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# 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

43 under the Kyoto Protocol to reduce its emissions of the basket of six major greenhouse gases  
44 [3] and has declared its intention to put itself on a path towards a reduction in CO<sub>2</sub> emissions  
45 of 80% by about 2050 [4]. GHG emissions have attracted the most attention from researchers  
46 and policy makers possibly because they can be more readily quantified than other impacts,  
47 however, GHG emissions are just one of a range of parameters that should be considered in  
48 assessing environmental impacts. Others are ozone depletion, water consumption, toxicity,  
49 eutrophication of lakes and rivers, and resource depletion [5, 6 and 7].

50

51 The current practices in architecture and construction sectors are responsible for a high  
52 percentage of the environmental impacts produced by the developed countries [8]. In the  
53 European Union, the construction and building sectors are responsible for about 40% of the  
54 overall environmental burden. The construction and occupation of homes in the UK are  
55 responsible for the consumption of 40% of primary energy in the country [9]. In case the other  
56 30% of the building stock (non-residential) is considered, the impact of buildings is greater  
57 [10].

58

59 Using large quantities of raw materials by the construction industry also involves high energy  
60 consumption. Choosing materials with a high content of embodied energy requires an initial  
61 high level of energy consumption in the building production stage but also determines future  
62 energy consumption in order to fulfil heating, ventilation and air conditioning demands [11].  
63 Concrete is an essential reported construction material with the global annual consumption of  
64 1 ton per capita [12]. It has been identified as a carbon intensive material, while cement being  
65 the key component of concrete as it is responsible for 5–7% of the world's carbon emissions  
66 [11]. The on-site construction process is another source of carbon emission, mostly contributed  
67 from fuel consumption in material transportation and heavy equipment, waste treatment  
68 management and embodied carbon in temporary materials [13].

69

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

76

77 When it comes to flooring systems, Lopez-Mesa et al. [15] claimed that for the case of  
78 residential buildings, the environmental impact of a structure with precast hollow core concrete  
79 floors is 12.2% lower than that with cast-in-situ floors for the defined functional unit using the  
80 life cycle analysis (LCA) methodology. Dong et al. [14] compared the carbon emissions of  
81 precast and traditional cast-in-situ construction methods based on a case study of a private  
82 residential building in Hong Kong and performed an LCA study to consider the system  
83 processes from cradle to end of construction. The comparison was conducted based on eight  
84 scenarios at four levels, for example, cubic meter concrete, precast facade, a group of façade  
85 elements, and an entire apartment. It was found that the precast construction method can lead  
86 to 10% carbon reduction for one cubic meter concrete. Jaillon et al. [16] stated that the use of  
87 precast method could lead to 52% of waste reduction and 70% of timber formwork reduction.  
88 Wong and Tang [17] compared the precast and cast-in-situ concrete with the system boundary  
89 from 'cradle to site' and concluded that the precast method can reduce carbon emissions.  
90 Dobbelsteen et al. [18] found that for the case of office buildings, energy consumption during  
91 building operation accounts, on average, for 77.5% of the environmental impact, whereas the  
92 use of building materials is responsible for 19.5%. It was also found that the supporting

93 structure is responsible for almost 60% of the environmental impact caused by building  
94 materials. Therefore, the supporting structure is responsible for about 11.7% of the whole  
95 environmental impact. Reza et al. [19] investigated three types of block joisted flooring  
96 systems (concrete, clay, and expanded polystyrene (EPS) blocks) using life cycle analysis  
97 (LCA). The selection of three sustainable flooring systems in Tehran (Iran) was based on the  
98 triple-bottom-line (TBL) sustainability criteria. Analytical hierarchy process (AHP) is used as  
99 a multi-criteria decision making technique that helps to aggregate the impacts of proposed (sub)  
100 criteria into a sustainability index (SI) through a five-level hierarchical structure. The detailed  
101 analysis shows that the EPS block is the most sustainable solution for block joisted flooring  
102 system in Tehran.

103  
104 Moreover, the use of lightweight materials in various applications adds great advantages when  
105 compared to heavyweight construction, such as in partition walls as it has been proven that  
106 they constitute to the higher contribution of the overall material inputs in the built environment  
107 [20]. A new lightweight sandwich membrane (new lightweight partition wall) was recently  
108 developed and evaluated using the LCA methodology, which comprises the environmental,  
109 functional and economic life cycle analysis. Two reference partition walls were used to  
110 compare with new lightweight partition wall to identify the advantages of the new lightweight  
111 partition wall: (i) the traditional heavyweight partition wall (hollow brick wall); and (ii) the  
112 lightweight gypsum panels wall (plasterboard wall). From the comparison, it was found that  
113 the new lightweight solution could be more sustainable than both standard solutions of hollow  
114 brick partition walls (HCM), and plasterboard partition walls (LRP).

115  
116 In conclusion, the environmental impact of construction materials does not only depend on the  
117 material itself but also the way the components are put in place, its maintenance requirements  
118 and system's longevity, the travel distance from purchasing to the site, etc. [21]. This means  
119 that the selection of materials and the design of the structural system requires a rigorous LCA  
120 study. As Malin illustrates [22], this type of evaluation is a task for expert scientists and  
121 consulting companies specialised in the environmental impact. The calculation of the  
122 environmental indicators (Life Cycle Impact Assessment - LCIA) requires the detailed  
123 appreciation of the life cycle inventory databases, especially, their composition and the critical  
124 inclusion of the system boundary and allocation rules [23].

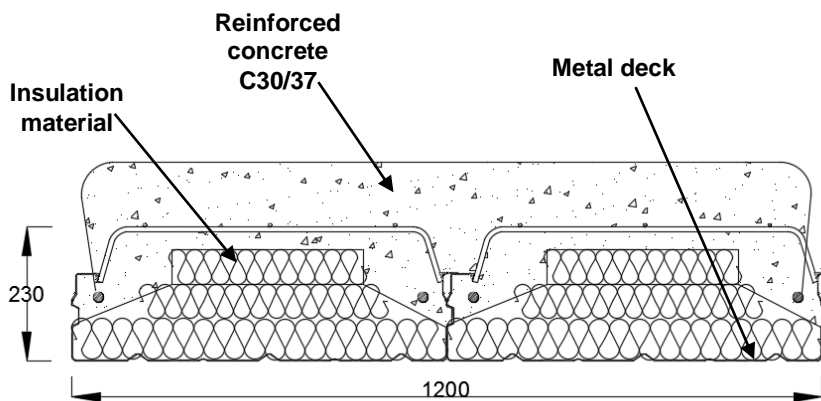
125  
126 When LCA is applied to study a building, the product studied is the building itself, and the  
127 assessment is defined according to a certain level while it contains all material processes. This  
128 level is called "whole process of building" and there is a plethora of available tools to work  
129 at this level, such as BREEAM, (UK) [24]. When the LCA is applied to study a part of the  
130 building, a building component or a material, the level is called "building material and  
131 component combination" (BMCC), and at this case, it is important to recognize the component  
132 impact equivalent according to the functional unit of the building. The functional unit could be  
133 one of many (e.g., m<sup>2</sup>, m<sup>2</sup> internal space, m<sup>3</sup>, each, number of occupants, etc.) in the case of  
134 whole building LCAs. The most commonly used functional unit in the life cycle assessment of  
135 buildings is square meter floor area [24]. It is important to note that all the environmental  
136 impacts calculated within one LCA study should refer to the chosen functional unit.

137  
138 There are a few available life cycle inventory (LCI) databases such as ATHENA, Ecoinvent  
139 version 3.4, and AusLCI [25]. The most recognised databases for material embodied energy  
140 and carbon dioxide in the UK is the Inventory of Carbon and Energy (ICE) Beta 2, developed  
141 by University of Bath [26]. ATHENA is the most suitable for use in the USA and Canada, as  
142 it contains the most comprehensive database of American products and processes. Ecoinvent

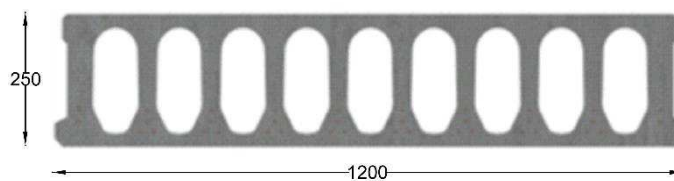
143 contains Swiss and European product and process data. Data quality in LCA studies on  
 144 buildings is a major concern due to the high rate of change and high technical improvements  
 145 in the building industry. Therefore, the age, regional origin, and accuracy of the inventory data  
 146 influence the accuracy and validity of the studies. A major focus over the last two decades in  
 147 Europe, Canada, and the USA has been to produce region-specific LCI databases.  
 148

149 **2. Objectives**

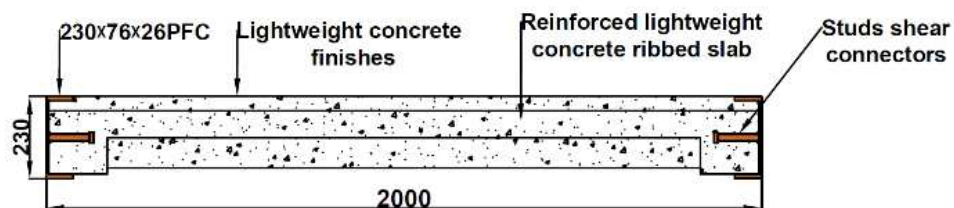
150 This paper studies the ecological impacts of three types of flooring systems used for internal  
 151 floors in buildings and they are evaluated using TRACI method. The first type of the flooring  
 152 system, Cofradal 260mm floor, is a solution used with the Composite Slim Floor Beam (CoSFB)  
 153 in residential buildings. The second type, hollow core precast floor, is used with slimflor beams  
 154 and ultra-shallow floor beams in residential buildings. The third type is a proposed  
 155 prefabricated flooring system, which is developed along with the LCA methodology in terms  
 156 of the materials selection (i.e., lightweight concrete and thin-walled steel). Figs. 1, 2 and 3  
 157 depict the sections of the examined flooring systems [27, 28, 29, and 30]. The recently proposed  
 158 flooring system [29, 30] is also designed in a way to have an efficient transportation and  
 159 installation capacity.  
 160



161 Figure 1: Cofradal 260mm floor section [27]



162  
 163 Figure 2: Hollow core precast floor section [28]



164  
 165  
 166  
 167 Figure 3: Prefabricated ultra-shallow flooring system (PUSS) [29, 30]

### 168 3. Integrated environmental-economic performance

#### 169 3.1. Environmental performance (LCA)

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

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

184

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

189

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

195

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

203

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

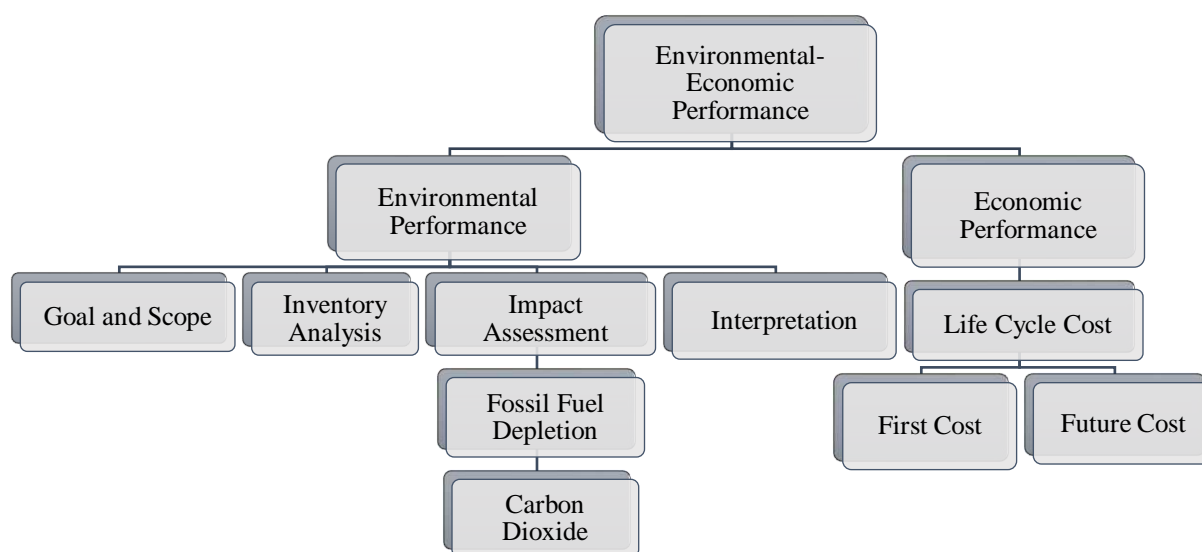
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208 Impact assessment is used by the ISO series 14040 [31-33] to characterize and normalize the  
209 environmental impacts. The first stage of the life cycle impact assessment is to select the impact  
210 categories, category indicators, and characterization. The next stage is to assign the LCI results  
211 to the selected impact categories and the last stage multiplies the inventory results by the  
212 characterization factors. Impact categories are divided into two types; the midpoint categories  
213 and the endpoint categories. Midpoints are concerned with environmental problems whereas  
214 endpoints are concerned with the damage that these environmental problems can cause. In ISO  
215 14042 standard, a distinction is made between obligatory elements, such as the classification

216 and characterization, and optional elements, such as normalisation, ranking, grouping, and  
 217 weighting. According to ISO 14042, the general framework of a life cycle impact assessment  
 218 (LCIA) method is composed with obligatory elements (classification and characterization) that  
 219 convert LCI results into an indicator for each impact category that leads to a unique indicator  
 220 using numerical factors based on value-choices.

221  
 222 (d) The final stage in the LCA is the interpretation, which aims to analyse the results and reach  
 223 the conclusions through explaining the boundaries and providing recommendations. These  
 224 recommendations are based on the outcomes of the previous phase of the LCA or LCI study.  
 225 Life cycle interpretation also intends to provide an easily understandable, complete, and  
 226 harmonious presentation of the results of an LCA or an LCI study, in agreement with the scope  
 227 definition of the study.

228



229

Figure 4: Overall performance steps

230

231

### 232 2.1.1. Existing Standards for LCA

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

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

244

## 245 2.1.2. Scope

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

### 248 2.1.2.1 Functional Unit

249 The functional unit is the unit of comparison in the LCI. In this study, one square meter (m<sup>2</sup>)  
250 of flooring system fulfilling similar requirements regarding a live load of 2kN/m<sup>2</sup> and a span  
251 of 7.8m is chosen. This is chosen according to the maximum span of Cofradal slab which is  
252 7.8m and can take a live load of 2kN/m<sup>2</sup>. Therefore, the same live load was applied for all  
253 studied flooring systems and with the same span regardless their capacity. All emissions,  
254 energy consumption and materials are based on this functional unit, e.g. MJ/m<sup>2</sup>, kg CO<sub>2</sub>e/m<sup>2</sup>  
255 etc.

### 256 2.1.2.2. System Boundaries

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

### 261 2.1.2.3. Definition of Impact Categories and Calculations Methodology

262 The scope step also includes the specification for which impact categories are to be covered in  
263 the impact assessment step. This is typically done by selecting one of the available calculation  
264 methodologies. Each methodology defines the impact categories that are used to generate  
265 results. Some methodologies also define a weighting scheme by which different impact  
266 categories are combined into more generic results. The calculation methods are classified  
267 according to the regions such as European and North American [34].  
268

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

### 272 2.1.2.4. Characteristics of studied flooring systems

273 Shallow-floor construction is characterized by integrating the steel beam into the slab's  
274 thickness. The steel section consists of a hot rolled beam with a welded plate underneath it to  
275 provide the bearing for incoming slabs. The width of the welded plate is larger than the bottom  
276 flange of the hot rolled section, hence the slab elements can be easily placed. The shallow-floor  
277 beam (SFB) can be incorporated into any type of slab. Prefabricated or partially prefabricated  
278 concrete slabs can fit perfectly with the SFB; a quick and safe erection is assured. By using this  
279 type of construction systems the structural depth of the floor is reduced and thus the overall  
280 height of the building is effectively reduced while the total number of floors can be increased  
281 within the predefined allowed building envelope. Mechanical and Electrical (M&E) services  
282 such as cooling and heating devices are quickly installed due to the absence of down stand steel  
283 beams. However, due to the small beam height, the design of the SFB is governed by the  
284 stiffness of the system and hence spans are limited.  
285

286 A good example of slim-floor construction is the Composite Slim Floor Beam (CoSFB) which  
287 has been based on the development of an advanced composite connection by using concrete  
288 dowels. This flooring system has been used with the Cofradal260 slab (composite floor slab)

289 which consists of a cold-rolled metal deck, a thermal insulation layer and a concrete layer  
290 which reduces the overall weight of the flooring system. This flooring system is fully  
291 prefabricated, hence it reduces the energy consumption, CO<sub>2</sub> emissions, construction cost and  
292 potential site repair and maintenance costs are still high.

293

294 Another type of flooring systems which is used with the slimflor beams is the hollow core  
295 precast units. This flooring system contains voids that run continuously along their length,  
296 which helps reduce dead weight and material cost. The construction of the hollow composite  
297 precast slab in the site involves further work to complete the construction, such as placing the  
298 concrete topping layer on site, because it is not a fully prefabricated flooring system, thus the  
299 energy consumption, CO<sub>2</sub> emissions, construction cost and potential site repair and  
300 maintenance costs are still high.

301

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

306

307 The selected flooring systems include:

308 • Cofradal 260mm slab

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

318 • Hollow composite precast slab

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

325 • Prefabricated Ultra-Shallow flooring System (PUSS)

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

333 The proposed flooring system exercises the sustainability approach in the selection of its  
334 components using sustainable materials such as lightweight aggregate concrete (Lyttag

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

343  
 344

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

348

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

Flooring systems	Description	Thickness, width, span, Dimensions	Overall floor weight kN/m <sup>2</sup>	Live load kN/m <sup>2</sup>
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

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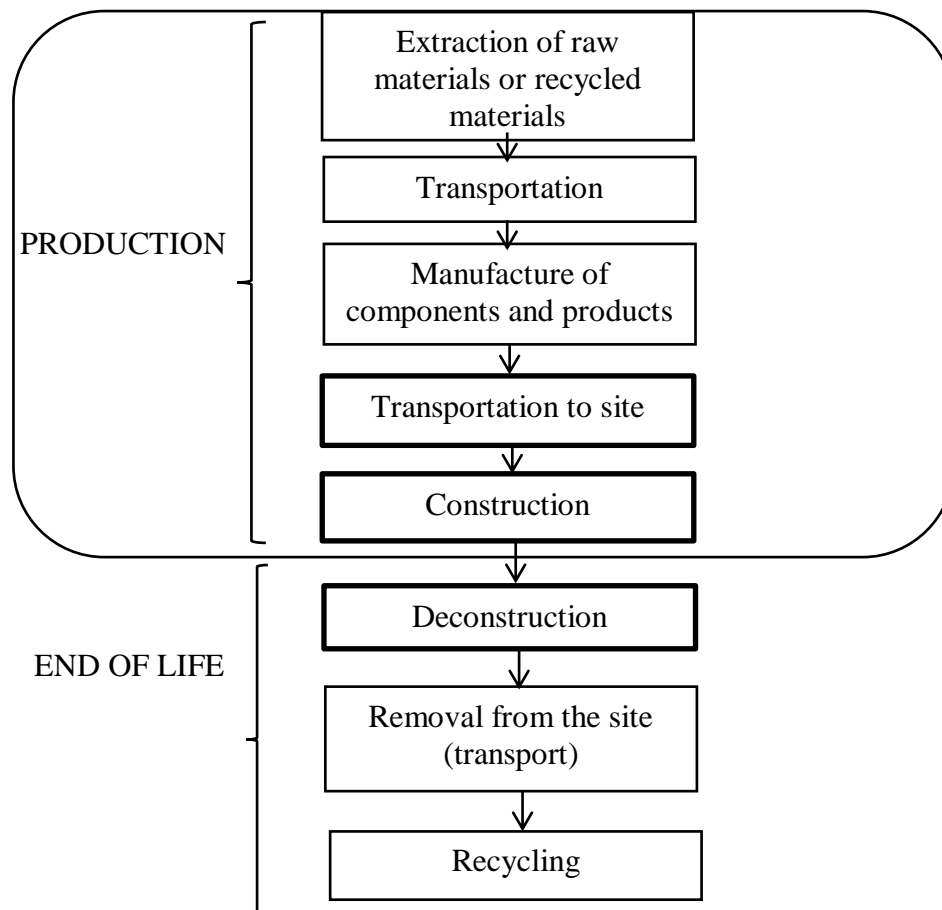


Figure 5: A simplified lifecycle process flow chart showing production boundary for the case study

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357

### 358 2.1.3. Life cycle inventory analysis

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

- 365 • The Inventory of Carbon and Energy [30].
- 366 • Life cycle assessment of concrete, master thesis [36].
- 367 • CO<sub>2</sub> Emissions and energy consumption during the construction of Concrete structures [37].

368

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

372

#### 373 2.1.3.1. Pre-use phase

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

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

380 2.1.3.2. Use and maintenance phase

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

384 2.1.3.3. End of life phase

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

389

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

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Material	Embodied Energy Coefficient (MJ/kg)	Embodied Carbon Coefficient (kg CO <sub>2</sub> 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 <sub>2</sub> e/hr)
Tower crane of 100 ton	720	53.23
Pumps	540	46.12
Equipment	Embodied Energy Coefficient (MJ/m <sup>3</sup> )	Embodied Carbon Coefficient (kg CO <sub>2</sub> e/m <sup>3</sup> )
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 <sub>2</sub> 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

442 flooring system has 817.49 MJ/m<sup>2</sup> lower than the precast flooring system which has 976.96  
 443 MJ/m<sup>2</sup> and lower than the Cofradal flooring system which has 1142.68 MJ/m<sup>2</sup>.

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

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

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

464 • Transportation:

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

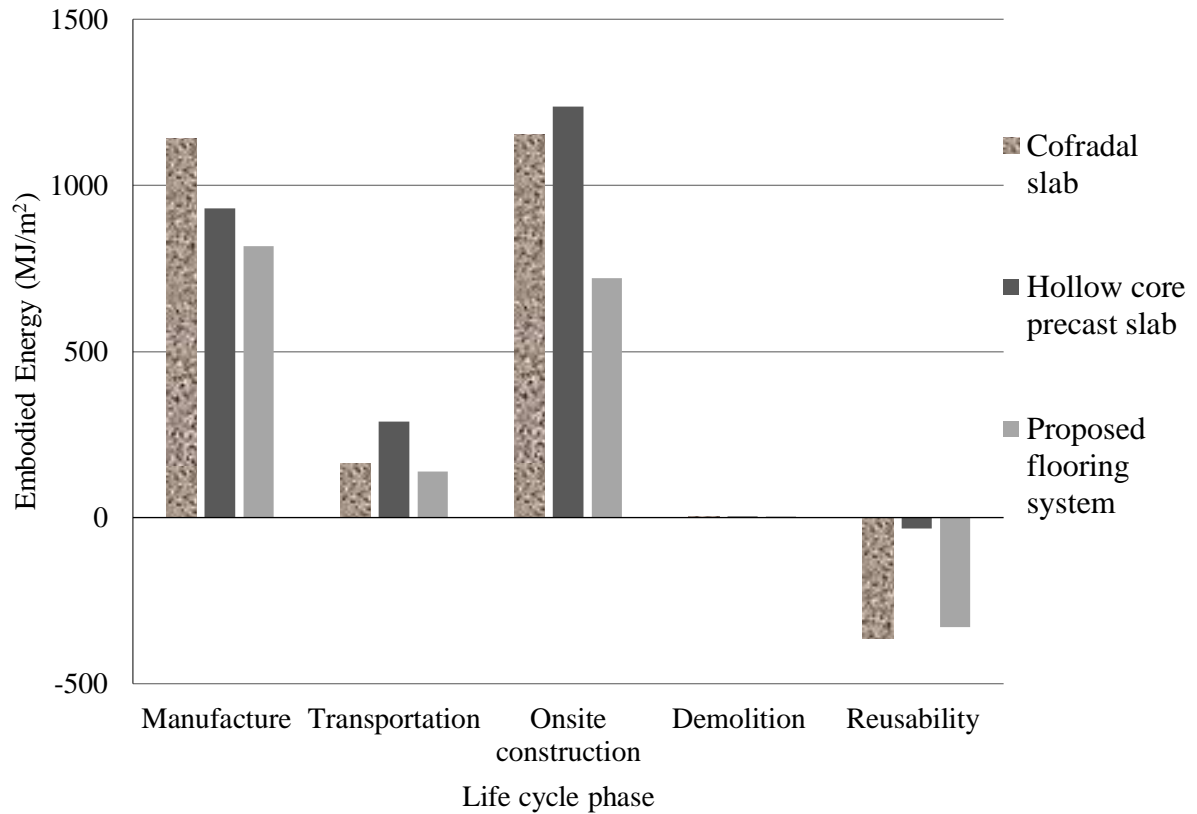
472  
 473 Vukotic et al. [43], reported that the value for transportation of materials to the construction  
 474 site may vary between 7% and 10% of total embodied energy. Zabalza [44], demonstrated that  
 475 this value is approximately 6% of the total embodied energy. In this paper, the values for  
 476 material transportation is 7% of total embodied energy.

477 • Onsite construction equipment:

478 The construction and erection of building assemblies require the use of a range of manual and  
479 power operated tools and equipment such as compressors, saws, welders, and drills [45]. The  
480 values of embodied energy and air emissions of related equipment are derived from source  
481 [37].

482  
483 Figures 6-9 depict the Embodied Energy, Global Warming Potential of the studied flooring  
484 systems.

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Figure 6: Embodied Energy by life cycle phase

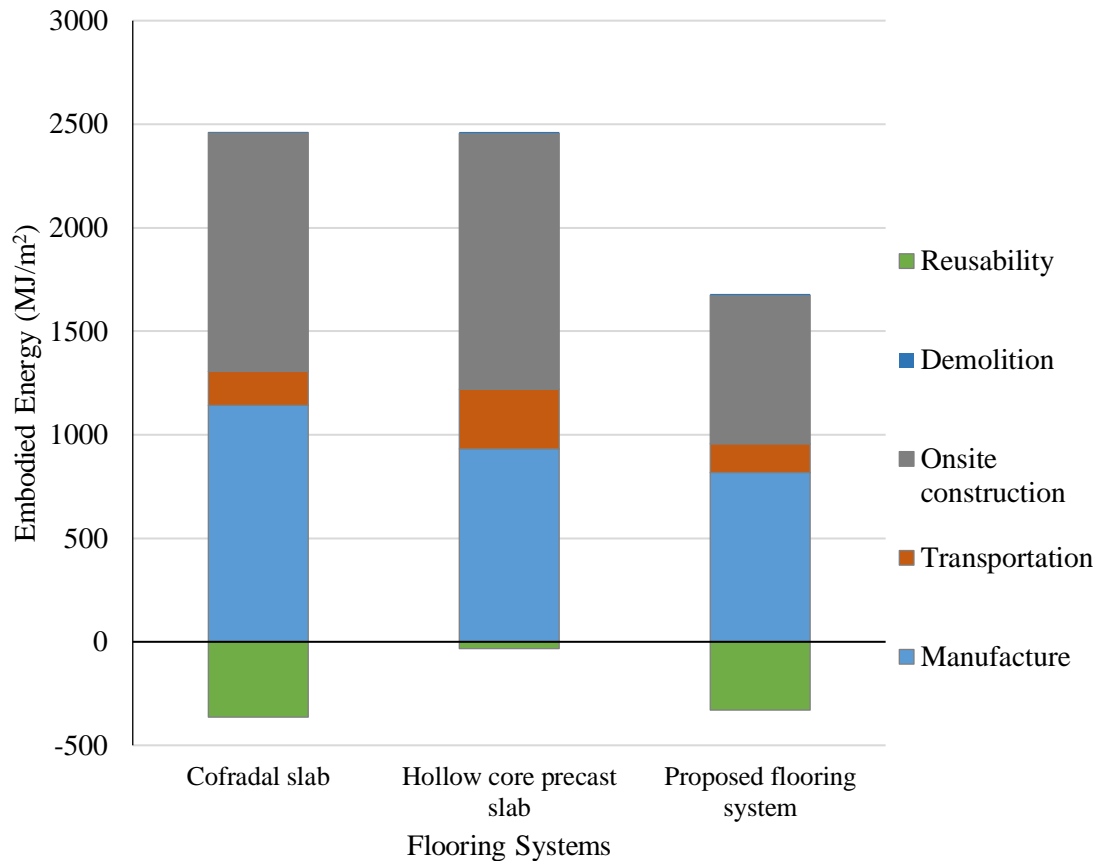


Figure 7: Embodied Energy by flooring systems

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490

#### 491 2.1.4.2. End-of-life

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

499

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

504

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

512

513 Figures 8 and 9 show a breakdown of Global Warming Potential by each phase of the life cycle  
 514 of flooring systems. Proposed flooring system emits less than 60% of the emission of the  
 515 Cofradal260 slab, and less than 65% of the hollow composite precast slab. This is due to the  
 516 energy intensity of reinforced concrete with high cement content.  
 517

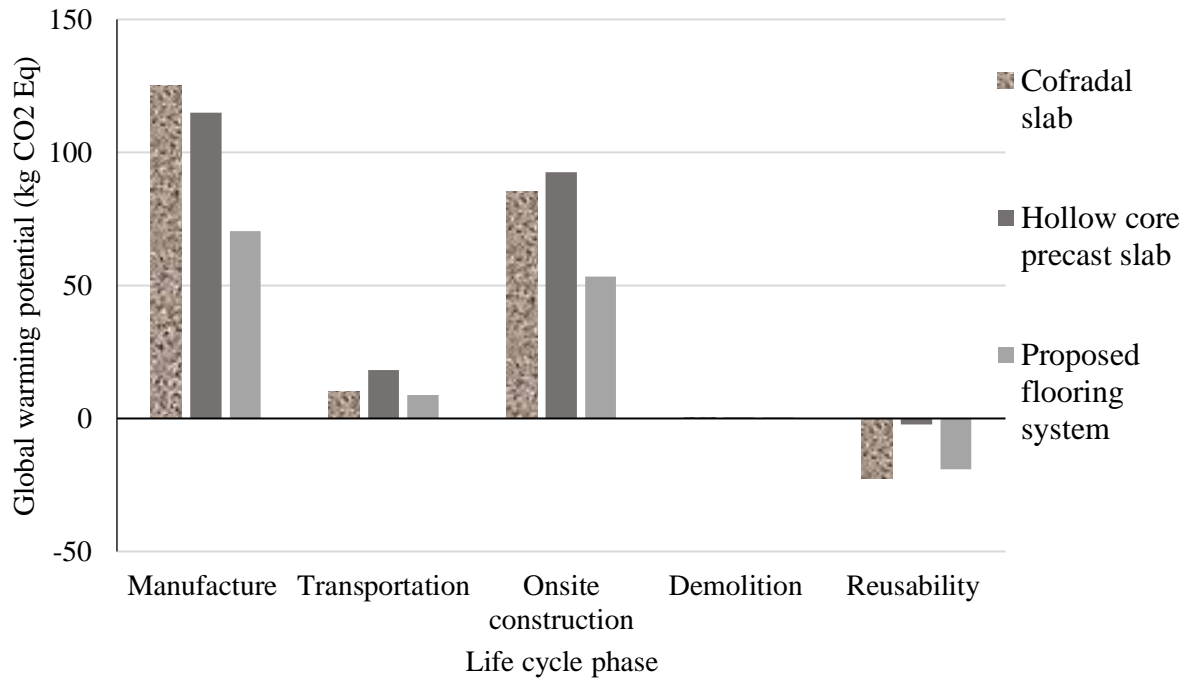


Figure 8: Global Warming Potential by life cycle phase

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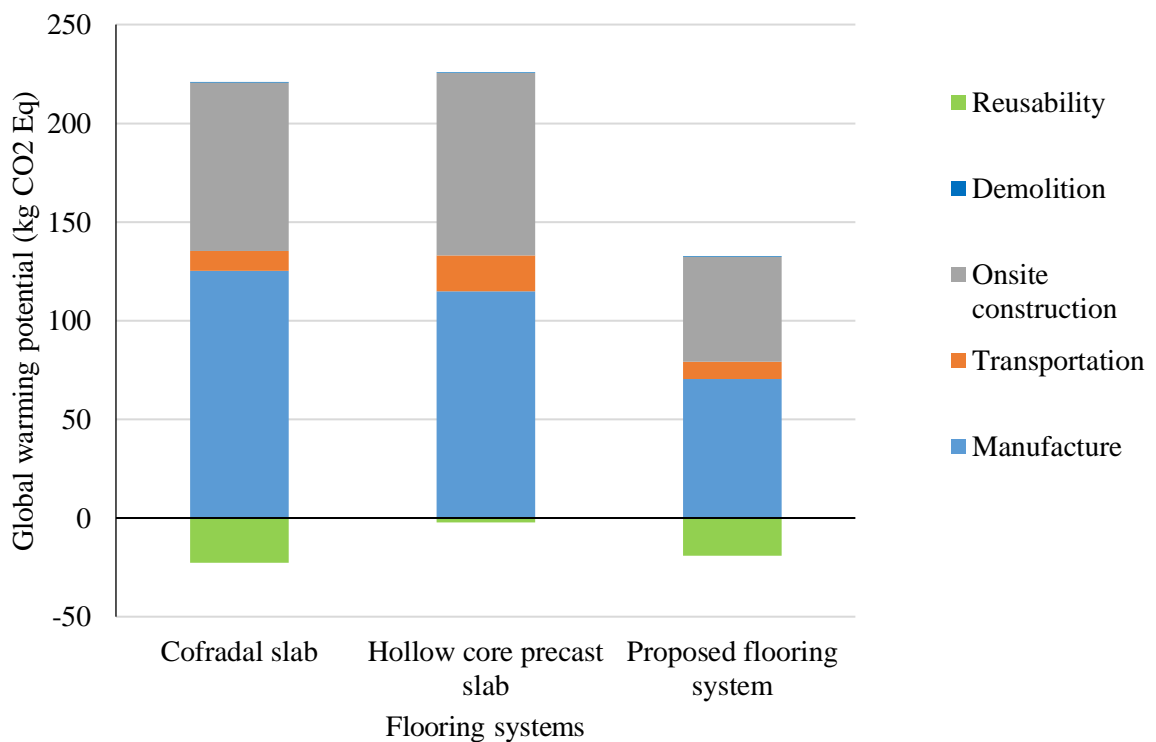


Figure 9: Global Warming Potential by flooring systems

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522     **2.2. Economic performance (LCC)**

523     2.2.1. Importance of LCC

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

532  
533     The economic analysis of building design solutions can be used in two different ways. When a  
534     range of possible designs is still being considered, then life cycle costing can be used as a  
535     comparison tool to work out the life cycle costs of each design as a part of the decision-making  
536     process and select the best alternative. LCC can also be used for predicting and assessing the  
537     cost performance of constructed assets (ISO 15686-5:2008) [47].

538  
539     2.2.2. Existing standards for LCC

540     An international code of practice for life cycle costing is provided by ISO 15686-5 [48] in  
541     relation to the built environment. This code is part of a series of standards covering service life  
542     planning, the long-term understanding of building elements, components, and equipment. ISO  
543     15686-5 makes the distinction between life cycle costing and whole life costing, here explained  
544     in Figure 10.

545  
546     According to the ISO definition, life cycle costing includes the initial construction and through-  
547     life activities associated with a built asset while whole life costing also includes non-  
548     construction activities and income generation such as receiving rent from tenants. The  
549     implication is that life cycle costing will be more relevant to designers, contractors, and facility  
550     or asset managers, whereas whole life costing will be more appropriate to owner-occupiers,  
551     developers, and landlords.

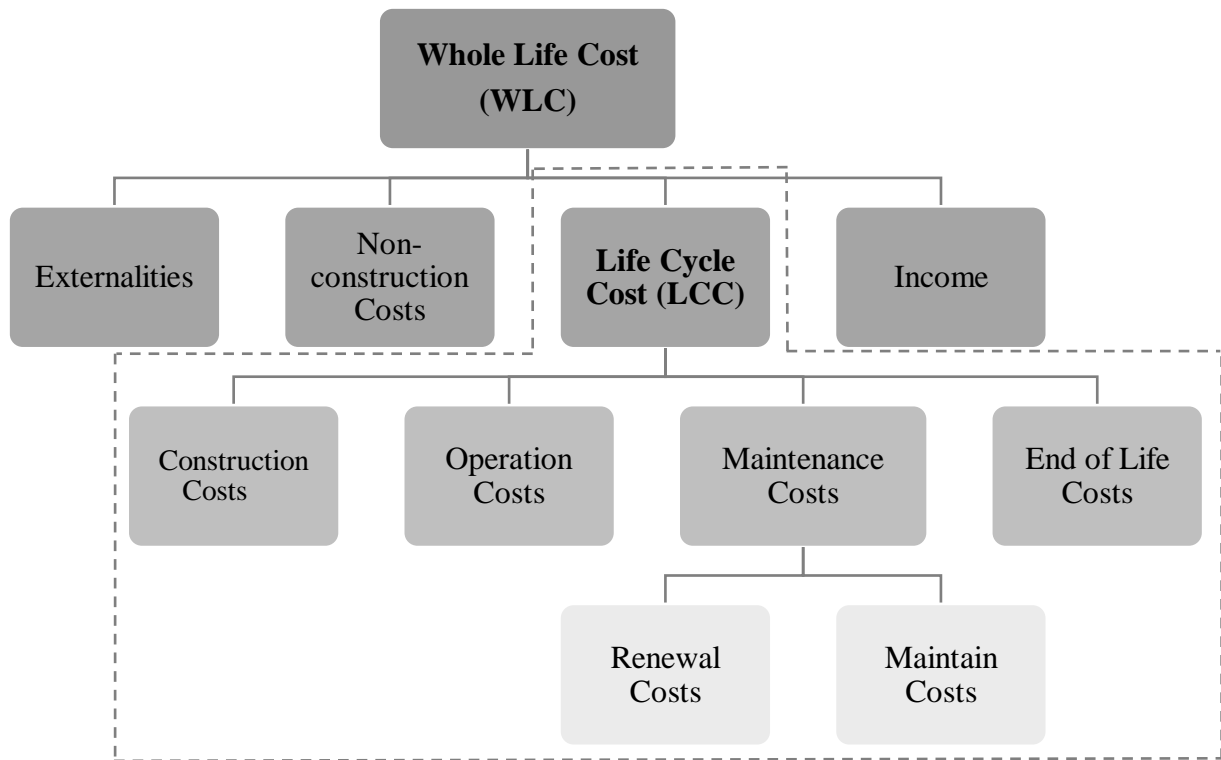


Figure 10: Definitions of whole life cost and life cycle cost based on ISO 15686-5 [43]

552

553

### 554 2.2.3. Discount Rate selection

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

559

560 Therefore, the discount rate is variable in time. In the UK, the Treasury (UK government  
 561 practice) rules specified a discount rate to be used for a given year; similar rates are established  
 562 in other countries [48]. For the life cycle costing on public sector projects, a discount rate of  
 563 3.5% per annum is stipulated by Treasury rules for all projects up to 30 years. For longer  
 564 timescale and public sector projects typically infrastructure buildings, a series of lower  
 565 discounts rates are applied to different project years. This study used a 3.5% discount rate for  
 566 0–30 years, in line with the UK government practice.

### 567 2.2.4. Study period selection

568 The study period is another fundamental factor in the life cycle cost analysis. The usual  
 569 situation is that a single study period is applied to all the alternatives being assessed. There are  
 570 special circumstances when different study periods are applied to different alternatives, but in  
 571 this study, the calculated results must be presented as equivalent annual costs. The study period  
 572 may be defined by the client or may be proposed by the project team. As shall be seen, the  
 573 outcomes of life cycle costing can be extremely sensitive to the study period, and the choice  
 574 should always be backed up with a strong argument. For new build or refurbishment projects,  
 575 study periods of between 15 and 25 years are commonly used, but longer or shorter periods  
 576 can be used. Shorter periods may be used for projects concerned with building services systems

577 or interior fit-out. For the life cycle costing of building services installation, the life expectancy  
578 of the equipment is often used as the study period. Longer periods may be used for  
579 infrastructure works. In all cases, the study period should be informed by the client's business  
580 plan.

#### 581 2.2.5. Costs data collection

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

584

#### 585 2.2.6. Calculations of LCC

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

$$594 \text{LCC} = C_C + C_{\text{EOL}} \quad (1)$$

595 Where LCC is the total life cycle costs of a flooring system,  $C_C$  is the construction costs,  $C_U$  is  
596 the usage costs,  $C_{\text{EOL}}$  is the end of life costs.

$$597 \text{FC} = \text{PV} \times (1 + f)^n \quad (2)$$

$$598 \text{DPV} = \text{FC}/(1 + d)^n \quad (3)$$

599

600 Where  $\text{FC}$  = future cost,  $\text{PV}$  = present value,  $\text{DPV}$  = discounted present value,  
601  $f$  = inflation rate,  $d$  = discount rate, and  $n$  = number of years.

602 The construction costs  $C_C$  include the costs of the production and transport of construction  
603 materials as well as the labour and energy costs for the construction of the flooring system and  
604 developer's profits:

605

$$606 C_C = C_{\text{CM\&T}} + C_{\text{L\&OH}} + C_{\text{MF}} \quad (4)$$

607

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

611

#### 612 2.2.7. Impact assessment of the LCC results

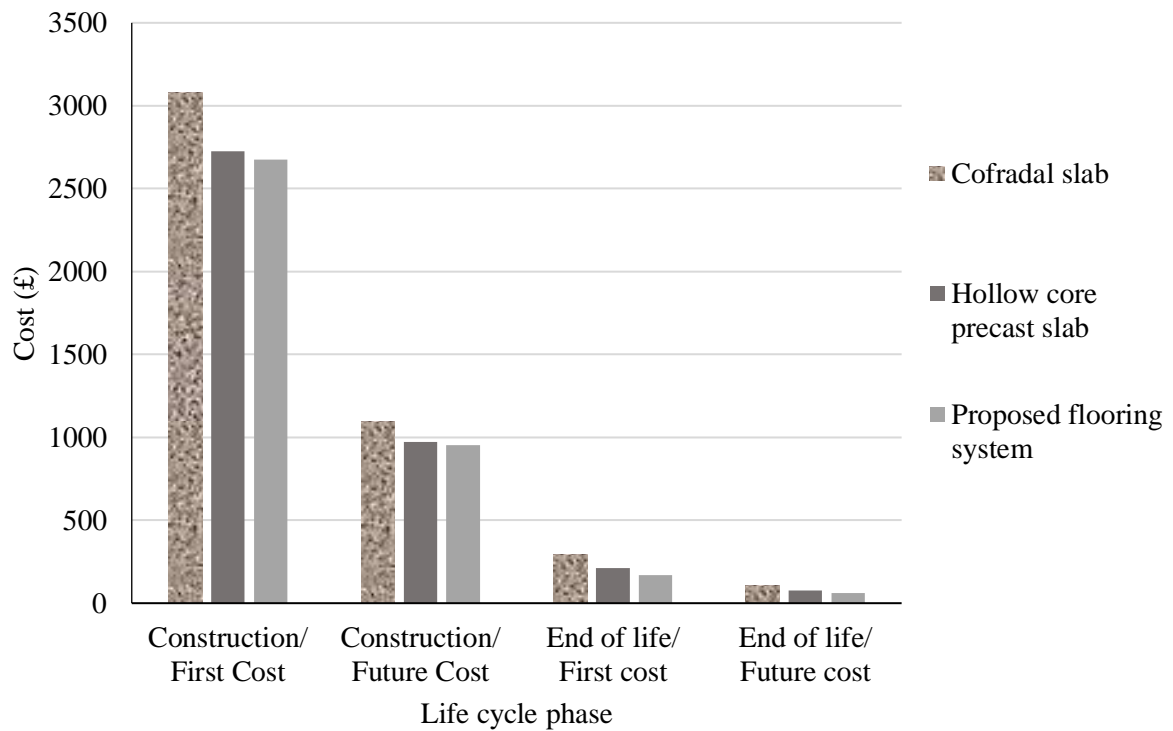
613 The economic performance was evaluated with the beginning of a product purchase and  
614 installation. The study period ends at a fixed date in the future when is the end-of-life time for  
615 flooring systems. The time value of money was accounted in LCC method by considering a  
616 real discount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

622 slab costs by about 11% and 42%, and less than the construction and end-of-life costs of hollow  
 623 composite precast slab by about 13% and 19%, respectively. Figures 11 and 12 show the first  
 624 and future costs of the studied flooring systems.

625 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

626



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Figure 11: First and Future costs of life cycle phase

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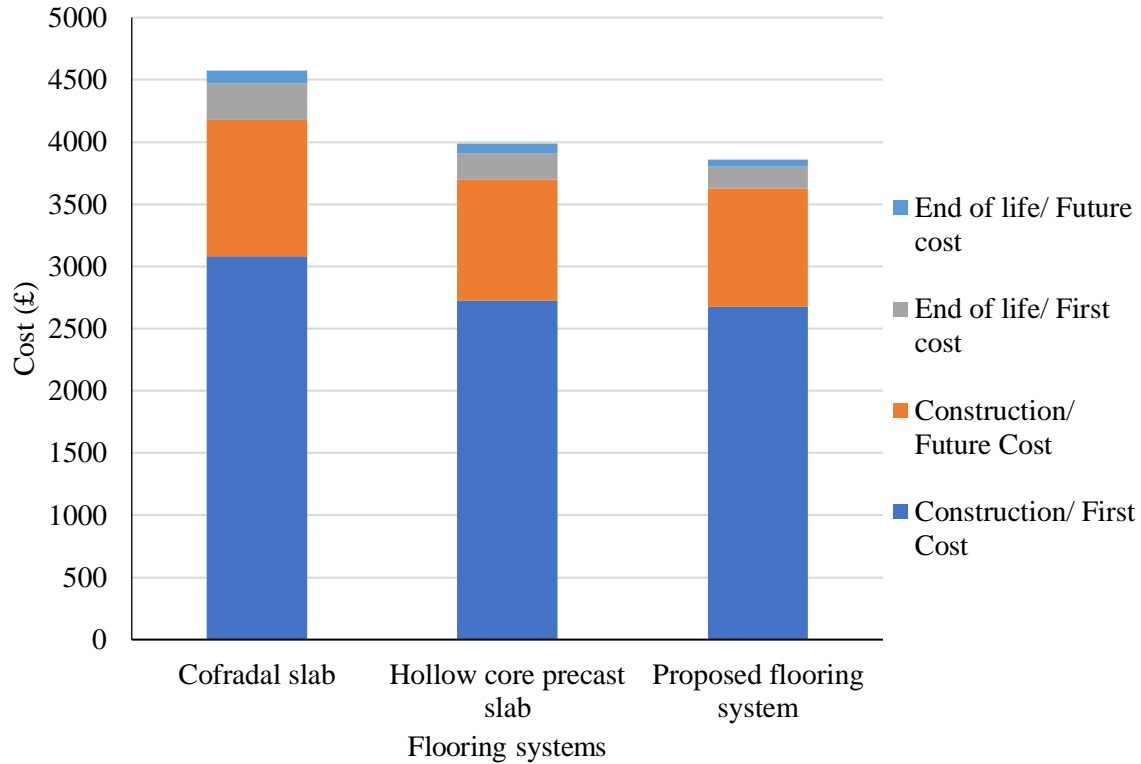


Figure 12: First and Future costs by flooring systems

632

633

### 634 3. Discussion and concluding remarks

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

652

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

659 GHG emissions compared with the hollow composite precast slab for the manufacturing phase.  
660 For the onsite construction, the proposed fully prefabricated flooring system reduced 37.5%  
661 for both embodied energy and embodied GHG emissions compared with the Cofradal slab, and  
662 53.50% for embodied energy and 53.12% for embodied GHG emissions compared with the  
663 hollow composite precast slab. For the transportation, the proposed fully prefabricated flooring  
664 system reduced 15.86% for embodied energy and 15.12% embodied GHG emissions compared  
665 with the Cofradal slab, and 52.28% for embodied energy and 51.9% for embodied GHG  
666 emissions compared with the hollow composite precast slab . Regarding the reusability, the  
667 proposed fully prefabricated flooring system has a reduced 9.25% of embodied energy and  
668 15.56% of embodied GHG emissions compared with the Cofradal260 slab. The reduction  
669 percentage in embodied energy and embodied GHG emissions for the proposed flooring system  
670 compared with the hollow composite precast slab was higher than the Cofradal slab for both  
671 transportation and onsite construction phases based on this data analysis. This is related to the  
672 fact that hollow composite precast slab is a semi prefabricated slab with a cast in-situ finishing  
673 layer while the proposed flooring and Cofradal slabs are fully prefabricated flooring systems  
674 including the finishing layer; this raises the amounts of embodied energy and embodied GHG  
675 emissions. In contrast, the reduction percentage in embodied energy and embodied GHG  
676 emissions for proposed flooring system compared with the Cofradal slab was higher than the  
677 hollow composite precast slab for both manufacture and reusability phases. The reason is  
678 based on the use of materials with high intensity of embodied energy and embodied GHG  
679 emissions such as rock wool insulation material and concrete with high cement content.

680

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

695

696 The life cycle cost of these three flooring systems was also investigated in this study. Outcomes  
697 show that the proposed flooring system reduced 13.08% of the construction cost and 41.83%  
698 of the end-of-life cost in comparison with the Cofradal260 slab, 1.87% of construction cost and  
699 18.95% of end-of-life cost in comparison with the hollow composite precast slab. The  
700 reduction percentage of the cost is not too high; this is related to the fact that the life cycle cost  
701 study only covers two phases. Therefore, as a further work, it is recommended to extend the  
702 life cycle cost of this study to cover the whole phases, which represents a challenging task in  
703 finding the necessary data for the whole life cycle cost phases from the industry.

704

705 In conclusion, this study has examined the embodied energy and embodied GHG emissions in  
706 the semi and fully prefabrication flooring systems in five stages, the life cycle cost in two  
707 phases. Analysis of the characteristics and differences of embodied energy and embodied GHG  
708 emissions between semi and full prefabrication practice shows the different sources and factors

709 related to emissions. Full prefabrication practice, such as the PUSS system, induces lower  
710 energy consumptions, lower emissions, and lower costs compared with the semi and fully  
711 prefabrication construction of other currently used systems and makes it a good suggestion for  
712 the European building market.

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