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Demolishing or Renovating? Life Cycle Analysis in the Design Process for Building Renovation: The ProGETonE Case

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Abstract: It is well known that a large part of the existing European building stock needs to be renovated to increase structural and energy performance. Unfortunately, deep renovations come with high initial costs, and therefore, owners and real estate developers often prefer complete demolition and reconstruction. Both options depend on specific factors, and to select which option could be the closest to the optimal scenario, it is necessary to evaluate all environmental, social, and economic indicators. Life Cycle Analysis is of great significance to evaluate building sustainability, in particular through the comparison between different design alternatives. However, the life cycle impacts of the construction stage depend on selected materials and technologies that can be subject to change during the subsequent stages of the design process, i.e., moving from preliminary design to detailed design and execution plans. With the aim of understanding the role of LCA during the design process, the case study of "ProGETonE—Proactive Synergy of Integrated Efficient Technologies on Buildings' Envelopes" has been addressed, leading to the observation that the impacts, in particular the global warming potential (GWP), raised significantly. Building Information Modelling (BIM) helped the information sharing and management of this project, which consists of the deep renovation and architectural reshaping of an existing student residence through the construction of integrated façade systems.

Keywords: life cycle assessment; ProGETonE; deep renovation; BIM; designing process

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1. Introduction

The concept of sustainability was introduced in 1972 at the first United Nations (UN) conference on the environment, but only in 1987 was the goal of sustainable development clearly defined in the Brundtland report [1], which, after the UN conference on environment and development in 1992, became the new paradigm of development itself [2]. Sustainability in the construction sector is the subject of particular attention, as it is a sector to which a high share of environmental impacts can be attributed. Building projects involve high consumption of raw materials, energy consumption, pollution emissions, and waste production in the construction phase, the use and maintenance phase, and the demolition or renovation phase. The UN Agenda for Sustainable Development to 2030 "Sustainable Development Goals—SDGs" include in goal no. 11 "Make cities and human settlement inclusive, safe, resilient and sustainable" the pursuit of the sustainability of human settlements [3]. These settlements are also responsible for a large proportion of land use, and consequently, there is a need for the transition to a more sustainable impact while safeguarding the objectives that Europe and the UN have set themselves to protect environmental heritage and the landscape [3].

The 2021 report of the United Nations Environment Programme points to some extremely significant data [4]. The construction sector is currently responsible for the consumption of around 40% of the primary energy available worldwide and at the same time is responsible for near 40% of greenhouse gas emissions, contributing massively to climate change [5]. In addition to this, the structural technologies based on cement conglomerate commonly used for new buildings result in a high percentage of the total impact of construction on the environment. It is worth considering that cement industry in the world produces about 400 million tons of materials every year that are added to the extraction of aggregates, sand, and gravel, which amounts to 40 to 50 billion tons per year. These values have tripled in the last 10 years due to the increase in urbanization, not to mention that 1/3 of the world's drinking water and 1/4 of the world's timber are destined for construction. Even during the demolition and disposal phase, construction activity's transformation of territory confirms construction as one of the industries that cause the greatest damage to the environment; in fact, it produces one-fourth of the global waste destined for landfills and incinerators (Figure 1). Finally, one of the high-impact elements of the regeneration of a building's heritage through recovery and renovation is that of the production, right from the early stages of the construction work, of a large amount of waste that must then be disposed of and/or, if possible, reused [6,7].

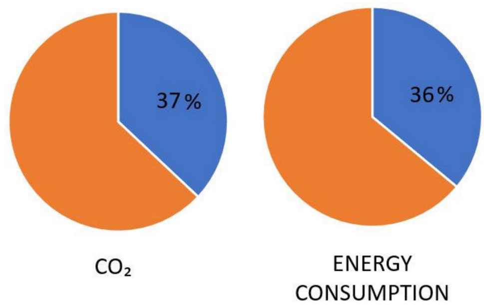


Figure 1. Share of construction-industry-related sustainability indicators (units in percentage): CO_2 emissions andenergy consumption. Blue sectors show the share of buildings construction industry, orange ones other industries (adapted with permission from Ref. [4] 2021, UNEP). Blue: construction; orange: other industries.

In addition to this, it must be considered that the high average age of buildings in most European countries indicates the need to increase structural safety, especially with respect to seismic hazard. Actually, due to the evolution of technical regulations, about 60% of existing buildings in Italy do not meet current seismic standards [8]. All these buildings are potentially vulnerable to earthquakes, unless their structure is adapted to meet current safety requirements. The application of seismic construction standards has a great impact on building design and construction principles.

Therefore, a deep-renovation project for an existing building has two different tasks: to increase the performance of the building structure following a seismic event and to increase the energy performance of the building envelope and of the Mechanical, Electrical, and Plumbing (MEP) services. There is no established common definition of deep renovation, either regionally or internationally, nor is there a clear distinction between the terms "deep renovation" and "deep retrofit". Experts found that renovation was the term most commonly used in the EU, while retrofit was the term used in the US. In general, deep energy renovation is a term for a renovation that captures the full economic energy efficiency potential of the improvement project, with a main focus on the building shell leading to very high energy performance. Energy savings of renovated buildings are typically 75% or more than the state of the existing buildings before the renovation [9]. By analogy, the same order of magnitude can be applied to the seismic vulnerability of structures.

The ProGETonE pilot project addresses an innovative building renovation strategy. Deep renovation of an existing building has been pursued through the construction of an exoskeleton (GET system), which guarantees high energy efficiency and improved structural safety. This innovative design strategy was developed as the foundation of a European Union H2020 research project [6,10]. ProGETonE stands for Proactive Synergy of Integrated Efficient Technologies on Buildings' Envelopes, and it has the goal of providing the market with an innovative external structure to be created to increase the performance of a building in terms of energy requirements, seismic safety, and social and economic sustainability. Sustainability of deep-renovation projects versus demolition and new construction is addressed through this project. Moreover, the present research work focuses on Life Cycle Assessment (LCA), analyzing two subsequent stages of design: the Concept Design Stage (CDS) and Technical Design Stage (TDS).

LCA methods use a rational approach that changes and evolves by acquiring knowledge of the technologies employed. The LCA methodology is codified by the International Standard ISO 14040:2006 [11] and is defined as follows: "Objective environmental assessment technique for the qualification of the environmental impacts of a product or process during all phases of the life cycle, through the systematic measurement of all physical exchanges to and from the environmental system". The innovative concept of the LCA approach is that any hypothesis of change and/or improvement to the system under study can be evaluated totally, addressing the impact of the entire life cycle on the product or process.

2. Literature Review and ProGETonE Case Study

Construction operators are becoming more and more involved in the debate concerning the strategic choice between demolishing and rebuilding or alternatively renovating and recovering existing residential buildings. These two strategic alternatives aimed at urban regeneration at the building scale have been considered for decades, nationally and internationally [12].

It is well known that the age of the existing building stock in Europe, combined with the energy conservation and zero land consumption objectives pursued by sustainability strategies, will increase the need for deep-renovation building projects. In addition to this, Italy and the majority of southern Europe countries and the Netherlands are subject to frequent and strong seismic activity (both tectonic and induced earthquakes), which makes predictable a very high number of future construction rehabilitation projects to improve structural safety [5].

The issue at stake is whether the demolition process and the consequent reconstruction of a building, creating a new system with increased structural and energy performance levels, are more sustainable in terms of environmental impact than the renovation and performance improvement processes for the same building. The scientific evidence in favor of one or the other approach is still under discussion and indeed still affected by uncertainty [12], as it is linked to constraints and conditions within the specific context.

Evidently, deep renovation of existing buildings should only be compared with demolition and reconstruction if considering the same final level of structural and energy standards accomplished. The correlation between the two alternatives should be therefore be based on social-economic aspects, comprehensive environmental impacts, and specific benefits.

Back in 1998, the economic and financial objectives considered by Ohemeng [8] were derived from a careful analysis of the needs of users and were already supported by a decision-making model based on value analysis. Intervention hypotheses were compared, and in the case of commercial private construction, demolition and reconstruction were recommended as the best choice. One year later, a technical report of the US Army Corps of Engineers [13] fully addressed the issue of reuse and recycling of materials in demolition and reconstruction processes, introducing a cost–benefit approach with the aim of environmental sustainability. The methodology is still current and highlights that actual costs may vary in relation to several factors: size and type of work; possibility of developing reuse based on operational constraints due to the site; the capacity and availability of recycling plants; the construction phases and the work schedule; tax and economic charges; the experience of the personnel employed for demolition; and the micro-urban context. The environmental impact can be assessed with an estimation approach based on an environmental scoring matrix. A few years later, Power [12] compared the arguments in favor of demolition and those in favor of redevelopment, indicating the following benefits of the recovery of the existing building stock: maintenance of the ownership structure, image benefits for the built context, speed of intervention, less inconvenience for residents, and in general, benefits for the community and the socio-economic context. Because of this, building redevelopment should be encouraged by state incentives, in particular addressing energy efficiency of buildings.

In recent years, Guardigli, Gulli, and Mazzoli [14] analyzed the same topic in relation to the Italian post-war residential building stock with a global cost approach, indicating the need for a context-based positive environment for the success of renovation projects. The fundamental study by Fiore, Donnarumma, and Sicignano [15] indicates that there are multiple variables to be considered, such as the ones concerning environmental sustainability, structural safety, durability, service life, and economic aspects, and it proposes a multi-criteria evaluation that uses the Analytic Hierarchy Process method [16]. Alba-Rodriguez et al. [17] consider the economic and environmental impacts of rehabilitation versus new construction projects for a damaged existing building in Spain, and overturn the theses of many previous authors, indicating that the repair and retrofit work often has a lower impact. To support this hypothesis, Guardigli, Bragadin, Ferrante, and Gulli [18,19] put renovation projects into a life-cycle-planning perspective, analyzing the various potential design alternatives needed to upgrade energy and structural performances of residential buildings and suggesting a new connected external structure (GET system) with energy and seismic functions as a potential solution. Artino, Caponetto, Evola, Margani, and Marino [20] propose a decision-making analysis tool for the seismic and energy renovation of reinforced concrete structures. This holistic approach takes into account the existing energy and structural performance, the timing and costs of construction, the environmental impact, and the disturbance to the occupants.

However, green building design decisions can be mainly driven by energy efficiency rating and carbon emissions accounting [21]. Thibodeau, Bataille, and Sie [22] indicate that for building renovation projects, LCA methodologies provide most building environmental assessment information. Ismaeel and Ali [23] address the environmental assessment of deep-renovation projects for historic buildings, considering the "Richordi Berchet" pilot study and comparing green building rating systems such as the Leadership in Energy and Environmental Design (LEED) system and environmental assessment methodologies such as LCA. Costantino, Benedetti, and Gulli [24] address the issue of circular economy in the construction sector by applying the paradigm of rebuilding to regenerate urban suburbs, using the digital twin strategy as a decision-making tool. Therefore, the literature review indicates that environmental rating systems and LCA can certainly play an important role in guiding building renovation strategies. There is, in fact, a research gap in the sustainability comparison between demolishing and reconstruction versus deep renovation because of a lack of understanding of different and potential impacts of both regeneration options. The evaluation of the initial impacts and service life impacts is of capital importance, but the sustainability assessment can yield different outputs depending on the specific case. Therefore, LCA tools and methods can help designers to model the impacts of different design alternatives to better address sustainability goals. As the modelling of the building and its life cycle impact is needed, the digitalization of the building design process with the Building Information Modelling strategy provides the potential for LCA understanding in the different stages of the design process [25]. Different stages of the design process are defined differently in different national contexts. The International Energy Agency provides a joint model for the designing phases of a building [26], splitting the process into nine stages. The Royal Institute of British Architects (RIBA), instead, indicates eight stages [27], even in countries where there is no formal process for building design. The stages of the RIBA 2020 plan of work are the following: strategy definition; preparation and briefing; concept design; spatial coordination; technical design; manufacturing and construction; handover; and use. Previously, concerning Building Information Modelling (BIM), the level of definition for a building project was included in the PAS 1192-2:2013 standard for BIM good practice [28], thus defining a very similar BIM-oriented plan of work: brief, concept, definition, design, build and commission, handover and closeout, and operation.

Because there is a distinction between the tools used by designers and planners during the early design stages and those used during the detailed design stages, two main steps can be identified: the early design (Concept Design) and the detailed design (Technical Design) [29]. Early design sketches and preliminary evaluation of building technology lead to preliminary LCA that can be very different from the one performed in the detailed design stages, often including Building Information Modelling (BIM) tools that lead to much more detailed LCA and Life Cycle Cost (LCC) analysis. Concerning BIM dimensions, the RICS International BIM implementation guide [30] addresses BIM-based sustainability analysis (6D BIM) both in the Concept Design Stage (CDS) and in the detailed Technical Design Stage (TDS).

The ProGETonE pilot project is of paramount importance because it presents a deep-renovation method that addresses most of the needed requirements for the building regeneration process [31], and the life cycle approach is one of the most powerful assessment processes for building sustainability. Different LCAs are performed in different stages of the building design process, because of the availability of data and information concerning the designed object. A research gap between the LCA estimates in CDS and TDS has been found. The research work in this study aims to evaluate and compare the differences in the LCA estimates performed in CDS and TDS, for the specific and innovative case study of ProGETonE.

Specifically, the case study in question is an extension project for a building dating back to the 1980s, used as a student residence and located in the Zografou district of Athens (Figure 2).

Figure 2. The building in Athens before the renovation project.

The original structure is composed of a reinforced concrete frame, while the enclosure is composed of hollow bricks without thermal insulation and aluminum and single-glass wood frames, therefore having low energy efficiency. The building's deep-renovation project includes a new steel structure next to the existing one (exoskeleton) and intervenes in particular in the part of the structure facing north, creating a buffer layer within which the vertical connections on the aforementioned façade are arranged, with two extensions that wrap for a short distance the long sides of the building, hosting the extensions of the rooms. The interventions are designed to increase the resistance of the building as a whole and secondarily to locally reduce the remaining vulnerabilities, minimizing or avoiding uncomfortable and extremely invasive solutions if applied extensively. In addition to this, the exoskeleton provides space for housing new and more sustainable air climatization systems, photovoltaic panels, and external thermal insulation to improve the energy efficiency

(Figure 3). In doing so, the ProGETonE program tries to follow a holistic approach with the least possible increase in environmental impact. The added economic value of the building derives from the augmented usable area.

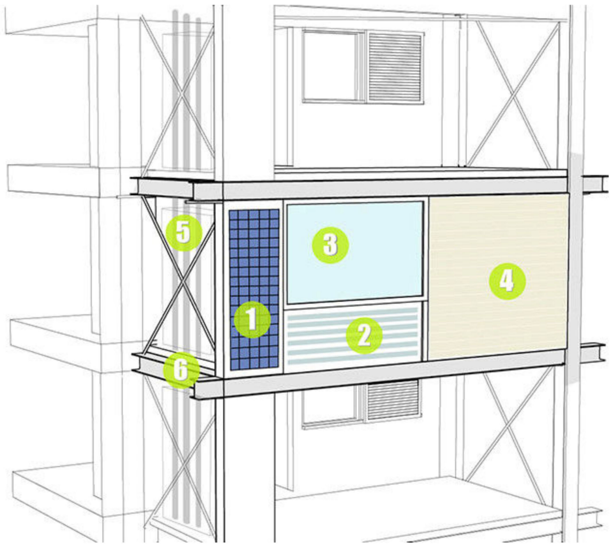


Figure 3. Exoskeleton (GET system) layout per housing unit during CDS: 1. Photovoltaic surface; 2. Opaque envelope; 3. Transparent envelope; 4. Flexible façade system; 5. Housing system installation; 6. Main supporting structure.

3. Methodology

The study started with trying to understand if renovation was a good choice, compared to demolition. Then, following the deep-renovation solution, design alternatives were presented in Concept Design Stage (CDS) and Technical Design Stage (TDS), in order to quantify the impacts of the project and possibly select the most sustainable solutions.

3.1. Stages of the BIM-Based Building Design Process and LCA

With the purpose of focusing on the LCA estimates, the design process was simplified in two different stages, the Concept Design Stage (CDS) and the Technical Design Stage (TDS) (Figure 4). CDS includes the following stages of the RIBA plan of work: strategic definition, preparation and briefing, and concept design.

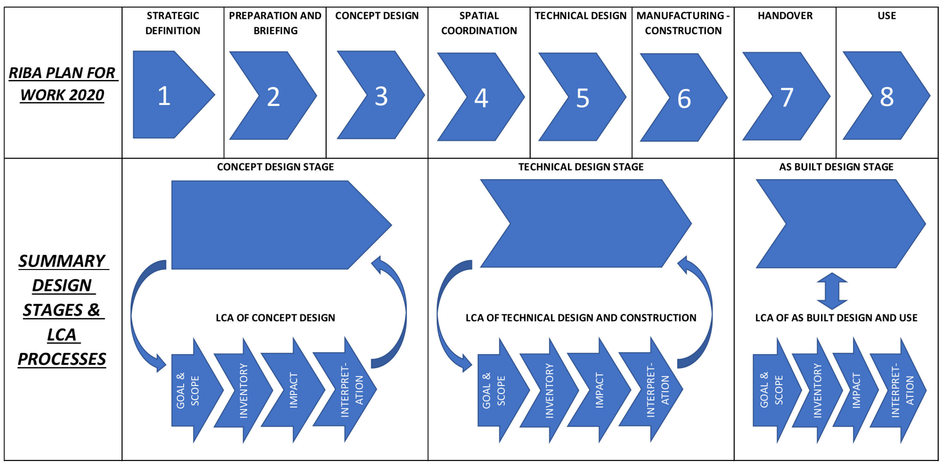


Figure 4. Sequence of design stages of the designing process from RIBA 2020 Plan of work [27] and comparison with summary design stages and LCA estimates.

TDS, instead, includes the following: spatial coordination, technical design, and some parts of the manufacturing and construction stage. The as-built stage was not considered, because construction is not completed yet.

LCA results depend on many factors, particularly on materials, building components, their production, and their transportation to site. A Bill of Quantities is the primary dataset needed for LCA inventory.

Therefore, for the purposes of LCA interpretation, different stages bring different results. In CDS, there can be different information delivered to the LCA. Continuing to follow the RIBA plan of work, concerning the delivery of process information, it is possible to assume that CDS includes the following information: client requirements, business case, project brief, feasibility studies, site information, project budget, project program, procurement strategy, responsibility matrix, information requirements. All these contents are very important for the delivery of the following design stage, but focusing in particular on LCA, two of them are of capital importance: feasibility studies and project budget. Feasibility studies, in fact, include the evaluation of different design alternatives, such as, for instance, the use of different materials and components for the building envelope and structure. From this standpoint, the structure can be made of different materials, with various embodied energies and impact potentials. Because the building structure is significantly massive and LCA impacts depend on mass quantities, the evaluation of different design structural alternatives through LCA plays a strategic role.

TDS provides additional information. The information content of this stage includes the following: project brief updating (or derogations), project strategies definition, outline specification, and cost plan. The following executive design information or construction information is delivered: planning application, manufacturing information, construction information, and final specifications, including building regulation applications. Even in this case, two different sets of design documentation are of capital importance: specifications and cost plans. Technical specifications include material properties, certifications and documentation requirements of each building component, and product or semi-finished product of the designed building system. These two sets of documentation are of capital importance for the LCA estimates. In fact, product specifications and quantities of products embodied in the building create the environmental impact and LCA of the building systems.

The research work in this paper focuses on the different outputs of the LCA estimates performed in CDS and TDS (Figure 4). Cost plan, Bill of Quantities, product specifications, and design alternatives for the structure of the ProGETonE building renovation project are considered, and the resulting LCA estimate is evaluated.

The building components defined during CDS were derived from the preliminary drawings of the research proposal (Figure 3), while TDS included BIM modeling, with the aim of addressing 6D BIM dimension, i.e., sustainability [30] (Figures 5 and 6).

The components of the execution phase of the project were modeled with Autodesk Revit® 2020 v. 25.0.3.0 BIM software, and 5 revit files were created that make up the overall project:

a. Site—topographical site;
b. Main Str—existing structural components;
c. Main Arc—existing architectural components;
d. GET Str—new ProGETonE structural components;
e. GET Arc—new ProGETonE architectural components.

Using the “Link Revit” command located in the “Insert” section of the Autodesk Revit ribbon, all the files were imported into a single model in order to have an overall picture of the added parts and the existing structure. During the modeling phase, it was necessary to ensure that all the files were positioned in the same way without any insertion error and that the elements contained an adequate amount of information in order to be recognized even outside the Revit environment.

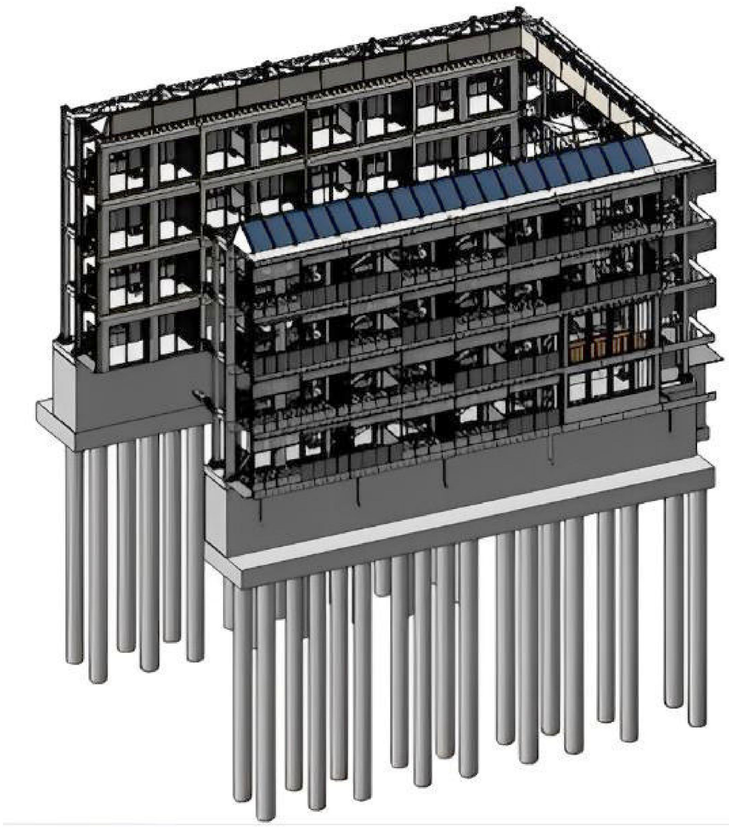


Figure 5. BIM model of the GET system during TDS.

Figure 6. BIM model of the whole renovated building, technical design stage.

In the BIM model, all parts and entities were categorized into "families" and subcategories. In Table 1, the major families included in the parametric model are presented. Each of these families unfolds into further subcategories: for example, in "Structural Foundations" we find the subsets "Curb", "Screed", "T-flange", "H flange", "Concrete pillar", and "Stalls", while the "Doors" family is divided into "Double internal door", "Single internal door", "French window", "Sliding door", and "Single leaf door" (Table 1) and so on.

Table 1. BIM families of the parametric model of the student residence building.

Families	Families	Families
Special Equipment	Walls	Inclined ramps
Structural Links	Curtain Panels	Railings
Ductwork	Walkaways	Stairs
Suspended ceilings	Floors	Piping systems
Detail Elements	Doors	Structural beam system
Structural Foundations	Steel profiles	Roofs
Generic Templates	Fittings	Protective pipes

The different categories of building objects for the project create a product breakdown structure that enables creating a quantity survey and a cost plan, including a detailed Bill of Quantities.

The interoperability of softwares allowed a more immediate exchange of information between different designing tools. As for the case study, the parametric model was exported to IFC and then inserted into a third-party software for the preparation of the LCA evaluation.

3.2. The LCA Evaluation in Concept Design and Technical Design

Because the design stage is of paramount importance in a building construction project and the LCA estimate can be performed to indicate the best design alternatives, the structure of the LCA methodology as proposed by ISO 14040 was applied in CDS and in TDS. The LCA approach is divided into 4 phases: a. definition of the objective and scope (Global and Scope Definition); b. Inventory analysis (Life Cycle Analysis, LCI), c. Life Cycle Impact Assessment (LCIA); d. Life Cycle Interpretation [11].

As mentioned before, a preliminary LCA was performed during CDS to establish the convenience of renovation in relation to demolition and reconstruction. Subsequently, the objective was to understand the best design alternatives to reduce the environmental impact (Figure 7).

The scope of the performed assessment was cradle to grave. For the specific studies per product or element, the operational phase and part of the deconstruction were not included, because data were depending on other building components and it was not possible to disaggregate them. The operational phase was limited to the whole-building approach and the Photovoltaic (PV) systems. The selected impact assessment was the method ReCiPe 1.11 (December 2014) Midpoint Hierarchist, even if the focus has been put on the global warming potential category (GWP) [32].

According to ISO 14040:2006, the scope of the LCA analysis must include the product system(s), functional unit, system boundaries, selected impact categories to be taken into account, and the final impact assessment methodology and interpretation method. The definition of the boundaries of the system under analysis is an operation that depends on the objective of the study itself and influences its results, as changing system boundaries inevitably imply changing results. The functional unit identifies the qualitative and quantitative aspects of the product, service, or function on which to base the analysis. It is the reference unit of measurement for all incoming and outgoing data and is intended to provide a reference to which to link the outgoing and incoming flows. For the ProGETonE case study, the functional unit was the exoskeleton (or GET system); all the impacts were referred to 1 m^2 net usable area of exoskeleton (Figure 7).

Inventory analysis consists of the collection and quantification of incoming and outgoing flows for a given product system and the organization of this data according to an analog model of the entire life cycle of the system. The objective of this phase is to calculate all the necessary raw materials and the estimation of consumption in terms of energy, soil, and water throughout the life cycle of the system. All data refer to the functional unit adopted.

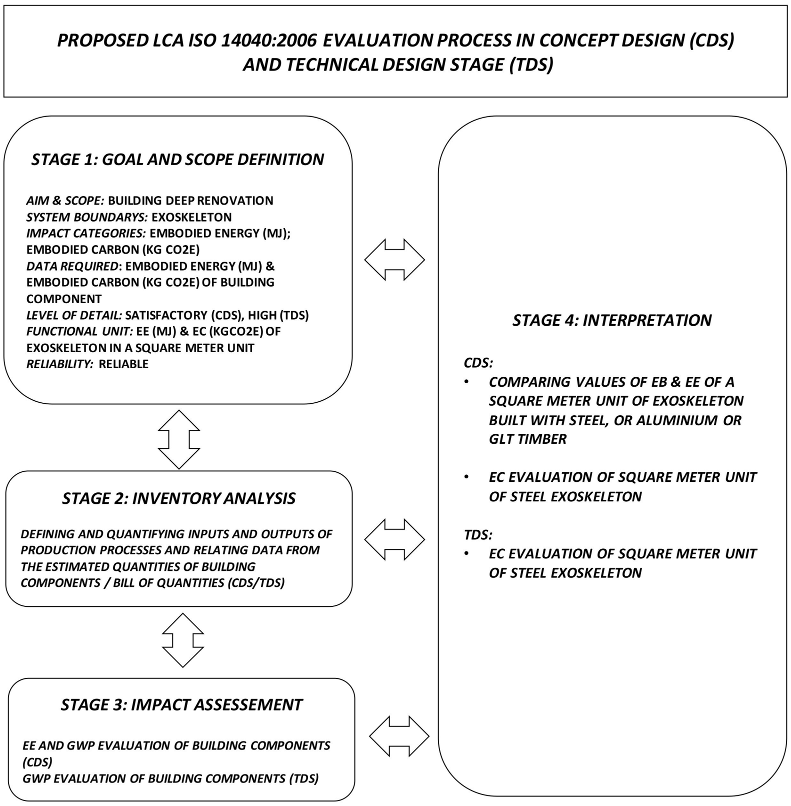


Figure 7. Proposed ISO 14040:2016 [11] evaluation process in CDS and TDS.

For the preliminary analysis in CDS, the inventories were built at a higher level by an Excel file [18] and a more detailed level through the openLCA® software by including datasets from ecoinvent database. For most of the materials, the inventory analyses of building components were built in this stage, with literature data [33] for the parametric LCA evaluation of the GET system and with Ecoinvent database for the complete modelling [19,32]. When a material or its equivalent was inexistent in this database, the information was retrieved from scientific papers. In the TDS, the inventory analysis of building components was performed with the OneClick LCA database, using the Greek dataset. Data quality was considered inside the admissible limits for the different evaluations. In the CDS stage, it was just a comparison between different building strategies, while in the TDS stage, the aim was to evaluate the environmental impact to be compared with that of the CDS.

The LCA impact analysis considers the results of the previous phase and evaluates the environmental impacts on human health and the environment. LCA method usually takes into account the following three main impact categories: human health, ecosystem quality, and resources.

- Human Health: generally includes respiratory effects, the effects of carcinogenics and ionizing radiation, ozone layer depletion, and climate change.
- Ecosystem Quality: includes the categories of ecotoxicity, acidification, eutrophication, and land occupation.
- Resources: includes the use of renewable or non-renewable energy sources, water use, and forests' destruction.

The selected environmental impact indicators, validated and shared by the international scientific community, are shown in Table 2 [34,35].

Table 2. Environmental indicators used to express the results obtained through the application of the LCA methodology. Adapted from [34,35].

Impact Indicator	Impact Category	Description	Units of Measurement
TPES	Total primary energy usage	Consumption of non-renewable energy resources	[MJ]
GWP	Global Warming Potential	Increase in average atmospheric temperature caused by greenhouse gas emissions	[KgCO_2eq]
ODP	Ozone Depletion Potential	Degradation of the ozone layer	[KgCFC11eq]
EP	Eutrophication Potential	Lowering of oxygen content in soils and surface waters	[KgPO_4eq]
AP	Acidification Potential	Lowering of pH in lakes, rivers, forests, and soils	[KgSO_2eq]
POCP	Photochemical Ozone Creation Potential	Pollution caused by the presence of unburnt hydrocarbons and nitrogen oxides	[KgC_2H_4eq]

In CDS, only two main LCA indicators were considered, embodied energy (EE) and global warming potential (GWP). Embodied energy (EE) is the sum of all the energy required to produce any goods or services, considered as if that energy was incorporated or 'embodied' in the product itself; global warming potential (GWP) is a relative measure of how much heat a greenhouse gas traps in the atmosphere. GWP is expressed as a factor of carbon dioxide (whose GWP is standardized to 1). In the subsequent TDS, only GWP indicator was used for the LCA impact evaluation. After LCA impact evaluation, the interpretation phase was performed. An improvement in the reliability of LCA impact indicator values can be developed by iterative processing, i.e., reviewing the preceding phases to improve impact results' reliability (Figure 7).

3.3. The LCC Estimate

Concerning the Life Cycle Cost (LCC) estimate, the analysis in CDS was directed by two main goals: to identify the most impactful cost categories, allowing strategies to decrease or control the costs, and to point out the advantages of investing in renovating a building when compared with the possibility of demolition and reconstruction following the guidelines of a seismic-resistant and nearly Zero-Energy Building (nZEB). Firstly, a parametric LCC estimate was performed in the CDS to compare Life Cycle Costs of different design strategies with different materials (steel, aluminum, and timber). Therefore, after choosing the steel-based design alternative, a more detailed LCC estimate was performed [18]. A dedicated LCC tool was developed in the framework of the project using an Excel spreadsheet supported by macros, considering the main cost categories indicated in the reference standards [36,37]. This tool includes the main influencing parameters (related to the building, the energy use, financial aspects, and others) in order to obtain a high number of results according to different operation scenarios. Critical parameters are energy price escalation, discount rate, steel exoskeleton investment (which accounts for 16% of construction costs), and building lifetime. According to ISO 15686-5 [36], the results were given using the Net Present Value (NPV) calculation. The sensitivity analysis is one of the techniques suggested by the standard ISO 15686-5 to indicate the uncertainty and risk associated with the LCC analysis. The parameters considered for the sensitivity analysis were the period of the analysis, the real discount rate, the inflation rate, process variation, and energy price escalation. The periods of analysis were chosen according to literature values and own experience. The real discount rate, the inflation rate, and the energy price variation were based on data collected from Eurostat. The range of price variation was based on the examination of market values and own experience [19,32].

4. Results

4.1. Concept Design Stage

Forecasted values of LCA and LCC was initially obtained in CDS. In CDS, only two main LCA indicators were considered, embodied energy (EE) and global warming potential (GWP), by using the Polytechnic of Milan database by Lavagna [33]. Three design alternatives for the exoskeleton—GET system—were considered: steel structure, aluminum structure, and XLAM structure (Table 3). The technical drawing details are shown in Figure 4.

Table 3. GWP and EE of considered structural materials [33].

	GWP ($kgCO_2eq/kg$)	EE (MJ/kg)
Steel structure	1.7	35
Aluminum structure	22	217
XLAM structure	−1.42	7.8

The following impacts were then calculated per housing unit (corresponding to 20 m^2 of GET system floor area), showing the negative GWP of the XLAM structure due to the carbon sequestered in trees and its minor EE compared to the design alternatives considered in CDS (Tables 4 and 5).

Table 4. GWP indicator estimate in the early design of CDS.

	Total Estimated Mass per Housing Unit (kg)	Total GWP per Housing Unit ($kgCO_2eq$)	Total GWP per m^2 of Housing Unit ($KgCO_2eq/m^2$)
Steel structure	1500	2550	127.50
Aluminum structure	900	19,800	990
XLAM structure	1246	−1769.32	−88.46

Table 5. EE indicator estimate in the early design of CDS.

	Total Estimated Mass per Housing Unit (kg)	Total EE (MJ)	Total EE per m^2 of Housing Unit (MJ/m^2)
Steel structure	1500	52,500	2625
Aluminum structure	900	195,300	9765
XLAM structure	1246	9718.8	485.94

As a result of these evaluations and considering the requested structural performance of the exoskeleton, i.e. the GET system, it was decided to select the steel structure design alternative for the following Technical Design Stage [18]. This decision was also supported by the LCC analysis. In fact, a forecasted value of an LCC of the proposed reinforcing external structures of the GET system was then estimated. This value was dependent on materials: structural steel, structural aluminum, or cross-laminated timber panels (XLAM). The basic assumptions were the following [18]:

- Economic life: 50 years.
- Discount rate: 2.75%.
- GET Structure area per housing unit: 20 m^2.
- Structure Costs:
  - Steel structure—€ 3.50/kg;
  - Aluminum Structure—€ 8.00/kg;
  - XLAM structure—€ 2000/m^3.

The LCC estimate was performed with the global cost methodology, using the ISO 15459 procedure [37]. The inflation rate was not considered, as it would be the same for the three design alternatives. Therefore, the final results, in terms of comparing economic convenience of the alternatives, do not depend on this parameter (Table 6).

Table 6. Global cost estimates in the early design (CDS) per square meter of housing unit.

	Initial Cost/m^2	Yearly Maintenance Cost/m^2	Global Cost 50 Years/m^2
Steel structure	€ 262.50	€ 0.68	€ 283.69
Aluminum structure	€ 360.00	€ 0.94	€ 389.29
XLAM structure	€ 250.00	€ 0.65	€ 270.25

Average yearly maintenance costs were estimated to be 0.26% of initial costs (exposed structures, after Di Giulio, 2002) [38]. Actually, even if LCA and LCC analyses indicated XLAM structure as the most convenient in terms of both the environmental impact and the global cost assessment, the steel structure was chosen for the exoskeleton because of the need to guarantee a better reinforcement performance in time.

After this parametric estimation referred to the GET system, a global estimation of the deep-renovation intervention was also performed in the CDS with the software openLCA® and the Ecoinvent database. This evaluation considered the complete design of the GET system [19,32] (Figure 7). LCA and LCC analyses were also carried out considering the impacts of the various components of the ProGETonE building in Athens: external insulation, new additions (modular façades), new heat pumps (Clivet ELFOPack, by Clivet Spa, Italy), controlled mechanical ventilation (VMC) (Savio Aircare ES by Savio Thesan Spa, Italy) and photovoltaic panels (Anerdgy Multifunctional Roof Edge by Anerdgy AG, Switzerland).

Considering the total components of the GET system, the whole renovation in Athens has in the concept stage an estimated total GWP of 1000 tCO_2eq for a period of 100 years, whereas for a period of 50 years, the GWP was around 700 tCO_2eq. This GWP is referred to the complete construction, all around the building. Considering only the exoskeleton (GET system), the GWP was 225 kgCO_2eq (Figure 8). The windows, the exoskeleton, and the PV installation were the most impactful components of the GET system. Wooden windows were recommended to reduce the impact. For a period of analysis of 50 years, the exoskeleton is the most impactful component of the GET system (Figure 8).

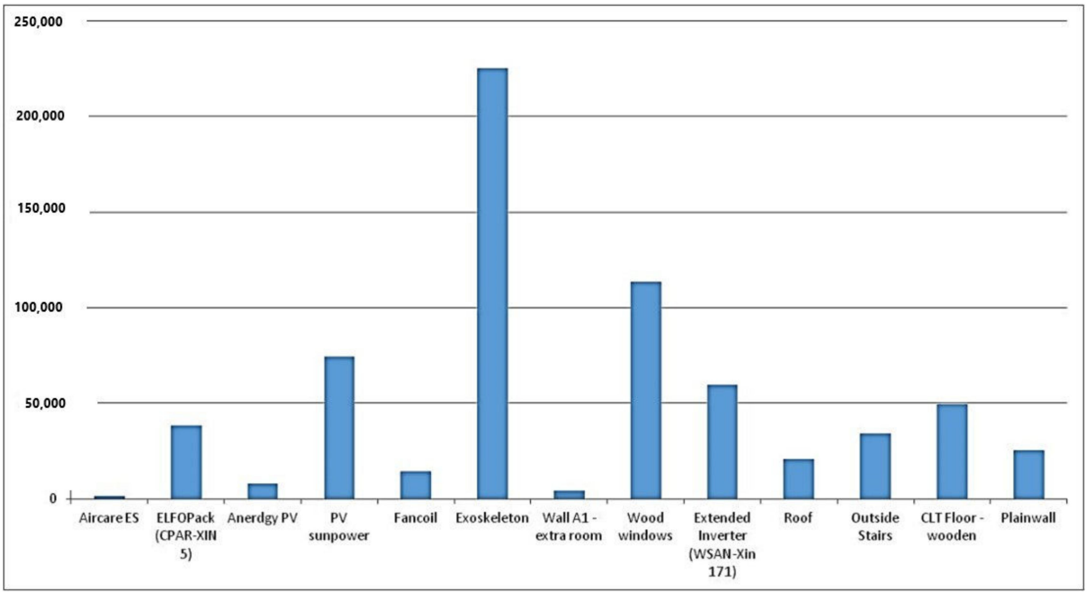


Figure 8. Impact of total components of the GET system [kgCO_2eq] for a period of analysis of 50 years.

Considering the costs in the EU scenario (LCC without real estate value increase), it can be stated that for the Athens pilot building, over 50% of the assessed scenarios outcomes foresee savings between 4 M€ and 6 M€ when choosing the GET renovation over the demolition or new building option. When analyzing the GET renovation as a percentage of the demolition and new building option, the median value is around 50%. For the Greek scenario (including real estate value increase), it can be stated that most of the assessed scenarios' outcomes foresee savings between 1 M€ and 3 M€ when choosing the GET renovation over the demolition and new construction option. When analyzing the GET renovation as a percentage of the new solution, the median value is around 75%. The median value of the LCC for the GET renovation in the different scenarios, including the real estate value increase, is 5 M€ [19,32].

Only half of the building was later renovated with the GET system; therefore, this estimation must be divided by two. The total area of the renovated building is 4400 square meters, while the total area of the GET system, i.e., the 4 floors of the exoskeleton, is 167.96 m^2 per floor, for a total of 671.84 m^2. Therefore, the estimated total GWP value per square meter of the exoskeleton is equal to 167.45 $kgCO_2e/m^2$.

4.2. Technical Design Stage (TDS)

The analysis for TDS was then performed using the 3D BIM model (Figure 7). The quantity takeoff function and the analysis of the cost plan allowed performing the LCA estimate of the embodied carbon (EC) with the One Click LCA LTD® 2022 software, version 0.14.0 database version 7.6 (Figure 9). The dataset used was that of the One Click LCA® software. The software dataset was focused on the Greek construction industry, while the system boundaries included the whole GET system (built only in half of the building) and all the related building renovating activities, as listed in the cost plan of the building. The dataset includes the Environmental Product Declaration (EPD) certificate, together with the other building products that are used by OneClick LCA®. EC is considered as the amount of carbon emissions from production (A1–A3), transportation (A4), and construction (A5).

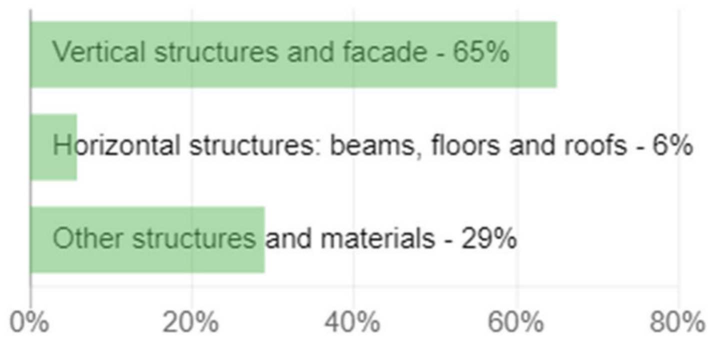


Figure 9. Percentage of embodied carbon stored in different parts of GET system.

The overall environmental impact of all the works constructed within the project (structural works, external stairs, various systems) considering only the total area of the exoskeleton is equal to 510.21 $kgCO_2eq/m^2$.

However, in the previous stage, only the exoskeleton GET structure was considered in the LCA analysis. Therefore, deducting the other contributions and leaving only the item "vertical structures and facades", an environmental impact of 235.53 $kgCO_2eq/m^2$ can be obtained. The used software version by default sets the life cycle to 60 years, while the other impacts were computed for 50 years. Therefore, by manual computation, the GWP impact for 50 years is for the total intervention equal to 425.18 $kgCO_2eq/m^2$, while for the exoskeleton, it is only 196.28 $kgCO_2eq/m^2$.

This impact in the design phase was underestimated and amounted to 127.50 $kgCO_2eq/m^2$ with parametric estimates and 167.45 with complete modelling.

As expected, the largest carbon emissions are from the steel structure, 69% of the total impact (Figure 10). Second is the construction category with 18%, which includes all the works relating to the "construction/installation process", therefore including construction site operations, construction site management, and transport of site waste. Among the other items, the one relating to "transport to the construction site", which includes the impacts of transporting a product from the factory to the construction site, has a very small impact compared to the others. This impact depends mostly on the OneClick LCA® software dataset, and it can vary depending on the material and the transport chain and its intermediate stages, which include wholesaler or storage (Figure 9).

Figure 10. EC in life cycle phases A1–A5 (without foundations and demolition of balconies).

The LCA in the TDS included both impacts grouped by a classification breakdown structure in life cycle stages A1–A5 (Figure 11).

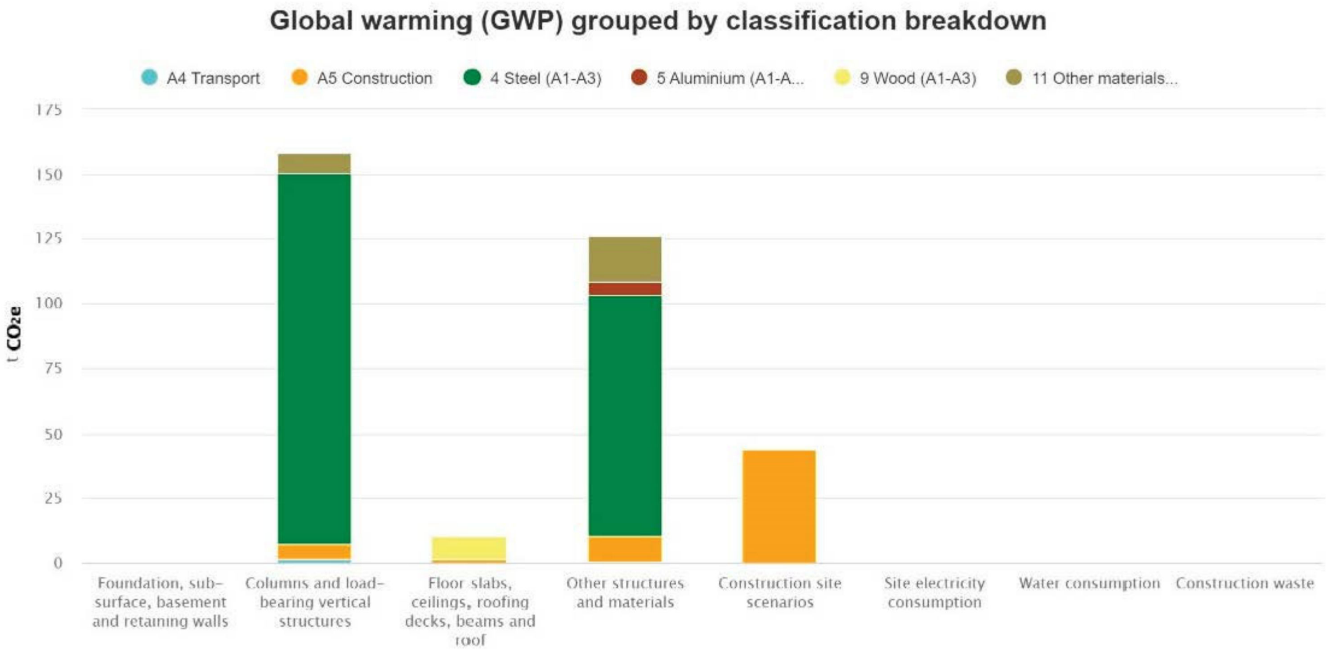


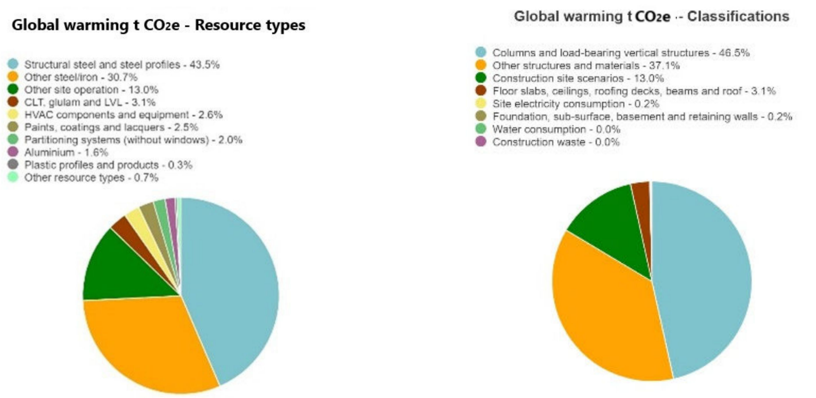
Figure 11. Global Warming GWP by classification breakdown in life stages A1–A5.

A data sheet where GWP quantities and material masses are compared was made in the TDSl to evaluate the different contributions of steel, aluminum, and wood to global warming emissions (Table 7).

Table 7. GWP and material mass of steel, aluminum, and wood in the technical design stage.

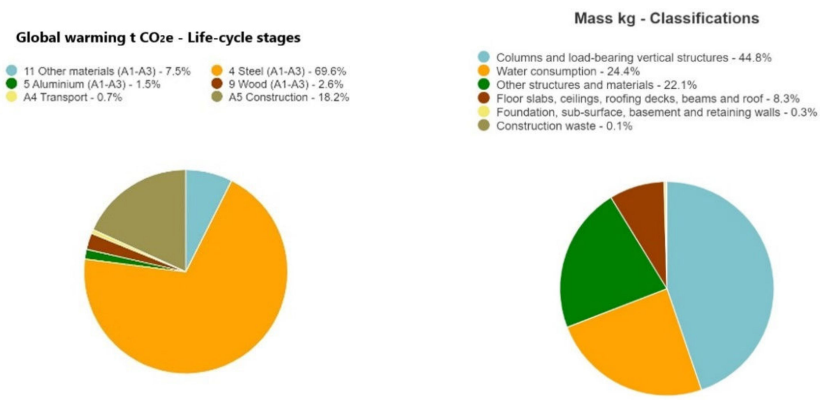
	Result Category	Global Warming t CO_2eq	Global Warming kg CO_2eq/m^2	Mass of Raw Materials t	Mass of Raw Materials kg/m^2
4	Steel (A1–A3)	237	352	118	176
5	Aluminum (A1–A3)	5	8	0	0
9	Wood (A1–A3)	9	13	15	22
11	Other materials (A1–A3)	25	38	12	18
A1–A3	Constructions materials	279	415	146	217
A4	Transport to the building site	2	3	0	0
A5	Construction/installation process	62	92	60	89

Finally, the LCA output data of all materials are summarized in the following pie charts. It should be noted that foundations were considered outside the system boundaries of the LCA analysis in the CDS, because they were not included in the initial parametric design. Therefore, they were also not included in the following LCA evaluation in TDS even if their impact would have been noticeable (Figure 12a,b, and Figure 13a,b).



(**a**) (**b**)

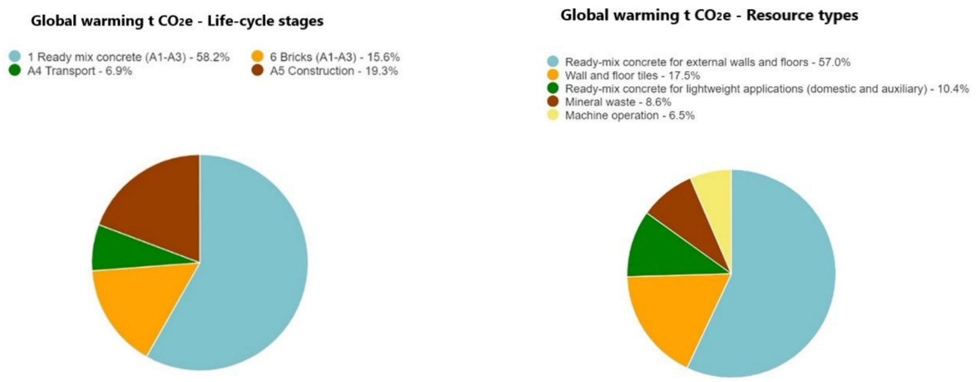
Figure 12. (**a**) tCO_2eq emissions by resource type; (**b**) tCO_2eq emissions per construction component.



(**a**) (**b**)

Figure 13. (**a**) Percentages of GWP (tCO_2eq) emissions by life cycle stage; (**b**) Percentage of mass (kg) per construction component.

These impacts must be added to the ones due to the preparation of the building for the installation of the GET structure, i.e., the demolition of the reinforced concrete balconies, which has an impact equal to 18.74 $kgCO_2eq/m^2$ (50 years). This impact was not considered in the design stage, as there were no balconies in the reference building on which the concept was first applied. The impacts of concrete works are shown in Figure 14a,b.



(**a**) (**b**)

Figure 14. (**a**) Reinforced concrete: percentage of $kgCO_2eq$ emissions by life cycle stage. (**b**) Reinforced concrete: percentage of $kgCO_2eq$ emissions by resource type.

Finally, the result for the total LCA impact of the ProGETonE building renovation project in the technical design stage, including all the works constructed to perform the building retrofit (structural works/GET system, external stairs, various systems, demolitions), is the total value of 443.92 $kgCO_2eq/m^2$ in a life cycle of 50 years.

5. Discussion

In the ProGETonE case, the impact of the embodied carbon of the GET structure was underestimated in the Concept Design Stage (CDS), as GWP equals 127.50 $kgCO_2$ eq/m^2 with parametric modelling and equals 167.45 $kgCO_2eq/m^2$ with complete modelling. In the Technical Design Stage (TDS), instead, the GWP was estimated as 196.28 $kgCO_2eq/m^2$; this is 54% higher than the CDS parametric estimate and 17% higher than the CDS complete modelling. The causes of this underestimation can be many. Firstly, the innovative structural solution had no precedents, and a database of such a type of exoskeletons does not exist. Secondly, the size of components for such an external superstructure was underestimated in CDS due to the lack of technical information on possible technical solutions for construction details, which were designed in the subsequent technical design stage after structural modelling and computation. Finally, the application of local building seismic regulations in Greece led to a general oversizing of building structures, i.e., of the component of the exoskeleton. All of these causes produced an increase in the size and mass of all building steel components, and a corresponding increase in the LCA impact resulted in the increase in the embodied carbon estimates. It should be noted that the foundation structures of the exoskeleton were not considered in the concept stage, and to be consistent with this estimate, they also have not been considered in the presented technical design LCA estimate. The contribution of a foundation of reinforced concrete slab with reinforced concrete poles will surely yield a larger impact of GWP production. In addition to this, the total LCA impact of the ProGETonE building renovation project in the technical design stage, including all the works constructed to perform the building retrofit (structural works/GET system, external stairs, various systems, demolitions) that were not considered in the concept design, is an even larger impact. The total value of carbon emissions of the complete deep-renovation project is 443.92 $kgCO_2eq/m^2$, which is more than 3 times larger than the estimated parametric LCA impact of the concept stage of the exoskeleton. This incredible increase in the estimated impact is due the lack of details and of completeness belonging to the concept design stage. However, this can be considered standard for an innovative research project that develops a new and unprecedented experimental approach.

The convenience of a regeneration project is related to the possibility of reaching the same performance levels of a new building that is also in the use stage: in this regard, these performances showed complete success. It can therefore be said that the reason why deep-renovation projects are not pursued does not derive from environmental convenience but rather from the fact that demolition and reconstruction projects are much easier to conduct and perhaps even faster, from the point of view of ordinary construction operators.

ProGETonE has required a lot of design effort and also has seen an increase in costs and impacts from the early stage of design to the design development. On top of that, according to this being a preliminary project, students living in the building were not supposed to leave during construction work, but finally, they had to leave due to additional refurbishment interventions inside the building, thus increasing total project costs.

This also clarifies the fact that light renovation projects are mostly common in recent years in Europe: they are characterized by lighter construction site operations and lower initial construction costs. In any case, in the ProGETonE project, additional costs were justified by an increase in floor surface and higher final performance levels, while in the case of light renovation, the increase in building performance would have been minor.

6. Conclusions

The Concept Design Stage has the task of defining the construction materials and building components included in the building and specifically in the GET system, which is used as exoskeleton and extension. Therefore, LCA evaluation for CDS has the goal of comparing different design alternatives with the available data. As previously mentioned in the method section, this evaluation can have a quite large range of tolerance, as it is a comparison, i.e., LCA (and LCC) outputs will be evaluated in relation to each other. The LCA evaluation in the Technical Design Stage, instead, is based on the detailed or executive cost plan. Therefore, the range of accuracy has to be very small. Therefore, the use of updated and specific datasets is of capital importance. In any case, from the standpoint of the evaluation of the LCA outputs in the different stages of the designing process, it can be said that the total GWP estimate of the Concept Design should be conceptually higher than the Technical Design one, to avoid taking project risks. This was not the case in the considered pilot study, because of the use of innovative technologies and a lack of experience concerning the specific deep-renovation strategy of the project. The GWP in TDS is, indeed, 54% higher than in CDS in the very first evaluation step performed with parametric modelling, or 17% higher than CDS when including the complete modelling.

In any case, there is no doubt that the overall environmental impact of a renovation project is much smaller than a demolition and reconstruction project. In fact, considering the average impact of new structures and of a demolition phase, which create a large amount of mass because of the new construction process and a large amount of waste because of the demolition, a deep renovation surely can reduce the overall impact of construction. This is due to the total balance of built and demolished quantities of materials versus the renovation case without considering the use or operation stage. Therefore, overall, the deep-renovation strategy of ProGETonE is surely more environmentally sustainable than demolition and reconstruction, but reliable LCA results require important technical insights.

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Abbreviations

AP	Acidification Potential
CDS	Concept Design Stage
XLAM	Cross-Laminated Timber Panels
EC	Embodied Carbon
EE	Embodied Energy
EPD	Environmental Product Declaration
EP	Eutrophication Potential
GET System	Exoskeleton
POCP	Photochemical Ozone Creation Potential
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MEP	Mechanical Electrical and Plumbing
nZEB	Nearly Zero-Energy Building
NPV	Net Present Value
ODP	Ozone Depletion Potential
ProGETonE	Proactive Synergy of Integrated Efficient Technologies on Buildings' Envelopes
RIBA	Royal Institute of British Architects
TPES	Total Primary Energy Usage
TDS	Technical Design Stage
UN	United Nations
VMC	Ventilation Mecanique Controlee/Controlled Mechanical Ventilation

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