# LIFE CYCLE ASSESSMENT (LCA) AND COST (LCC) STUDIES OF LIGHTWEIGHT COMPOSITE FLOORING SYSTEMS

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## Abstract

The growing need to save material and energy resources, together with the increasing concern over the material impact on the built environment economy has led the need for redesigning critical structural elements and systems. Flooring systems are the top amongst the list of the highest impact after the partition walls when comparing to other non-load bearing construction elements. This paper focuses on the advantages of lightweight flooring systems and contributes towards the development of a novel prefabricated ultra-shallow and lightweight flooring system. The used methodology comprises the environmental (by applying the TRACI method) and economic life cycle analysis (LCA). The environmental and economic impacts of three types of flooring systems are studied and compared. The first type is a prefabricated floor (Cofradal 260mm), is a common solution in residential buildings in France, the second type is a hollow core precast floor with an in-site concrete finishing layer, and the third type is the proposed system. The assessment showed that the embodied energy and embodied GHG emissions of the proposed flooring system are 28.89% and 37.67% lower than the one using Cofradal floor, and 20.18% and 35.09% lower the one using hollow core precast floor units. LCA showed that the proposed flooring system reduced 13.08% of construction cost and 41.83% of end of life cost in comparison with the Cofradal260 slab, and 1.87% of construction cost and 18.95% of end of life cost in comparison with the hollow composite precast slab.

Key words: Life Cycle Analysis (LCA); Composite Flooring Systems; Embodied Energy; Embodied Emissions; GHG Emissions

## 1. Introduction

The rapid economic development consumes a lot of resources and degrades the environment. One of the primary concerns of environmental impacts is the climate change and it is attributed to the emissions of greenhouse gases (GHGs). The temperature growth is connected with an increased atmospheric concentration of GHGs, while carbon dioxide is the most important anthropogenic GHG [1].

In recent years, assessing and controlling carbon emissions have become a basic strategy to achieve sustainable developments. The European Community and 37 industrialised countries through Kyoto Protocol committed to reducing greenhouse gases (GHG) emissions by 18% lower than the 1990's level from 2013 to 2020 [2]. The UK has a legally compulsory target under the Kyoto Protocol to reduce its emissions of the basket of six major greenhouse gases [3] and has declared its intention to put itself on a path towards a reduction in $CO_2$ emissions of 80% by about 2050 [4]. GHG emissions have attracted the most attention from researchers and policy makers possibly because they can be more readily quantified than other impacts, however, GHG emissions are just one of a range of parameters that should be considered in assessing environmental impacts. Others are ozone depletion, water consumption, toxicity, eutrophication of lakes and rivers, and resource depletion [5, 6 and 7].

The current practices in architecture and construction sectors are responsible for a high percentage of the environmental impacts produced by the developed countries [8]. In the European Union, the construction and building sectors are responsible for about 40% of the overall environmental burden. The construction and occupation of homes in the UK are responsible for the consumption of 40% of primary energy in the country [9]. In case the other 30% of the building stock (non-residential) is considered, the impact of buildings is greater [10].

Using large quantities of raw materials by the construction industry also involves high energy consumption. Choosing materials with a high content of embodied energy requires an initial high level of energy consumption in the building production stage but also determines future energy consumption in order to fulfil heating, ventilation and air conditioning demands [11]. Concrete is an essential reported construction material with the global annual consumption of 1 ton per capita [12]. It has been identified as a carbon intensive material, while cement being the key component of concrete as it is responsible for 5–7% of the world's carbon emissions [11]. The on-site construction process is another source of carbon emission, mostly contributed from fuel consumption in material transportation and heavy equipment, waste treatment management and embodied carbon in temporary materials [13].

There are various factors that influence the impact of the building construction on the environment and the responsibility is shared by owners, developers, architects and engineers, finance institutions, government authorities, contractors, material suppliers, labourers, tenants, building managers, operation and maintenance personnel, recyclers salvagers, and landfill/incinerator managers [14]. Designers (architects and engineers) have an important role; the selection of materials and construction systems.

When it comes to flooring systems, Lopez-Mesa et al. [15] claimed that for the case of residential buildings, the environmental impact of a structure with precast hollow core concrete floors is 12.2% lower than that with cast-in-situ floors for the defined functional unit using the life cycle analysis (LCA) methodology. Dong et al. [14] compared the carbon emissions of precast and traditional cast-in-situ construction methods based on a case study of a private residential building in Hong Kong and performed an LCA study to consider the system processes from cradle to end of construction. The comparison was conducted based on eight scenarios at four levels, for example, cubic meter concrete, precast facade, a group of façade elements, and an entire apartment. It was found that the precast construction method can lead to 10% carbon reduction for one cubic meter concrete. Jaillon et al. [16] stated that the use of precast method could lead to 52% of waste reduction and 70% of timber formwork reduction. Wong and Tang [17] compared the precast and cast-in-situ concrete with the system boundary from 'cradle to site' and concluded that the precast method can reduce carbon emissions. Dobbelsteen et al. [18] found that for the case of office buildings, energy consumption during building operation accounts, on average, for 77.5% of the environmental impact, whereas the use of building materials is responsible for 19.5%. It was also found that the supporting structure is responsible for almost 60% of the environmental impact caused by building materials. Therefore, the supporting structure is responsible for about 11.7% of the whole environmental impact. Reza et al. [19] investigated three types of block joisted flooring systems (concrete, clay, and expanded polystyrene (EPS) blocks) using life cycle analysis (LCA). The selection of three sustainable flooring systems in Tehran (Iran) was based on the triple-bottom-line (TBL) sustainability criteria. Analytical hierarchy process (AHP) is used as a multi-criteria decision making technique that helps to aggregate the impacts of proposed (sub) criteria into a sustainability index (SI) through a five-level hierarchical structure. The detailed analysis shows that the EPS block is the most sustainable solution for block joisted flooring system in Tehran.

Moreover, the use of lightweight materials in various applications adds great advantages when compared to heavyweight construction, such as in partition walls as it has been proven that they constitute to the higher contribution of the overall material inputs in the built environment [20]. A new lightweight sandwich membrane (new lightweight partition wall) was recently developed and evaluated using the LCA methodology, which comprises the environmental, functional and economic life cycle analysis. Two reference partition walls were used to compare with new lightweight partition wall to identify the advantages of the new lightweight partition wall: (i) the traditional heavyweight partition wall (hollow brick wall); and (ii) the lightweight gypsum panels wall (plasterboard wall). From the comparison, it was found that the new lightweight solution could be more sustainable than both standard solutions of hollow brick partition walls (HCM), and plasterboard partition walls (LRP).

In conclusion, the environmental impact of construction materials does not only depend on the material itself but also the way the components are put in place, its maintenance requirements and system's longevity, the travel distance from purchasing to the site, etc. [21]. This means that the selection of materials and the design of the structural system requires a rigorous LCA study. As Malin illustrates [22], this type of evaluation is a task for expert scientists and consulting companies specialised in the environmental impact. The calculation of the environmental indicators (Life Cycle Impact Assessment - LCIA) requires the detailed appreciation of the life cycle inventory databases, especially, their composition and the critical inclusion of the system boundary and allocation rules [23].

When LCA is applied to study a building, the product studied is the building itself, and the assessment is defined according to a certain level while it contains all material processes. This level is called ''whole process of building'' and there is a plethora of available tools to work at this level, such as BREEAM, (UK) [24]. When the LCA is applied to study a part of the building, a building component or a material, the level is called ''building material and component combination'' (BMCC), and at this case, it is important to recognize the component impact equivalent according to the functional unit of the building. The functional unit could be one of many (e.g., $m^2$, $m^2$ internal space, $m^3$, each, number of occupants, etc.) in the case of whole building LCAs. The most commonly used functional unit in the life cycle assessment of buildings is square meter floor area [24]. It is important to note that all the environmental impacts calculated within one LCA study should refer to the chosen functional unit.

There are a few available life cycle inventory (LCI) databases such as ATHENA, Ecoinvent version 3.4, and AusLCI [25]. The most recognised databases for material embodied energy and carbon dioxide in the UK is the Inventory of Carbon and Energy (ICE) Beta 2, developed by University of Bath [26]. ATHENA is the most suitable for use in the USA and Canada, as it contains the most comprehensive database of American products and processes. Ecoinvent contains Swiss and European product and process data. Data quality in LCA studies on buildings is a major concern due to the high rate of change and high technical improvements in the building industry. Therefore, the age, regional origin, and accuracy of the inventory data influence the accuracy and validity of the studies. A major focus over the last two decades in Europe, Canada, and the USA has been to produce region-specific LCI databases.

## 2. Objectives

This paper studies the ecological impacts of three types of flooring systems used for internal floors in buildings and they are evaluated using TRACI method. The first type of the flooring system, Cofradal 260mm floor, is a solution used with the Composite Slim Floor Beam (CoSFB) in residential buildings. The second type, hollow core precast floor, is used with slimflor beams and ultra-shallow floor beams in residential buildings. The third type is a proposed prefabricated flooring system, which is developed along with the LCA methodology in terms of the materials selection (i.e., lightweight concrete and thin-walled steel). Figs. 1, 2 and 3 depict the sections of the examined flooring systems [27, 28, 29, and 30]. The recently proposed flooring system [29, 30] is also designed in a way to have an efficient transportation and installation capacity.

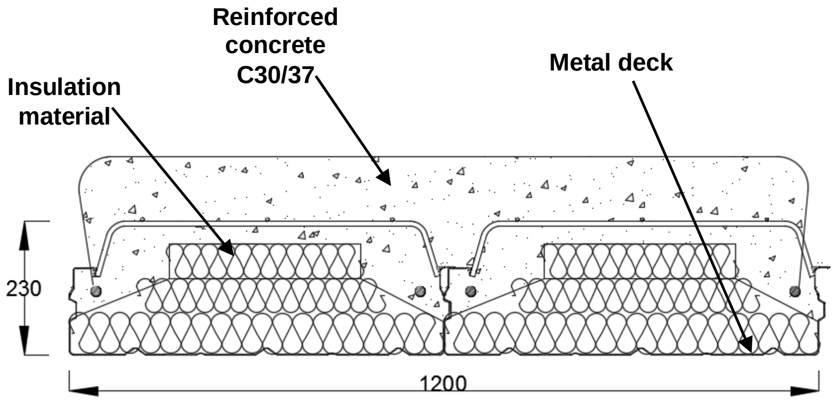


Figure 1: Cofradal 260mm floor section [27]

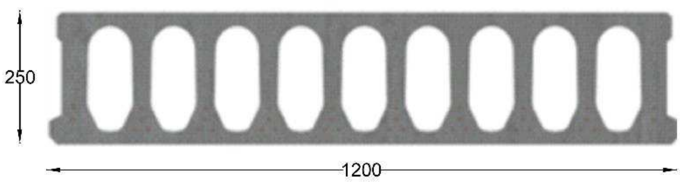


Figure 2: Hollow core precast floor section [28]

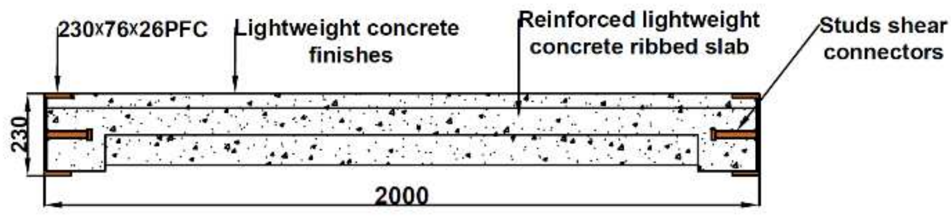


Figure 3: Prefabricated ultra-shallow flooring system (PUSS) [29, 30]

## 3. Integrated environmental-economic performance

### 3.1. Environmental performance (LCA)

A cradle-to-grave approach was adopted for the LCA study to determine the environmental impact of the three aforementioned distinctive types of flooring systems considering the following stages; raw materials acquisition, product manufacture, transportation, installation, and eventually recycling and/or waste management. The use and maintenance stage (operation stage) is not included in this study due to lack of information about this stage. The framework of the LCA study is shown in Figure 4, and is consisted of four major steps:

- **Step 1**: Identify scope, define the boundaries and the functional unit.
- **Step 2**: Model the processes and resources involved in the product system, collate the Life Cycle Inventories of these processes and resources and generate any new inventories required.
- **Step 3**: Analyse the life cycle impacts in terms of mid-points (impact categories) and end-points (system categories).
- **Step 4**: Evaluate and interpret results as well as generate a report for decision making.

Most LCA methods employ the principles of the International Standards Organization (ISO) series, which are known as the series 14040 within the more general ISO 14000 series on environmental management systems [9]. These documents describe four general steps that have to be carried out in any LCA:

(a) Initially, the researcher composes the aims, boundaries, and limitations of the study, and sets significant assumptions - generally definitions of system boundaries, such as the full lifetime of the product or one phase of its manufacturing; functional units such as $m^2$ of floor area; quality of the data, etc. All these assumptions should be specified at this early stage, as they determine the direction of the study. The study will be assessed in the interpretation stage.

(b) Life cycle inventory is the second step of the LCA. It includes the collection of the data and calculation methods, and it is considered as the most important and time-consuming stage since this data will be the basis for the study. It has been also connected with the scoping exercise as the data collection, and other cases may lead to redefinition or refinement of the system limitations. For instance, the lack of data may result in changing the objectives or the scope of the study. Therefore, data completeness is pivotal. Life cycle inventory phase (LCI) usually uses databases of building materials and component combinations.

(c) The impact assessment evaluates potential environmental impacts. The purpose of this phase is to estimate the importance of all environmental burdens obtained in the LCI by analysing their influence on selected environmental loads.

Impact assessment is used by the ISO series 14040 [31-33] to characterize and normalize the environmental impacts. The first stage of the life cycle impact assessment is to select the impact categories, category indicators, and characterization. The next stage is to assign the LCI results to the selected impact categories and the last stage multiplies the inventory results by the characterization factors. Impact categories are divided into two types; the midpoint categories and the endpoint categories. Midpoints are concerned with environmental problems whereas endpoints are concerned with the damage that these environmental problems can cause. In ISO 14042 standard, a distinction is made between obligatory elements, such as the classification and characterization, and optional elements, such as normalisation, ranking, grouping, and weighting. According to ISO 14042, the general framework of a life cycle impact assessement (LCIA) method is composed with obligatory elements (classification and characterization) that convert LCI results into an indicator for each impact category that leads to a unique indicator using numerical factors based on value-choices.

(d) The final stage in the LCA is the interpretation, which aims to analyse the results and reach the conclusions through explaining the boundaries and providing recommendations. These recommendations are based on the outcomes of the previous phase of the LCA or LCI study. Life cycle interpretation also intends to provide an easily understandable, complete, and harmonious presentation of the results of an LCA or an LCI study, in agreement with the scope definition of the study.

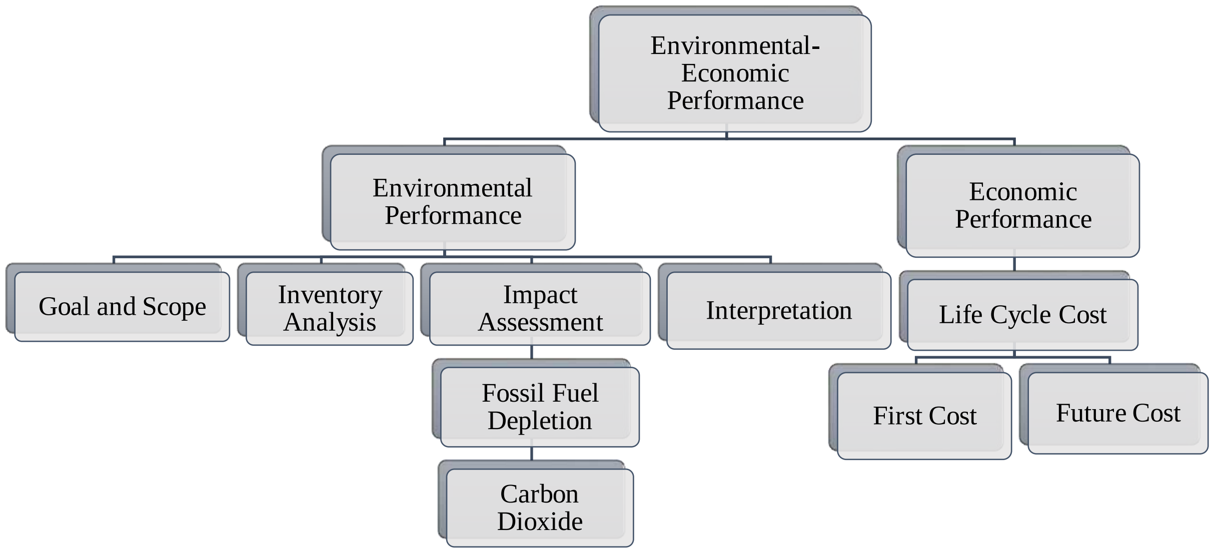


Figure 4: Overall performance steps

### 2.1.1. Existing Standards for LCA

Life cycle assessment is standardised through a range of ISO documents which include:

- ISO 14040: 2006 [31] Environmental management-life cycle assessment - Principles and framework. This standard outlines the major steps in the LCA process but does not describe the LCA technique in detail.
- ISO 14044: 2006 [32] Environmental management-life cycle assessment-Requirements and guidelines. This standard supports ISO 14040 with more details about each step of the LCA.
- ISO/TR 14049: 2012 [33] Environmental management - Life cycle assessment-Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis. This standard particularly shows the key elements of the inventory analysis phase of LCA.

### 2.1.2. Scope

The scope of this research is to evaluate a new fully prefabricated proposed flooring system and compare it with the current state-of-the-art sustainable flooring systems.

#### 2.1.2.1 Functional Unit

The functional unit is the unit of comparison in the LCI. In this study, one square meter ($m^2$) of flooring system fulfilling similar requirements regarding a live load of $2kN/m^2$ and a span of 7.8m is chosen. This is chosen according to the maximum span of Cofradal slab which is 7.8m and can take a live load of $2kN/m^2$. Therefore, the same live load was applied for all studied flooring systems and with the same span regardless their capacity. All emissions, energy consumption and materials are based on this functional unit, e.g. $MJ/m^2$, kg $CO_2e/m^2$ etc.

#### 2.1.2.2. System Boundaries

The system studied includes the entire life cycle of the flooring systems listed above, including manufacturing of building materials, construction, operation, and demolition. Transportation for each life cycle phase is also included. The impact categories studied are Embodied Energy and Global Warming Potential (GWP).

#### 2.1.2.3. Definition of Impact Categories and Calculations Methodology

The scope step also includes the specification for which impact categories are to be covered in the impact assessment step. This is typically done by selecting one of the available calculation methodologies. Each methodology defines the impact categories that are used to generate results. Some methodologies also define a weighting scheme by which different impact categories are combined into more generic results. The calculation methods are classified according to the regions such as European and North American [34].

This study is focused on the environmental problems that these flooring systems will cause during their entire life. Therefore, the LCIA results are calculated at midpoint level using the TRACI method [35].

#### 2.1.2.4. Characteristics of studied flooring systems

Shallow-floor construction is characterized by integrating the steel beam into the slab's thickness. The steel section consists of a hot rolled beam with a welded plate underneath it to provide the bearing for incoming slabs. The width of the welded plate is larger than the bottom flange of the hot rolled section, hence the slab elements can be easily placed. The shallow-floor beam (SFB) can be incorporated into any type of slab. Prefabricated or partially prefabricated concrete slabs can fit perfectly with the SFB; a quick and safe erection is assured. By using this type of construction systems the structural depth of the floor is reduced and thus the overall height of the building is effectively reduced while the total number of floors can be increased within the predefined allowed building envelope. Mechanical and Electrical (M&E) services such as cooling and heating devices are quickly installed due to the absence of down stand steel beams. However, due to the small beam height, the design of the SFB is governed by the stiffness of the system and hence spans are limited.

A good example of slim-floor construction is the Composite Slim Floor Beam (CoSFB) which has been based on the development of an advanced composite connection by using concrete dowels. This flooring system has been used with the Cofradal260 slab (composite floor slab) which consists of a cold-rolled metal deck, a thermal insulation layer and a concrete layer which reduces the overall weight of the flooring system. This flooring system is fully prefabricated, hence it reduces the energy consumption, $CO_2$ emissions, construction cost and potential site repair and maintenance costs are still high.

Another type of flooring systems which is used with the slimflor beams is the hollow core precast units. This flooring system contains voids that run continuously along their length, which helps reduce dead weight and material cost. The construction of the hollow composite precast slab in the site involves further work to complete the construction, such as placing the concrete topping layer on site, because it is not a fully prefabricated flooring system, thus the energy consumption, $CO_2$ emissions, construction cost and potential site repair and maintenance costs are still high.

A new flooring system was recently proposed and it is developed at the University of Leeds along with the methodology of Life Cycle Assessment (LCA) in terms of the selection of its materials (i.e., lightweight concrete and lightweight steel) while the benefits of full prefabrication are exploited [17, 18].

The selected flooring systems include:

• Cofradal 260mm slab

It is constructed using galvanized profiled steel sheeting with a tensile strength of 320 $N/mm^2$ fitted with a mineral wool insulation layer and reinforced concrete top layer with C30/37 and reinforcing bars welded on the steel sheeting. This welding provides a connection point between the tensioned steel and the compressed concrete creating a composite behaviour between the steel sheeting and the top concrete. The Mineral wool layer with a density of 50 $kg/m^3$ is an effective shuttering bed for the concreting of the top of the slab. This layer is provided for thermal insulation between levels if needed, acoustic resistance. The overall depth of slab is 260mm with a width of 1200mm and maximum span of 7.8m. This system is a fully prefabricated steel-concrete composite slab produced in-house and ready to be fixed on site.

• Hollow composite precast slab

This is constructed from normal concrete C40/50 with voids that run continuously along its length. The overall depth of the slab is 300mm including the concrete topping layer (50mm) with a width of 1200mm and maximum span of 10.5m. The slab is fabricated under controlled factory conditions. The concrete topping layer is placed on site, on the top surface of hollow core slabs to create a continuous level finished surface. Therefore, this system is a semi prefabricated slab and ready to be fixed on site.

• Prefabricated Ultra-Shallow flooring System (PUSS)

The recently proposed flooring system is constructed from the concrete floor, which is in the form of T ribbed slab sections using reinforced lightweight aggregate concrete C25/30. The actual floor system supports finishes layer and thermal insulation pads connected with each other [17, 18]. The steel edge beams encapsulate the floor slab in the middle and connected with concrete slab using shear connections (studs and dowels). The overall depth of the floor is 300mm with a width of 2000mm and a maximum span of 12m. This system is a fully prefabricated steel-concrete composite slab produced in-house and ready to be fixed on site.
The proposed flooring system exercises the sustainability approach in the selection of its components using sustainable materials such as lightweight aggregate concrete (Lytag

aggregate or Leca aggregate) and lightweight steel members. An analytical Life cycle assessment of materials for the proposed flooring system was developed and compared with the Cofradal slab [17]. From the study it was found that the proposed flooring system reduces the embodied energy and embodied carbon by about 17.94% and 9.33%, respectively compared with the Cofradal slab. The structural performance of the proposed flooring system has been proven analytically using the stress block method. An experimental campaign regarding the push-out tests were carried out in the Heavy Structures Laboratory of the University of Leeds [18].

The depth for the three flooring systems for a 7.8 m span (max. for Cofradal slab) and an imposed load of 2 kN/m$^2$ presented in table 1. Figure 5 shows flow chart of production boundary for the case study.

Table 1: The characteristics of material inputs for the flooring systems

| Flooring systems | Description | Thickness, width, span, Dimensions | Overall floor weight kN/m$^2$ | Live load kN/m$^2$ |
|---|---|---|---|---|
| Cofradal 260mm slab | Cofradal260 slab (composite floor slab) | 260mm x 1.2m x 7.80m | 2.8 | 2.5 |
| Hollow composite slab | Reinforced concrete floor slab with finishing | 200mm x 1.2m x 7.8m | 5.1 | 2.5 |
| PUSS | Composite flooring system with lightweight reinforced concrete T ribbed slab connected with two steel edge C- channel beams using studs and dowels | 230mm x 2.0m x 7.8m | 2.61 | 2.5 |

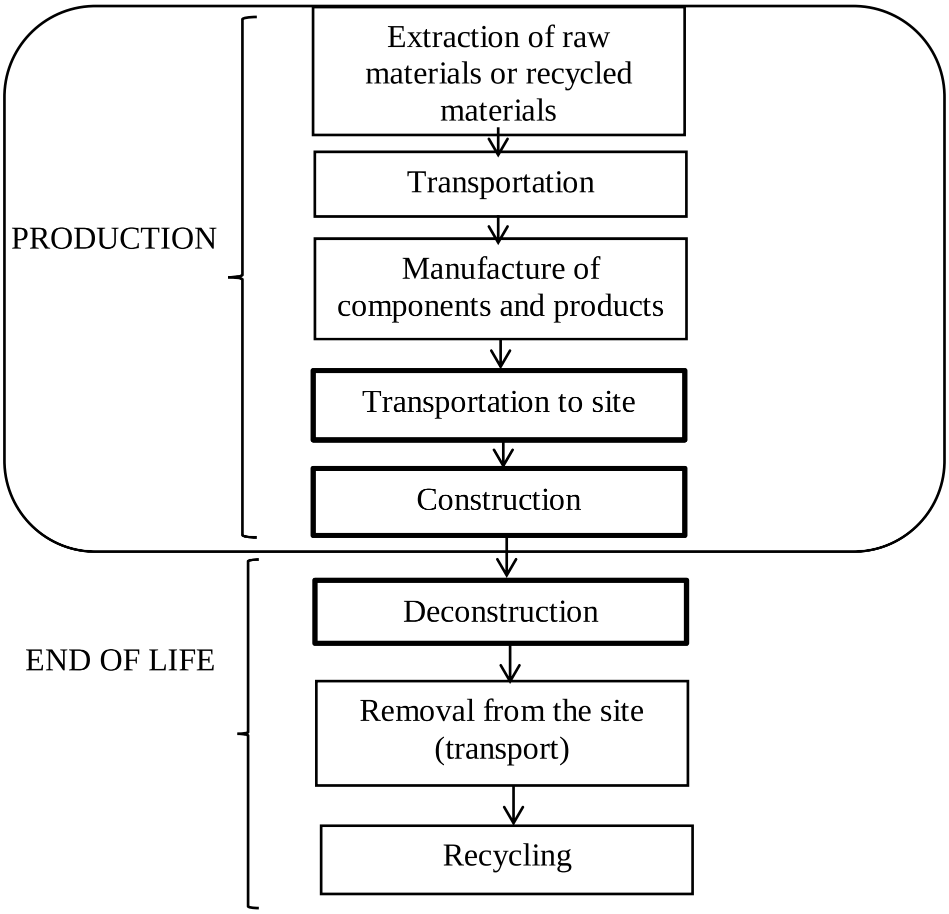


Figure 5: A simplified lifecycle process flow chart showing production boundary for the case study

### 2.1.3. Life cycle inventory analysis

Inventory analysis is accurately quantifying the inventory flows with inputs such as the raw materials, water, and energy, as well as outputs, including the air emissions, releases to land and water effluents for a product system. In this study, carbon emissions coefficients and embodied energy coefficients for materials, processes, and fuels were derived where possible from the UK or relating to the country of production as shown in Table 2, 3 and 4. A number of sources and databases were used including:

- The Inventory of Carbon and Energy [30].
- Life cycle assessment of concrete, master thesis [36].
- $CO_2$ Emissions and energy consumption during the construction of Concrete structures [37].

The last two references has been used due to provide a detailed information about the embodied energy and embodied carbon data for concrete demolition and operation of construction equipment from the European counties.

#### 2.1.3.1. Pre-use phase

The embodied energy and air emissions associated with construction materials during their extraction, processing, and manufacture represent the largest portion of total embodied energy and air emissions in buildings. Yohanis et al. [38] demonstrated that this is about 78% in a residential building and about 92% in an office building. These figures have nearly a 15%

discrepancy, mostly arising from a wide variety of building materials used, different building size, and their different functions [39, 40, 41, and 42].

#### 2.1.3.2. Use and maintenance phase

Embodied energy and air emissions associated with the maintenance of flooring system activities (e.g., refurbishment) were ignored due to lack of information about this particular stage.

#### 2.1.3.3. End of life phase

The last phase of the flooring system life involves energy and emissions related to demolition, recycling processes, and transportation. The emissions from this stage are mainly owing to the energy consumption of the mechanical demolition equipment. All data on energy consumption of demotion equipment was derived from source [36, 37].

Table 2: Embodied carbon and embodied energy coefficients for the production of materials [30]

| Material | Embodied Energy Coefficient (MJ/kg) | Embodied Carbon Coefficient (kg $CO_2$e/kg) |
|---|---|---|
| Cement | 5.5 | 0.93 |
| Sand | 0.081 | 0.0048 |
| Gravel | 0.083 | 0.0052 |
| Water | 0.01 | 0.001 |
| Reinforcing concrete (25/30 MPa) | 0.86 | 0.132 |
| Precast concrete (40/50 MPa) | 0.45 | 0.029 |
| Concrete (40/50 MPa) | 1.0 | 0.151 |
| Reinforcing steel bar | 17.4 | 1.4 |
| Stud/dowel | 17.4 | 1.4 |
| Metal Deck | 22.6 | 1.54 |
| Steel Section | 21.50 | 1.42 |
| Rock wool Insulation | 16.8 | 1.12 |

Table 3: Embodied carbon and embodied energy coefficients for operation of construction equipment [37]

| Equipment | Embodied Energy Coefficient (MJ/hr) | Embodied Carbon Coefficient (kg $CO_2$e/hr) |
|---|---|---|
| Tower crane of 100 ton | 720 | 53.23 |
| Pumps | 540 | 46.12 |
| Equipment | Embodied Energy Coefficient (MJ/$m^3$) | Embodied Carbon Coefficient (kg $CO_2$e/$m^3$) |
| Concrete compactor | 1.18 | 0.2 |

Table 4: Embodied carbon and embodied energy coefficients for the end of life of materials [30, 36]

| Material | Embodied Energy Coefficient (MJ/kg) | Embodied Carbon Coefficient (kg $CO_2$e/kg) |
|---|---|---|
| Steel recycling | 13.1 | 0.75 |
| Reinforcing steel bar recycling | 11 | 0.74 |
| Concrete demolition | 0.007 | 0.00054 |

#### 2.1.3.4. Life cycle impact assessment

The LCIA results are calculated at midpoint level using the TRACI method [35]. The LCIA phase was initially focused on the characterization step and thus the following indicators were considered:

• EE: (Embodied Energy) as an indicator relevant to the total primary Energy resource consumption;

• GWP: (Global Warming Potential) as an indicator relevant to the greenhouse effect; Characterization factors for the embodied energy and global warming potential from TRACI method are used in this study.

### 2.1.4. Impact assessment of the LCA results

#### 2.1.4.1. Pre-use Phase

• Manufacturing:

Material embodied energy is related to the acquisition of raw materials, their processing, and manufacturing. Paradoxically, Figure 6 demonstrates that the three flooring systems have completely different embodied energy global warming potential during this stage; the proposed flooring system has 817.49 MJ/m$^2$ lower than the precast flooring system which has 976.96 MJ/m$^2$ and lower than the Cofradal flooring system which has 1142.68 MJ/m$^2$.

Table 5 presented the embodied energy and global warming potential of the studied flooring systems at each life cycle stage.

Table 5: Embodied energy, global warming potential at each life cycle stage

| Life cycle phase | Flooring systems | Embodied Energy (MJ/m$^2$) | Global Warming Potential (kg $CO_2$ Eq/m$^2$) |
|---|---|---|---|
| Manufacture | Cofradal260 slab<br>Hollow composite precast slab<br>Proposed flooring system | 1142.68<br>976.96<br>817.49 | 125.11<br>120.56<br>70.40 |
| Transportation | Cofradal260 slab<br>Hollow composite precast slab<br>Proposed flooring system | 164.11<br>296.96<br>138.07 | 10.25<br>18.56<br>8.7 |
| Onsite construction | Cofradal260 slab<br>Hollow composite precast slab<br>Proposed flooring system | 1152<br>1238.06<br>720 | 73.79<br>81.20<br>46.12 |
| Demolition | Cofradal260 slab<br>Hollow composite precast slab Proposed flooring system | 3.67<br>4.07<br>3.94 | 0.28<br>0.31<br>0.304 |
| Reusability | Cofradal260 slab<br>Hollow composite precast slab<br>Proposed flooring system | -363.60<br>-33.66<br>-329.96 | -22.68<br>-2.26<br>-19.15 |

- Transportation:

Embodied energy and global warming potential of material transportation includes herein the fuel combustion arising from the transportation of materials by diesel fuel truck 20 ton from manufacturing plant to the construction site. The transportation distance considered for the flooring systems was 100 km according to (ICE) Beta 2 [30]. The values for Cofradal slab transportation impacts are 164.11 MJ/m$^2$, 296.96 MJ/m$^2$ for the hollow composite precast slab values and 138.07 MJ/m$^2$ for the proposed flooring system - representing approximately 7% of total embodied energy.

Vukotic et al. [43], reported that the value for transportation of materials to the construction site may vary between 7% and 10% of total embodied energy. Zabalza [44], demonstrated that this value is approximately 6% of the total embodied energy. In this paper, the values for material transportation is 7% of total embodied energy.

• Onsite construction equipment:

The construction and erection of building assemblies require the use of a range of manual and power operated tools and equipment such as compressors, saws, welders, and drills [45]. The values of embodied energy and air emissions of related equipment are derived from source [37].

Figures 6-9 depict the Embodied Energy, Global Warming Potential of the studied flooring systems.

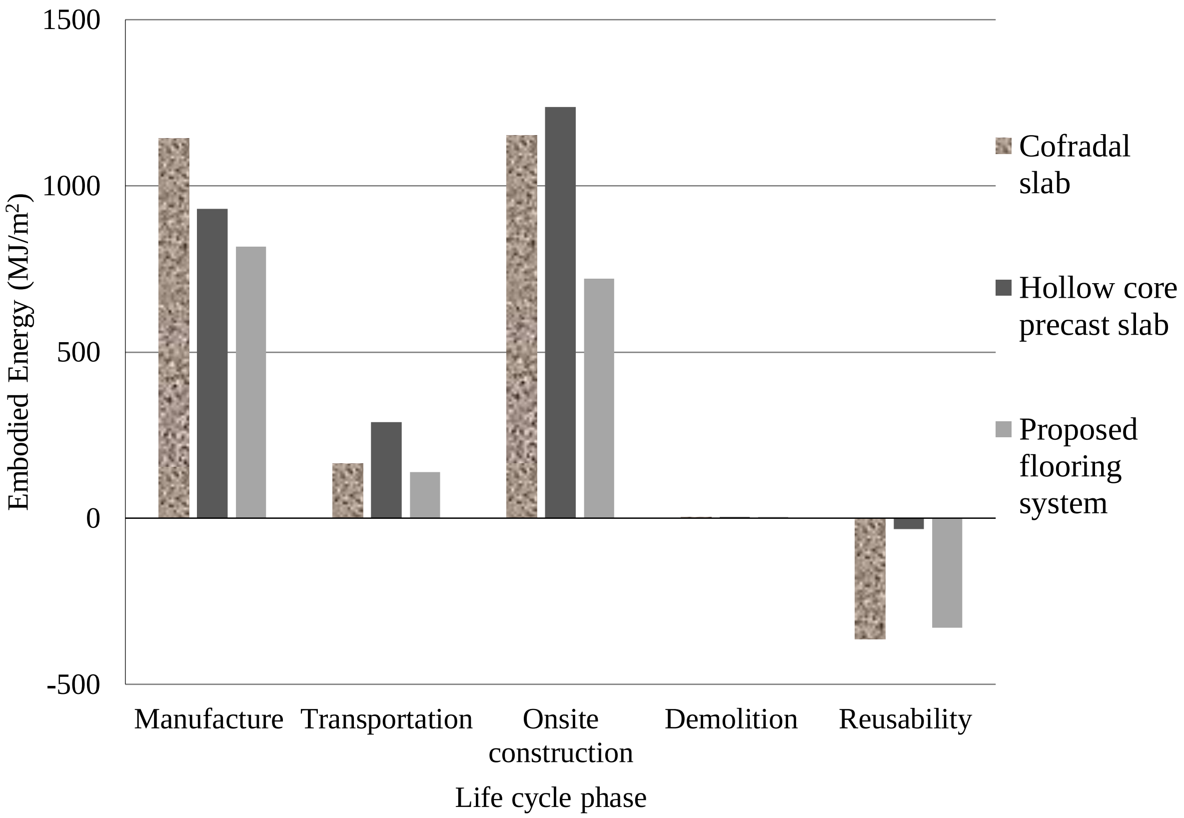


Figure 6: Embodied Energy by life cycle phase

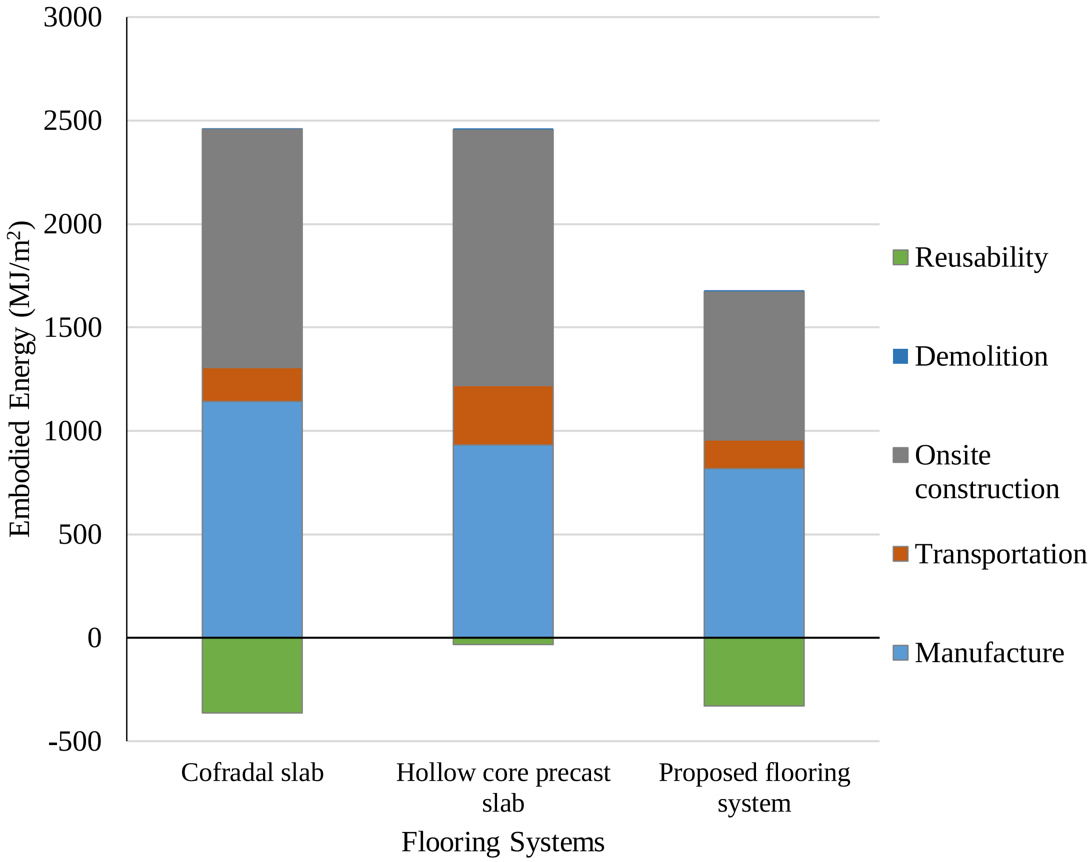


Figure 7: Embodied Energy by flooring systems

2.1.4.2. End-of-life

End-of-life embodied energy accounts for impacts associated with building demolition, including waste transportation and reusability potential. For this paper, the ICE inventory provides information about the reusability values of building materials. For steel beam and metal deck, approximately the 95% can be reused for full benefits while the 5% is lost and goes to landfill. Regarding the reinforcement bars, the 75% is reusable. Concrete has been only considered at the demolition stage [37], as no information has been provided by the ICE inventory [30] with regards to its demolition and recycling method.

Energy consumed during demolition stage proved to be the least important parameter of the building's life cycle. Any change in demolition practices does not have a direct impact on the reduction of air emissions associated with it due to the marginal value of energy consumed during the demolition of flooring systems.

As it was aforementioned, the recycling process is considered for the steel components only due to uncertainties associated with the prediction of concrete recycling. The embodied energy was 363.60 MJ/m$^2$, 33.66 MJ/m$^2$, and 329.96 MJ/Mm$^2$ for Cofradal260 slab, hollow composite precast slab, and proposed flooring system, respectively. This highlights that the end-of-life reusability can play a significant role in the embodied energy analysis and the reduction of air emission. However, it is worth to note that the prediction of future demolition seems to be one of the major difficulties in the selection of the best method for waste management.

Figures 8 and 9 show a breakdown of Global Warming Potential by each phase of the life cycle of flooring systems. Proposed flooring system emits less than 60% of the emission of the Cofradal260 slab, and less than 65% of the hollow composite precast slab. This is due to the energy intensity of reinforced concrete with high cement content.

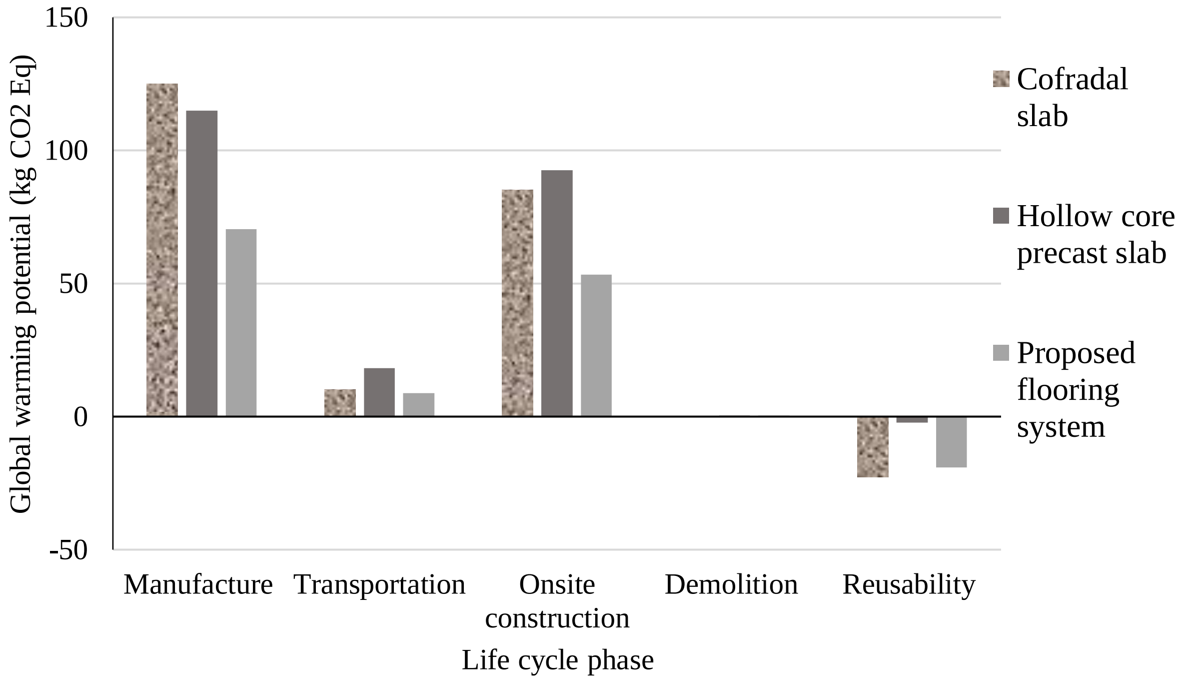

Figure 8: Global Warming Potential by life cycle phase

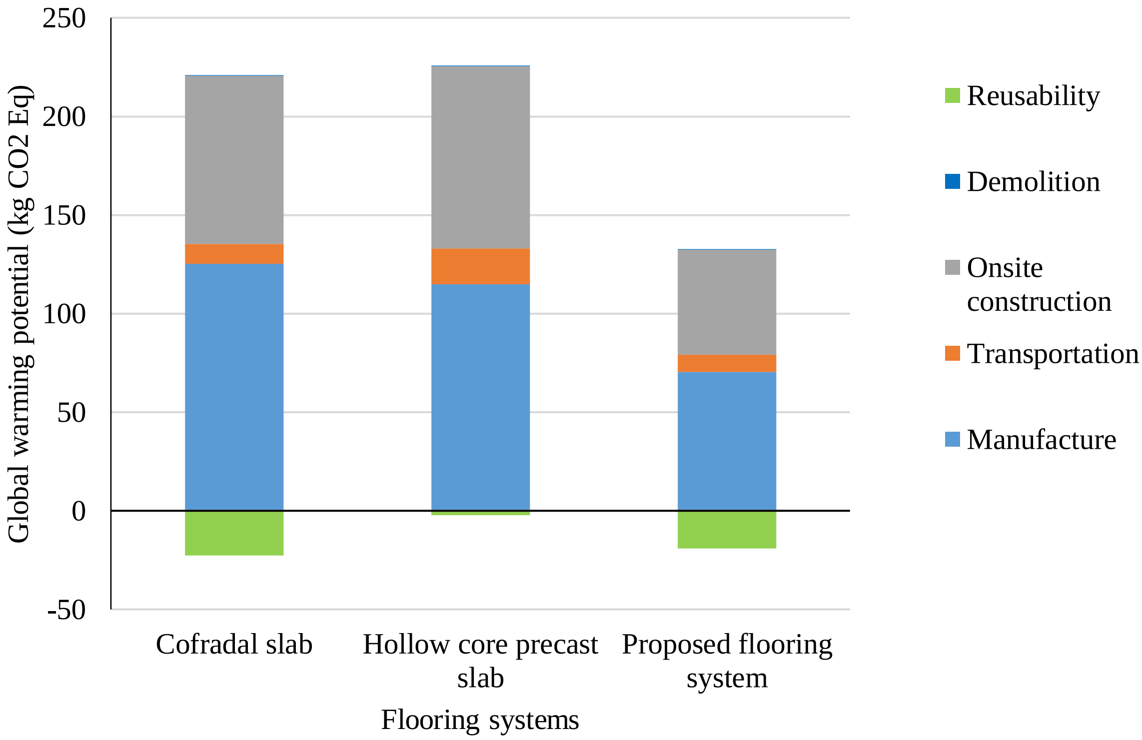

Figure 9: Global Warming Potential by flooring systems

## 2.2. Economic performance (LCC)

### 2.2.1. Importance of LCC

It is important that the fundamental arguments supporting life cycle costing, its core principles and the restrictions on how it can be used, are understood by everyone involved in scoping, designing, and delivering the project. For public sector procurement, the government has set out a policy of making decisions on the basis of best value rather than lowest initial cost, which is the essence of life cycle costing. This is emphasised in the UK Construction 2025 strategy document dated July 2013. By working in partnership, the construction industry and Government jointly aspire to achieve, by 2025, a 33% reduction in both the initial cost of construction and the life cycle cost of assets [46].

The economic analysis of building design solutions can be used in two different ways. When a range of possible designs is still being considered, then life cycle costing can be used as a comparison tool to work out the life cycle costs of each design as a part of the decision-making process and select the best alternative. LCC can also be used for predicting and assessing the cost performance of constructed assets (ISO 15686-5:2008) [47].

### 2.2.2. Existing standards for LCC

An international code of practice for life cycle costing is provided by ISO 15686-5 [48] in relation to the built environment. This code is part of a series of standards covering service life planning, the long-term understanding of building elements, components, and equipment. ISO 15686-5 makes the distinction between life cycle costing and whole life costing, here explained in Figure 10.

According to the ISO definition, life cycle costing includes the initial construction and through-life activities associated with a built asset while whole life costing also includes non-construction activities and income generation such as receiving rent from tenants. The implication is that life cycle costing will be more relevant to designers, contractors, and facility or asset managers, whereas whole life costing will be more appropriate to owner-occupiers, developers, and landlords.

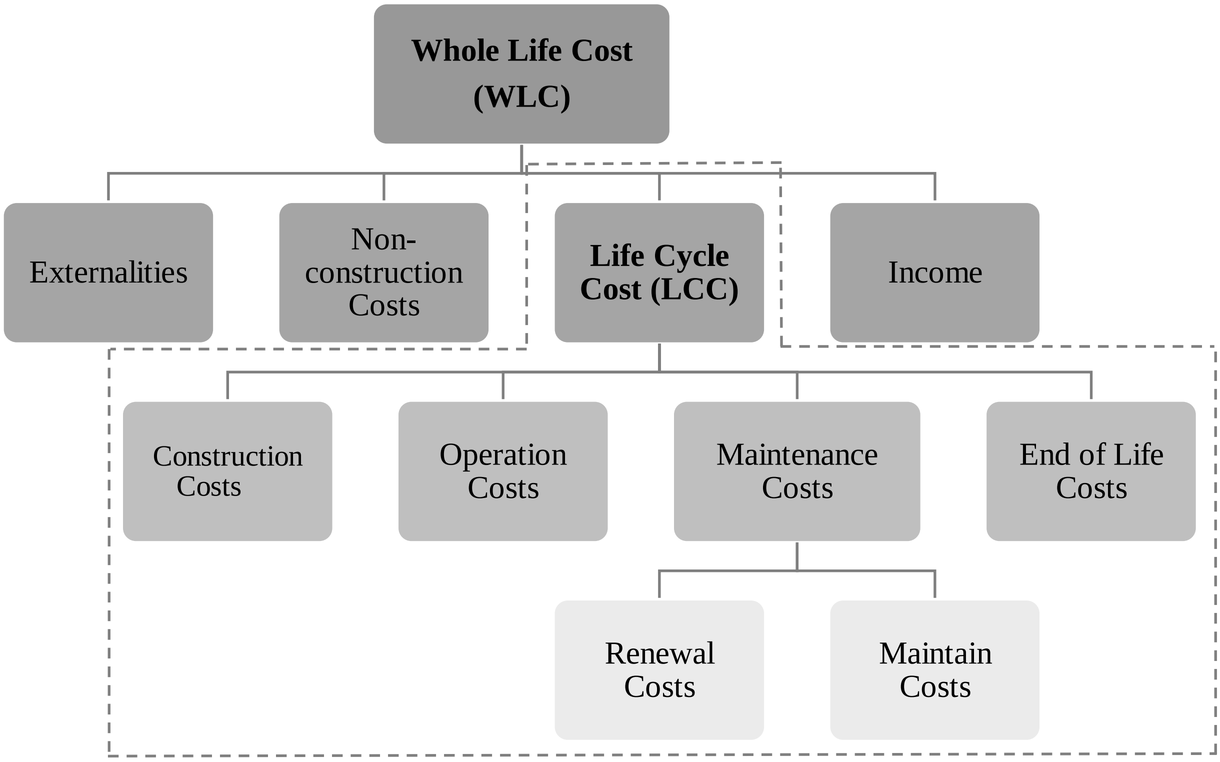


Figure 10: Definitions of whole life cost and life cycle cost based on ISO 15686-5 [43]

### 2.2.3. Discount Rate selection

The discount rate is a fundamental characteristic of the analysis. The same discount rate must be applied to all the models within the analysis so that the comparison is valid. This rate reflects the time value of money, which is used to evaluate future costs in relation to present costs, accounting for the prevailing interest rate and (indirectly) the inflation rate.

Therefore, the discount rate is variable in time. In the UK, the Treasury (UK government practice) rules specified a discount rate to be used for a given year; similar rates are established in other countries [48]. For the life cycle costing on public sector projects, a discount rate of 3.5% per annum is stipulated by Treasury rules for all projects up to 30 years. For longer timescale and public sector projects typically infrastructure buildings, a series of lower discounts rates are applied to different project years. This study used a 3.5% discount rate for 0–30 years, in line with the UK government practice.

### 2.2.4. Study period selection

The study period is another fundamental factor in the life cycle cost analysis. The usual situation is that a single study period is applied to all the alternatives being assessed. There are special circumstances when different study periods are applied to different alternatives, but in this study, the calculated results must be presented as equivalent annual costs. The study period may be defined by the client or may be proposed by the project team. As shall be seen, the outcomes of life cycle costing can be extremely sensitive to the study period, and the choice should always be backed up with a strong argument. For new build or refurbishment projects, study periods of between 15 and 25 years are commonly used, but longer or shorter periods can be used. Shorter periods may be used for projects concerned with building services systems or interior fit-out. For the life cycle costing of building services installation, the life expectancy of the equipment is often used as the study period. Longer periods may be used for infrastructure works. In all cases, the study period should be informed by the client's business plan.

#### 2.2.5. Costs data collection

The construction costs have been derived from a common industry reference which is the SPON's price books [49].

#### 2.2.6. Calculations of LCC

Similar to the environmental (LCA) studies, LCC studies the life cycle of a product to evaluate its economic influence. It estimates all relevant costs including construction, use (i.e., operation, maintenance, repair, and replacement) and end-of-life waste management (disposal) throughout the life period at their present value (PV) as in Eq. (1). Future costs (i.e., operation, maintenance, and disposal) are calculated using Eq. (2) for present values at an estimate of future inflation, and are then discounted using Eq. (3) to present value at a suitable discount rate. In this paper, the construction cost and end-of-life costs were considered, the operation cost was not considered due to the lack of information for the operation stage.

$$\mathrm{LCC} = \mathrm{C_C} + \mathrm{C_{EOL}} \qquad (1)$$

Where LCC is the total life cycle costs of a flooring system, Cc is the construction costs, Cu is the usage costs, $C_{EOL}$ is the end of life costs.

$$\mathrm{FC} = \mathrm{PV} \times (1 + f)^n \qquad (2)$$
$$\mathrm{DPV} = \mathrm{FC}/(1 + d)^n \qquad (3)$$

Where FC = future cost, PV = present value, DPV = discounted present value, f= inflation rate, d = discount rate, and n = number of years.
The construction costs $C_C$ include the costs of the production and transport of construction materials as well as the labour and energy costs for the construction of the flooring system and developer's profits:

$$\mathrm{C_C} = \mathrm{C_{CM\&T}} + \mathrm{C_{L\&OH}} + \mathrm{C_{MF}} \qquad (4)$$

Where $C_{CM\&T}$ costs of extraction, production, and transport of construction materials $C_{L\&OH}$ labour and overhead costs $C_{MF}$ fuel costs for the machinery used in the construction of the flooring systems.

#### 2.2.7. Impact assessment of the LCC results

The economic performance was evaluated with the beginning of a product purchase and installation. The study period ends at a fixed date in the future when is the end-of-life time for flooring systems. The time value of money was accounted in LCC method by considering a real discount rate. This discount rate converted the future costs to their equivalent present value. The unit costs for flooring system, including installation costs, were extracted from SPON's price books [50]. The end-of-life costs were derived from sources [49, 50, and 51]. A 3.5% real discount rate was used to adjust cash flows to present values with a projection lifetime of 30 years [48]. Table 6 shows the first and future costs for the analysed flooring systems. The construction cost and end-of-life cost of proposed flooring system are less than the Cofradal260 slab costs by about 11% and 42%, and less than the construction and end-of-life costs of hollow composite precast slab by about 13% and 19%, respectively. Figures 11 and 12 show the first and future costs of the studied flooring systems.

Table 6: First and future costs of flooring systems

| Cofradal slab | | | | Hollow composite precast slab with finishing | | | | Proposed flooring system | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Construction phase | | End of life phase | | Construction phase | | End of life phase | | Construction phase | | End of life phase | |
| First (£) | Future (£) | First (£) | Future (£) | First (£) | Future (£) | First (£) | Future (£) | First (£) | Future (£) | First (£) | Future (£) |
| 3079 | 1097 | 294 | 104 | 2727 | 972 | 211 | 75 | 2676 | 953 | 171 | 61 |

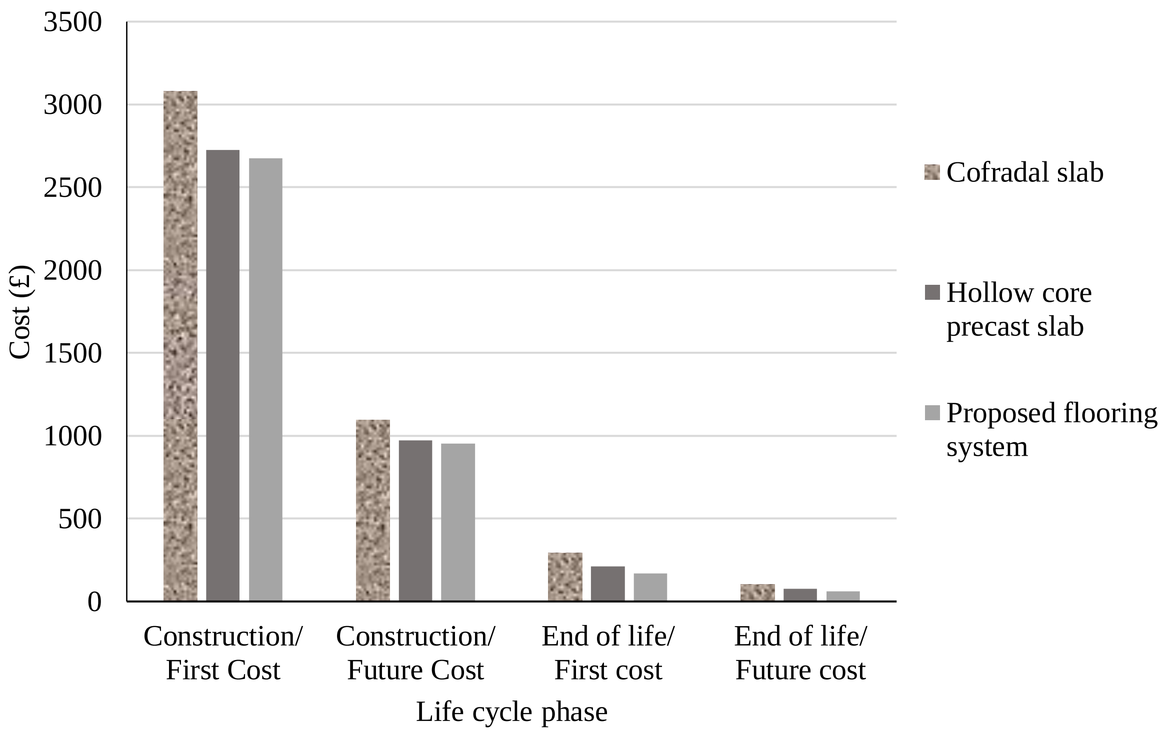


Figure 11: First and Future costs of life cycle phase

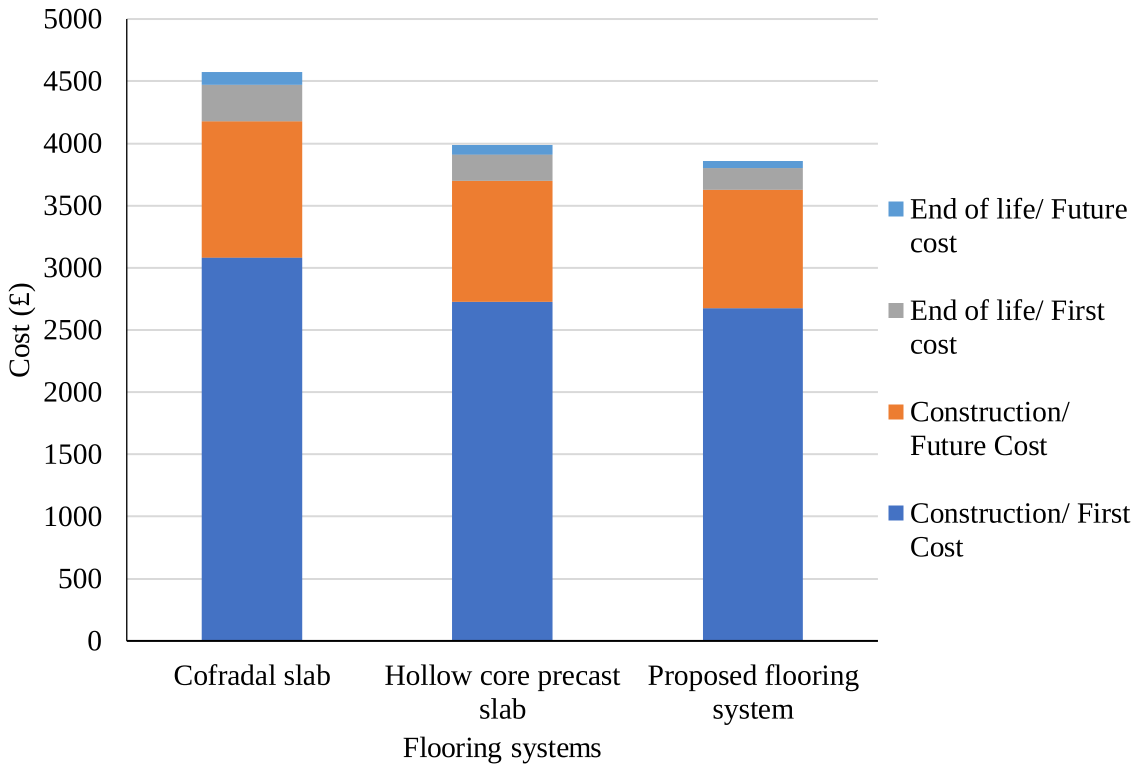


Figure 12: First and Future costs by flooring systems

## 3. Discussion and concluding remarks

The building construction process emits substantial quantities of GHG emissions. Various construction methods generate different amounts of GHG emissions in the construction stage. Prefabrication is an environmentally friendly alternative to traditional construction methods (cast in situ construction methods). Its construction technologies and processes are different from those of the conventional one, as well as its GHG emissions. This study focuses on semi and fully prefabrication methods for flooring systems. The semi-prefabrication method is represented by a hollow core precast flooring system with casting in place finishing layer, whereas the full prefabrication method is represented by the Cofradal flooring system and the proposed prefabricated flooring system (PUSS). Specifically, this study identifies a calculation boundary and five energy consumptions and GHG emission sources for semi and full prefabrication. These include embodied energy and embodied GHG emission of manufacturing, transportation of building materials, transportation of construction waste, transportation of prefabricated components, and the operation of equipment and construction techniques, demolition and reusability. In addition, this study also investigates the life cycle cost of these flooring systems including both the construction and end-of-life phases. A comparison of these flooring systems that adopt semi and fully prefabrications is employed to illustrate the differences and characteristics of energy consumptions, GHG emissions, and cost.

The main contributors of embodied energy and embodied GHG emission are the manufacturing and onsite construction of flooring systems, which accounts for 40.4%. The following contributors are the transportation of building materials and transportation of prefabricated elements, accounting for 5.8%. Results indicate that the proposed fully prefabricated flooring system reduced 28.45% of embodied energy and 43.73% of embodied GHG emissions compared with the Cofradal260 slab, 16.32% of embodied energy and 41.60% of embodied

GHG emissions compared with the hollow composite precast slab for the manufacturing phase. For the onsite construction, the proposed fully prefabricated flooring system reduced 37.5% for both embodied energy and embodied GHG emissions compared with the Cofradal slab, and 53.50% for embodied energy and 53.12% for embodied GHG emissions compared with the hollow composite precast slab. For the transportation, the proposed fully prefabricated flooring system reduced 15.86% for embodied energy and 15.12% embodied GHG emissions compared with the Cofradal slab, and 52.28% for embodied energy and 51.9% for embodied GHG emissions compared with the hollow composite precast slab . Regarding the reusability, the proposed fully prefabricated flooring system has a reduced 9.25% of embodied energy and 15.56% of embodied GHG emissions compared with the Cofradal260 slab. The reduction percentage in embodied energy and embodied GHG emissions for the proposed flooring system compared with the hollow composite precast slab was higher than the Cofradal slab for both transportation and onsite construction phases based on this data analysis. This is related to the fact that hollow composite precast slab is a semi prefabricated slab with a cast in-situ finishing layer while the proposed flooring and Cofradal slabs are fully prefabricated flooring systems including the finishing layer; this raises the amounts of embodied energy and embodied GHG emissions. In contrast, the reduction percentage in embodied energy and embodied GHG emissions for proposed flooring system compared with the Cofradal slab was higher that the hollow composite precast slab for both manufacture and reusability phases. The reason is based on the use of materials with high intensity of embodied energy and embodied GHG emissions such as rock wool insulation material and concrete with high cement content.

The key approach to enhance embodied energy and embodied GHG emissions reduction in semi-prefabrication are reducing the amount of offsite casting work, making reasonable and economically efficient proportions of concrete, and selecting off-site factories that are near the projects or material distribution centres. In the full prefabrication, the main methods to enhance the reduction in embodied energy and embodied GHG emissions reduction are by reducing the amount of used concrete by optimising the design of reinforced concrete through changing the shape such as using ribbed slab in the proposed flooring system, reducing the use of high intensity embodied energy, and embodied GHG emissions' materials - for instance using lightweight aggregate concrete with lower amounts of cement content and recycled aggregate as used in the proposed flooring system, increasing the width of the prefabricated elements this will reduce the amounts of embodied energy and embodied GHG emissions of onsite construction as in increase in the width of the proposed flooring from 1.2m to 2.0m. These aspects will gain increased recognition by more governments and clients as the competition in the prefabrication market increases.

The life cycle cost of these three flooring systems was also investigated in this study. Outcomes show that the proposed flooring system reduced 13.08% of the construction cost and 41.83% of the end-of-life cost in comparison with the Cofradal260 slab, 1.87% of construction cost and 18.95% of end-of-life cost in comparison with the hollow composite precast slab. The reduction percentage of the cost is not too high; this is related to the fact that the life cycle cost study only covers two phases. Therefore, as a further work, it is recommended to extend the life cycle cost of this study to cover the whole phases, which represents a challenging task in finding the necessary data for the whole life cycle cost phases from the industry.

In conclusion, this study has examined the embodied energy and embodied GHG emissions in the semi and fully prefabrication flooring systems in five stages, the life cycle cost in two phases. Analysis of the characteristics and differences of embodied energy and embodied GHG emissions between semi and full prefabrication practice shows the different sources and factors related to emissions. Full prefabrication practice, such as the PUSS system, induces lower energy consumptions, lower emissions, and lower costs compared with the semi and fully prefabrication construction of other currently used systems and makes it a good suggestion for the European building market.

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