	Connecting GIFA floor to CFS profiles

Grinding machine	1.5	0.64	44.85		Electricity, medium voltage, production RER, at grid/RER	To cut GIFA floor on site
Screwdriver	3	0.327	0.98		Electricity, medium voltage, production RER, at grid/RER	Screws
Tow truck	2.99	15	44.85		Electricity, medium voltage, production RER, at grid/RER	Handling of components
Lift truck	5.33			37.31	Diesel at refinery/RER	Handling of components
Forklift	0.5			3.5	Diesel at refinery/RER	Handling components

Table 7. Discarded material in the construction process

Material	**Discarded parts in construction**	**Unit**	**Source**	**Dataset**
Galvanized CFS profiles	30	[kg]	Ecoinvent 3	Recycling*
Knauf Diamant (15 mm)	44	[m^2]	Primary data	
Knauf GIFAfloor (28 mm)	6	[m^2]	Primary data	
Floor heating/ cooling GIFAfloor Klima (32mm)	4	[m^2]	Primary data	
Aquapanel Outdoor + Render (12.5 mm)	9	[m^2]	Primary data	
Exterior Basecoat	94	[kg]	Ecoinvent 3	Disposal, building, cement (in concrete) and mortar, to final disposal
VIP	0	[kg]	Primary data	Substitution and closed loop method
Mineral wool	45	[kg]	Ecoinvent 3	Disposal, building, mineral wool
Membrane LDS 0.04	0	[kg]	Primary data	

* The methodology and equations for calculating the environmental impacts of recycling are reported in Appendix 10 of the Worldsteel methodology report (2017)

4.2.4. End of life phase [C1; C4; D]

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 [C1] of the ELISSA Mock-up. Table 8 summarized the quantities of materials that were recycled (i.e. CFS profiles, [D]), reused (i.e. VIP panels [D]) and landfill (i.e all the other materials [C1]). As it can be seen, all the steel members and components were collected for recycling. It is worth noticing, that in reality, the CFS technology, making exclusive use of mechanical connections and without any welding, would allow the steel members to be disassembled and reused. However, Italian laws, at the moment, do not allow any reuse of structural components and, consequently there is a lack of management structure for collection and reuse of steel components. The disassembly took about 8 days, starting from the scaffolding mounting, and table 9 summarized the equipment used in the deconstruction phase.

Table 8. 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 9. Equipment information for the 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

4.3 Life Cycle Impact assessment (LCIA) of the ELISSA mock-up

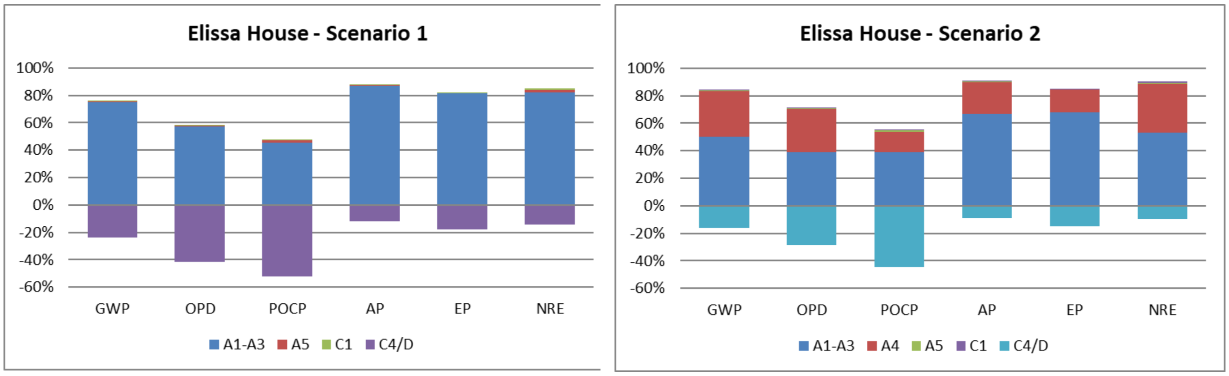
The results of the environmental analysis are presented according to the data format of the Environmental Product Declaration (EPD) standard (UNI EN 15804:2012). Indeed, the environmental outcomes are expressed through six impact categories: Global Warming Potential (GWP), Ozone Depletion Potential (OPD), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), Eutrophication Potential (EP), and Non Renewable Energy (NRE). This methodology is chosen so that future researchers can use the data for further studies. Indeed, in the following sections, both histograms and tabular values are always provided.

4.3.1. Life cycle of ELISSA mock-up

Figures 9a to 9e and tables 10 and 11 show the results of LCA of the ELISSA mock up for the 5 considered transportation scenarios. All figures show the results for the six environmental categories in percentage, to allow comparison. In particular, figure 10a and table 10 demonstrates that, when the transport is not considered, then the main environmental 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 process provides several benefits mainly due to the recycling of steel and reuse of VIP (Modules C4; D).

Table 10. Results of Life Cycle impact assessment of the ELISSA house from cradle to grave, scenario 1.

Env. Indicators	**Unit**	**Production**	**Construction**	**End of life**		**Total**
				Deconstruction/Demolition	Disposal/Recycling	
		A1-A3	**A5**	**C1**	**C4/D**	
GWP	kg CO_2 eq	1,25E+04	1,11E+02	4,10E+01	-3,94E+03	**8,71E+03**
OPD	kg CFC_{-11} eq	1,73E-03	1,76E-05	2,43E-05	-1,26E-03	**5,12E-04**
POCP	kg C_2H_4 eq	7,66E+00	2,61E-01	9,29E-02	-8,75E+00	**-7,36E-01**
AP	kg SO_2 eq	7,90E+01	6,03E-01	3,49E-01	-1,10E+01	**6,90E+01**
EP	kg PO_4 eq	2,65E+01	1,66E-01	8,41E-02	-5,82E+00	**2,09E+01**
NRE	MJ eq	1,83E+05	3,31E+03	3,40E+03	-3,24E+04	**1,57E+05**



(a) (b)

(c)

(d)

(e)

Figure 9. LCA of the overall Mock-up: a) transport scenario 1; b) transport scenario 2; c) transport scenario 3; d) transport scenario 4; e) transport scenario 5.

The overall LCA can be very sensitive to the transportation scenario. Indeed, when the real transportation scenario is considered in the LCA of the ELISSA mock-up (scenario 2, figure 9b), which required most of the components to be transported from Germany and Switzerland to Southern Italy, then the environmental impacts of transportation account for about the 33% of GWP, 31% of OPD, 15% of POCP, 23% of AP, 16% of EP and 35% of NRE. However, also in this scenario, the A1-A3 phase still accounts for the higher percentage of the impacts. Scenario 3 shows that in the case of collecting the components from manufacturers in close proximity to Naples, then the transportation impacts becomes negligible (figure 9c, impacts approximately equal to 1% in all categories). Scenario 4 (figure 9d) and scenario 5 (figure 9e) shows instead the how the impact of transportation increases as the distance increases.

Table 11. Environmental impacts for the transport scenarios 2, 3, 4 and 5.

Env. Indicators	Transport Scenario 2	Scenario 3	Scenario 4	Scenario 5
	A4	A4	A4	A4
GWP	8.11E+03	2.13E+02	3.32E+03	1.10E+04
OPD	1.39E-03	3.65E-05	5.70E-04	1.89E-03
POCP	2.96E+00	7.75E-02	1.21E+00	4.00E+00
AP	2.77E+01	7.26E-01	1.13E+01	3.75E+01
EP	6.40E+00	1.68E-01	2.62E+00	8.66E+00
NRE	1.20E+05	3.14E+03	4.90E+04	1.62E+05

In the following sections, the interpretation of the environmental results related to the production and construction phase (A1-A3 modules) and the EoL of Elissa mock-up (C4-D) of the scenario 1 (that do not takes into account the transportation) is presented.

4.3.2. LCIA of the production and construction phases

The design of the building is the most crucial step in development of buildings with low carbon energy, because it defines the materials and the building components for structure and finishing. This phase includes the material production (i.e. A1- A3 modules), and the building construction (A5 module). One of the main CFS buildings feature is their lightness, compared with more traditional construction systems. Indeed, the ELISSA mock-up weights 400 kg/m^2, where in particular the structural part composed of steel profiles and structural panels weight 121 kg/m^2, of which 64 kg/m^2 is the weight of the steel structural components. As shown in figure 9a and in table 10 the material production (A1 – A3 module) is indeed the larger responsible for the environmental impacts of the CFS house mock-up, been responsible for the 75% of total GWP, 57% of ODP, 46% of POCP, 87% of AP, 81% of EP and 82% of NRE. The impact evaluated in this phase also takes into account the waste produced in this stage, and includes the recycling of the steel and landfill of all the other construction waste (table 7). Figure 9a also clearly states that the impact of the construction process (A5 module) is neglected (approximately 1% in all categories).

Looking in detail to the material production phase [A1-A3], it is worth analyse the impacts of the materials used for walls (table 12 and figure 10) and floors (table 13 and figure 11) realization. It appears clear that in both cases CFS profiles plays a major role. This demonstrates that, in spite the lightness of the structural components, and the limited amount of material used, the steel is responsible of the higher contribution in terms of environmental impacts. This is mainly due to the manufacturing process that requires high temperature and the large amount of fossil fuel consumption as well as by the zinc coating process, and the release of ammonia and particulates during that process (Classen et al 2009, World Steel Association 2011). The zinc coating is of fundamental importance for the protection of CFS profiles having thicknesses between 1 and 2mm from potential corrosion problems, and consequential structural integrity. In particular, the total of CFS used for structural and non-structural components is responsible for 59% and 79% of GWP, 24% and 92% of OPD; 73% and 84% of POCP; 66% and 79% of AP; 74% and 89% of EP; 58% and 79% of NRE, in walls and floors respectively. In addition, the VIP panels in the walls realization, also play a crucial role in terms of OPD (75%).

VIP panels are the second most influential material contributing roughly to 19% of the GWP, 9% of the POCP, 14% of AP, 17% of EP, 23% of the NRE. The manufacturers (e.g. VA-Q-TEC) claim that 95-99% of all impacts are owed to the production of the core material [It is made of pressed fumed silica (82% w), opacifier (14% w) and polyester fiber fleece (4% w) and the manufacturing process of 1kg of VIP requires 0.3kWh of electricity]. It is demonstrated that the impact of VIP are much greater of conventional insulation materials such as mineral wool.

Table 12. LCA numerical impact of the ELISSA wall production

		Structural (_s)		**Non Structural (_ns)**						
Env. Impact	**Unit**	**Galvanized CFS_s**	**Diamant_s**	**Galvanized CFS_ns**	**Exterior basecoat**	**Membrane LDS**	**Mineral wool**	**Aquapanel**	**VIP**	**Diamant_ns**
GWP	kg CO2 eq	3,72E+03	5,27E+02	1,40E+03	1,01E+02	1,68E+01	2,70E+02	3,08E+02	1,67E+03	5,27E+02
OPD	kg CFC-11 eq	2,60E-04	1,17E-08	9,79E-05	3,70E-06	4,23E-09	1,60E-05	3,74E-08	1,13E-03	1,17E-08
POCP	kg C2H4 eq	2,71E+00	1,73E-01	1,02E+00	3,27E-02	3,40E-02	2,86E-01	1,43E-01	4,67E-01	1,73E-01
AP	kg SO2 eq	2,55E+01	3,47E+00	9,60E+00	1,59E-01	4,63E-02	1,75E+00	1,02E+00	7,38E+00	3,47E+00
EP	kg PO4--- eq	9,59E+00	4,13E-01	3,61E+00	4,44E-02	5,72E-03	4,38E-01	1,05E-01	3,11E+00	4,13E-01

NRE	MJ eq	5,40E+04	7,25E+03	2,03E+04	7,04E+02	6,35E+02	4,81E+03	1,85E+03	2,92E+04	7,25E+03

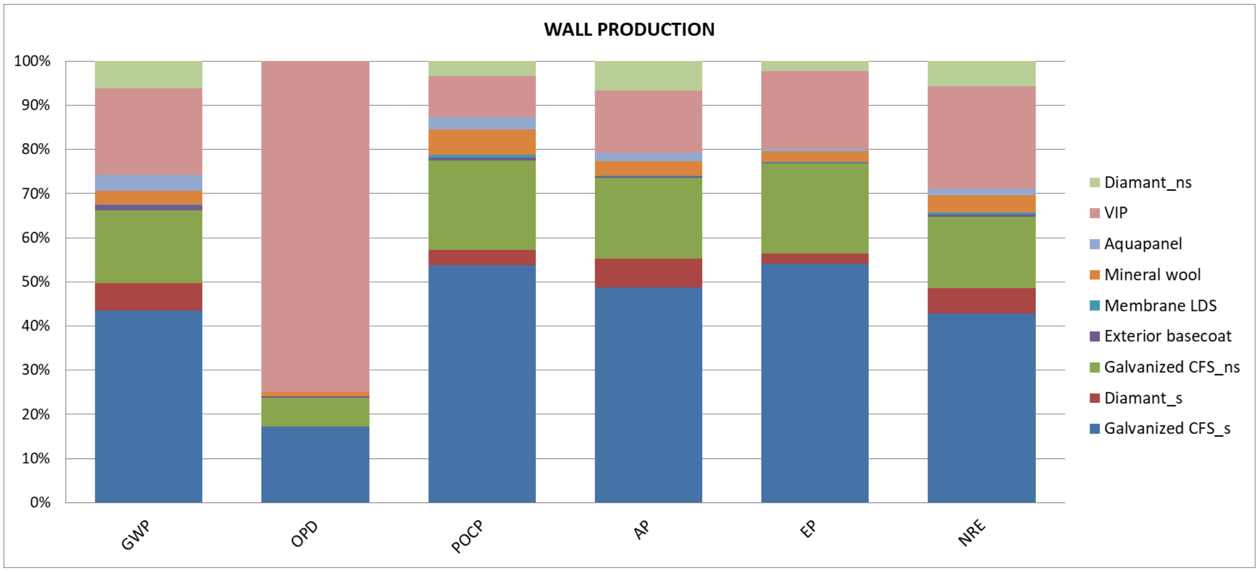


Figure 10. LCA of walls production

Table 13. LCA numerical impact of the ELISSA floor production

		Structural (_s)		Non Structural (_ns)			
Env. Impact	**Unit**	**Galvanized CFS_s**	**GIFAfloor_s**	**Galvanized CFS_ns**	**Mineral wool**	**Diamant**	**GIFAFloor_ns**
GWP	kg CO2 eq	2,97E+03	3,33E+02	1,42E+02	1,27E+02	1,66E+02	2,06E+02
OPD	kg CFC-11 eq	2,08E-04	7,42E-09	9,93E-06	7,53E-06	3,71E-09	4,58E-09
POCP	kg C2H4 eq	2,17E+00	1,09E-01	1,03E-01	1,34E-01	5,47E-02	6,76E-02
AP	kg SO2 eq	2,04E+01	2,19E+00	9,74E-01	8,21E-01	1,09E+00	1,35E+00
EP	kg PO4--- eq	7,66E+00	2,61E-01	3,66E-01	2,06E-01	1,30E-01	1,61E-01
NRE	MJ eq	4,31E+04	4,58E+03	2,06E+03	2,26E+03	2,29E+03	2,83E+03

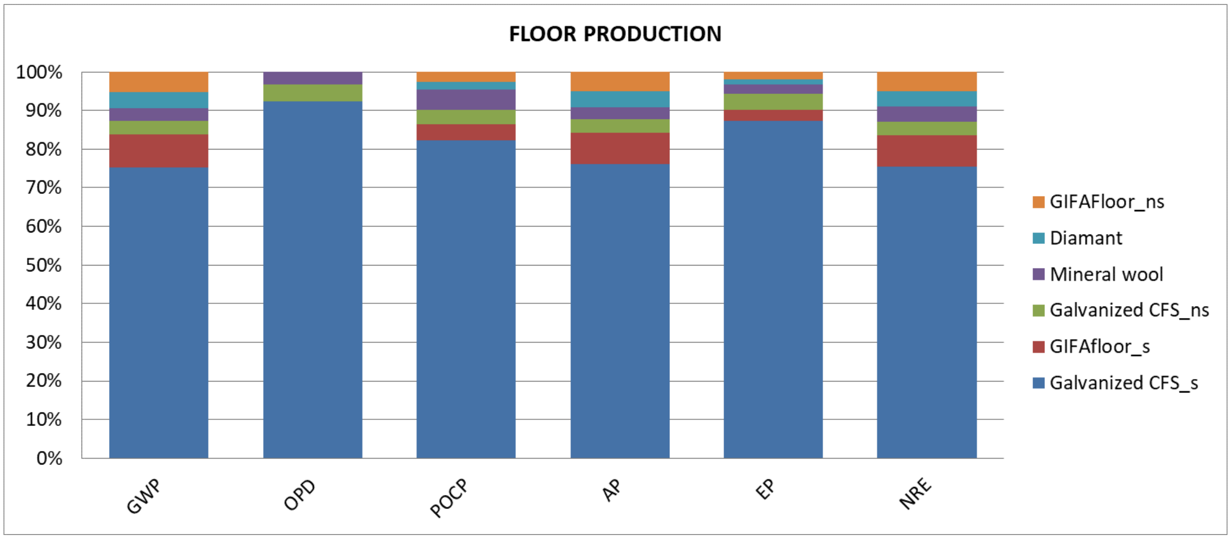


Figure 11. LCA of Floors production

4.3.3. LCA of the End of life phase

The deconstruction of ELISSA mock up included many manual operations in order to avoid damage and compromise the integrity of insulation layers and in particular of VIP that can be recycled. This last, indeed, can be recycled and used as insulation layer in another wall configurations. CFS steel members also have the potential to be reused. Indeed, the use of mechanical connection, i.e. screws between CFS profiles and structural panels would allow the reuse of those CFS members and even the wall composed by CFS profiles, structural panels and internal insulation could be disassembled by the finishing and reused for new applications. However, the current lack of specific legislations for the reuse of building components is limiting the applicability of this process in many countries, as Italy. Therefore, in this work the reuse of CFS members and/or wall panels is not considered. Instead, it is considered the recycling of steel, and VIP panels separately. The aforementioned building materials (VIP panels and galvanized steel) can contribute to the production of new products substituting virgin materials. On the one hand, VIP core can be collected and recycled into new VIP panels by avoiding the production of silicon carbide, fumed silica and cellulose fibre. On the other hand, galvanized steel can be recycled through electric arc furnace (EAF) route to produce new semi-finished steel products like ingots and slabs.

Figure 9a and table 10 show that the deconstruction phase (C1 module) can be neglected. This is in line with the findings of previous studies (Vitale and al. 2017). Figure 9a also clearly demonstrates that the credits given by the recycling (C4-D module) balance the impacts. Table 14 and figure 12 show the distribution of impacts and credits for all the materials at the EoL, and quantifies the recycle of steel materials and the reuse of VIP panels (C4-D modules) that provide environmental beneficial effects. In particular, in ODP category, VIP presents negative environmental impacts. It clearly appears that, in this category, the VIP recycling provide environmental benefits. It means that the environmental credits of the EoL process of VIP are higher than the impact related to the production and construction processes of VIP materials.

Table 14. LCA numerical impacts of the waste management in the EoL phase

Env. Impact	**Unit**	**Exterior basecoat**	**Mineral wool**	**Galvanized CFS**	**Diamant**	**Aquapanel**	**VIP**
GWP	kg CO2 eq	3,78E+00	1,94E-01	-2,45E+03	1,04E+02	1,33E+01	-1,61E+03
OPD	kg CFC-11 eq	9,95E-07	5,10E-08	-3,21E-05	1,02E-09	1,31E-10	-1,23E-03
POCP	kg C2H4 eq	8,54E-03	4,38E-04	-2,03E+00	6,23E-01	7,98E-02	-7,44E+00
AP	kg SO2 eq	2,14E-02	1,10E-03	-8,20E+00	8,50E-02	1,09E-02	-2,90E+00
EP	kg PO4--- eq	5,49E-03	2,81E-04	-5,43E+00	5,98E-02	7,65E-03	-4,60E-01
NRE	MJ eq	1,05E+02	5,37E+00	-3,26E+04	3,59E-05	4,59E-06	0,00E+00

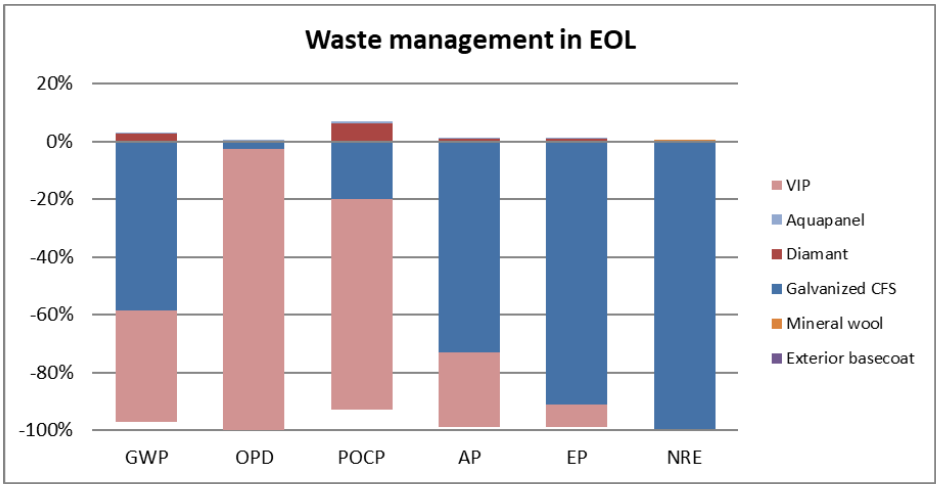


Figure 12. LCA of waste management in EoL (C4; D modules)

4.4 Comparison between ELISSA mock up wall and a traditional wall

4.4.1 Goal and scope definition

In order to compare the environmental impacts of the ELISSA house with more traditional construction techniques, this section presents a preliminary environmental comparison between 1m^2 of the ELISSA house with 1m^2 of a reinforced masonry building having the same thermal profile (figure 13). The comparison is limited to the only wall because, the ELISSA project payed main attention in the definition of wall systems, that is the one having the major environmental impacts and it is also the main resisting subsystem for seismic loads.

The traditional wall considered for this comparison is composed of perforated clay bricks (350 mm thick), reinforced with reinforced concrete, insulated with 200 mm of mineral wool, and finished with render. Table 15 reports the bill of material for 1 m^2 of wall, together with material density and thermal resistance of each material. A total thickness of 550mm, allows this wall to achieve the same thermal performance of the ELISSA mock up (U = 0.12 W/m^{2}K). As for the ELISSA mock-up, the comparison is carried out with an LCA. This last is conducted at the product level, which means that it is referred as a compilation of materials that are assembled together into the final products (Kellenberger et al. 2008).

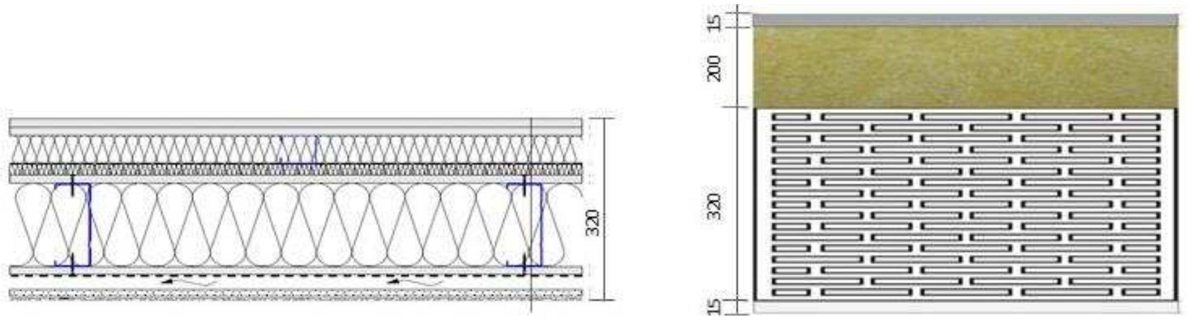


Figure 13. Traditional masonry building wall, considered in comparison to the ELISSA wall.

Table 15. Bill of material for 1m^2 of a traditional reinforced brick wall.

Material	Thickness (mm)	Density (kg/m^3)	Weight (Kg/m^2)	λ
External render	15	1800	27	0.89
Mineral wool	200	50	7.5	0.035
Perforated clay units 5.7/1.6	350	750	252.7	0.14

Internal render	15	1000	15	0.39
Concrete	300	2380	171.4	
Reinforcing Steel	-	7800	7.7	
Total U				**0.12 W/m^{2}K**

The two wall systems (Elissa wall and Conventional wall) are examined during their life cycle, from “cradle to gate”. The analysis involves two major stages: the initial manufacturing of building materials from the extraction of raw materials until the manufacturing of the finished product (A1-A3), and the End of Life (EoL) treatment of the waste material (C4-D). Transportations are not taken into account, because as defined previously the ELISSA house aims to be used in a variety of countries, so transportation will varies case by case. The construction phase (A5) and the deconstruction (C1) are also excluded, because while for the ELISSA wall, it would be possible to consider the real construction and deconstruction process, and the associated energy and fuel consumption, it would not be true for the conventional wall. A schematic description of the applied system boundaries is shown in figure 14.

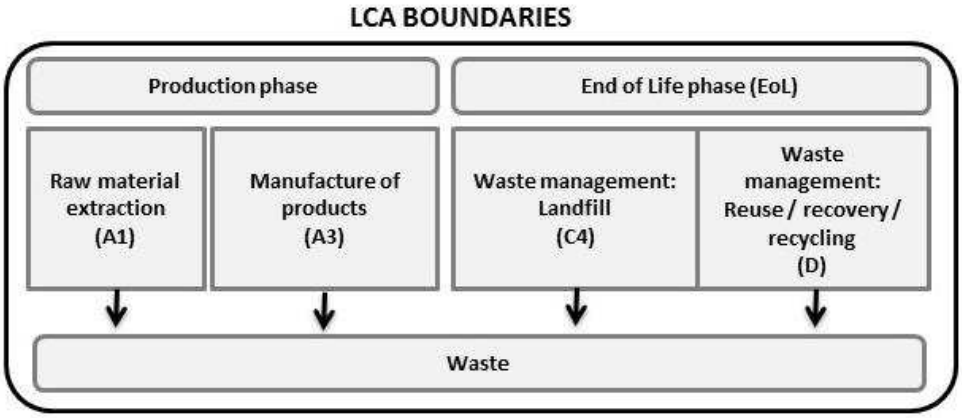


Figure 14. System boundaries for the comparison of 1m^2 of walls

4.4.2. Inventory analysis

4.4.2.1. *Production phase (A1 – A3)*

The two wall systems are compared based on a 1 m^2 of external wall at 100% opacity. In this square meter, all building materials are introduced. For the sake of consistency, both wall panel contain both load bearing and non-load bearing elements, so that they provide the same characteristics in terms of structural design. Therefore, for the conventional wall, a reinforced masonry wall is considered. Table 16 shows the bill of materials used for one square meter of conventional clay brick reinforced masonry wall and the source used for the definition of the environmental impacts.

Table 16. Material amount and data source

Material	**Quantity**	**Unit**	**Source**	**Dataset**
External render	27	[kg/m^2]	Ecoinvent 3	Cement mortar, at plant/CH U
Mineral Wool	7.5	[kg/m^2]	Ecoinvent 3	Rock wool, packed, at plant/CH U
Perforated Clay units	253	[kg/m^2]	Ecoinvent 3	Brick, at plant/RER U
Internal plaster	15	[kg/m^2]	Ecoinvent 3	Lime mortar, at plant/CH U
Concrete	171.3	[kg/m^2]	Ecoinvent 3	Concrete, normal, at plant/CH U
Reinforced steel	7.71	[kg/m^2]	Ecoinvent 3	Steel, converter, low-alloyed, at plant/RER U Hot rolling, steel/RER U
Total weight	481.51			

4.4.2.2. *End of Life (C4-D)*

While for the EoL of the Elissa Mock-up, the reference is still table 7, for the EoL of the conventional wall, almost all the material are considered to be reused. Table 17 indeed schematize the considered EoL scenario.

Table 17. Waste scenario for the conventional wall

Material	**Recycling**	**Reuse**	**Landfill**
External render	100%		
Mineral Wool	-	-	100%
Perforated Clay units		100%	
Internal plaster	100%		
Concrete	100%		
Reinforced steel	100%		

4.4.3. Assessment

Table 18 and figure 15 show the comparison between the conventional wall and the ELISSA wall.

For the sake of clarity, metal nails, screws and fasteners are neglected from the analysis as it is assumed that their contribution is relatively low comparing the proportion of their mass to the total mass of the functional unit.

Table 18. LCA results for the comparison between the conventional wall and the ELISSA wall from cradle-to-gate

		$1m^2$ Conv wall	**$1\ m^2$ ELISSA wall**
GWP	kg CO2 eq	1,13E+02	4,20E+01
ODP	kg CFC-11 eq	8,42E-06	3,47E-07
AP	kg SO2 eq	2,15E-01	2,19E-02
EP	kg PO4 eq	1,28E-01	2,88E-01
POPC	kg C2H4 eq	7,63E-02	5,49E-02
NRE	MJ Primary	1,23E+03	5,77E+02

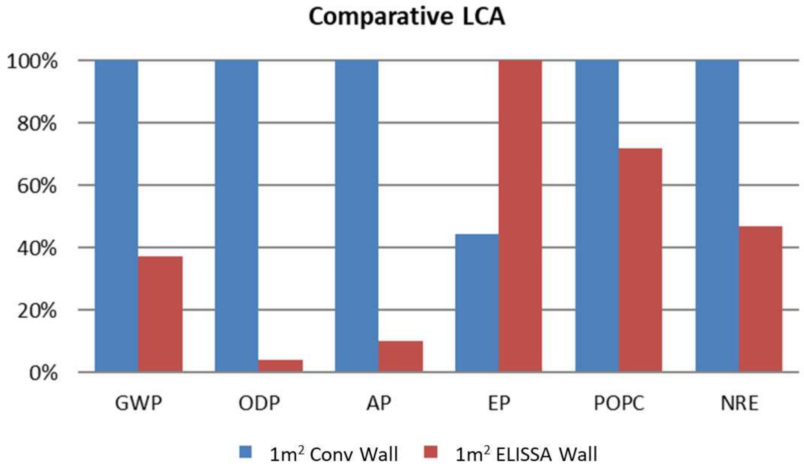


Figure 15. Results of Life Cycle impact assessment

The comparative analysis shows that the conventional wall has environmental impacts higher than the ELISSA wall in almost all LCA categories. Which means that the ELISSA walls in 320 mm of thickness is able to provide the same thermal transmittance of a conventional reinforced masonry wall having a thickness of 550 mm, while having a better environmental profile. It is particularly notable that the ELISSA wall shows a GWP 63% lower than the conventional wall. In the EP indicator, instead, the ELISSA wall presents the largest impact, mainly due to the production process of the hot-dip galvanized steel, as described in the previous sections.

5. 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 was realized in Naples at the end of an FP7 research program to test a CFS system characterized by high seismic and thermal performance. The mock-up allowed the Authors to critically look at the construction and deconstruction phases of the prototype and to gather the data for the life cycle analysis presented in this paper. This LCA analysis, indeed, accounts the materials quantities and equipment used for the construction and deconstruction of the housing prototype, and 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, then the structural components (i.e. galvanized CFS profiles and Diamant 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. The comparison of the environmental impacts of the different structural and non-structural materials within the walls and the floors of the ELISSA house also clearly indicated the high impacts of the structural system. It is also notable that in particular in the floor, the amount of materials used for the steel structure is relatively high, and that further studies could investigate how to improve structural efficiency of floors, while also reducing the amount of material. This paper indeed shows that optimized floor systems could be developed to achieve both high structural performance going hand in hand with reducing overall environmental impacts. The paper also shows the comparison of one square metre of a conventional wall made of reinforced concrete masonry with a square metre of the ELISSA house, where the two systems have comparable thermal properties. The comparison shows that the ELISSA wall has environmental impacts that are much lower of a traditional construction system. This work demonstrates, based on a real case, that a structural system based on CFS components can provide environmental impacts that are half of a conventional system, while at the same time saving on material quantities (one square meter of ELISSA house weights less than half of a conventional reinforced masonry wall having same thermal performance) and is less than half of it thickness. The paper also shows that, in a logic of circular economy, many of the non-structural components that have been adopted in this case study have the potential to be reintroduced in the life cycle, and that when this will become admissible by the National Governments, the lightweight steel systems based on CFS profiles will be really capable to provide a fundamental contribution towards a circular economy future.

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