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Life Cycle Analysis of Innovative Technologies: Cold Formed Steel System and Cross Laminated Timber

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Abstract: Reducing the embodied and operational energy of buildings is a key priority for construction and real estate sectors. It is essential to prioritize materials and construction technologies with low carbon footprints for the design of new buildings. Off-site constructions systems are claimed to have the potential to deliver a low carbon build environment, but at present there are a lack of data about their real environmental impacts. This paper sheds lights on the environmental performance of two offsite technologies: cold formed steel and cross laminated timber. Specifically, the environmental impacts of a CFS technology are discussed according to six standard impact categories, which includes the global warming potential and the total use of primary energy. The study is based on a detailed cradle to gate life cycle analysis of a real case study, and discusses the impacts of both structural and non-structural components of CFS constructions. As a useful frame of reference, this work compares the environmental impacts of 1 m^2 of walls and floors of CFS technology with those of cross laminated timber, which is spreading as innovative off-site technology for the development of nearly zero energy buildings, and a conventional reinforced masonry technology, which is largely adopted in the Italian construction sector. The paper concludes with the necessity to optimize structural systems to reduce the overall embodied carbon impacts.

Keywords: life cycle analysis; cold formed steel; cross laminate timber; net zero; embodied carbon; greenhouse gases

Citation: Iuorio, O.; Gigante, A.; De Masi, R.F. Life Cycle Analysis of Innovative Technologies: Cold Formed Steel System and Cross Laminated Timber. *Energies* **2023**, *16*, 586. https://doi.org/10.3390/en16020586

Academic Editors: Umberto Berardi and Davide Borelli

Received: 11 November 2022
Revised: 26 December 2022
Accepted: 27 December 2022
Published: 4 January 2023

1. Introduction

The built environment is accountable for 42% of the EU's total energy consumption and for about 35% of the greenhouse gas emissions [1]. There is an utmost urgency to reduce the carbon footprint of both existing constructions and new buildings. Numerous European policies and legislations have been recently emanated to advance and support the environmental sustainability of the construction sector. They promote the adoption of life cycle assessment used from the early stage of the design process to critically evaluate and optimize the use of material and guide towards the adoption of construction systems, processes and materials having lower environmental impacts, minimized waste and minimized water consumption. The trend is to move towards mandatory reporting of carbon emissions in the build environment, along with limiting embodied carbon (EC) emissions in projects.

The life cycle assessment (LCA) of a building includes embodied energy (EE) and operational energy. Operational energy typically has a larger impact on the total life cycle energy of a building over long lifetimes. However, as the operational efficiency of new buildings is improved, the relative significance of the embodied impacts of construction materials and processes increases [2]. Therefore, for buildings having short life-time span, the impact of embodied carbon over their full life-cycle impact is extremely significant [3]. In recognition of this, significant attention is now being paid to the quantification and reduction of the embodied carbon impacts of construction products. In the most complete form, the term 'embodied carbon' (EC) refers to the lifecycle greenhouse gas emissions, referred to as carbon dioxide equivalents (CO_2e), which arise through the manufacture and transportation of construction materials and components, during the construction process, the maintenance and the end-of-life of a construction, including demolition, reuse and recycling.

However, the embodied carbon evaluation can be restricted to pre-defined system boundaries. For example, in [4], the EE and EC contributions are calculated as the energy consumed and emissions triggered by mining, processing and manufacturing of materials ("cradle to gate"), while [5] evaluated the embodied emissions, considering a 'cradle-to-site' approach, including the materials transport to construction site. Studies have also started to quantify the impact of recycling and reuse. For instance, Peng et al. [6] have found that if the construction material is recycled, the total embodied carbon saving potential from 2018 to 2060 in China would be of 92.26 Mt CO_2e. Among the construction systems, the prefab sector is specifically embracing the challenges of producing energy-efficient dwellings by lowering both EC and operational energy. Prefab constructions, also known as offsite, have the capacity to consistently produce high energy efficient offsite buildings [7]. However, there is a lack of scientific studies that can demonstrate this. Therefore, this study looks at two very promising off-site technologies, i.e., cold formed steel (CFS) and cross laminate timber (CLT). They are the focus of this study as they are dry construction systems, currently having exponential grow thanks to their capacity of delivering high structural performance in seismic areas while also having low carbon footprint. This paper proposes a detailed comparison between three different technologies: cold formed steel (CFS), cross laminate (CLT) and a traditional reinforced masonry system. Specifically, starting from a real case study, which is a school building in Southern Italy, the environmental impacts in a cradle-to-gate perspective of the CFS technology are analysed. The embodied carbon emissions are calculated by using real project data, with the aim to develop useful data for future designers and researchers. Then, the most environmentally intensive components, such as the walls and roof, are compared with the other two technologies: CLT, which is finding wide application in nearly zero energy building, and a conventional reinforced masonry technology. The proposed comparison allows the evaluation of the difference in terms of carbon footprint between two innovative solutions, which designers could select for improving the global sustainability of the building sector.

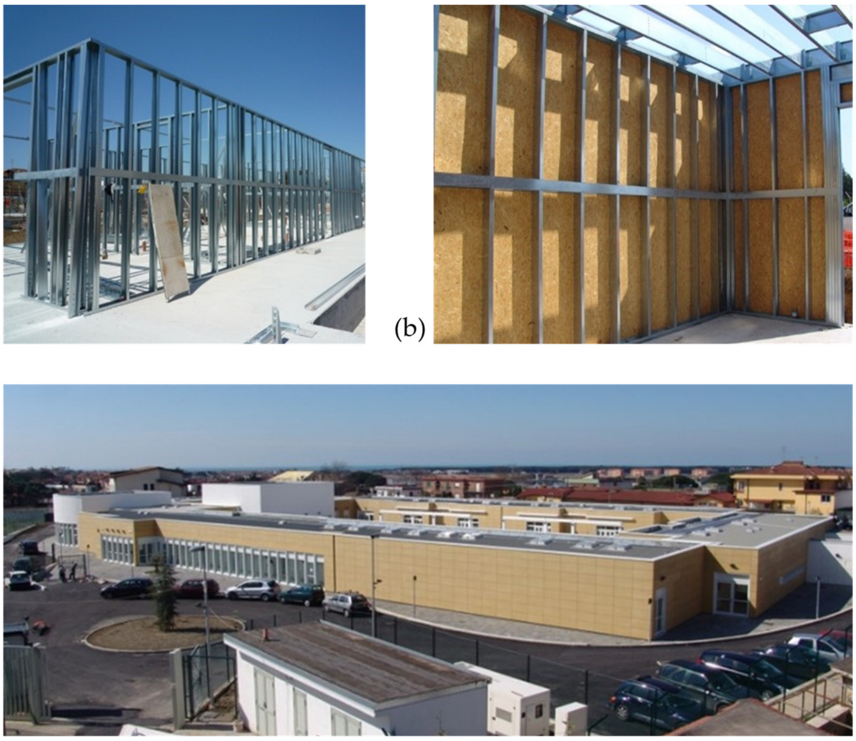
Therefore, Section 2 describes the case studies with a detailed description of the structural and technological systems adopted in the examined CFS, CLT and traditional systems; Section 3 describes the methodological approach adopted for the cradle-to-gate life cycle assessment of the investigated CFS school and for the comparison between walls and roof of the CFS buildings, the NZEB building developed for the same climatic zone, and having CLT as primary structure, and those of a traditional construction widespread in the same region. Section 4 shows and discusses the obtained results, and Section 5 indicates the necessary steps that the construction sector should take to reduce its environmental impacts.

2. Case Studies

This section presents the investigated case studies. Note that, while the CFS school is discussed in detail, so that a comprehensive understanding of the system and of the environmental impacts of all structural and non-structural components is possible, instead, only the strictly necessary information are given for the comparison with the CLT case study and the traditional masonry building.

2.1. CFS System

The "Foundation and Primary Stage School" (British Force School, Figure 1) is a nursery and primary school realized in 2009 for the British Armed Forces in Naples, Italy [8]. The school covers an area of about 3000 m^2 and has a usable area of about 2600 m^2. This school was a pioneer in adopting the CFS system in Italy, to respond the customer's requirements of fast delivery while enabling high seismic performance and high energy efficiency. The building is located in an area of medium seismic intensity, a grade 2 seismic zone according to the Italian classification [9], and was designed according to an elastic approach with coefficient of structure equal to 1. It was also designed and built to achieve the best energy class. The CFS system adopted for the British school is based on stick-built construction, which entails CFS components being formed and cut to size in the factory, then transported on site where they were assembled with mechanical fasteners. The decision to adopt such a level of prefabrication was dictated by difficult site access, that limited the possibility of using heavy tracks and bringing large prefab components. Figure 1 shows the construction process of CFS components, from CFS walls erection (Figure 1a) to wall bracing and roof erection (Figure 1b) and the final result (Figure 1c). The opaque elements of the building made with a CSF structure are described in detail in the following sub-paragraphs.



(a) (b) (c)

Figure 1. CFS school construction process: (**a**) CFS structural walls, (**b**) Sheathing of CFS walls, and construction of the roof, (**c**) Finishing and final result.

Structural and Technological System

The building is set on a continuous slab foundation, which is composed of reinforced concrete beams 800 mm height and with the width ranging between 500 and 1500 mm. All the spaces among the beams are filled with recycled plastic modular elements, having sizes in plan 58 × 58 mm and 700 mm high, and a 100 mm thick reinforced concrete slab. This solution was chosen to realize a perfect planar surface, which facilitated the introduction of all the required cables and pipes for the water, electrical and mechanical systems. The foundation sets also the basis for the ground floor, as shown in Figure 2.

The walls were realized and assembled on site with 150 × 50 × 10 × 1.5 mm studs (C lipped channel), which are spaced at 600 mm and connected at the ends to 152 × 40 × 1.5 mm U section wall tracks. All CFS profiles are made by zinc coated and dip-hot galvanized S320 steel. To understand the environmental sustainability of CFS profiles, it is important to notice that they can be manufactured to precise measurements, having minimal job site scrap and consequent minimal waste, which can certainly then be recycled. These characteristics make CFS system particularly appropriate for a sustainable management of building sites [10]. CFS walls were braced with 9 mm thick type 3 OSB panels (ISO 6308, 1980) on both sides of the walls. S/HD10B metal-to-metal connectors [11] and HIT-RE 500 with HIS adhesive-bonded anchors were placed as hold-down connections at the corners of resisting walls and 8 mm mechanical connection were instead used as shear anchors along the walls. The wall stratigraphy is reported in Figure 3 and aimed at the eco-efficiency of the building in its life-cycle, starting from the use of eco-compatible materials, to the choice of envelope solutions as energetically efficient, and integrated with envelope passive energy strategies. Specifically, the insulation is achieved with 100 mm hemp fibre placed within the studs, two panels of CELENIT for a total thickness of 75 mm on the exterior of the load bearing walls, an air gap of 35 mm and a cement-based panel, used as finishing.

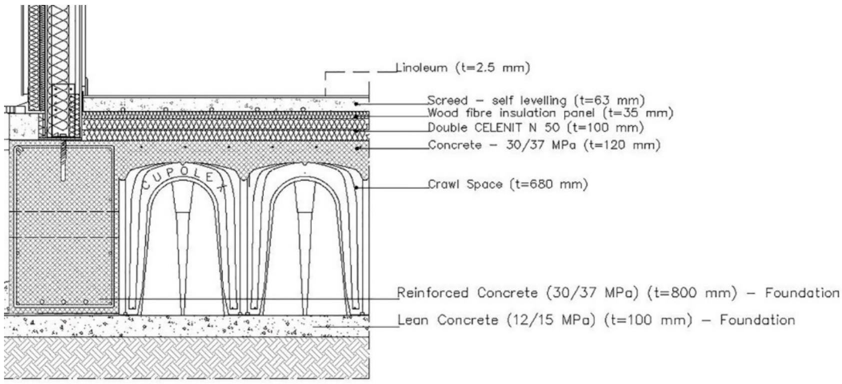


Figure 2. Foundation and ground floor sections.

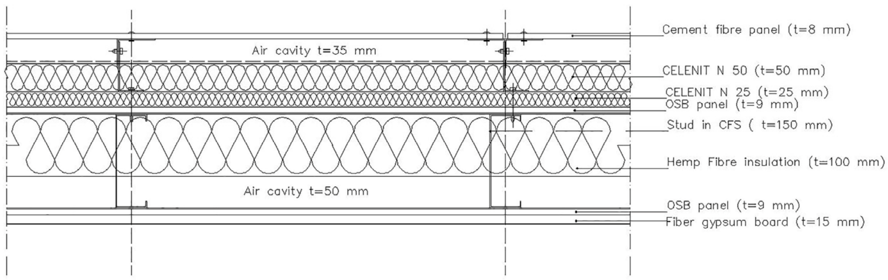
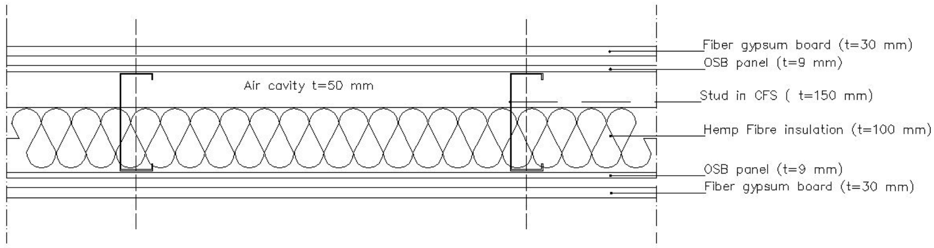


Figure 3. External wall section of the British Foundation school.

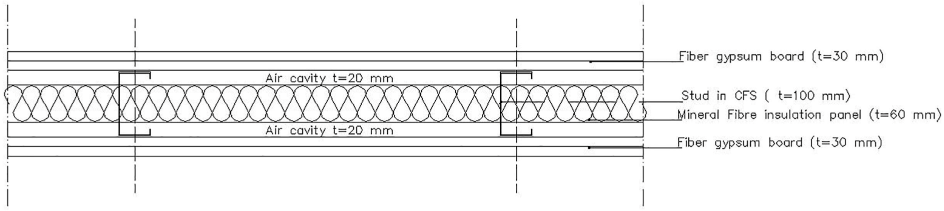
Internally, 15 mm gypsum-based boards are included to achieve the required fire performance. The internal walls are described in Figure 4, and are divided in load-bearing and not-load-bearing. The load-bearing are also composed of 150 mm wide studs, braced on both sides by 9 mm OSB type 3 panels, finished with two gypsum-based panels on both sides. The building has been structurally designed according to a "sheathing braced methodology" [12] that counts on the collaboration between studs and sheathing panels. The not-load-bearing walls [13] comprise 100 mm width studs, completed on both sides with two gypsum-based panels.

The roof is realized by 300 × 50 × 20 mm CFS joists, with thickness ranging between 1.50 and 3.00 mm, spaced at 600 mm. CFS tracks connected the joists at each end of the floor, and were made of 303 × 50 × 1.50 mm or 306 × 50 × 3.00 mm U sections. On the top flanges of floor joists, OSB panels are screwed and solid blocks, realized by 250 × 50 × 20 × 1.50 mm C-sections, are placed between the end joists to provide edge support to the sheathing. The floor, overall, acts as a diaphragm with joists as primary member and the OSB sheathing panels acting as bracing system.

The roof is insulated externally with 2 CELENIT boards of 25 mm thickness each, and one hemp fibre 100 mm thick, and completed with a soundproof corrugated metal sheet, placed on an adjustable load-bearing structure to obtain the required slope for the rain collection. Figure 5 includes all details.



(**a**)



(**b**)

Figure 4. Internal wall sections: (**a**) load-bearing wall; (**b**) non-load-bearing wall.

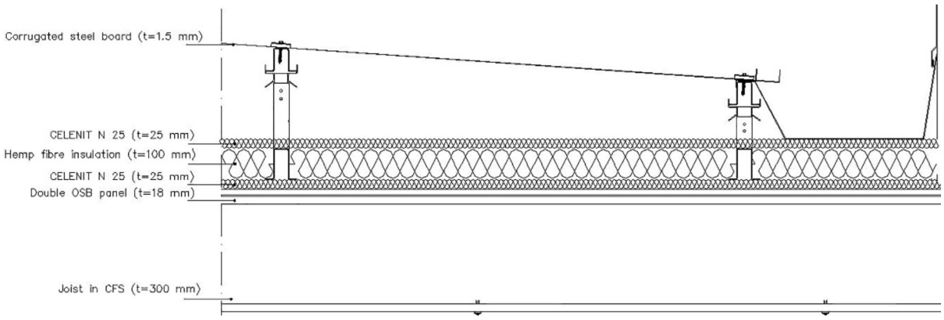


Figure 5. Roof section.

2.2. *Cross Laminated Timber Technology*

Cross laminated timber systems (CLT) are composed of CLT panels (walls and floors) having load-bearing function. CLT is a prefabricated system suitable for the construction of load-bearing walls as well as for the construction of attics and sloping roofs. It is ideal for anti-seismic constructions thanks to its excellent mechanical properties. The CLT panels are usually delivered to the construction site ready for assembly. CLT systems are an alternative dry-construction system to CFS, which are recently becoming widespread thanks to the eco-sustainability of the production process, the achievable high energy efficiency of the building system, and good weight-to-performance ratio and sound insulation properties. The CLT system is often considered for green building designs because the main raw materials are the wood and glues that do not emit solvents or formaldehyde. An example of application of CLT is the BNZEB, which is a nearly zero energy detached house built in Benevento, a city in Southern Italy. The building is located in the same climatic zone [14] as the previously presented CFS case study. The structure is designed for a seismic zone 1, characterized by very high seismic risk [9] and with a coefficient of structure equal to 1.5. The BNZEB is described in detail in Ascione et al. [15,16]. The vertical load-bearing structure is made of 9.5 cm thick CLT panels with five crossed layers. Each layer is composed of side-by-side solid wood boards, class C24, which have a thickness of 1.9 cm. The overlapping layers are crossed and rotated with respect to each other by 90°. The tree essence of which the layers are made is the spruce. The vertical load bearing panels represent the totality of the perimeter walls and internal partitions of the building. The panels are generally continuous and are interrupted only at the intersections with orthogonal walls. The continuity of the various panels was established by seeking the right compromise between production, construction and structural needs. The walls have the task of absorbing both the vertical and horizontal loads (accidental loads, earthquake and wind). In particular, the vertical panels have a membrane-like structural behaviour and are connected to the foundation by metal Hold-Downs anchors arranged on both panel faces at the beginning and end of each wall panel, as well as at the beginning and end of each doorway or window. The panels do not rest directly on the ribs of the concrete slab below the building, but between the latter and the panels themselves; 9.5 × 12 cm levelling strips are interposed, connected to the panels by means of anchoring screws. Wall-to-wall crossover connections are made using crossed anchor screws. The roof deck is also made with five-layer CLT panels whose thickness is equal to 12 cm. Each layer is composed of solid wood boards, class C24, which have the following thicknesses of 1.9–2.15–3.9–2.15–1.9 cm. The roof panels have a plate behaviour and are connected to the vertical wall panels with metal angles and screws. Strips of soundproofing material are interposed between the roof and wall panels. The CLT is coupled to one or more layers of wood wool thermal insulation, with different density and thermal conductivity, respectively, in the case of walls and roof, as shown in Figure 8b and Figure 9b. The thermal transmittance of the walls is 0.17 W/m^2 K while the thermal transmittance of the roof is 0.23 W/m^2 K.

2.3. Traditional Construction

The majority of traditional constructions in Southern Italy are reinforced masonry systems. Therefore, in this study, a traditional construction composed of perforated clay bricks (350 mm thick), filled with reinforced concrete, lined with 70 mm of mineral wool, and completed with render is considered. This configuration, with a total thickness of 550 mm, has a thermal transmittance of 0.22 W/m^2 K. The considered roof is a traditional flat roof made of concrete blocks, as retrieved by the independent Technical Report UNI/TR 11552, which is part of the update of UNI/TS 11300, developed as set of new regulations for the energy reduction in buildings by the European Commission [17–20]. For the aim of the comparison to the retrieved roof stratification, 100 mm of expanded polystyrene (EPS) with thermal conductivity (λ) equal to 0.035 W/mK is added to allow the roof to reach a U value equal to 0.28 W/m^{2}K [21].

3. Life Cycle Analysis (LCA)

3.1. Goal and Scope Definition

The goals of the LCAs developed in this study are: 1. to investigate the environmental impacts of the CFS system in a cradle-to-gate approach, to understand what are the components which are mostly responsible for the overall EC; 2. To compare the EC of a CFS system with that of a CLT system and a traditional reinforced masonry system.

3.2. LCA Methodology

The life cycle analysis (LCA) is carried out from "cradle-to-gate" and includes both structural and non-structural components of the investigated construction systems. The LCA boundaries include only the production stage (A1–A2–A3), as indicated in Figure 6.

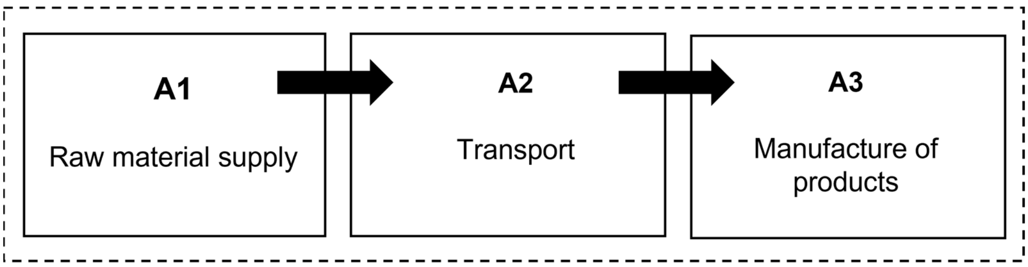


Figure 6. Cradle-to-gate system boundaries. According to EN 15978.

Modules A1, A2 and A3 are indicated as a single aggregated module A1–A3, which comprises the impacts of all materials and products' production and supply, as well as waste processing during the production stage. More specifically, the module "raw material supply" (A1) considers the emissions caused by raw materials when taken from nature, transported to industrial plants and processed. The "transport impacts" module (A2) involves the emissions due to the transport of raw materials from providers to the manufacturing plant and then to the construction site. The "manufacturing" module (A3) includes the impacts of production and fuels used by machines, plus transformation of the waste generated in the manufacturing production until end-of-waste state. A1–A3 module includes all the steps from the cradle-to-gate of the building components adopted for the case study construction. The total GHG emissions deriving from phases A1 to A3 represent the embodied emissions of the building.

The life cycle analysis is developed with the use of One Click LCA automated life cycle assessment software [22], according to the requirement of the EN 15978 standard [23], which is in line with the ISO 14040/44 standard [24]. Specifically, this study adopts the Center of Environmental Science of Leiden University (CML) methodology, to evaluate the environmental impacts in accordance with the EN 15978 and EN 15804 standards [23]. The CML methodology is integrated in One Click LCA and allows the development of environmental impact assessments of products and processes [25]. In this study, the life cycle impact analysis considers six standard impact categories, as reported in Table 1.

Table 1. Adopted impact categories.

Impact Category	Abbreviation	Unit
Global warming potential	GWP	$kgCO_{2\text{-}eq}$
Acidification potential	AP	$kgSO_{2\text{-}eq}$
Eutrophication potential	EP	$kgPO_{4\text{-}eq}$
Ozone depletion potential	ODP	$kgCFC_{11\text{-}eq}$
Formation of ozone of lower atmosphere	POCP	$kgC_2H_{4\text{-}eq}$
Total use of primary energy	TUPE	MJ

According to the LCA methodology, the bill of materials has been calculated for each study, and then for each material the corresponding cradle-to-gate impacts have been evaluated on the basis of the corresponding EPD, retrieved in the One Click databases. When the precise material was not available, then the environmental profiles of materials, which are similar in terms of thermophysical properties, country of production and production process were considered (Figure 7).

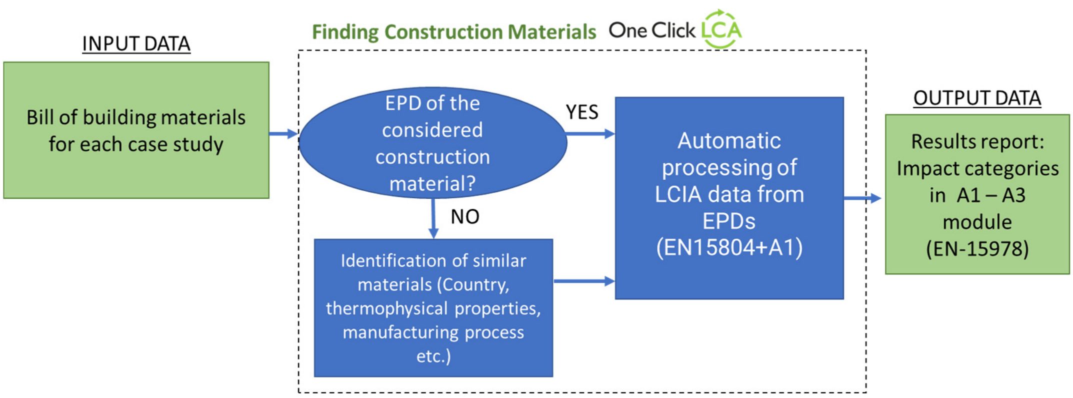


Figure 7. Workflow scheme.

Among all the impact categories, the global warming potential (GWP), which is defined as a relative measure of how much heat a greenhouse gas traps in the atmosphere, is calculated in carbon dioxide equivalents, meaning that the greenhouse potential of emission is given in relation to $CO_{2\text{-eq}}$. In addition, among the other EN standard impact categories, the total use of primary energy is considered, which represents the amount of both non-renewable and renewable primary energy (MJ), excluding those used as raw materials. For the sake of simplicity, in this study the Total Use of Primary Energy will be indicated by the acronym TUPE.

3.3. Functional Units for the LCA Comparisons

The functional units for the comparison of the three investigated systems (CFS, CLT and traditional construction) are 1 m^2 of wall without glazed elements and 1 m^2 of roof. All panels include both load-bearing and non-load-bearing elements.

Figures 8 and 9 show the sections of the three analysed construction typologies (i.e., CFS, CLT and traditional construction) for both walls and roofs, while Table 2 reports their thermal transmittance values and the whole thickness.

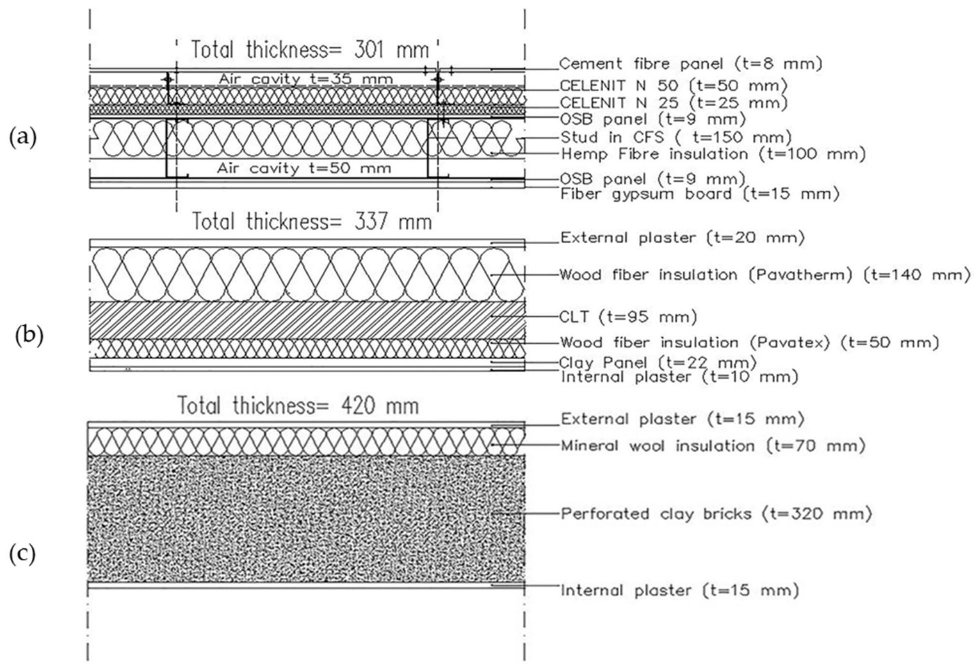


Figure 8. Wall configurations: (**a**) CFS; (**b**) CLT; (**c**) traditional.

Table 2. Total thickness and thermal transmittance values.

Wall	Total Thickness [mm]	U [W/m^2 K]
CFS	301	0.220
CLT	337	0.172
Traditional	420	0.217
Roof	**Total Thickness [mm]**	**U [W/m^2 K]**
CFS	169.5	0.290
CLT	498	0.229
Traditional	470	0.283

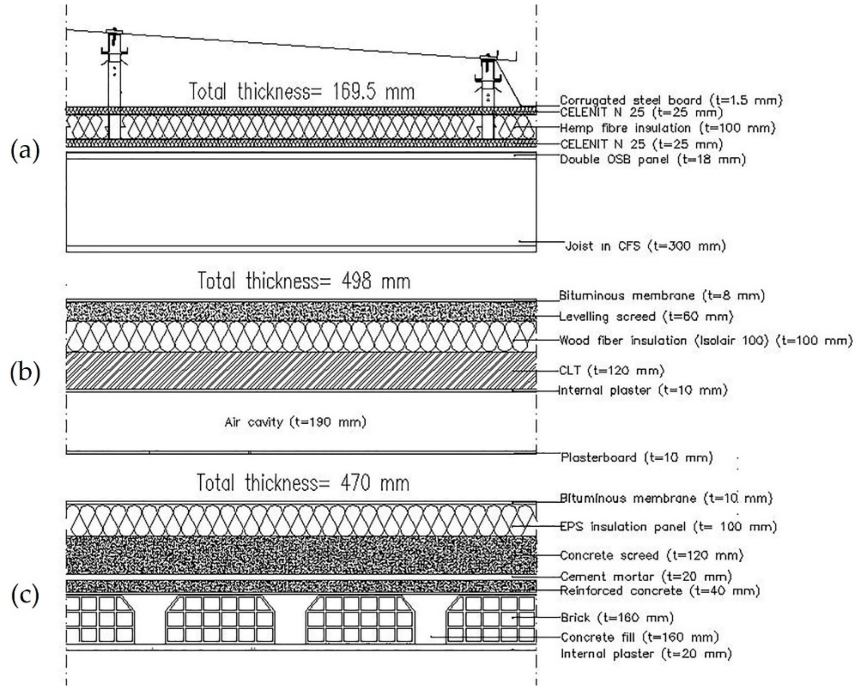


Figure 9. Roof configurations: (**a**) CFS; (**b**) CLT; (**c**) traditional.

3.4. Life Cycle Inventory (LCI for the A1–A3 Phase) for the CFS Case Study

In order to analyse the environmental impact of the CFS case study, the following Tables 3–7 show the quantities of materials used for the walls (both load-bearing and non-load-bearing walls) and roof of the British Force School, making the distinction between materials for structural and non-structural components.

Table 3. Bill of materials: foundation.

Construction Material	Quantity	Struct./Non-Struct.
Concrete (12/15 MPa)	199 m^3	Non-Struct.
Concrete (30/37 MPa)	424 m^3	Struct.
Reinforcement	18.3 ton	Struct.

The environmental data source and the relative upstream database for each investigated material is reported in Appendix A. Through this information, the life cycle inventory phase for the CFS system was completely characterized.

Table 4. Bill of materials: ground floor.

Construction Material	Quantity	Struct./Non-Struct.
Crawl space	1994 m^2	Struct.
Concrete (30/37 MPa)	240 m^3	Struct.
Wood wool panels—CELENIT N 50	199.4 m^3	Non-Struct.
Linoleum	1994 m^2	Non-Struct.
Wood fibre Insulation	80 m^3	Non-Struct.
Screed self levelling	126 kg	Non-Struct.

Table 5. Bill of materials: load-bearing walls.

Construction Material	Quantity	Struct./Non-Struct.
Cold Formed steel (CFS)	44.6 ton	Struct.
OSB panels	52.6 m^3	Struct.
Wood wool panels—CELENIT N 25	28 m^3	Non-Struct.
Wood wool panels—CELENIT N 50	56 m^3	Non-Struct.
Fibre-cement panels	8.9 m^3	Non-Struct.
Gypsum fibreboard—Knauf Vidifire	106 m^3	Non-Struct.
Hemp Fibre insulation	300 m^3	Non-Struct.

Table 6. Bill of materials: non load bearing walls.

Construction Material	Quantity	Struct./Non-Struct.
Cold Formed steel (CFS)	6.4 ton	Non-Struct
Mineral fibre insulation	46 m^3	Non-Struct.
Gypsum fibreboard—Knauf Vidifire	46 m^3	Non-Struct.

Table 7. Bill of materials: roof.

Construction Material		Quantity	Struct./Non-Struct.
Cold Formed steel (CFS)	ton	50.9	Struct.
OSB panels	m^3	45	Struct.
Wood wool panels—CELENIT N 25	m^3	126	Non-Struct.
Hemp Fibre insulation	m^3	252	Non-Struct.
Corrugated galvanized steel	m^2	2524	Non-Struct.

3.5. Life Cycle Inventory (LCI for the A1–A3 Phase) for the Comparison between CFS, CLT and Traditional System

For the second aim of this paper, which is the comparison between 1 m^2 of wall and roof of the CFS, CLT and traditional system, presented in Section 2, the bill of materials have been also calculated as reported in Tables 8–10. For each material, the environmental data source and the thermal conductivity are also reported.

Some criticalities can be underlined for the selection of the EDPs. The values available in the One Click LCA tool are mostly related to materials of recent construction with manufacturing processes that may have undergone important changes over the years, compared to the original construction period of the chosen traditional configurations (see Section 4.2). Building materials of the same type and with similar density and the thermal conductivity among those available are considered. For example, the perforated concrete blocks considered for the wall and the hollow roof bricks are produced by CERANOR S.A. [26] (Spain), with environmental product declaration (EPD 008-007). When the data were not available from the manufacturer, the professional database GABI/Thinkstep [27] was used.

Table 8. Bill of material, thermal conductivity and data source: CFS configurations for 1 m^2 of wall and roof.

	Construction Material	Mass per Unit [kg/m^2]	λ [W/m K]	Environment Data Source (EPD Number)
Wall	Fibre-cement panels	16	1.310	EPD Grossformatige Faserzementplatten pigmentiert beschichtet Carat/Reflex/Avera/Zenor/Aura/Integral/Plan Swisspearl Group AG (EPD-SWP-20180031-IAD1-DE)
	OSB panels (wall)	5.4	0.156	Oekobau.dat 2017-I, EPD SWISS KRONO OSB Panels SWISS KRONO Tec AG (EPD-KRO-20150067-IBD2-EN)
	Wood wool panels—CELENIT N 25 (wall)	11.5	0.070	EPD ACOUSTIC AND THERMAL PANELS CELENIT ABE, AE, AB, A, NB, N (S-P-00477)
	Wood wool panels—CELENIT N 50	18	0.070	EPD ACOUSTIC AND THERMAL PANELS CELENIT ABE, AE, AB, A, NB, N (S-P-00477)
	CFS	5.9	48	EPD Cold-Formed Steel Products (4789752901.101.1)
	Gypsum fibreboard—Knauf Vidifire	19.9	0.350	EPD Gypsum fibreboards Knauf Bulgaria (EPD-KNB-20130006-IAC1-EN)
	Hemp Fibre insulation (wall)	4	0.040	EPD EKOLUTION® HEMP FIBRE INSULATION (S-P-01961)
Roof	OSB panels (roof)	10.8	0.156	Oekobau.dat 2017-I, EPD SWISS KRONO OSB Panels SWISS KRONO Tec AG (EPD-KRO-20150067-IBD2-EN)
	Wood wool panels—CELENIT N 25 (roof)	23	0.070	EPD ACOUSTIC AND THERMAL PANELS CELENIT ABE, AE, AB, A, NB, N (S-P-00477)
	Hemp Fibre insulation (roof)	4	0.040	EPD EKOLUTION® HEMP FIBRE INSULATION (S-P-01961)
	CFS	13.8	48	EPD Cold-Formed Steel Products (4789752901.101.1)
	Corrugated galvanized steel	11.8	-	EPD for AlumiGard, MagnaFlow and ZinaCore pre-painted roofing and cladding for use in Australia (S-P-01540)

Table 9. Bill of material, thermal conductivity and data source: CLT configurations for 1 m^2 of wall and roof.

	Construction Material	Mass per Unit [kg/m^2]	λ [W/m K]	Environment Data Source (EPD Number)
Wall	Internal gypsum plaster (wall)	12	0.910	Oekobau.dat 2017-I, EPD GIPSPUTZ Bundesverband der Gipsindustrie e.V. (EPD-BVG-20140073-IAG1-DE)
	External gypsum plaster	20	0.910	Oekobau.dat 2017-I, EPD GIPSPUTZ Bundesverband der Gipsindustrie e.V. (EPD-BVG-20140073-IAG1-DE)
	Clay panel	35.2	0.353	MDEGD_FDES (INIES_DISO20161116_164615, 5730)
	Wood fibre insulation panel—Pavatex	2.8	0.038	EPD PAVAFLEX flexible woodfibre insulation material Pavatex SA (EPD-PAV-20150043-IBA4-EN)
	Wood fibre insulation panel—Pavatherm	18.2	0.04	EPD Woodfibre insulation materials produced in the wet process 135–200 kg/m3 PAVATEX SA (EPD-PAV-2013254-CBG2-EN)
	Cross Laminated timber (wall)	47.5	0.130	EPD del pannello in legno X-LAM Cross Laminated Timber (S-P-01408)
Roof	Cross Laminated timber (roof)	60	0.130	EPD del pannello in legno X-LAM Cross Laminated Timber (S-P-01408)
	Wood fibre insulation panel—Isolair 100	14.5	0.041	FDES (INIES_IPAN20191004_110244, 12569)
	Plasterboard	4.8	0.072	EPD PPC Italia Gyproc Wallboard 13 mm (S-P-00938)
	Internal gypsum plaster (roof)	12	0.910	Oekobau.dat 2017-I, EPD GIPSPUTZ Bundesverband der Gipsindustrie e.V. (EPD-BVG-20140073-IAG1-DE)
	Levelling screed	22.8	0.129	EPD for Ultraplan, Ultraplan Eco, Ultraplan Maxi, Novoplan Maxi (S-P-00908)
	Bituminous membrane	6.4	0.130	Single layer mechanically fastened modified bitumen roof waterproofing system, Bitumen Waterproofing Association (2014) (NEPD00268E)

Table 10. Bill of material, thermal conductivity and data source: traditional configurations for 1 m^2 of wall and roof.

	Construction Material	Mass per Unit [kg/m²]	λ [W/m K]	Environment Data Source (EPD Number)
Wall	Internal plaster (wall)	15	0.390	EPD Gypsum plasters ALFA, BETA, GAMMA, ZETA, SPRINT, TEMPO (INIES_CEND20201217_102244, 26218)
	External plaster	27	0.890	Oekobau.dat 2020-II
	Perforated clay bricks	252.7	0.140	DAP Ladrillos y bloques cerámicos para revestir (EPD 008-007)
	Mineral wool	3.5	0.035	ACUSTILAINE MD 50 60 mm, Saint Gobain Cristaleria 2013 (ES054277-4)
	Concrete, normal-strength (wall)	171.4	-	One Click LCA
	Bricks	111	-	EPD Ladrillos y Bloques cerámicos para revestir. Pieza P según norma UNE-EN 771-1 (EPD 008-007)
	Steel for reinforcement (wall)	7.7	-	EPD Hot-rolled reinforcing steel for concrete in bars and coils (S-P-00255)
	Internal plaster (wall)	15	0.390	EPD Gypsum plasters ALFA, BETA, GAMMA, ZETA, SPRINT, TEMPO (ITB EPD No 083/2018)
Roof	Concrete, normal-strength (roof)	147	-	One Click LCA (-)
	Steel for reinforcement (roof)	14	-	EPD Hot-rolled reinforcing steel for concrete in bars and coils (S-P-00255)
	Screed	240	1.160	EPD NHL based screed floor (Sella, DOMUSVR, OPUS-C Masetto) (EPD-Miniera San Romedio Srl-89-EN)
	Cement mortar	40		Oekobau.dat 2022 (-)
	Bituminous membrane	12	0.170	Single layer mechanically fastened modified bitumen roof waterproofing system, Bitumen Waterproofing Association (2014) (NEPD00268E)
	EPS	2.3	0.035	Enviromental Product Declaration: ECO ESPANSO K100 (EPDITALY0029)
	Internal plaster (roof)	28	0.900	FDES (INIES_CEND20201217_102244, 26218)

4. Results

4.1. Life Cycle Impact Assessment (LCIA) of CFS School

According to the adopted approach, the EC of the building amounts to approximately 767 tons of CO_2e (Table 11). As shown in Figure 10, 28% of these GHG emissions are due to the materials and quantities used in the roof, 26.9% to the walls (load-bearing and not-load-bearing walls), 21% to the ground floor composition, and 24.1% to the materials used in foundations. Therefore, considering the specificity of construction, it is possible to say that, for the CFS case study, about 55% of the GWP is concentrated in the building materials above ground, and about 45% in the foundation and ground floor. Among the other impact categories analysed, the contribution of the materials included in the ground floor almost completely covers the impacts quantified in AP, EP, ODP and POCP with percentages equal to 98%, 96%, 97.8% and 99.7%, respectively. Regarding TUPE, there is an incidence of about 32% of the materials used both in the walls and in the roof, of 27% in the case of the ground floor and of about 8% for the materials used in foundations.

Table 11. Global LCIA Results.

	GWP	AP	EP	ODP	POCP	TUPE
	$tonCO_{2\text{-eq}}$	$kgSO_{2\text{-eq}}$	$kgPO_{4\text{-eq}}$	$kgCFC_{11\text{-eq}}$	$kgC_2H_{4\text{-eq}}$	MJ
TOTAL	767	88	97	1.9	700	10,054,000

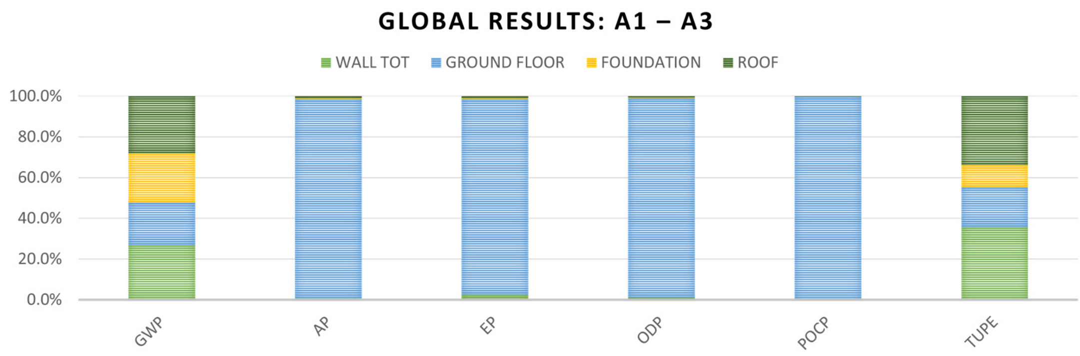


Figure 10. LCIA results: incidence percentages in each impact category.

Starting from the global results obtained in each impact category, the following paragraphs analyse in detail the percentage incidence of the individual materials within each building component with CFS framing system, distinguishing, where possible, between the impacts given by the structural and non-structural parts.

4.1.1. Walls

The impact assessment of the walls takes into account all materials included in both external and internal walls, i.e., structural and non-structural walls, with the exception of windows and doors. As stated in Section 2.1, the load-bearing walls includes the CFS profiles, as well as the OSB panels. The results obtained for the structural walls are shown in Figure 11 and Table 12. The structural components are responsible for 51.5% of the total GWP of the walls, of which 80% is due to CFS components (studs, tracks, flat straps, and blockings) and 20% to the OSB.

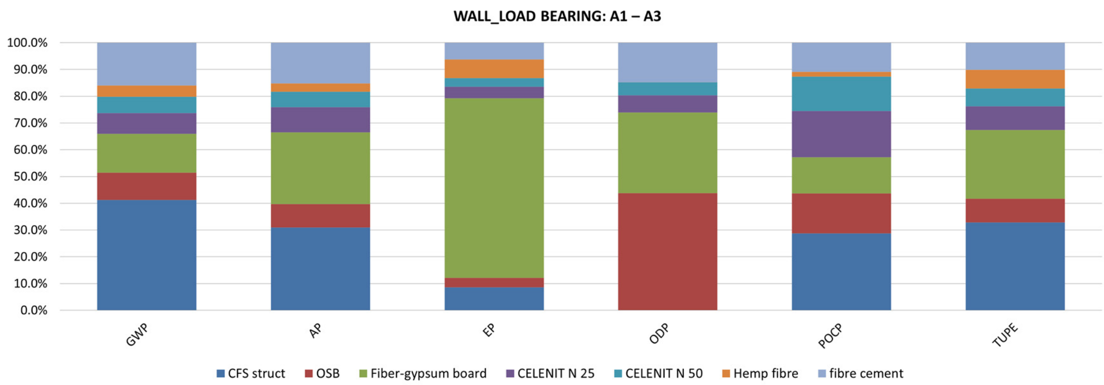


Figure 11. LCIA results: load-bearing walls.

Table 12. Results of Life Cycle impact assessment: load-bearing walls.

Material		**GWP**	**AP**	**EP**	**OPD**	**POCP**	**TUPE**
		ton$CO_{2\text{-eq}}$	**ton$SO_{2\text{-eq}}$**	**ton$PO_{4\text{-eq}}$**	**kg$CFC_{11\text{-eq}}$**	**ton$C_2H_{4\text{-eq}}$**	**MJ**
Structural	CFS struct	7.56×10^4	1.61×10^2	1.51×10	5.78×10^{-6}	1.38×10	
	OSB	1.88×10^4	4.54×10	6.29	8.41×10^{-3}	7.16	
Non-structural	Fibre-gypsum board	2.65×10^4	1.39×10^2	1.18×10^2	5.78×10^{-3}	6.49	
	CELENIT N 25	1.42×10^4	4.85×10	7.56	1.24×10^{-3}	8.23	
	CELENIT N 50	1.12×10^4	3.00×10	5.67	9.32×10^{-4}	6.17×10	
	Hemp Fibre	7.76×10^3	1.64×10	1.22×10	3.48×10^{-6}	8.63×10^{-1}	
	Fibre Cement	2.93×10^4	7.87×10	1.10×10	2.84×10^{-3}	5.20	
Total		1.83×10^5	5.19×10^2	1.76×10^2	1.92×10^{-2}	4.79×10	

The three thermal insulation panels cause about 18.1% of the embodied carbon of the walls. Despite the larger quantity, natural hemp fibre insulation is much more sustainable than the wood wool insulation panels. Furthermore, it is surprising that the CELENIT N 25 has a greater impact than the CELENIT N 50. Indeed, an emission factor equal to 509 $kgCO_2e/m^3$ emerges from the EPD of CELENIT N insulation panel for a thickness of 25 mm. Among the remaining materials of the load bearing walls, the fibre-gypsum board and the fibre cement panel are responsible for 14.5% and the 16% of EC, respectively. As for the other considered impact categories, the structural CFS is the most impacting building material in terms of AP (31%), followed by the fibre-gypsum board (26.8%). In addition, the fibre-gypsum board involves 67% of the EP of the walls. Regarding ODP, the impact of CFS is negligible, while the most impacting materials are the OSB and fibre-gypsum board, with percentages of 43.8% and 30.1%, respectively. Moreover, 30.1% of the photochemical ozone creation potential of the structural walls is caused by the insulating panels in wood wool (CELENIT N 50 and CELENIT N 25). Structural materials (structural CFS and OSB) account for about 43.7% (28.7% and 15%, respectively) in the POCP indicator, while the fibre-gypsum board represents about 14% of this. The materials that involve the greatest total use of primary energy are the structural CFS and the fibre-gypsum boards, respectively, with percentages of 32.9% and 25.7%. In this case, the percentage of incidence of non-structural materials is approximately 58.3%. Finally, with the exception of the GWP, the non-structural building materials present in the load-bearing walls of the BSF have overall larger impacts than the structural materials, with an average percentage of 61.3% considering all examined impact categories. This is mainly due to the high impact of the fibre-gypsum boards and the CELENIT 25 and CELENIT N 50 insulating panels, as well as to the greater amount of materials with a non-structural function (see Tables 5 and 12).

In the same way, Figure 12 and Table 13 show LCA results for non-load-bearing walls in which there are no materials with structural function.

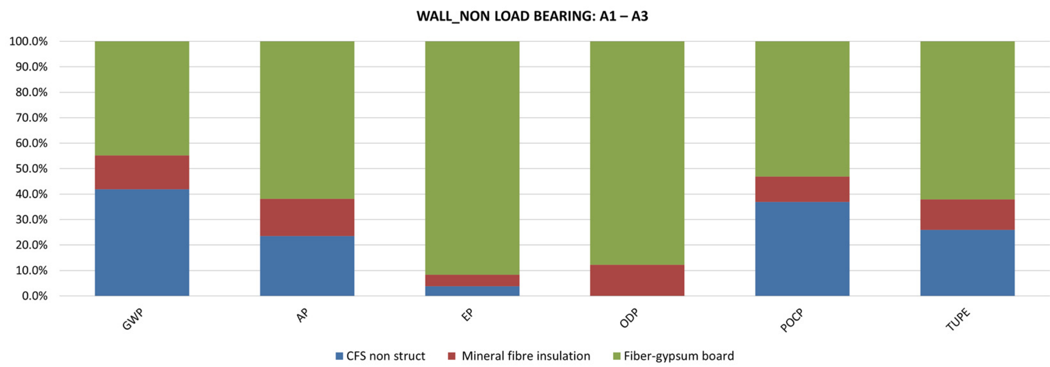


Figure 12. LCIA results: non-load-bearing walls.

Table 13. Results of Life Cycle impact assessment: non-load-bearing walls.

Material	GWP	AP	EP	OPD	POCP	TUPE
	$tonCO_{2\text{-eq}}$	$tonSO_{2\text{-eq}}$	$tonPO_{4\text{-eq}}$	$kgCFC_{11\text{-eq}}$	$tonC_2H_{4\text{-eq}}$	MJ
CFS non-struct.	1.09×10^4	2.33×10	2.17	8.31×10^{-7}	1.98	1.47×10^5
Mineral Fibre insulation	3.46×10^3	1.44×10	2.53	3.47×10^{-4}	5.31×10^{-1}	6.71×10^4
Fibre-gypsum board	1.17×10^4	6.12×10	5.18×10	2.50×10^{-3}	2.85	3.50×10^5
Total	2.60×10^4	9.89×10	5.65×10	2.85×10^{-3}	5.36	5.64×10^5

In general, it is observed that, in all analysed impact categories, the least sustainable material is the fibre-gypsum board, followed by the non-structural CFS. In terms of GWP, the fibre-gypsum board is responsible for 44.8% and the non-structural CFS for 41.9%. For EP and ODP indicators, the fibre-gypsum board is responsible for 91.7% and 87.8%, respectively. Furthermore, 62.1% of the total primary energy use is due to the fibre-gypsum board and 26% to non-structural CFS.

The mineral fibre insulation panel is the most sustainable material and affects an average of 11.1% of the indicators assessed. In general, the magnitude of the analysed impacts is clearly lower for non-structural walls than for structural ones. As can be seen from Tables 12 and 13 and from what is reported in Section 3.2, this is certainly due to the smaller number of materials involved and to the smaller quantities. For example, the total GWP of the non-load-bearing walls is equal to 14.2% of the total GWP calculated for load-bearing walls.

4.1.2. Roof

The roof is composed of CFS profiles (joists, floor tracks, blockings and flat straps) with the OSB panels acting as the structural components, and is completed by CELENIT N 50 insulation panels, hemp fibre insulation panels and corrugated galvanized steel sheets acting as non-structural materials. As can be seen in Figure 13, the materials that most affect the embodied carbon are the CFS (40.2%), CELENIT N 25 (29.9%) and corrugated galvanized metal sheets (19.3%); the respective impact is reported in Table 14. Structural materials cover 47.8% of the GWP. As in the case of the walls, the hemp fibre insulation has lower impact than CELENIT N, involving just 3% of the GWP. Despite the thickness of 100 mm, the hemp fibre insulation panel seems to be an extremely sustainable material (emission factor of 21.8 $kgCO_2e/m^3$) when compared to the impact caused by the double CELENIT N (25 mm) insulation panels used in the roof. Regarding AP, the percentages are equal to 45.1%, 26.8% and 21.8% for the corrugated galvanized metal sheets, CELENIT N 25 and CFS, respectively. Structural materials cover 29.9% of AP. The most impacting material in terms of eutrophication is CELENIT N 25 (37.7%), followed by the galvanized steel sheet (24.4%) and CFS (19.9%). This is the impact category in which the hemp fibre insulation panel has the greatest impact (11.8%).

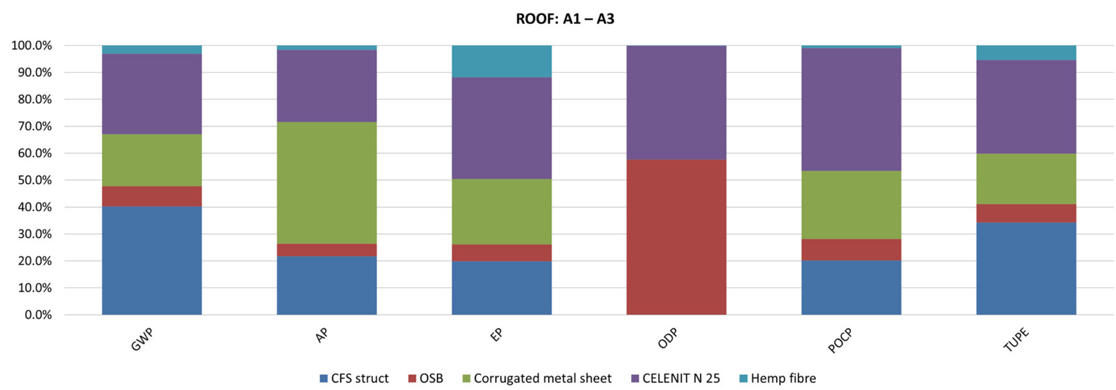


Figure 13. LCIA results: Roof.

Table 14. Results of Life Cycle impact assessment: Roof.

Material		AP	EP	OPD	POCP	TUPE
	GWP $tonCO_{2\text{-eq}}$	$tonSO_{2\text{-eq}}$	$tonPO_{4\text{-eq}}$	$kgCFC_{11\text{-eq}}$	$tonC_2H_{4\text{-eq}}$	MJ
Structural	CFS structural	8.63×10^4	1.84×10^2	1.72×10	6.60×10^{-6}	1.57×10
	OSB	1.62×10^4	3.93×10	5.43	7.30×10^{-3}	6.19
Non- Structural	Corrugated metal sheet	4.14×10^4	3.81×10^2	2.11×10	6.10×10^{-8}	1.96×10
	CELENIT N 25	6.43×10^4	2.27×10^2	3.27×10	5.36×10^{-3}	3.56×10
	Hemp fibre insulation	6.52×10^3	1.38×10	1.03×10	3.00×10^{-6}	7.20×10^{-1}
Total		2.15×10^5	8.45×10^2	8.68×10	1.27×10^{-2}	7.78×10

Structural materials account for 23% of the eutrophication potential of the roof. As regards ODP, the impacts are due exclusively to OSB (57.6%) and CELENIT N 25 (42.3%), while in terms of the formation of ozone of the lower atmosphere, CELENIT N 25 accounts for 45.7%, followed by the galvanized steel sheet (25.2%). The structural materials, CFS and OSB, account for 20.2% and 8%, respectively, in POCP. Finally, in terms of TUPE, non-structural materials impact about 58.9%, with incidence percentages of 34.7%, 18.7% and 5.4% of CELENIT N 25, galvanized steel sheet and hemp fibre insulation, respectively. The CFS and the OSB account for 34.2% and 6.9%, respectively.

4.1.3. Most Contributing Materials and Components

Table 15 shows the most contributing materials in terms of global warming according to the approach used in this paper (cradle-to-gate) and on the basis of what has been assessed in detail for the CFS walls and roof.

Table 15. Overall and percentage impact of each British Defense School construction material.

Resource	Cradle to Gate Impacts (A1–A3) (Tons of CO_{2eq})	Cradle to Gate (A1–A3) Percentage Incidence
CFS	173	40.0%
Wood Wool panels	90	20.7%
Corrugated steel	41	9.6%
Fibre-gypsum board	38	8.8%
OSB	35	8.1%
fibre cement	29	6.8%
Hemp fibre	14	3.3%
Mineral fibre insulation	12	2.7%

The materials causing the greatest embodied carbon are the CFS and the wood wool panels, with 173 tons of CO_2e (40%) and 90 tons of CO_2e (20.7%), respectively.

In particular, the environmental profile of CFS manufactured by ClarkDietrich and declared in a corresponding EPD was chosen for the present study. In the environmental declaration, with reference to a declared unit of one metric tons of CFS Product (1000 kg), the LCIA results (CML v4.2) reported in EPD show a GWP equal to 1770 kgCO_2e in A1–A3 module. The production of raw material inputs (A1) accounts for most of the EC of CFS (93%) which is mainly attributed to the steel coil that is cold formed to realize the structural components. Energy and utility consumption (in the form of electricity, natural gas and water) are the most significant contributions to the impact of the manufacturing stage (A3).

Regarding wood wool thermal insulation panels, the investigated building adopts two typologies of wood wool panels, i.e., CELENIT N25 and CELENIT N50, which have a thickness of 25 mm and 50 mm, respectively.

As indicated in the EPDs available in One Click LCA, the CELENIT panels are made of spruce pine wood (47% in mass) coming from sustainable management forests and mineral binders (52% in mass), mainly composed of Portland cement and marble sawdust. The wood wool is exposed to a mineralization treatment, which reduces the natural deterioration, while keeping the mechanical properties, and increases the fire resistance. Portland cement is adopted as coating to provide high resistance to water and frost as well as to increase the wood wool resistance to bending and compression. In detail, the percentage composition of the raw materials included in 1 kg of panel is reported in Table 16.

Table 16. Wood wool—percentage composition (1 kg of panel).

Material	% in Weight
Portland cement	37%
Spruce wood and water (wood: 80%; water: 20%)	47.30%
Marble sawdust	15%
Calcium diformate	0.3%
Calcium chloride	0.2%
Alkylate	0.2%

Source: S-P-00477 (International EPD System).

The data elaboration has been performed with GABI software v. 7.3.0.40 (Sphera–GaBi solutions, Chicago, IL, USA). Primary data refer to 2015 and have been collected at CELENIT's plant located in Onara di Tombolo (ITA), whereas selected generic data have been retrieved from Ecoinvent 3.1, GaBi and ELCD databases. From the LCIA results (CML v4.6) the emission factors are about 509 $kgCO_2e/m^3$ and 200 $kgCO_2e/m^3$, respectively, for CELENIT N 25 and CELENIT N 50. As stated in the EPD, the biogenic carbon storage is calculated separately from the GWP results of building materials A1–A3 and not subtracted from the calculation.

These emission factors are interesting since, despite the reduced thickness, 1 m^3 of CELENIT N 25 is considerably more impactful than 1 m^3 of CELENIT N 50. Although not explicitly stated in the EPD, as Figure 14 shows, the reasons for this unexpected result are to be sought mainly in the processing phases of the insulating panels as the thickness decreases. Furthermore, it can be seen that the EC, due to the manufacturing (A3), is, in general, predominant and covers almost 93% in both cases.

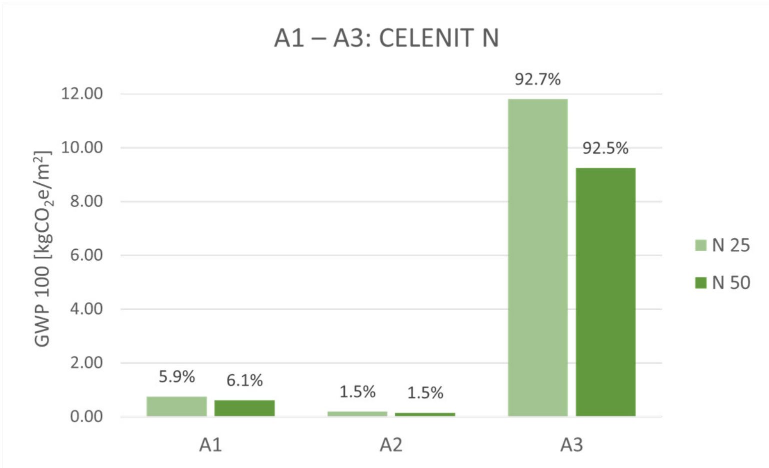


Figure 14. LCIA results for CELENIT N (25 mm and 50 mm).

4.2. Results for the Comparison of CFS, CLT and Traditional

Table 17 and Figure 15 show the life cycle assessment results for the square meters of the three investigated external wall configurations, while Table 18 and Figure 16 show those for the roof configurations. For external walls, in terms of GWP the CFS has the highest value with 123 $kgCO_2e/m^2$, although the result is very close to the GWP calculated for the traditional wall, which equates to 108 $kgCO_2e/m^2$. Among the building materials included in the traditional configuration, the main contribution is given by the perforated clay bricks which are responsible for 65% of the GWP. Other important contributions are given by concrete (20%) and steel reinforcement (24%) used as brick reinforcement. However, from the obtained results it can be seen that their impact is due to the high quantities per square metre of wall rather than the embodied emissions deriving from stages A1 to A3.

Table 17. LCA results: external walls.

		1 m^2 CFS	**1 m^2 CLT**	**1 m^2 Traditional**
GWP	$kgCO_{2\text{-eq}}$	1.23×10^2	4.88×10	1.08×10^2
AP	$kgSO_{2\text{-eq}}$	3.26×10^{-1}	1.45×10^{-1}	1.15×10^{-1}
EP	$kgPO_{4\text{-eq}}$	6.47×10^{-2}	1.05×10^{-1}	1.89×10^{-2}
OPD	$kgCFC_{11\text{-eq}}$	1.02×10^{-5}	3.38×10^{-6}	1.06×10^{-6}
POCP	kg Ethenee	3.44×10^{-2}	2.83×10^{-2}	1.64×10^{-2}
TUPE	MJ	1.83×10^3	8.98×10^2	1.44×10^3
GWP	$kgCO_{2\text{-eq}}$	1.23×10^2	4.88×10	1.08×10^2

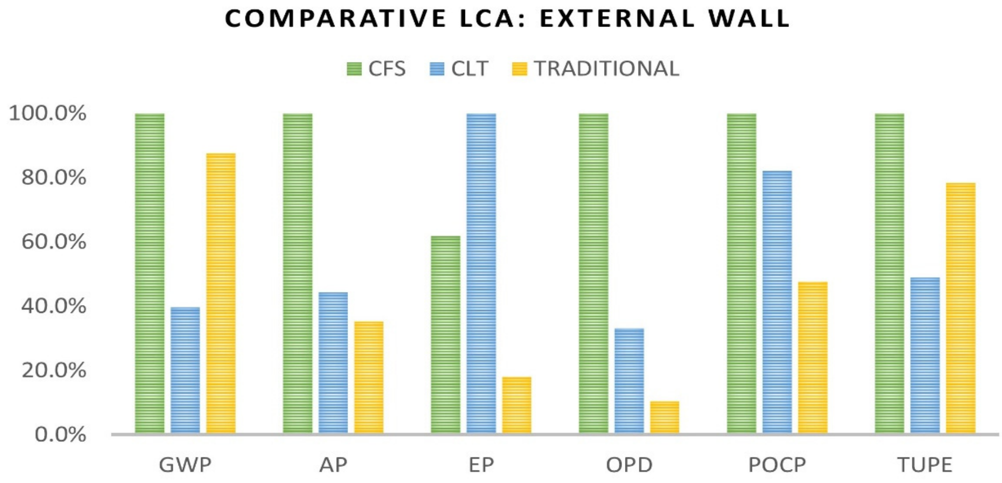


Figure 15. Results of Life Cycle impact assessment: External Wall.

Table 18. LCA results: roof.

		1 m^2 CFS	**1 m^2 CLT**	**1 m^2 Traditional**
GWP	kg $CO_{2\text{-eq}}$	8.51×10	6.42×10	9.76×10
AP	kg $SO_{2\text{-eq}}$	3.35×10^{-1}	8.96×10^{-2}	2.41×10^{-1}
EP	kg $PO_{4\text{-eq}}$	3.44×10^{-2}	2.29×10^{-1}	6.18×10^{-2}
OPD	kg $CFC_{11\text{-eq}}$	5.02×10^{-6}	5.12×10^{-6}	4.23×10^{-5}
POCP	kg $C2H_{4\text{-eq}}$	3.08×10^{-2}	4.41×10^{-2}	2.72×10^{-2}
TUPE	MJ	1.34×10^3	1.03×10^3	1.34×10^3
GWP	kg $CO_{2\text{-eq}}$	8.51×10	6.42×10	9.76×10

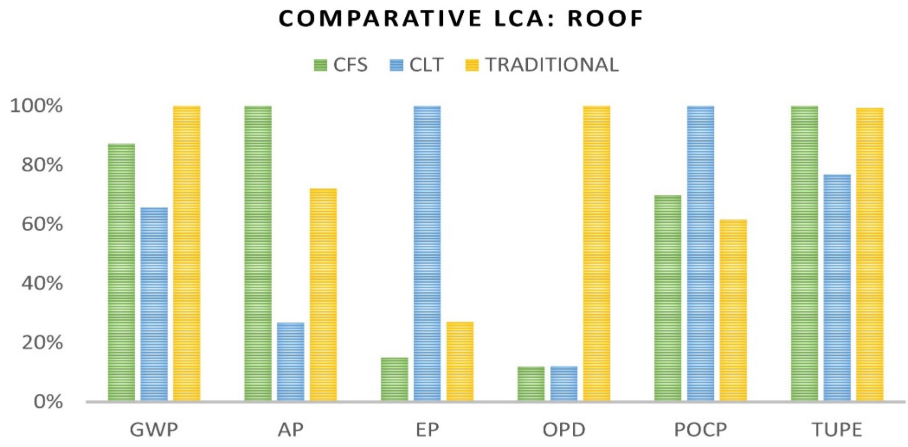


Figure 16. Results of Life Cycle impact assessment: Roof.

The internal and external plaster are responsible, respectively, for 1.2% and 5.6% of the estimated GWP for the wall. As reported in Table 10, the quantity of external plaster per square metre of wall is almost double the quantity of internal plaster. Furthermore, on the basis of the adopted environmental profiles, the EC coefficient of the internal plaster is equal to 0.0949 kgCO_2e/kg while that of the external plaster is 0.23 kgCO_2e/kg. Finally, the ECC value of the mineral wool insulation panel of the wall is the highest (1 kgCO_2e/kg), and this is due to the very low density of this material (50 kg/m^3). The thickness of 70 mm corresponds to 7.5 kg of thermal insulation per m^2 of wall. Consequently, the insulation panel is responsible for 3.4% of the total GWP calculated for the traditional configuration.

In the case of the CLT technology, the EC emissions are equal to 49 kgCO_2e. However, it must be underlined that the external wall of the British School (CFS) also complies with the thermal transmittance limit value currently envisaged by Italian legislation for the construction of a nearly zero-energy building in the climatic zone to which the case study belongs. However, in terms of environmental sustainability, there is an important gap with respect to the current target for the new building.

For the roof, the results obtained in terms of $kgCO_2e/m^2$ show greater comparability between the three analysed cases. In this case, the value obtained with traditional solutions is the highest and equal to 98 $kgCO_2e/m^2$, i.e., +15.3% compared to CFS and +53% compared to CLT. The configuration foreseen for the BNZEB (CLT) is the best one, both in terms of sustainability and energy efficiency. The configuration envisaged for the CFS roof achieves a level of thermal insulation comparable to that obtained in the case of the CLT, with a total thickness reduced by more than 50% but with a carbon footprint per m^2 increased by 32.8%.

For the same configurations, Figure 15 shows the comparisons in terms of LCA considering all the impact categories. From the comparison it can be observed that the CFS wall has the higher impact in terms of AP, OPD, POCP and TUPE. In these impact categories, the traditional external wall, with a thermal transmittance equal to the CFS and a total thickness of 420 mm, has on average an impact equal to 42.9% of that of CFS. Instead, the external wall with laminated wood technology has an impact on average equal to 52.1% of CFS in the same indicators. The CLT wall is the least sustainable in terms of eutrophication potential (EP). For this indicator, the traditional wall shows an impact 82% lower than the wood wall. The eutrophication potential of the CFS wall is equal to 61.8% compared with the wood wall.

For the roof, from the obtained results, it is clear that the wood technology is the most sustainable in the GWP, AP and TUPE categories, while it is the most impactful in terms of EP and POCP categories. In addition to the GWP, the traditional solution is the most impactful in the of ODP indicators. The CFS and X-LAM configurations show lower ODP (of around 88%) than the traditional roof. In terms of TUPE, the impacts of the CFS roof and the traditional roof show negligible differences while the impact of the wood roof is lower by about 33%. Finally, as regards the AP, the least sustainable configuration is the CFS.

5. Conclusions

Sustainable buildings should have low or zero carbon emissions, considering both construction and operation. Choices of material can have a huge impact on this. As with many aspects of sustainability, comparing EC figures can be tricky. This is mainly true for innovative technologies for which there is a limited number of scientific studies exploring their environmental assessments. Therefore, this paper focuses on two innovative technologies: cold formed steel (CFS) systems and cross laminated timber (CLT). Specifically, it analyses in detail a full real case study in CFS, which is the first CFS school built in Italy in a medium/high seismic risk area, which has been designed according to a conservative approach (elastic design) due to inexistent seismic design codes specifically applicable to the investigated structural system in the EU and Italy. The study develops a detailed cradle-to-gate life cycle analysis, and shows that the CFS opaque building components amount to about 55% of the total GWP, with approximately 421 tons of CO_2e. Around 28% of these emissions are due to the materials and quantities used in the roof, and 26.9% to the walls. The impact assessment of the walls indicates that the structural components are responsible for 51.5% of the total GWP of the walls, of which 80% is due to CFS components (studs, tracks, flat straps, and blockings) and 20% to the OSB. The three thermal insulation panels cause about 18.1% of the embodied carbon of the walls, with the natural hemp fibre insulation more sustainable than the wood wool insulation panels. As regards the roof, the materials that most affect the embodied carbon are the CFS (40.2%), wood wool insulation (29.9%) and corrugated galvanized metal sheets (19.3%). Structural materials cover 47.8% of the GWP. As in the case of the walls, the hemp fibre insulation has lower impact than insulation, involving just 3% of the GWP. Therefore, the study clearly shows that, overall, the CFS components are primarily responsible for the EC of the full buildings. Hence, any energy efficient design of CFS constructions should pay very careful attention to optimizing the structural system, as any percentage of reduction of the structural components will have a significant impact on the overall EC. To this end, the development of structural codes that would allow the ductile seismic design of CFS structures in EU could also support and incentivize an optimized design of CFS structure, and then CFS systems with lower EC.

Moreover, when CFS is compared to CLT and traditional reinforced masonry structure, this finding appears even clearer. This study indeed shows that, when 1 m^2 of wall and roof for each construction system are considered, then the results indicate that in terms of global warming potential, the CFS is the one having higher GWP impacts (123 $kgCO_2e/m^2$) when the wall composition is considered, while the traditional system is the one having higher impact for the roof (97.6 $kgCO_2e/m^2$). X-LAM walls, that also allow better energy performance in terms of thermal transmittance, show about 60% less GWP impact then CFS and about 55% compared to the traditional system. In case of the roof's materials, the GWP decreases around 25% and 34%, respectively, compared with CFS and the traditional system. The eutrophication potential is the impact category for which the X-LAM gives the worst results for both wall and roof; at the same time, in only the case of the wall's materials, the formation of ozone of lower atmosphere is increased by around 43% and 62%, respectively, compared to CFS and the traditional system.

The decision to compare the three construction systems, considering the embodied carbon per 1 m^2 of wall and roof, allows the broadening of the applicability of the observed results. Although future sensitivity analysis could improve the reliability of the obtained results, this study demonstrates that CLT is, at the present, the system with lower EC, and that for CFS to fully deliver environmentally sustainable systems, then optimization of the structural system should be prioritized, to reduce the quantity of the material and the consequent EC.

Furthermore, for a wider diffusion of CLT and/or CFS buildings, it would also be important in the future to evaluate the end-of-life impacts, as they can be critical to reducing the overall life-cycle impacts.

The new knowledge generated by the in-depth analyses, discussed in this paper, can make a significant contribution to the early-stage decision-making design process for selecting structural and non-structural building materials with lower EC. Finally, this paper highlights the importance of integrating structural engineering solutions with life cycle assessment. This synergy, especially if implemented in the design phase, can help improve the sustainability performance and reduce the carbon footprint of buildings.

Author Contributions: Conceptualization, O.I.; methodology, O.I. and A.G.; software, A.G.; validation, O.I.; formal analysis, O.I., A.G.; resources, O.I., R.F.D.M.; writing—original draft preparation, O.I. and A.G.; writing—review and editing, O.I., R.F.D.M.; visualization, A.G. and O.I.; supervision, O.I. and R.F.D.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by ESRC, grant number ES/V015923/1.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

Table A1. CFS school—Life Cycle Inventory: source of data.

Construction Material	Environment Data Source	Upstream Database
Crawl space	EPD AIRCRAB H35	ecoinvent
Concrete (12/15 MPa)	One Click LCA	ecoinvent
Concrete (30/37 MPa)	One Click LCA	ecoinvent
Reinforcement	EPD Hot-rolled reinforcing steel for concrete in bars and coils	ecoinvent
Screed self-levelling	EPD weber.floor 110Fine/120Reno/130Core/140Nova	ecoinvent
Cold Formed steel (CFS)	EPD Cold-Formed Steel Products	GaBi
Fibre-cement panels	EPD Grossformatige Faserzementplatten pigmentiert beschichtet Carat/Reflex/Avera/Zenor/Aura/Integral/Plan Swisspearl Group AG	GaBi
OSB panels	EPD-KRO-20150067-IBD2-EN	GaBi
Wood wool panels—CELENIT N 25	EPD ACOUSTIC AND THERMAL PANELS CELENIT ABE, AE, AB, A, NB, N	ecoinvent
Cold Formed steel (CFS)	EPD Cold-Formed Steel Products	GaBi
Gypsum fibreboard—Knauf Vidifire	EPD Gypsum fibreboards Knauf	GaBi
Hemp Fibre insulation	EPD EKOLUTION® HEMP FIBRE INSULATION	GaBi
Mineral fibre insulation	EPD Glass Mineral Wool Insulation with ECOSE Technology (0.031–0.033 W/mK), Knauf Insulation 2015	ecoinvent
Linoleum	FDES	ecoinvent
Wood fibre Insulation	Oekobau.dat 2017-I, EPD Wood fibre insulation materials STEICO	GaBi
Corrugated galvanized steel	EPD for AlumiGard, MagnaFlow and ZinaCore pre-painted roofing and cladding	GaBi

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