sustainability

MDPI

Article

Life Cycle Environmental Assessment of Light Steel Framed Buildings with Cement-Based Walls and Floors

Mona Abouhamad * and Metwally Abu-Hamd

Faculty of Engineering, Cairo University, Giza 12613, Egypt; abuhamd@eng.cu.edu.eg
* Correspondence: m.abuhamd@gmail.com

Received: 28 November 2020; Accepted: 17 December 2020; Published: 21 December 2020

check for updates

Abstract: The objective of this paper is to apply the life cycle assessment methodology to assess the environmental impacts of light steel framed buildings fabricated from cold formed steel (CFS) sections. The assessment covers all phases over the life span of the building from material production, construction, use, and the end of building life, in addition to loads and benefits from reuse/recycling after building disposal. The life cycle inventory and environmental impact indicators are estimated using the Athena Impact Estimator for Buildings. The input data related to the building materials used are extracted from a building information model of the building while the operating energy in the use phase is calculated using an energy simulation software. The Athena Impact Estimator calculates the following mid-point environmental measures: global warming potential (GWP), acidification potential, human health potential, ozone depletion potential, smog potential, eutrophication potential, primary and non-renewable energy (PE) consumption, and fossil fuel consumption. The LCA assessment was applied to a case study of a university building. Results of the case study related to GWP and PE were as follows. The building foundations were responsible for 29% of the embodied GWP and 20% of the embodied PE, while the CFS skeleton was responsible for 30% of the embodied GWP and 49% of the embodied PE. The production stage was responsible for 90% of the embodied GWP and embodied PE. When benefits associated with recycling/reuse were included in the analysis according to Module D of EN 15978, the embodied GWP was reduced by 15.4% while the embodied PE was reduced by 6.22%. Compared with conventional construction systems, the CFS framing systems had much lower embodied GWP and PE.

Keywords: life cycle assessment; cold-formed steel buildings; Athena Impact Estimator; global warming potential; primary energy

1. Introduction

The total life cycle energy consumed by a building is classified into embodied energy and operational energy. Embodied energy is the total amount of non-renewable primary energy required for all direct and indirect processes related to the construction of the building, its maintenance and end-of-life while operational energy is defined as the energy utilized in the use stage of the building. Similarly, the embodied greenhouse gas (GHG) emissions are the embodied Carbon Dioxide equivalent (CO_2eq) of greenhouse gases (Carbon Dioxide (CO_2), Methane (NH_4), Nitric Oxide (N_2O) and other fluorinated gases), which are emitted over the life cycle of the building. The global warming potential (GWP) is defined by The Intergovernmental Panel on Climate Change (IPCC) [1] as a relative measure of how much a given mass of GHG is estimated to contribute to global warming over a time scale of 100 years.

The buildings and construction sector accounted for 39% of energy and process-related greenhouse gas (GHG) emissions in 2018, 11% of which resulted from manufacturing building materials and products such as steel, cement, and glass [2]. Embodied energy and GHG emissions, originating from building construction and civil engineering projects, account for about 20% of the World's energy consumption and GHG emissions [3]. The world emitted 33 Gigatons of CO_2eq in 2019 with an average share of 4.3 tons CO_2eq per capita [2]. As an example, at the national level, Egypt's economic growth and expanding urban population are contributing to fast rising GHG emissions. Its fossil fuel-based power and transport sectors are among the most carbon intensive [4]. Egypt emitted 310 million tons of CO_2eq GHG emissions in 2016 with a share of 3.29 tons CO_2eq per capita/year [5].

The increase in GHG emissions has so far caused a global warming of 1 °C above pre-industrial levels. Under current policies, expected global warming is expected to reach the range 3.1–3.7 °C above pre-industrial levels by 2050 since the world's building stock is forecast to double in size to house a global population of 11 billion. The United Nation's Conference of Parties adopted in 2015 the Paris Agreement to take all necessary measures to limit global warming to 1.5 °C above pre-industrial levels [6]. The Intergovernmental Panel on Climate Change (IPCC) stated that reaching that target would require rapid, far-reaching, and unprecedented changes in all aspects of society [1]. IPCC recommended that the "1.5 °C-consistent pathways require building GHG emissions to be reduced by 80–90% by 2050, new construction to be fossil-free and near-zero energy by 2020", and the need for "an increased rate of energy refurbishment of existing buildings to 5% per annum in Organisation for Economic Co-operation and Development (OECD) countries. An enhanced construction would influence 42% of final energy consumption, about 35% of greenhouse gas emissions, and more than 50% of all extracted materials [7].

Therefore, Societies have therefore begun in recent years to re-evaluate their built environment with the objective of achieving higher performance in terms of their compliance with the both the economic and environmental aspects of sustainability. In the early 1990s, many nations began to adopt plans to significantly reduce their emissions within 20–50 years [8]. Many building design guidelines and rating systems were introduced in America, such as LEED, the Net Zero Energy Building Certificate, and the Living Building Challenge. The building sector has seen a marked increase in energy-efficient buildings in the past decade. For example, between 2008 and 2010, the percentage of total buildings that were low-energy dwellings rose from 0.7 to 7.2% [9]. Many countries have introduced sustainable building rating systems to rate the performance of buildings and promote green economies. By March 2010, there were 382 registered building-rating tools for evaluating energy efficiency, renewable energy, and buildings' sustainability [10].

In 2015, the international community adopted a set of 17 goals as a part of a new global agenda for sustainable development [6]. Among these goals are: Goal 11- Building sustainable communities and Goal 12- Achieving sustainable consumption and production. In order to achieve these goals; the building construction industry must fully consider the importance of balancing the three pillars of sustainability: economic, environmental, and social constraints when considering material selection, building structural systems, and long-term function of the building. It has become essential to explore the latest construction technologies and create innovative affordable building systems which are flexible enough to suit local climate, site conditions, cultural and living habits, and spatial standards. Innovative construction solutions also should reduce or eliminate errors due to the lack of skilled personnel on the site, and ideally should be assembled with simple tools and be erectable with minimum machinery. The light (cold-formed) steel framing system (CFS), shown in Figure 1, has emerged as an innovative and cost-efficient solution, adhering to most of the criteria specified for new sustainable buildings. The basic building elements of CFS systems are cold-formed C or U sections that are fabricated off-site into panels and then transported to site ready for erection. CFS framing systems have proven to be a worthy alternative to traditional systems using reinforced concrete framing or structural steel framing. Potential advantages of such light steel framing systems include high strength-to-weight ratio, high degree of dimensional exactness of the members, high recycled content, and ease of construction [11,12]. These qualities have led CFS construction systems to be an efficient alternative to traditional construction systems. The structural design of CFS systems is covered in North America by AISI [13] and in Europe by EN 1993 [14].

Figure 1. CFS Framing System [15].

An increasing focus on improving the environmental performance of human activities has led to the rapid expansion in the number of techniques that are now available to assist with identifying and quantifying environmental impacts [8]. These techniques include assessment tools, simulation tools, checklists, and guidelines, ranging from the very simple to the much more complex, and rely on different levels of data and professional input. As a response to the limitations of many of the tools and techniques used for quantifying environmental impacts in the past, the use and development of life cycle assessment (LCA) is now seen to be of critical importance. LCA aims to minimize the limitations of past assessment methods and increase the range of assessment criteria and depth of analysis. Due to its universality of application, it is considered the only valid method by which to compare the environmental impacts resulting from the alternative building materials, products, components, and services that are used within the built environment. LCA is a technique for analyzing environmental performance of products or processes over their entire life cycle, including raw material extraction, manufacturing, use and end-of-life disposal and recycling [16,17]. There are two types of LCA [8]:

1. Base line LCA, when LCA is used to assess an individual product or project with the goal of identifying areas of potential improvement in their environmental performance,
2. Comparative LCA, when LCA is used to compare environmental impacts of several alternatives that perform the same function in order to select the alternative with the lowest environmental impact.

LCA is typically performed during design development to determine whether an alternative specification or scope of work is worthwhile. Ideally, this analysis should be carried out during the early stages of scheme design when decisions on the primary construction system are made [18]. At this stage it is unlikely that any detailed design work will have been undertaken beyond initial feasibility studies. Therefore, the analysis will be carried out using benchmark data and broad assessment of environmental impacts. Since the economic system does not fully account for external environmental effects, environmental resources may be used inefficiently. LCA is suited to complement economic information on buildings with information on their environmental impacts [3] and helps to take measures and action to increase the resource efficiency of buildings and construction.

Available studies on life cycle environmental analysis focus on traditional construction material and systems such as timber, reinforced concrete, and hot-rolled steel. Extensive reviews of life cycle assessment in the building industry are provided by Anand and Amor [19], Chau et al. [20], Geng et al. [21] and Nwodo and Anumbab [22].

EBC [3] presented a study of the assessment of embodied energy and CO_2eq for building construction that covered the present status of embodied energy and GHG emissions in addition to reviews of their calculation procedures and theoretical basis. Zeng and Chini [23] presented a review of research on embodied energy of buildings using bibliometric analysis of 398 papers published from 1996 to 2015. The review pointed out the major three research areas for embodied energy to be LCA, building design, and GHG emissions. Dixit [24] presented a literature review of life cycle embodied energy in residential buildings. The inconsistencies of reported embodied energy values pointed out a need to standardize the present assessment procedure of embodied energy calculations. De Wolf et al. [25] presented a review of current industry practice related to measuring embodied CO_2eq of buildings using multiple data sources to determine the difficulties in measuring and reducing embodied GHG emissions in practice. The paper pointed out the need for improved data quality and transparent LCA procedures. Chastas et al. [26] analyzed the results of 95 case studies to identify the range of embodied carbon emissions of residential buildings and concluded that the large scatter of results confirms a need for standardization in LCA methodology. Fenner et al. [27] presented a review of current procedures for calculating carbon footprint. They concluded that there was a need for a clear, accessible, and consistent procedure to assess the carbon emission from buildings. Rock et al. [28] analyzed more than 650 LCA case studies to investigate the global trends of life cycle GHG emissions. The analysis revealed an increase in relative and absolute contributions of embodied GHG emissions and emphasized the necessity to reduce GHG emissions by reducing both embodied and operational impacts. Birgisdottir et al. [29] presented the findings from a major five-year IEA research project which investigated the reduction of embodied energy and GHG emissions over the whole life of buildings. Annex 57 of the project titled "Evaluation of embodied energy and CO2eqfor building construction," collected and analyzed over 80 detailed quantitative and qualitative building case studies from the contributing countries. Simonen et al. [30] developed a database of building embodied carbon which contains over one thousand buildings. The study concluded that the initial embodied carbon of low-rise residential building's structure, foundation and enclosure is normally less than 500 kg CO_2eq/m^2. Gervasio et al. [31] proposed a framework for the quantification of benchmarks for the environmental impacts of buildings. Based on the developed framework, the life cycle GHG emissions is equal to 5–12 kg CO_2/m^2.yr while the total primary energy is equal to 68–186 MJ/m^2.yr. Rodrigues et al. [32] evaluated the embodied carbon and energy of an industrial building in Portugal. Their results showed an embodied carbon of 508.57 kg CO_2/m^2 and an embodied energy of 4908.68 MJ/m^2.

On the other-hand, there is an absence of detailed scientific research or case studies dealing with the potential environmental benefits of off-site construction associated with light steel CFS framed systems, particularly the reduced environmental impact resulting from the improved efficiency of material usage and waste reduction. The objective of the study is to calculate and quantify the life cycle environmental impacts of the CFS building construction system used in low and mid-rise residential and office buildings.

2. LCA Methodology

The general methodology for LCA in all sectors follows the four-stage framework recommended by ISO 14040 [16] and ISO 14044 [17]. The methodology consists of: (i) goals and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle analysis, and (iv) interpretation. The specific methodology for LCA in construction works is detailed in the European standard EN 15978 [33], which covers the environmental, economic, and social aspects of sustainability. Environmental assessment is performed according to a modular framework recommended by EN 15978 for LCA at the whole building level and by EN 15804 [34] for LCA at the product level. These standards introduced a modular concept for the definition of the system boundaries as shown in Figure 2. The potential environmental impacts over the building life cycle are allocated to the stage in which they occur thus enabling full transparency of the results. The information included in each module is as follows:

1. Product stage (Modules A1 to A3): includes the production of building materials from raw material supply until the gate of the factory.
2. Construction stage (Modules A4 and A5): includes transportation of building materials to the construction site and the construction process.
3. Use stage (Modules B1 to B7): includes all data related to use, repair, replacement, refurbishment, and operation use of energy and water.
4. End-of-life stage (Modules C1 to C4): includes data related to the building demolition/dismantling.
5. An additional module D which allocates the net benefits due to possible reuse or recycling of materials beyond building life cycle (BBL).

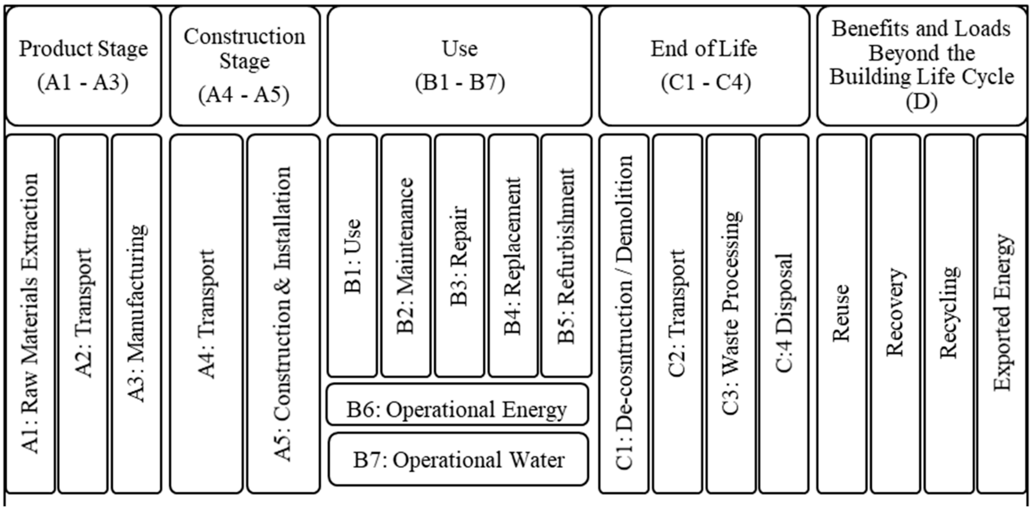

Figure 2. Modular LCA framework (adapted from [33]).

2.1. Goal and Scope

This phase defines purpose, objectives, functional and system boundary of the analysis. The goal of LCA in this research is a baseline life cycle analysis to calculate the environmental impacts of CFS building construction system and identify areas of potential improvements in the environmental performance. The scope of the study covers the whole building over its design life.

In order to compare LCA results over a much wider range of project types and geometry, the results are normalized with respect to some defined unit. EN15789 defines a "functional equivalent" to denote the technical characteristics and functionalities of the building that is being assessed. On the other hand, EN 15804 defines a "functional unit" to be used for the quantification of identified functions or performance characteristics of a product. The functional unit used in this research in the context of EN 15789 definition is one square meter of the building area per year. The system boundary follows the guidelines stated in EN 15978 from cradle to grave. The boundary is divided into production stage (A1 to A3), construction stage (A4 and A5), use stage (B1 to B7) and end-of-life stage (C1 to C4). An additional stage beyond the system boundary (Module D) is included to cover benefits due to possible reuse or recycling.

2.2. Life Cycle Inventory (LCI)

This phase consists of collecting all data related to inputs, processes, emissions, etc. of the whole life cycle:

1. In the production and construction phases, this involves raw material extraction, processing, manufacturing, and transportation to the site and building construction.
2. In the use phase, it involves the operating energy consumption associated with the building use, repair, and maintenance. The design life is usually assumed in the range of 40 to 60 years [35]. The present study is based on a design life of 50 years as suggested by the European design code EN 1990 [36].
3. In the end-of-life phase, it involves building demolition, recycling, and possible re-use. Different building components have different end of life scenarios according to their reuse/recycle potentials. These scenarios vary from complete demolition to reuse/resale of part or all the building.

The input to the analysis is the bill of building materials used for construction and the energy consumed during the use phase of the building. The input data related to the quantities of building materials used over the building life cycle can be quite intensive. Use of building information modeling (BIM) can facilitate the estimation of the required quantities for proposed design alternatives [37]. The workflow for estimating the quantities of building materials proceeds according to the following steps:

1. Develop 3D structural models for the building.
2. Utilize the structural analysis/design tool linked to the BIM software to perform the structural design considering the appropriate geometric, loading, material, and design code requirements.
3. Utilize the BIM 5D tool link to calculate the required material quantities.

In the use stage, the operating energy can be calculated using an energy simulation software such as eQuest [38]. The output of the analysis is a list containing the quantities of pollutants released to the environment and the amount of primary energy consumed.

The environmental burdens associated with all these processes require accurate data covering a wide spectrum of different production practices and geographical locations. Fortunately, there are many databases that can be used to estimate the environmental impacts of different processes. Examples are: ecoinvent [39] developed by the Swiss Center for life cycle inventories, Inventory for Carbon and Energy (ICE) [40] and Tool for Reduction and Assessment of Chemicals and other Environmental Impact (TRACI) [41] developed by the US Environmental Protection Agency EPA. In addition, most software tools used for life cycle assessment LCA such as SimaPro [42] and Athena [43] contain their own inventory data bases.

2.3. Life Cycle Assessment

In this phase the environmental impacts and input resources are quantified based on the inventory analysis. This phase consists of three mandatory elements [20]:

(a) Selection of impact categories: EN 15,978 recommends 25 indicators for LCA. Due to the complex nature of the many elements within the built environment, the impacts occurring throughout a building's life cycle cover a broad range of potential impact categories. Most of these are attributable to the manufacture and eventual disposal of materials, but also relate to the resources consumed during operation (such as energy and water. This complexity is one reason why building LCAs are often simplified by using a more streamlined LCA approach [8]. A streamlined LCA that chooses to assess only one environmental parameter may involve the consideration of only one or two different impact categories. Due to their relative importance, the most common indicators used in practice are the global warming potential (GWP) measured in weight of the equivalent emission of CO_2 and the amount of primary energy (PE) consumption.

(b) Assignment of LCI results (classification): which involves assigning the emissions, wastes and resources used to the chosen impact categories.

(c) Modeling category indicators (characterization).

The characterized results can then be normalized where necessary [8]. For a whole building assessment, this is often useful on a per unit of floor area basis to enable a comparison across building design options. The category indicator results for each impact category are divided by the total floor area of the building, which then facilitates the comparison of environmental impacts between buildings of varying size or characteristics. The results may be grouped according to the impact categories assessed or by life cycle stage. This latter grouping can be beneficial for identifying which life cycle stage of the building is responsible for the greatest environmental impacts so that environmental improvement strategies can be targeted towards these areas. Weighting factors can then be used to rank the importance of the different impact categories. This weighting will often be based on the particular circumstances surrounding the significance of different issues in the specific geographic location where these impacts are likely to occur.

There are several available computer programs that calculate the cradle-to-grave environmental impacts such as SimaPro [42], Athena Impact Estimator for Buildings [43]. In this research, the Athena Impact Estimator v5.04-0100 was used as detailed in section.

2.4. Sensitivity Analysis

LCA calculations described in the previous sections assume that all input values included in the assessment are known with certainty. These calculations are usually performed at early design stages and therefore use estimates of the input variables that are based on a minimum level of details. Accordingly, uncertainty will be associated with the output results. In order to help the decision makers benefit from LCA results, the uncertainty associated with the output results must be accounted for. This uncertainty can be tackled through replacing deterministic input variables with probabilistic ones and performing a sensitivity analysis [11]. Sensitivity analysis is a modeling technique best used to describe how much the model output results are affected by changes in the model input values. This analysis can also be very useful for the decision maker in deciding whether a more rigorous form of risk analysis is worth undertaking, and, if so, which forecasted input variables are to be investigated further. The present work, however, does not cover this aspect.

3. Application

3.1. Building Description

The presented LCA methodology was applied to an office building built at Cairo University in 2017. The outer dimensions of the building are 16,000 mm × 16,000 mm in plan. The building is used for administration occupancy and has five floors with height 3.5 m each as shown in Figure 3. Each floor hosts an average of four administrative offices in addition to the building services. A CFS construction system was selected over other conventional construction systems, e.g., reinforced concrete or structural steel, because of the following reasons:

1. CFS system has the least life cycle cost [11,12].
2. CFS system has a much shorter erection time due to off-site construction so that it shall has the least effect on the on-going activities on the university campus

The structural system of the building consists of the following elements:

1. Cold formed steel wall panels acting as bearing walls. Each panel is composed of CFS C-channel with dimensions 140 × 70 × 20 × 1.6 and spaced at 600 mm center to center. The panels are covered with 12 mm ferrocement boards mm from both sides.
2. Cold formed steel floor panels acting as floor beams. Each panel is composed of CFS C-joists with dimensions 250 × 70 × 200 × 3 mm and spaced at 600 mm center to center.
3. Flooring slab composed of 50 mm light reinforced concrete slab cast on metal deck.
4. Reinforced concrete strip footing foundations under all bearing walls.

Figure 3. University Building of Case Study.

The building is provided with the conventional building services in addition to a central HVAC system. All electromechanical services use electricity as an energy source except for heating which uses natural gas.

The goal of the present LCA is to evaluate the life cycle environmental impacts of the building. The scope is defined by the system boundary covering the entire life cycle of the building from cradle to grave (stages A to C according to EN 15978) in addition to possible benefits and loads from stage D due to reuse or recycling.

The scope of study covers only building materials related to the building structural members which include foundations, wall and floor framing, floor slabs and wall cladding. Remaining building elements such as floor tiles, painting, doors, and windows are excluded from the analysis because they are typically the same for all construction systems. Available studies [35] show that the environmental impacts associated with these components are negligible compared to the total life cycle impacts. The present LCA framework focuses on the structural components of the building and does not include the building materials related to finishes. Therefore, the environmental impacts associated with these components shall be neglected without any significant effect on the outcome of LCA.

3.2. *Bill of Material*

A 3D BIM model of the building was constructed based on the architectural design requirements. The structural model was then imported to a structural analysis and design software to perform the structural analysis and design. The resulting material quantities were extracted from the model as shown in Table 1. The units of measurement (UOM) in the table were specifically selected to match the definitions in the software. The energy consumption of the building was estimated using the energy simulation software eQUEST. The model incorporates building location, orientation, wall/floor construction, window properties, as well as HVAC systems, day-lighting and various energy control strategies. The output of the program consists of the annual consumption of electricity consumed annually as 144,632 Kwh and the amount of natural gas as 58.96 MMBtu.

Table 1. Bill of Building Materials.

Material Name	Quantity	UOM
Plain Concrete Foundation	30	m^3
Reinforced Concrete Foundation	66.24	m^3
Slab on Grade Concrete	38.4	m^3
Reinforcing bars	10.464	tons
Galvanized studs	46.08	tons
Galvanized decking	11.52	tons
Welded wire mesh	3.84	tons
Floor concrete	51.2	m^3
Galvanized decking	2.88	tons
Welded wire mesh	0.96	tons
Roof concrete	12.8	m^3
Fibercement siding	5700	m^2

3.3. LCA Using Athena Impact Estimator

The Athena Impact Estimator for Buildings (IE4B) is a software tool developed by the Athena Sustainable Materials Institute [43] for performing life cycle environmental assessment. The tool focuses on the LCA of building assemblies such as floors and walls or whole building systems and components. It incorporates a database that covers many of the commonly used building envelopes and structure types. The software includes 16 typical regions which cover a wide range of climate conditions. The user selects the region which best represents the location of the project. The database also covers transportation, on-site construction including a construction waste factor, and demolition processes. The methodology used in the software, see Figure 4, conforms to ISO 14040/14044 and EN15978.

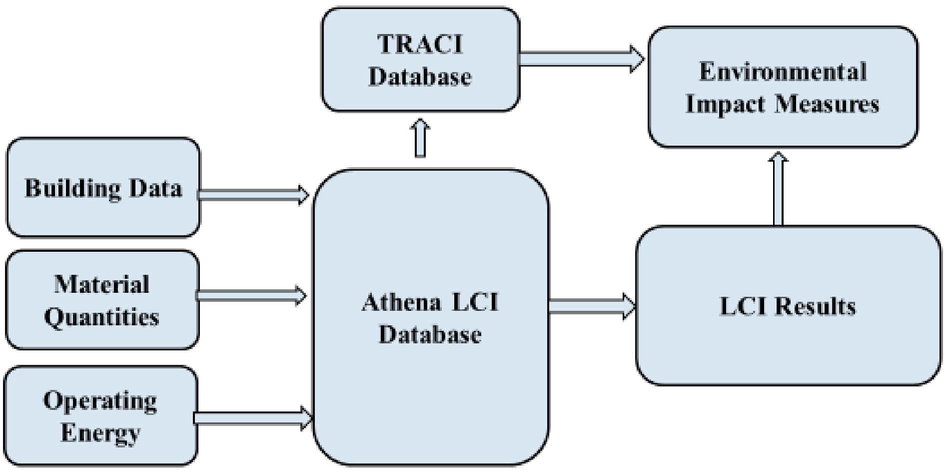

Figure 4. Life cycle methodology in Athena Impact Estimator for Buildings.

The Athena software calculates the environmental impacts associated with the following life cycle stages:

- Resource extraction (correspond to stages A1 and A2 in EN15978).
- Product manufacturing (correspond to stage A3 in EN15978).
- Construction of the building (correspond to stages A4 and A5 in EN15978). This stage covers the environmental impacts associated with:

  (i) Transportation of building material to construction site. The environmental impacts depend on the transportation trucks and the transportation distances.

  (ii) Construction Processes. Environmental impacts occur at site from the use of different construction equipment.

Average values accumulated in the database from similar existing projects are used for these items.

- Building occupancy and maintenance (correspond to stages B1 to B6 in EN15978). Environmental data related to stages B1 to B5 should be based on the expected maintenance and repair scenarios considering the assumed design life of each building. Building materials related to the structural components of the building do not usually need to be repaired or replaced over the design life of the building. On the other hand, environmental impacts related to stage B6 are calculated using an energy analysis software.
- Building demolition/deconstruction/materials at end-of-life disposition (disposal or transfer for recycling or reuse) (corresponds to stages C1 to C4 in EN15978). Detailed information on these processes do not usually exist at the design stage. Building elements have several end-of-life treatments depending on the possibilities of recycling or reuse of the building material and the construction system used. Steel members in CFS construction systems have very high potential for reuse/recycle while as other members made of concrete are mostly landfilled. Average estimates of environmental impacts related to this stage are used by The Athena software based on the analysis of demolition data of similar buildings.
- Beyond Building life impacts related to possible material recycling or reuse (correspond to Module D in EN 15978). Recycled steel is mostly reused in steel making plants to produce new steel.

Inputs associated with any of the processes defined in EN15978 and not specifically defined in Athena software can, however, be included in the analysis by specifying their contribution as "Extra Basic Materials".

IE4B calculates results for the following mid-point environmental measures in accordance with the USA EPA TRACI methodology: global warming potential (GWP), acidification potential, human health potential, ozone depletion potential, smog potential, eutrophication potential, primary and non-renewable energy consumption, and fossil fuel consumption.

The software does not estimate the operational energy associated with the use stage over the building life cycle. This input must be calculated externally using an energy simulation software such as eQuest. The software uses this data to calculate the associated primary energy and primary GWP. It should be noted that the energy simulation software calculates the delivered operating. IE4B converts this delivered energy into primary energy using suitable conversion factor which depend on the energy production method. Typical conversion factors are 3.4 for electricity and 1.4 for natural gas [8]. Finishes and electro-mechanical equipment are not included in the analysis.

The environmental profiles of building materials and operating energy used in IE4B typically reflect industry-average practice, i.e., not specific to any manufacturing plant or energy produced. Additionally, all LCI data in the software data base is specific to the region where the building is located. The benefits of possible recycling/reuse are reported "Beyond the Building Life Cycle (BBL)" in Module (D) of EN 15978.

The IE4B draws on its internal databases to perform the following calculations:

a. Scenario databases to quantify all life cycle material and energy use.
b. The Athena LCI Database to calculate a life cycle inventory.
c. The TRACI methodology to perform life cycle impact assessment.

4. LCA Results

The bill of materials and annual energy consumption were used as input to the Athena Impact Estimator. The design life was defined as 50 years. The software used this data to calculate the life cycle inventory using the built-in LCI database and then performed a life cycle impact assessment according to TRACI methodology. The results report includes the environmental impact indicators stated in Section 2.3. The indicators are calculated for the entire building and reported for a functional unit of one square meter of building area. The calculated environmental impact measures are classified by assembly group in Figure 5 and by life cycle stage in Figure 6.

Impact category	Unit	Foundations	Walls	Columns and Beams	Roofs	Floors	Total (A-D)
Global Warming Potential	**kg CO2 eq/m2**	**51.959**	**30.513**	**54.840**	**8.619**	**34.477**	**180.408**
Acidification Potential	kg SO2 eq/m2	0.202	0.233	0.354	0.042	0.168	0.999
HH Particulate	kg PM2.5 eq/m2	0.069	0.082	0.076	0.012	0.047	0.285
Eutrophication Potential	kg N eq/m2	0.045	0.011	0.016	0.005	0.022	0.100
Ozone Depletion Potential	kg CFC-11 eq/m2	0.000	0.000	0.000	0.000	0.000	0.000
Smog Potential	kg O3 eq/m2	4.277	2.842	7.505	0.866	3.466	18.956
Total Primary Energy	**GJ/m2**	**0.457**	**0.116**	**1.118**	**0.116**	**0.466**	**2.273**
Fossil Fuel Consumption	GJ/m2	0.386	0.115	0.747	0.086	0.343	1.677

Figure 5. Environmental Impact Measures by Assembly Group.

LCA Measures		PRODUCT (A1 to A3)	CONSTR. (A4 & A5)	USE (B2 to B6)	END OF LIFE (C1 to C4)	B B L (D)	TOTAL (A TO C)	TOTAL (A TO D)
Global Warming Potential	**kg CO2 eq/m2**	**190.192**	**16.815**	**4321.523**	**6.230**	**-32.829**	**4534.760**	**4501.931**
Acidification Potential	kg SO2 eq/m2	0.86	0.14	11.71	0.07	-0.08	12.79	12.71
HH Particulate	kg PM2.5 eq/m2	0.29	0.02	13.16	0.01	-0.03	13.47	13.44
Eutrophication Potential	kg N eq/m2	0.09	0.01	4.02	0.00	0.00	4.13	4.12
Ozone Depletion Potential	kg CFC-11 eq/m2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential	kg O3 eq/m2	13.37	3.99	93.86	2.35	-0.76	113.58	112.82
Total Primary Energy	**GJ/m2**	**2.137**	**0.195**	**74.649**	**0.092**	**-0.151**	**77.072**	**76.921**
Fossil Fuel Consumption	GJ/m2	1.700	0.188	50.347	0.091	-0.302	52.326	52.024

Figure 6. Environmental Impact Measures by Life Cycle Stage.

The two most commonly important environmental indicators are the Global Warming Potential and the Primary Energy. The analysis results related to these two indicators are discussed next.

5. Discussion of Results

5.1. Embodied Versus Operational Environmental Impacts

The embodied and operational impacts presented in Table 2 show an embodied GWP of 180.41 kg CO_2-eq/m^2. Eaton and Amato [44] performed a study of the embodied CO_2eq of steel, composite, reinforced and precast concrete office buildings, with results varying between 200 and 350 kg CO_2eq/m^2 for the structure only and between 600 and 850 k CO_2e/m^2 for the whole building. This comparison shows that the embodied GWP of CFS system associated with the whole building is much lower than similar traditional construction systems due to the low material masses used in CFS construction systems. Similarly, the embodied primary energy is equal to 2.27 GJ/m^2. Typical benchmark results for traditional building systems are: 5—11.6 GJ/m^2 reported by IEA [45] based on analyzing 80 buildings all over the world and 9 GJ/m^2 reported by Gervasio et al. [31] based on analyzing 76 buildings in Europe. Table 2 also shows that the percentages of embodied environmental impacts to the total environmental impacts is 4.7% for GWP and 3.1% for Primary Energy. Typical benchmark results are 6–20% reported by Chastas et al. [26] based on analysis of 90 residential buildings. This comparison shows that the relative environmental impacts of CFS construction systems are considerably lower than conventional construction systems.

Table 2. Embodied and Operational Environmental Impact Indicators (A-C).

	Global Warming Potential kg CO_2 eq/m^2	Primary Energy GJ/m^2
Embodied	180.41	2.27
Operational	4321.5	74.65
Total	4501.91	76.92

5.2. Life cycle Global Warming Potential

Life cycle global warming potential classified by the assembly group is shown in Figure 7 and classified by life cycle stage in Figure 8. The percentage contribution of each assembly group is shown in Figure 9. The building foundations have embodied GWP of 52 kg CO_2 eq/m^2 representing 29% of the total embodied GWP while as the CFS skeleton is responsible for 54.84 kg CO_2 eq/m^2 corresponding to 30% of the embodied GWP. The remaining part is shared among walls (17%), floors (19%), and roof (5%). On the other hand, classification by life cycle stage shows that the production stage is responsible for about 90% of the embodied GWP with a total of 190.192 kg CO_2 eq/m^2. The end of life has the least values of embodied GWP, with the construction stage averaging in values between production and end of life stages. When the benefits associated with recycling/reuse are included in the analysis, according to Module D of EN 15978, GWP is reduced by 32.83 kg CO_2 eq/m^2, equivalent to 15.4% of overall embodied GWP.

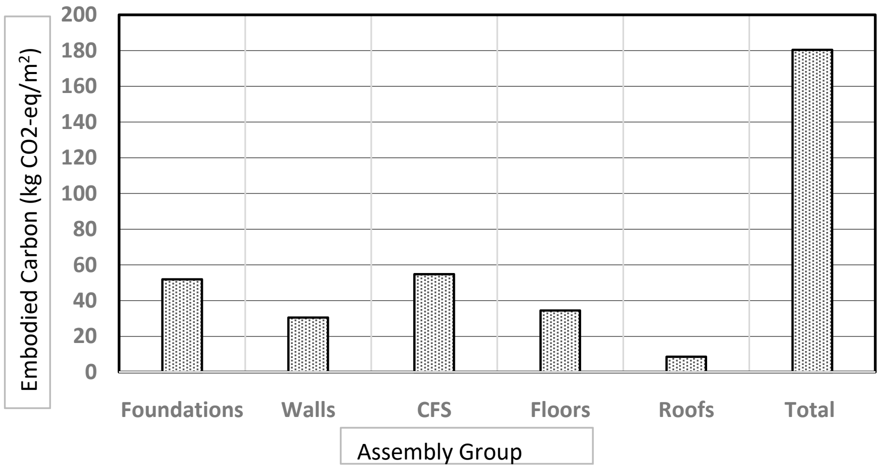

Figure 7. Life Cycle Global Warming Potential by Assembly Group.

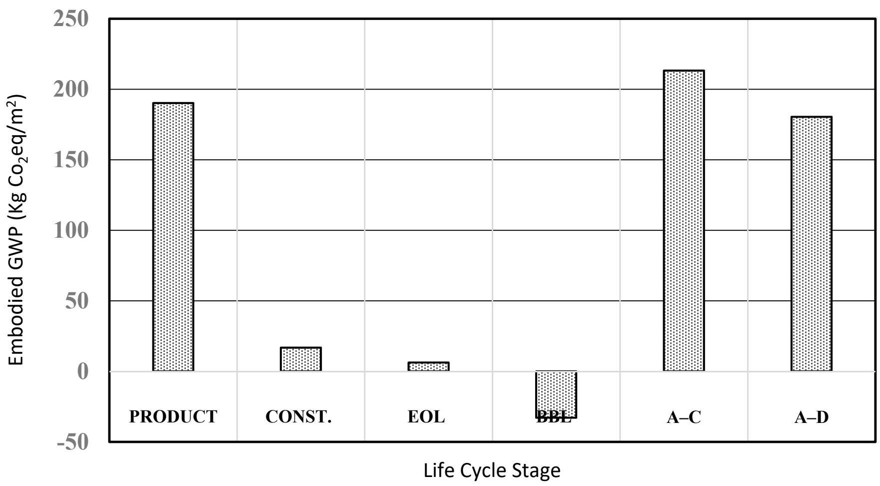

Figure 8. Life Cycle Global Warming Potential by Life Cycle Stage.

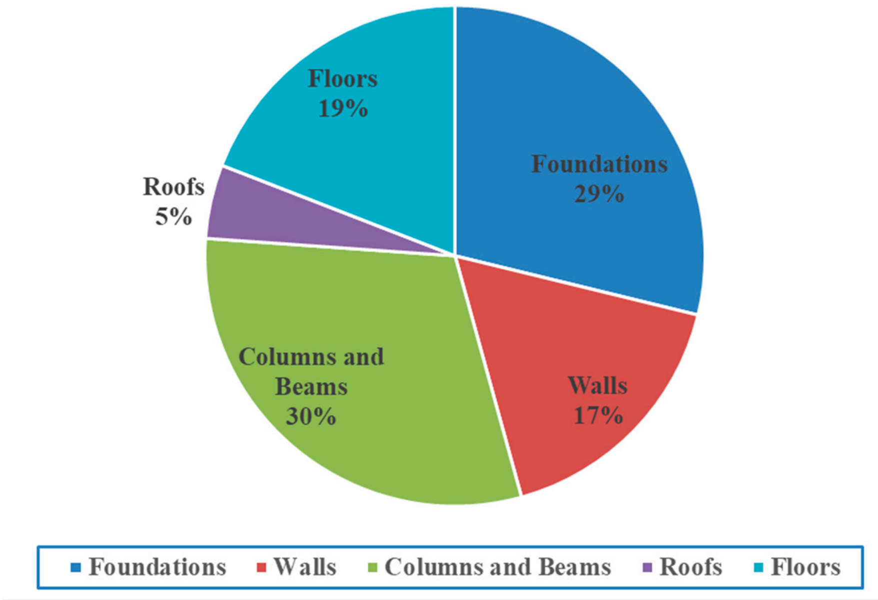

Figure 9. Percentage contribution of each assembly group in GWP.

5.3. Life Cycle Primary Energy

Life cycle embodied energy classified by assembly group is shown in Figure 10 and classified by life cycle stage in Figure 11. The percentage contribution of each assembly group is shown in Figure 12. CFS members have the highest embodied energy, reaching 49% of the total embodied energy, followed by footings and floors at 20% and 21%. The roof and walls have a smaller embodied energy percentage of 5%. On the other hand, classification by life cycle stage shows that the production stage is responsible for about 90% of the embodied energy with a total of 2.137 GJ/m^2 while as the end of life has the least values of primary energy, with the construction stage averaging in values between production and end of life stages. When the benefits associated with recycling/reuse are included in the analysis, according to Module D of EN 15978, the embodied primary energy is reduced by 0.150 GJ/m^2, equivalent to 6.22%.

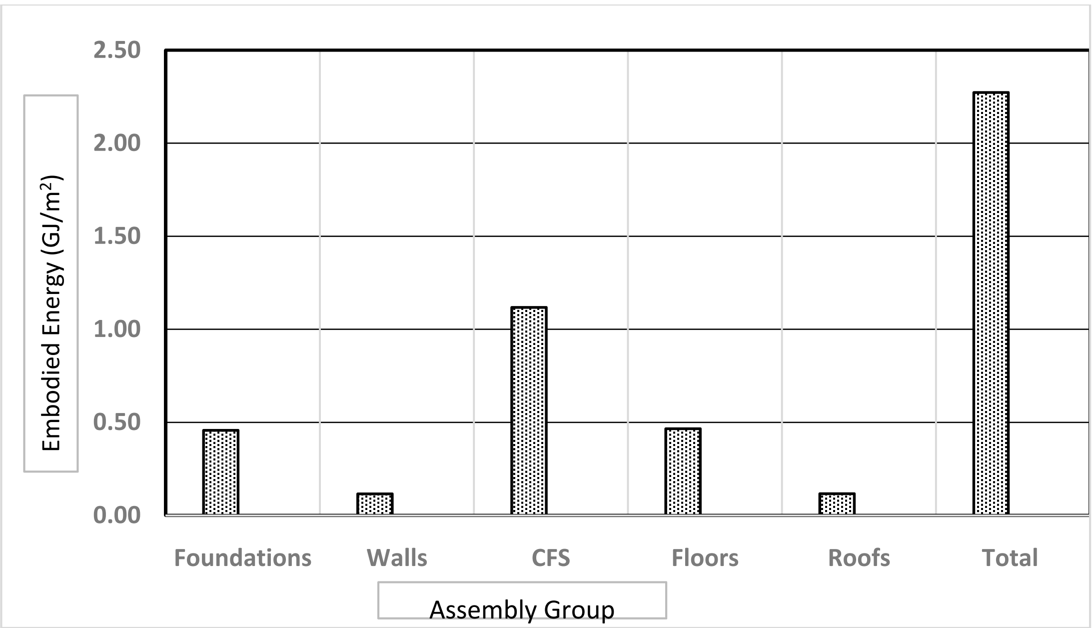

Figure 10. Life cycle embodied energy by assembly group.

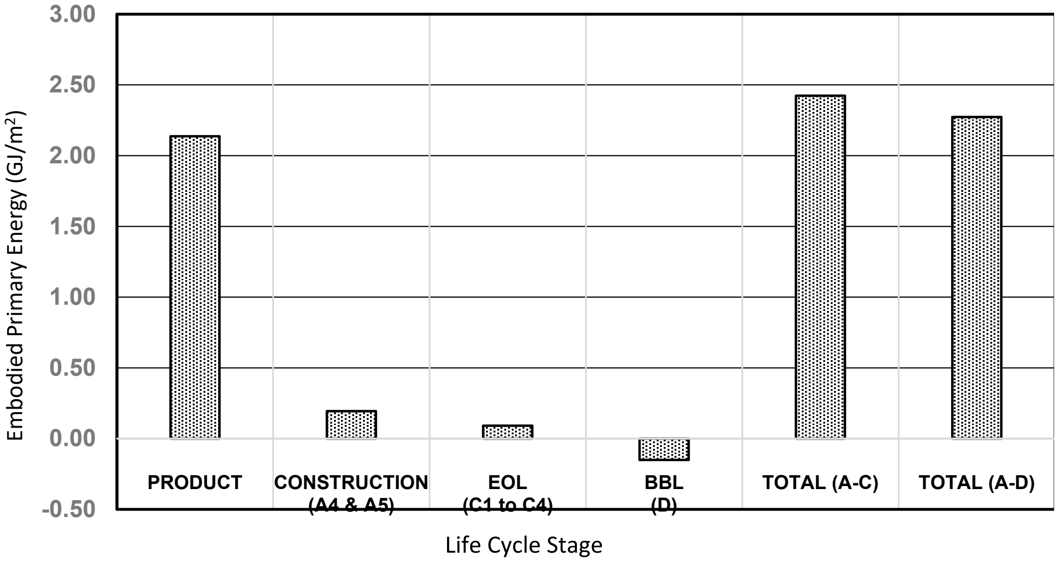

Figure 11. Life Cycle Embodied Energy by Life Cycle Stage.

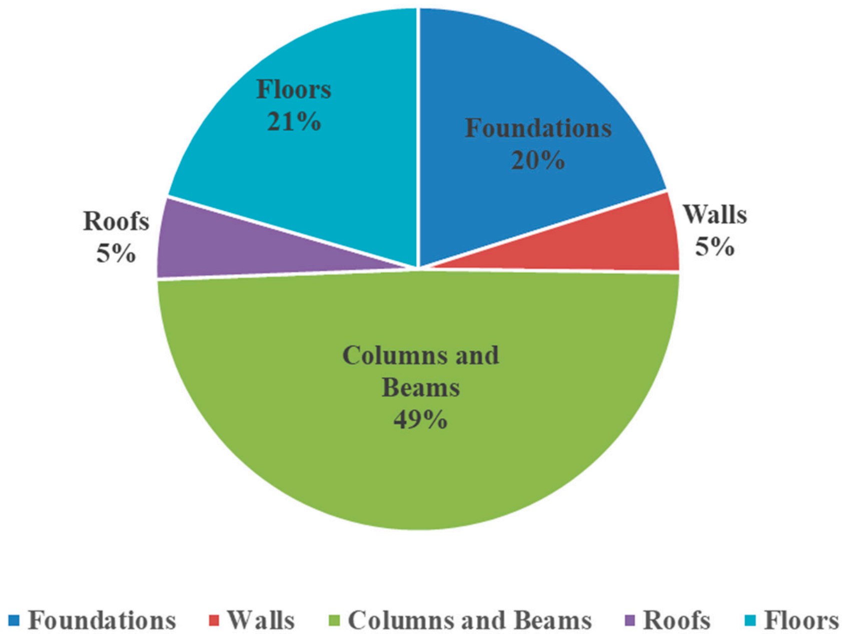

Figure 12. Percentage contribution of each assembly group in embodied energy.

6. Conclusions

In this research, the LCA methodology according to ISO 14040/ISO 14,044 was applied to calculate and quantify the environmental life cycle impact of CFS construction systems commonly used for low and mid-rise office and residential buildings. Using the building life cycle stages and system boundaries for LCA according to EN15978, the analysis considered the material and energy inputs from cradle to grave, based on a design life of 50 years and considering beyond boundary benefits (reuse/recycle). The following conclusions can be drawn from the results based on the studied case study.

1. The building foundations are responsible for 29% of the embodied GWP and 20% of the embodied energy while the CFS skeleton is responsible for 30% of the embodied GWP and 49% of the embodied energy.

2. The material production stage is responsible for 90% of the embodied GWP and embodied energy. When benefits associated with recycling/reuse are included in the analysis according to Module D of EN 15978, GWP is reduced by 15.4% while the embodied primary energy is reduced by 6.22%.
3. CFS framing systems have much lower embodied energy and global warming potential than conventional construction systems.

These results show that the construction system selection decisions taken early on in the design stage affect the expected environmental impacts of the building over its service life. Measuring and quantifying the embodied energy and carbon emissions can lead to a reduction of energy consumption and emissions, hopefully reaching the zero-energy and zero-emission state. The present work can be extended to include sensitivity analysis and other life cycle stages not considered in the present analysis.

Author Contributions: Conceptualization, M.A. and M.A.-H.; methodology, M.A.; software, M.A.; validation, M.A., M.A.-H.; formal analysis, M.A.; investigation, M.A.; resources, M.A.; data curation, M.A.; writing—original draft preparation, M.A.; writing—review and editing, M.A.; visualization, M.A.; supervision, M.A.; project administration, M.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. IPCC. Summary for Policymakers. In *Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways*; Masson-Delmotte, P., Zhai, H.O., Pörtner, D., Roberts, J., Skea, P.R., Shukla, A., Pirani, W., Moufouma-Okia, C., Péan, R., Pidcock, S., Eds.; World Meteorological Organization: Geneva, Switzerland, 2018; 32p.
2. GABC Global Alliance for Buildings and Construction. *International Energy Agency and the United Nations Environment Program: 2019 Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector*; United Nations Environment Program: Nairobi, Kenya, 2019.
3. EBC Evaluation of Embodied Energy and CO_2eq for Building Construction (Annex 57), Energy in Buildings and Communities Program, International Energy Agency. 2016. Available online: http://www.iea-ebc.org/Data/publications/EBC_Annex_57_Results_Overview.pdf (accessed on 6 December 2020.).
4. CIF Climate Investment Funds: Egypt. 2020. Available online: https://www-cif.climateinvestmentfunds.org/country/egypt. (accessed on 6 December 2020).
5. CAIT Total GHG Emissions Including Land-Use and Forestry, MENA. World Resources Institute. CAIT Climate Data Explorer. 2018. Available online: http://cait.wri.org (accessed on 18 May 2020).
6. United Nations. Transforming Our World: The 2030 Agenda for Sustainable Development. Available online: https://sustainabledevelopment.un.org/post2015/transformingourworld/publication (accessed on 6 December 2020).
7. European Comission. *Roadmap to a Resource Efficient Europe*; Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and the Committee of the Regions; European Comission: Brussels, Belgium, 2011.
8. Crawford, R. *Life Cycle Assessment in the Built Environment*; Spon Press: London, UK, 2011.
9. Langer, S.; Bekö, G.; Bloom, E.; Widheden, A.; Ekberg, L. Indoor air quality in passive and conventional new houses in Sweden. *Build. Environ.* **2015**, *93*, 92–100. [CrossRef]
10. Nguyen, B.K.; Altan, H. Tall-Building Projects Sustainability Indicator (TPSI): A New Design and Environmental Assessment Tool for Tall Buildings. *Buildings* **2012**, *2*, 43–62. [CrossRef]
11. AbouHamad, M.; Abu-Hamd, M. Framework for construction system selection based on life cycle cost and sustainability assessment. *J. Clean. Prod.* **2019**, *241*, 118397. [CrossRef]
12. Abouhamd, M.; Abu-Hamd, M. Life Cycle Cost Analysis of Light Steel Framed Buildings with Cement-Base Walls and Floors. In Proceedings of the Canadian Society of Civil Engineers Annual Conference, Montreal, Canada, 12–15 June 2019. paper CON-82.
13. AISI S100. *North American Standard for the Design of Cold-Formed Steel Members*; American Iron and Steel Institute: Washington, DC, USA, 2016.

14. EN 1993.2005. *Eurocode-Design of Steel Structures*; European Standard: Brussels, Belgium, 2005.
15. CERM-EX Cold-Formed Steel Structures. Available online: https://www.cerm-ex.com/cold-formed-steel-services (accessed on 9 December 2020).
16. ISO 14040: 2006. *Environmental Management—Life Cycle Assessment—Principles and Framework*; International Organization for Standardization (ISO): Geneva, Switzerland, 2006.
17. ISO 14044: 2006. *Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; International Organization for Standardization (ISO): Geneva, Switzerland, 2006.
18. Basbagill, J.; Flager, F.; Lepech, M.; Fischer, M. Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Build. Environ.* **2013**, *60*, 81–92. [CrossRef]
19. Anand, C.K.; Amor, B. Recent developments, future challenges, and new research directions in LCA of buildings: A critical review. *Renew. Sustain. Energy Rev.* **2017**, *67*, 408–416. [CrossRef]
20. Chau, C.; Leung, T.M.; Ng, N. A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. *Appl. Energy* **2015**, *143*, 395–413. [CrossRef]
21. Geng, S.; Wang, Y.; Zuo, J.; Zhou, Z.; Du, H.; Mao, G. Building life cycle assessment research: A review by bibliometric analysis. *Renew. Sustain. Energy Rev.* **2017**, *76*, 176–184. [CrossRef]
22. Nwodo, M.; Anumbab, C. A review of life cycle assessment of buildings using a systematic approach. *Build. Environ.* **2019**, *162*, 106290. [CrossRef]
23. Zeng, R.; Chini, A. A review of research on embodied energy of buildings using bibliometric analysis. *Energy Build.* **2017**, *155*, 172–184. [CrossRef]
24. Dixit, M.K. Life cycle embodied energy analysis of residential buildings: A review of literature to investigate embodied energy parameters. *Renew. Sustain. Energy Rev.* **2017**, *79*, 390–413. [CrossRef]
25. De Wolf, C.; Pomponi, F.; Moncaster, A. Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy Build.* **2017**, *140*, 68–80. [CrossRef]
26. Chastas, P.; Theodosiou, T.; Kontoleon, K.J.; Bikas, D. Normalizing and assessing carbon emissions in the building sector: A review on the embodied CO_2 emissions of residential buildings. *Build. Environ.* **2018**, *130*, 212–226. [CrossRef]
27. Fenner, A.E.; Kibert, C.J.; Woo, J.; Morque, S.; Razkenari, M.; Hakim, H.; Lu, X. The carbon footprint of buildings: A review of methodologies and applications. *Renew. Sustain. Energy Rev.* **2018**, *94*, 1142–1152. [CrossRef]
28. Röck, M.; Saade, M.R.M.; Balouktsi, M.; Rasmussen, F.N.; Birgisdottir, H.; Frischknecht, R.; Habert, G.; Lützkendorf, T.; Passer, A. Embodied GHG emissions of buildings—The hidden challenge for effective climate change mitigation. *Appl. Energy* **2020**, *258*, 114107. [CrossRef]
29. Birgisdottir, H.; Moncaster, A.; Wiberg, A.H.; Chae, C.; Yokoyama, K.; Balouktsi, M.; Seo, S.; Oka, T.; Lützkendorf, T.; Malmqvist, T. IEA EBC annex 57 'evaluation of embodied energy and CO2eq for building construction'. *Energy Build.* **2017**, *154*, 72–80. [CrossRef]
30. Simonen, K.; Rodriguez, B.; McDade, E.; Strain, L. Embodied Carbon Benchmark Study: LCA for Low Carbon Construction. Available online: http://hdl.handle.net/1773/38017 (accessed on 18 April 2020).
31. Gervasio, H.; Dimova, S. *Model for Life Cycle Assessment (LCA) of Buildings*; EUR 29123 EN; Publications Office of the European Union: Luxembourg, Luxembourg, 2018; ISBN 978-92-79-79973-0. Available online: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC110082/report_d1_online_final.pdf (accessed on 20 December 2020). [CrossRef]
32. Rodrigues, V.; Martins, A.A.; Nunes, M.I.; Quintas, A.; Mata, T.M.; Caetano, N.S. LCA of constructing an industrial building: Focus on embodied carbon and energy. *Energy Procedia* **2018**, *153*, 420–425. [CrossRef]
33. EN 15978:2011. *Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method*; European Standard: Brussels, Belgium, 2011.
34. EN, 2012. EN 15804:2012. *Sustainability of Construction Works—Environmental Product Declarations—Core Rules for Product Category of Construction Products*; European Standard: Brussels, Belgium, 2012.
35. Dixit, M.K. Life cycle recurrent embodied energy calculation of buildings: A review. *J. Clean. Prod.* **2019**, *209*, 731–754. [CrossRef]
36. EN 1990:2002. *Eurocode—Basis of Structural Design*; European Standard: Brussels, Belgium, 2002.
37. Abu-Hamd, M.; Atef, D.; Masoud, M. Application of 4D and 5D BIM in Cold Formed Steel Residential Buildings. In Proceedings of the 5th International Structural Specialty Conference, Canadian Society for Civil Engineering, London, ON, Canada, 8–11 June 2016. STR-862-1-10.
38. eQUEST, 2019, Energy Design Resources. Available online: http://www.doe2.com (accessed on 6 December 2020).

39. Ecoinvent. The Swiss Center for Life Cycle Inventory. Available online: https://www.ecoinvent.org (accessed on 6 December 2020).
40. Hammond, G.P.; Jones, C.I. Embodied Carbon: The inventory of Carbon and Energy (ICE). In *A BSRIA Guide—BG 10/2011*; Lowrie, F., Tse, P., Eds.; BSRIA Ltd.: Bracknell, UK, 2011.
41. TRACI. *Tool for the Reduction and Assessment of Chemicals and other Environmental Impacts*; US EPA: Washington, DC, USA, 2012.
42. PRé Consultants. SimaPro|The World's Leading LCA Software. Available online: https://simapro.com/ (accessed on 6 December 2020).
43. Athena Sustainable Materials Institute. Athena Impact Estimator for Buildings. Available online: http://www.athenasmi.org/ (accessed on 6 December 2020).
44. Eaton, K.; Amato, A. A comparative life cycle assessment of steel and concrete framed office buildings. *J. Constr. Steel Res.* **1998**, *46*, 1–3. [CrossRef]
45. IEA International Energy Agency. *Evaluation of Embodied Energy and CO_2 eq. for Building Construction (Annex 57)—Subtask 4: Case Studies and Recommendations for the Reduction of Embodied Energy and Embodied Greenhouse Gas Emissions from Buildings*; Institute for Building Environment and Energy Conservation: Tokyo, Japan, 2016.