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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 CO₂ 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].

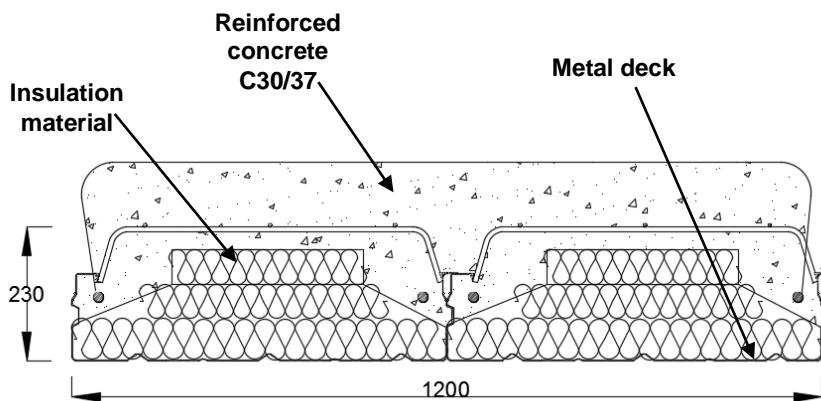
125
126 When LCA is applied to study a building, the product studied is the building itself, and the
127 assessment is defined according to a certain level while it contains all material processes. This
128 level is called "whole process of building" and there is a plethora of available tools to work
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^2 , m^2 internal space, m^3 , 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

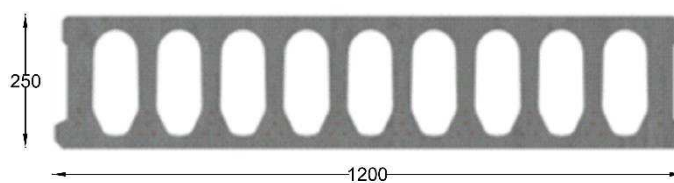
143 contains Swiss and European product and process data. Data quality in LCA studies on
 144 buildings is a major concern due to the high rate of change and high technical improvements
 145 in the building industry. Therefore, the age, regional origin, and accuracy of the inventory data
 146 influence 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**

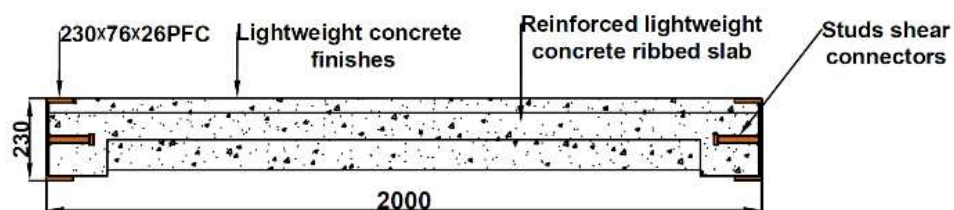
150 This paper studies the ecological impacts of three types of flooring systems used for internal
 151 floors in buildings and they are evaluated using TRACI method. The first type of the flooring
 152 system, Cofradal 260mm floor, is a solution used with the Composite Slim Floor Beam (CoSFB)
 153 in residential buildings. The second type, hollow core precast floor, is used with slimflor
 154 beams 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 m² 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

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

204

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

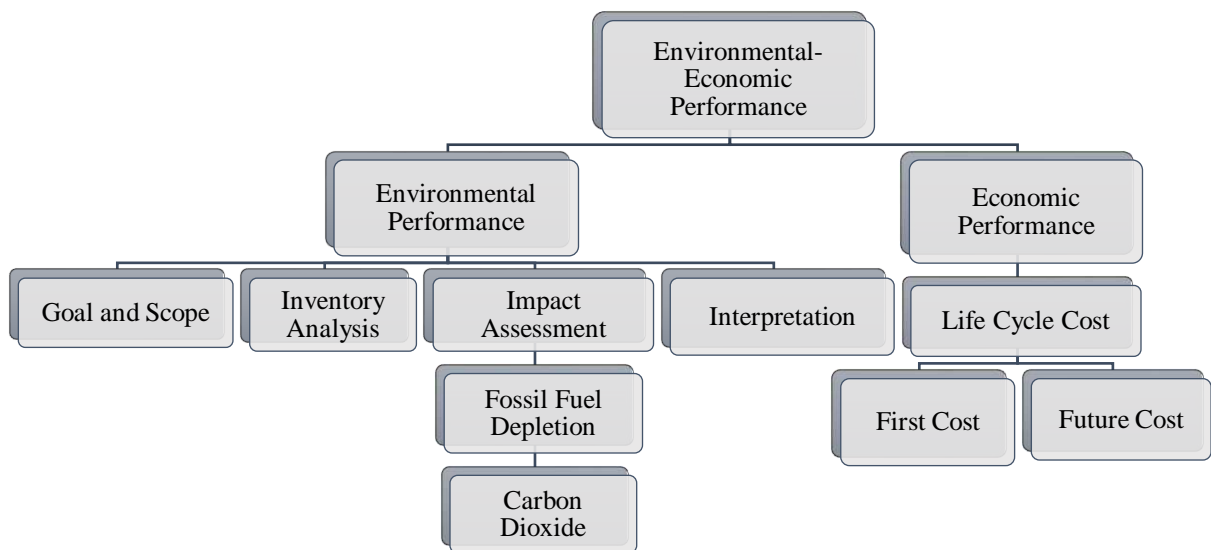
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209 Impact assessment is used by the ISO series 14040 [31-33] to characterize and normalize the
210 environmental impacts. The first stage of the life cycle impact assessment is to select the impact
211 categories, category indicators, and characterization. The next stage is to assign the LCI results
212 to the selected impact categories and the last stage multiplies the inventory results by the
213 characterization factors. Impact categories are divided into two types; the midpoint categories
214 and the endpoint categories. Midpoints are concerned with environmental problems whereas
215 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

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 (m²)
250 of flooring system fulfilling similar requirements regarding a live load of 2kN/m² 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/m². 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/m², kg CO₂e/m²
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, CO₂ 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, CO₂ 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/mm²
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/m³ 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/m² 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 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

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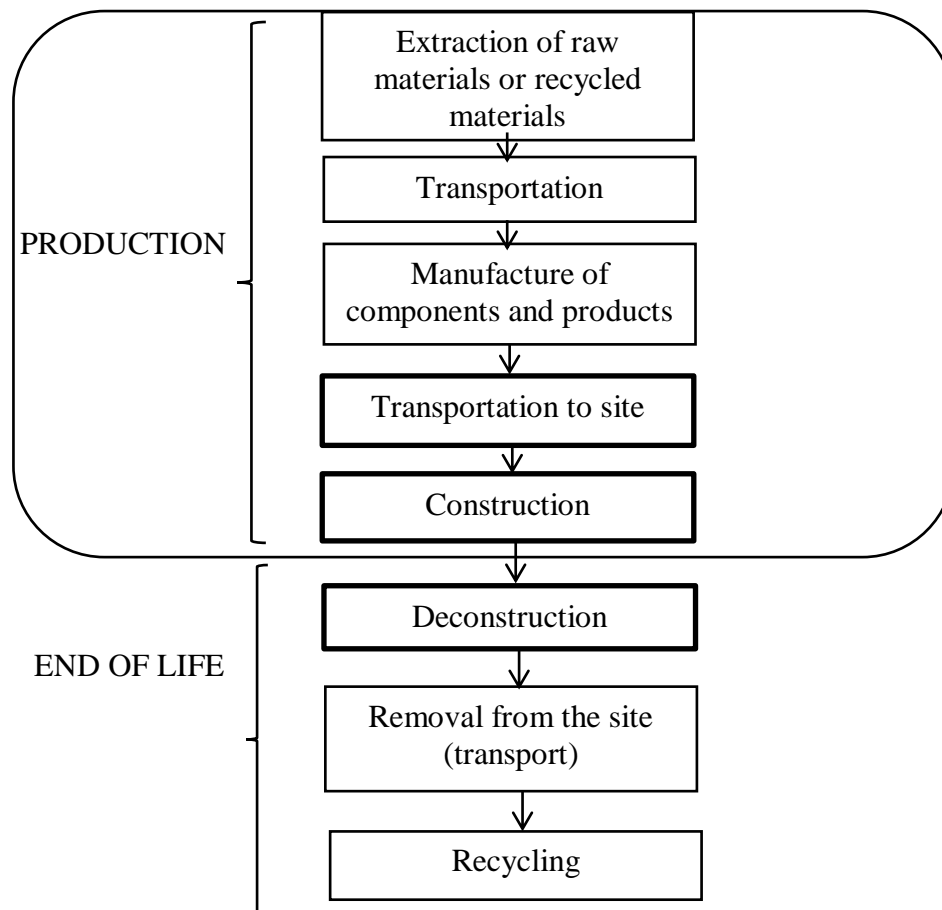


Figure 5: A simplified lifecycle process flow chart showing production boundary for the case study

356

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 • CO₂ 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 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

442 flooring system has 817.49 MJ/m² lower than the precast flooring system which has 976.96
 443 MJ/m² and lower than the Cofradal flooring system which has 1142.68 MJ/m².

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 ²)	Global Warming Potential (kg CO ₂ Eq/m ²)
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/m², 296.96 MJ/m² for the hollow composite precast slab
 470 values and 138.07 MJ/m² for the proposed flooring system - representing approximately 7% of
 471 total embodied energy.

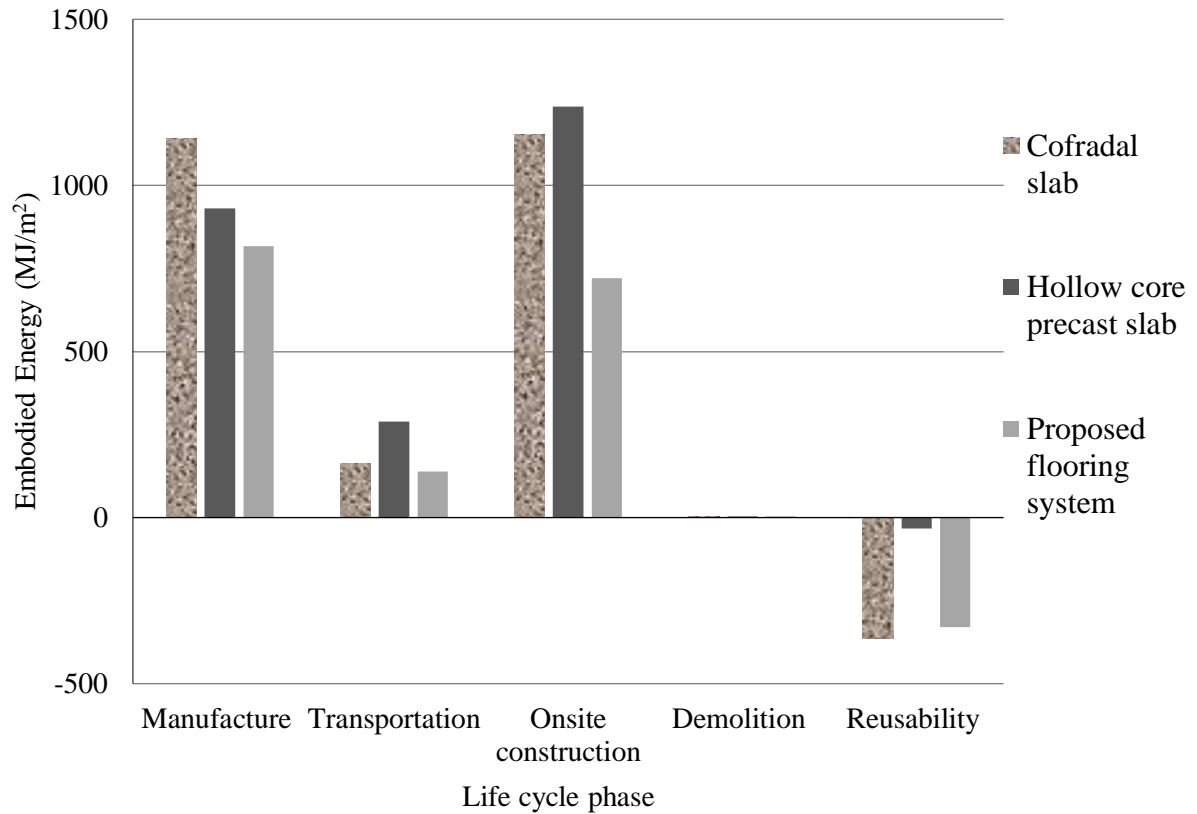
472
 473 Vukotic et al. [43], reported that the value for transportation of materials to the construction
 474 site may vary between 7% and 10% of total embodied energy. Zabalza [44], demonstrated that
 475 this value is approximately 6% of the total embodied energy. In this paper, the values for
 476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

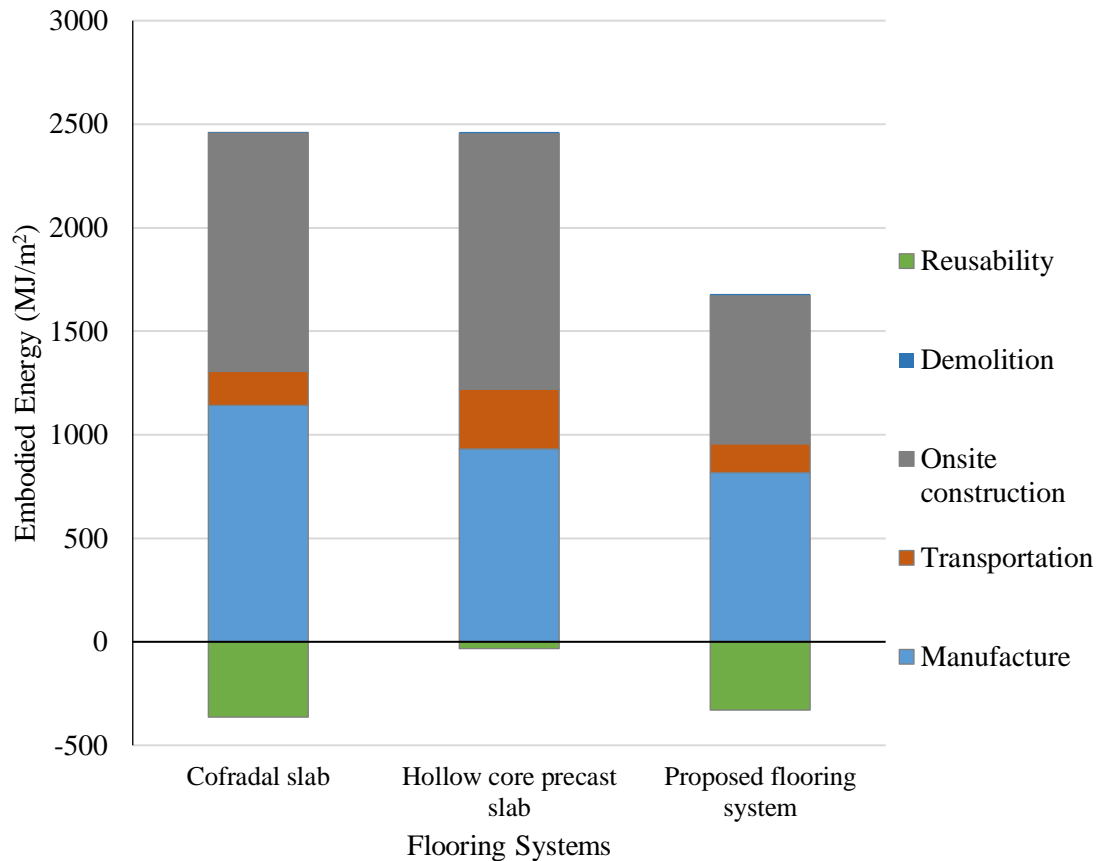


Figure 7: Embodied Energy by flooring systems

489

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/m², 33.66 MJ/m², and 329.96 MJ/Mm² 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

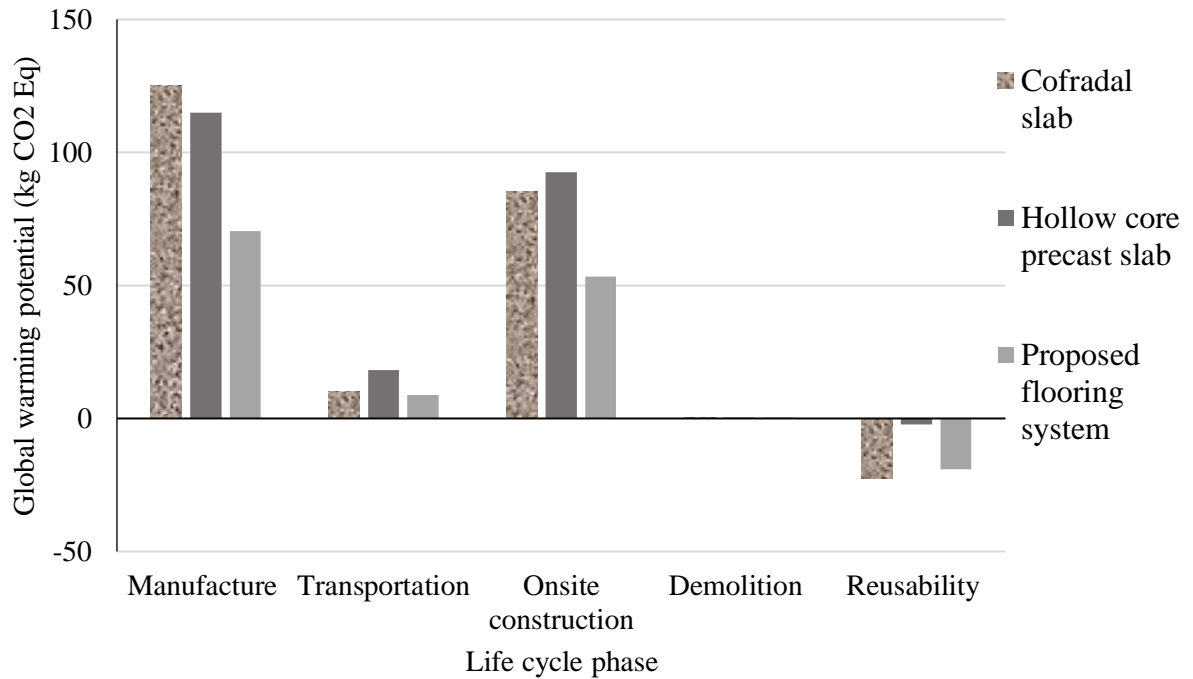


Figure 8: Global Warming Potential by life cycle phase

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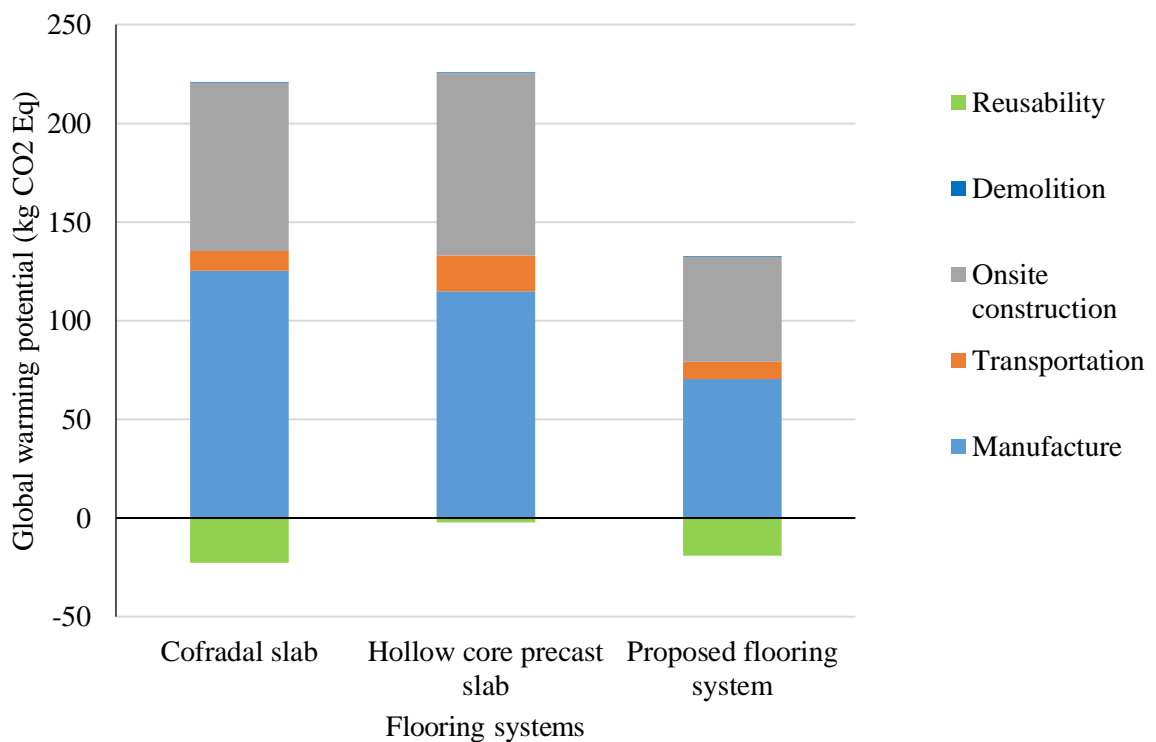


Figure 9: Global Warming Potential by flooring systems

520
 521

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.

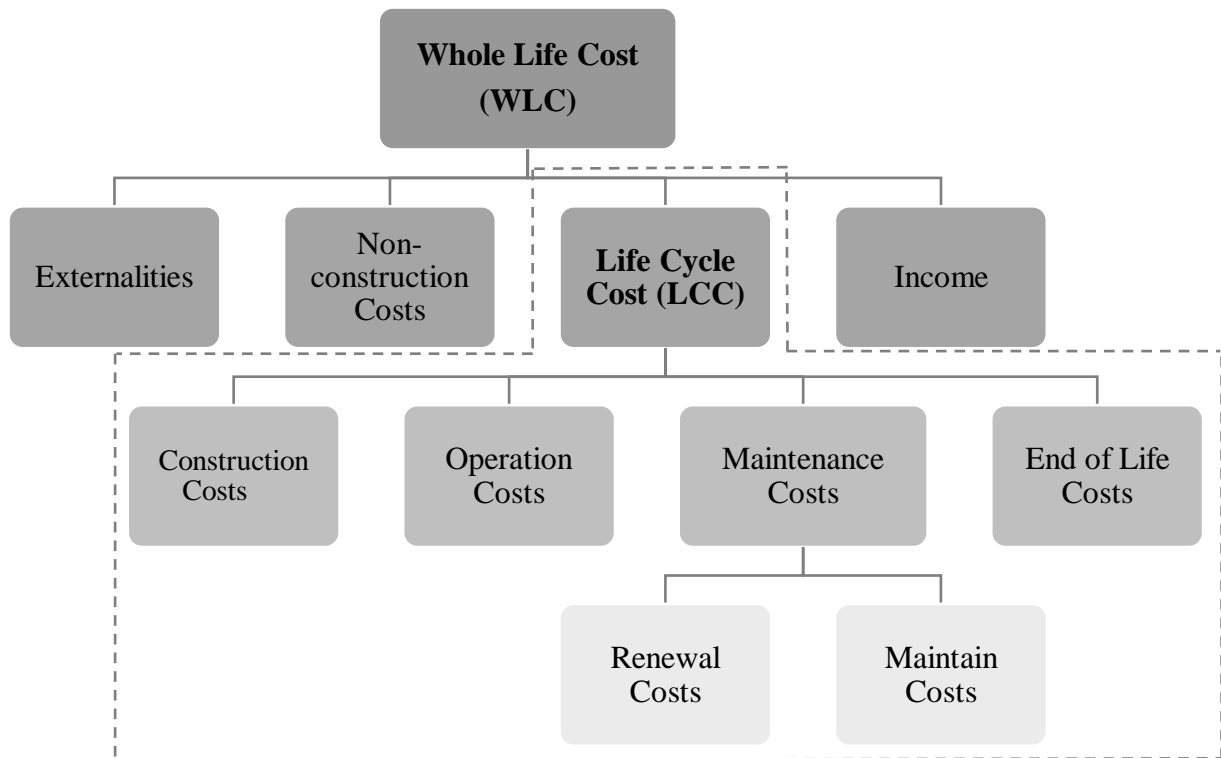


Figure 10: Definitions of whole life cost and life cycle cost based on ISO 15686-5 [43]

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_{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 FC = future cost, PV = present value, 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_{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

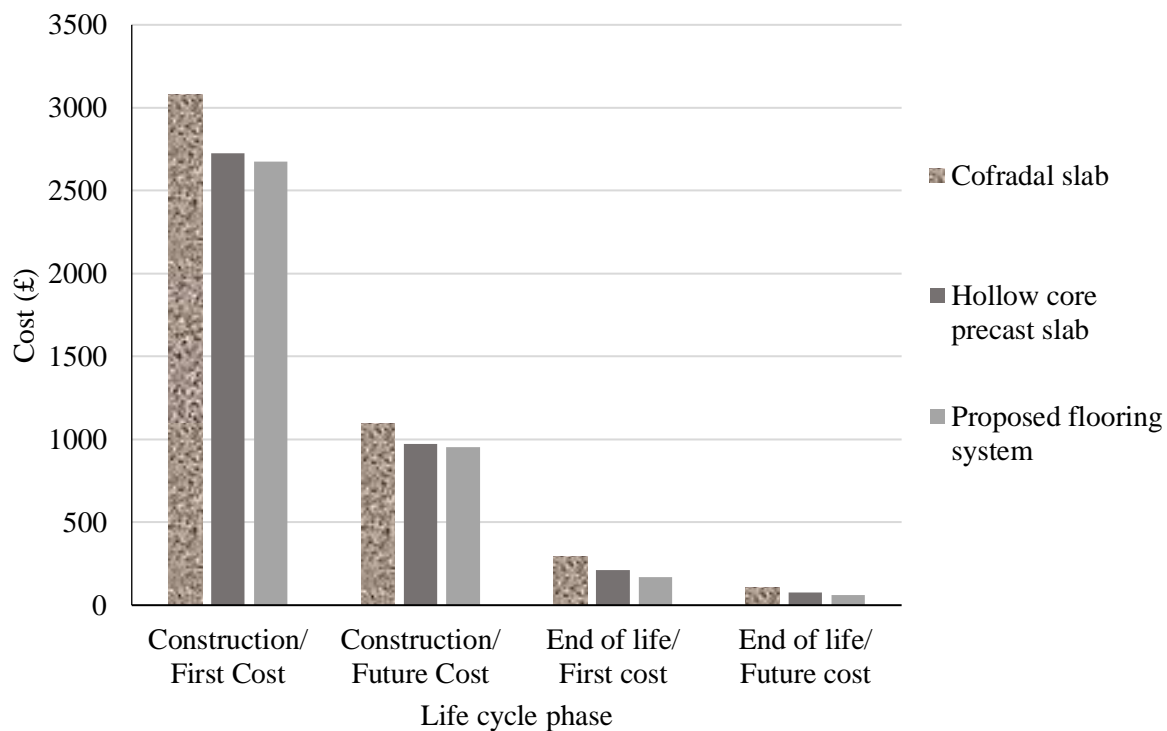
613 The economic performance was evaluated with the beginning of a product purchase and
614 installation. The study period ends at a fixed date in the future when is the end-of-life time for
615 flooring systems. The time value of money was accounted in LCC method by considering a
616 real discount rate. 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



627

Figure 11: First and Future costs of life cycle phase

628

629

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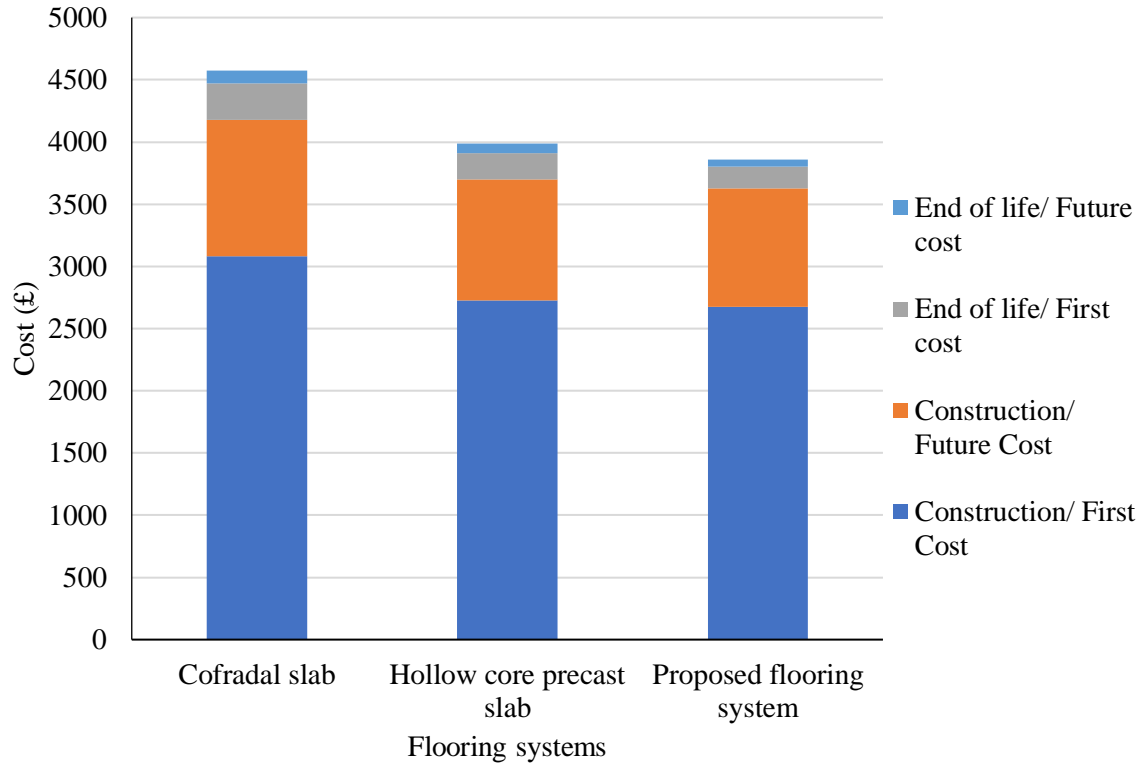


Figure 12: First and Future costs by flooring systems

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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