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Comparative life cycle assessment (LCA) of the composite prefabricated ultra-shallow slabs (PUSS) and hollow core slabs in the UK

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ABSTRACT

Life cycle assessment studies of precast construction methods highlight their superiority over traditional cast-in-situ construction in reducing buildings' environmental impacts. Among the extensively used precast structural elements, hollow core precast slabs have proven benefits with their practical implementation in flooring systems across various flooring spans and live loads. This paper presents a case study comparing the global warming potential and embodied energy impacts of a recently developed lightweight prefabricated composite flooring system (PUSS) with zinghollow core precast slabs in the UK. The analysis is based on 16 live load/flooring span scenarios, between 6 and 12m. The study examines the benefits and drawbacks of utilising different concrete types in PUSS flooring, namely normal weight concrete, lightweight aggregates concrete and geopolymer concrete. PUSS with GPC demonstrates potential savings of up to 50 % in GWP compared with hollow core slabs, while PUSS with LWC exhibits potential savings of up to 35 % in total EE compared with hollow core slabs.

1. Introduction

Over the previous decades, a continuous degradation of the environment was associated with the accelerated economic growth because of the substantial use of natural resources. Some of the key concerns of environmental impacts linked to this development include the extent of energy usage (embodied energy) and the climate change, primarily attributed to the release of greenhouse gases (GHGs). The rise of the GHGs concentration in the atmosphere is directly correlated with the annual increase of temperature, with carbon dioxide identified as the most significant anthropogenic GHG [1].

To achieve the global goals of controlling and assessing the emissions of GHGs, researchers and manufacturers are exploring the possibility of implementing more environmentally friendly practices and materials in every industry, including the construction industry. GHGs emissions are more readily quantified compared with other environmental impacts due to the availability of extensive inventory databases. This abundance of data facilitates more detailed and accurate research, making the study of GHGs emissions a prominent focus in environmental research. However, it is just one of several impact categories that should be considered in evaluating

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the environmental impacts, such as ozone depletion, eutrophication, acidification and human toxicity. Unfortunately, there is some shortage in data and inventories of some of these impact categories for specific construction materials and equipment [2–6].

1.1. Role of sustainable buildings

Achieving the net zero GHGs goal by 2050 is a collective responsibility shared by many stakeholders in the construction sector, starting from government authorities to on-site labours. Designers and engineers play a crucial role in mitigating impacts by focusing on sustainable design and sustainable construction practices of structural elements that lead to the reduction of the consumption of materials, especially materials with high carbon footprint [7].

Material selection is one of the main factors affecting the overall energy consumption and GHGs emissions of buildings. Construction industry is a primary consumer of the global materials, counting for around 40 % of the global consumption [8]. Thus, it is responsible for a huge proportion of the GHGs emissions and other environmental impacts. In addition, the cement industry alone is responsible for about 7 % of the worldwide carbon footprint [9]. Due to the huge demand for cement in construction projects, the world production of this construction material increases by around 7 % per annum compared with other materials [10]. Therefore, it is necessary to partially replace cement with alternative cementitious materials derived from industrial by-products, particularly ground granulated blast furnace slag (GGBS) and fly ash (FA). Additionally, the use of diverse recycled materials can serve as substitutes for aggregates, thereby diminishing the requirement for extracting aggregates through quarrying [11].

The utilisation of geopolymer concrete (GPC) within the construction industry represents a promising sustainable practice and an interesting area of research focused on developing innovative products derived from industrial by-products and wastes. GPC is produced by substituting the traditional Portland cement with geopolymer binders, which are made by activating aluminosilicate materials with alkaline solutions, such as sodium hydroxide (NaOH). Industrial materials like FA and GGBS have emerged as primary source materials for GPC due to their abundant alumina-silica compounds [12–14]. Extensive research has explored various geopolymer cements and concrete blends, revealing favourable properties such as high mechanical and chemical performance [15–20]. However, it is essential to note that the environmental impact of GPCs can significantly differ based on their specific compositions. Salas et al. [21] compared different GPC designs documented in the literature. The findings indicated a substantial variation in carbon emissions associated with producing 1m^3 of GPC, ranging from approximately 100 to over 300 kg $CO_{2,e}$.

Several studies have highlighted the benefits of employing lightweight over heavyweight materials in various construction applications. Mateus et al. [22] demonstrated the sustainability of lightweight materials in partition walls. The LCA study analysed and compared the environmental, economic, and functional life cycles of ten design alternatives for a new lightweight sandwich membrane (LSM) wall with two conventional partition wall systems: the traditional heavyweight conventional masonry partition wall (HCM) and the lightweight reference plasterboard partition wall (LRP). The comparison revealed the potential of the new lightweight solution to be more sustainable than both traditional systems, reducing the associated GWP by up to 85 % and 60 % in comparison to HCM and LRP, respectively.

On-site construction is another major contributor to energy consumption and CO_2 emissions, primarily for material transportation, heavy machinery, waste, and temporary materials [8]. Prefabrication is a process that demonstrated efficacy in reducing on-site construction, improving quality control and site safety, and mitigating environmental impacts, construction time, and labour requirements [11]. Dong et al. [8] conducted a LCA using cradle-to-site approach, comparing the carbon emissions of precast and traditional cast-in-situ construction for a residential building in Hong Kong. The study reported a 10 % reduction in carbon emissions for the precast method. Regarding flooring systems, López-Mesa et al. [23] found similar LCA outcomes, stating that residential structures with precast hollow core concrete floors have 12.2 % lower environmental impacts compared with those with cast-in-situ floors. This reduction is attributed to the diminished use of timber formwork in precasting, leading to reduced waste and carbon emissions compared with cast-in-situ methods [24,25].

In summary, the environmental impact of the construction process is influenced not only by the chosen material but also by factors such as construction procedures, component assembly methods, maintenance needs, transportation, and more. Thus, a thorough LCA study is essential to inform decision-making in material selection and structural design. Comparative LCA studies are widely utilised to assess the environmental impacts of alternative building materials and components based on equivalent functional behaviours. For instance, Anderson et al. [26] examined the effect of compression resistance and material mix design on the embodied carbon of concretes. Similarly, Hill et al. [27] and Grazieschi et al. [28] assessed how density and weight influence the environmental footprint of insulation panels with similar thermal resistance. Additionally, Asdrubali et al. [29] explored how factors like maintenance requirements, disassembly potential, and durability affect the life cycle impacts of walls that share comparable thermal performance and superficial mass. Furthermore, Hahnel et al. [30] analysed the effects of material selection on the environmental impacts of floors having similar structural performance. These studies underscore the importance of comparative assessments in identifying the most sustainable building practices.

1.2. Development of novel flooring systems

Flooring systems play a pivotal role in building's weight and material usage, necessitating a shift towards lighter systems to mitigate environmental impacts. Over the last decade, there has been a transition from traditional downstand steel beams to lighter, shallower, and often aka 'plug' composite systems, where the concrete slab sits at the bottom flange [31–33]. Research on these shallow systems expands on their vibration performance due to their thin and wide nature [34,35], and also on their fire performance as in these systems, the steel is partially protected by the concrete [36–38].

The growing call for sustainable practices has led to the development of innovative integrated floor slabs that enable wide spans and integrated building services. Various flooring systems have been developed, that offer advantages for residential and office buildings, malls and airport structures. Notably, slim floor construction, characterised by the integration of steel beams into slabs, has emerged as a focal point of research and resulted in the development of various products. This construction approach combines the benefits of prefabricated slab elements with steel-framed construction, resulting in an economically viable building solution that effectively meets the demands outlined above [39].

The industry's focus on achieving increased spans with minimal structural depth and flooring weight aligns with architectural and functional requirements, aiming to reduce the number of columns and foundations for a lighter and more sustainable construction, ultimately reducing time and costs. Consequently, different types of flooring systems have emerged, utilising new lightweight materials [40].

1.3. Studied flooring systems

The construction of shallow flooring is achieved by placing the slabs within the structural depth of the steel beams to form steel-concrete composite beams. Various slim floor systems have been introduced, such as SlimFlor®, Ultra-Shallow Floor Beam (USFB®) and Composite Slim-Floor Beam (CoSFB®). The main advantage of the aforementioned systems is the reduction of the depth of the flooring system and the overall height of the building. Therefore, such kind of systems became widespread in construction [33,41].

These slim floor construction systems have been used with various types of flooring slabs such as steel-decking composite slabs and hollow core precast slabs [42]. The use of prefabricated slabs in such systems has many advantages; one of them is the great performance in time and cost reduction [43,44]. Two types of precast flooring systems are selected to be part of this LCA case study.

- Hollow Core Precast Slabs:

Hollow core slabs stand out as the prevailing choice for prefabricated slabs in flooring and roofing applications worldwide. They are frequently utilised in slim floor construction and found to be a practical flooring solution. They have good fire resistance properties. In addition, they are renowned for their sustainability, the offsite manufacturing and the shape of this flooring provide efficiency in materials use and waste reduction [45–47]. Typically made from normal weight reinforced concrete C40/50 (having characteristic compressive cylinder strength of 40 MPa and cube strength of 50 MPa at 28 days), these slabs form solid prestressed concrete units with a standard width of 1200 mm and longitudinal voids, contributing to reduce weight and cost. Depending on their intended use and the required strength and span, the slab's depth ranges from 150 to 450 mm, and its span reaches up to about 20m for high-depth low-load configurations (Fig. 1). Additionally, on-site concrete is placed with a finishing layer of 50 mm thickness.

- Prefabricated Ultra-Shallow Slabs (PUSS®):

PUSS flooring system, introduced in 2017, has showcased in previous research its efficient production and the potential to develop high-strength, sustainable lightweight slim floor systems. The standard PUSS unit is designed with a relatively large unit width of 2m. Constructed by encasing a ribbed reinforced concrete slab within two parallel flange C-channel steel beams. The concrete provides a degree of fire protection to steel beams and prevent them from direct exposure to fire, enhancing their overall fire resistance. The system utilises novel shear connectors, including horizontally oriented web-welded shear studs (WWSS) and horizontal steel dowels welded to the webs [48]. The depth of the slabs ranges between 100 mm and 430 mm, depending on the required spans and design live loads, with span-to-depth ratios that can exceed 35 and spans reaching over 12m. PUSS offers several advantages. Its lightweight, achieved through troughs and ribs beneath the thin concrete flange and the use of lightweight concrete, facilitates the construction of lightweight buildings. Additionally, the prefabricated slab has a flat surface, and the finishing layer is integrated within the depth of the slab, eliminating the need for additional topping. The regular voids beneath the ribbed slab also allow for the passage of building services, placement of ceiling fittings, and incorporation of acoustic insulation materials within the slab's depth, reducing the overall required building height [49] (Fig. 2). Moreover, previous laboratory tests, including direct shear push-out and four-point bending tests, yielded promising outputs regarding the flooring system's structural performance, forming the basis for derived design equations [48,50].

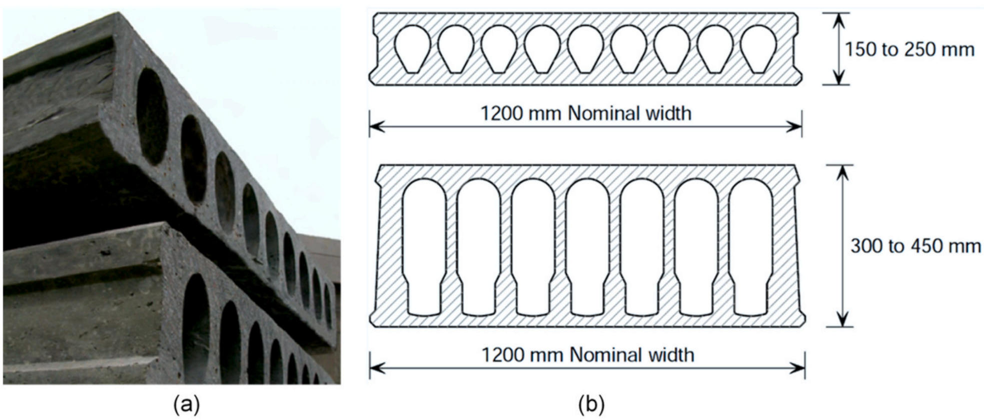

Fig. 1. (a) Hollow core floor units (b) Typical cross-sections for floor units [72].

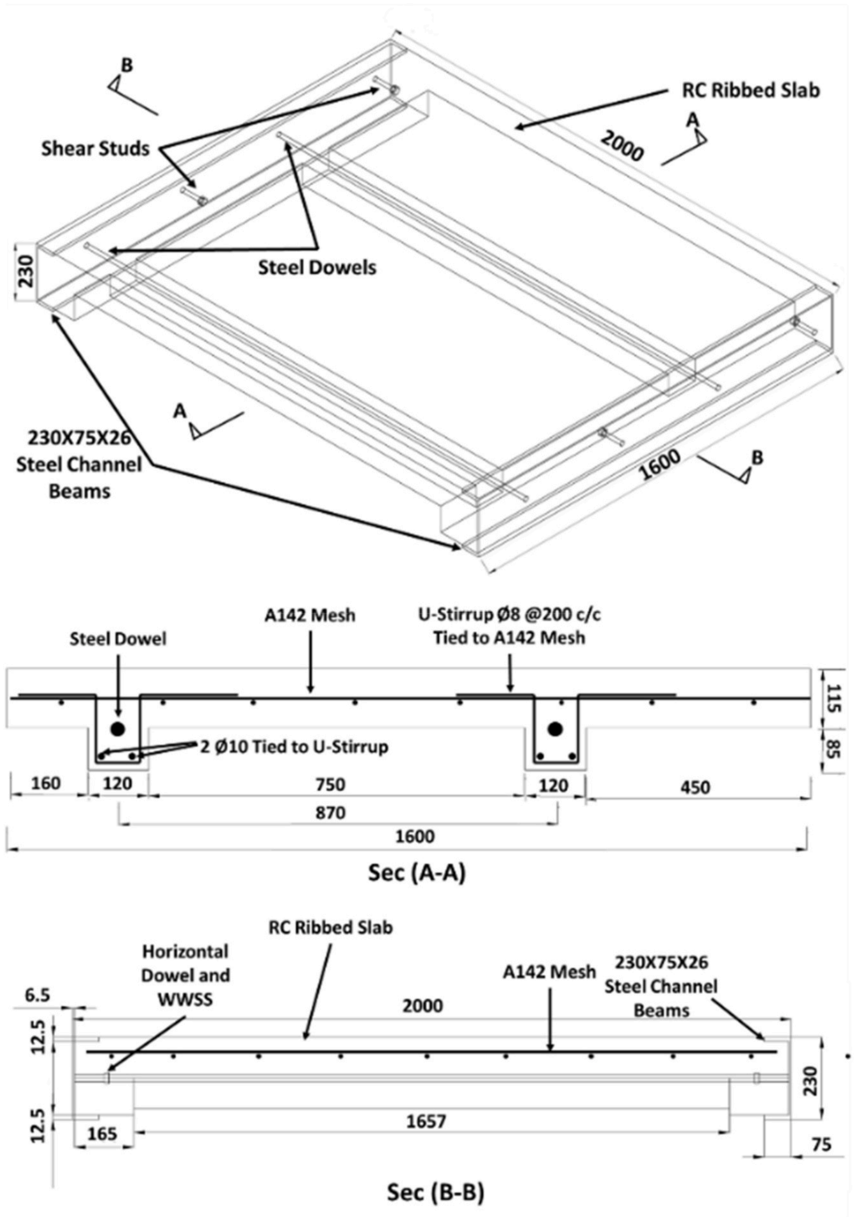

Fig. 2. Schematic drawing of typical segment of a 230 mm deep PUSS flooring unit with steel dowel and WWSS shear connection system [73].

In the LCA study presented in this paper, the environmental impacts associated with PUSS systems are evaluated by incorporating three distinct practical concrete types: normal weight concrete (NWC), lightweight aggregate concrete with Lytag aggregates (LWC), and geopolymer concrete (GPC). The comparative study is useful in identifying the option. GPC encompasses various concrete mixes, and Salas et al. [21] compiled literature data on different GPC mixes, evaluating their environmental impacts relative to strength. For this specific study, the objective is to model a GPC with low environmental impacts and satisfactory structural strength. Therefore, an Alkali Activated GPC with FA mix, as presented by Yang et al. [51], having a compressive strength of 40 MPa, was selected as the GPC for implementation in this research.

Therefore, this paper presents a Life Cycle Assessment (LCA) study of the ecological impacts of a total of four distinct slabs used in buildings internal floorings: hollow core precast slabs and three PUSS slabs with different concrete types. This is to quantify the environmental benefits of using the new flooring system and to understand if there are any important trade-offs. The depth of each flooring system for every live load/span scenario was manually designed to meet the necessary capacity requirements. For hollow core slabs, the depth was determined through manual design and evaluated against manufacturers' recommendations for specific live loads and spans to achieve optimal design outcomes. Changes in design also impact the amount of dead loads imposed on the flooring systems. Figs. 1 and 2 depict the sections of the analysed flooring systems, and Table 1 outlines the characteristics of each flooring system. In addition, Table 2 presents the details of concrete mix designs used in each flooring system.

2. Methodology

The adopted method herein for the LCA study is the Cradle-to-Grave approach, using an attributional methodology, to evaluate the global warming potential and embodied energy of the flooring systems in accordance to BS EN 15978 [52]. This include the life cycle stages from acquisition of raw materials (module A1), manufacturing of slabs (module A3), transportation (modules A2, A4, C2) and construction (module A5), as well as end of life (EOL) stages of the flooring systems, which covers demolition and disposal or recycling (modules C1, C3, C4).

The main part of any LCA is the quantification of all energy and material flows associated with a product or a system to develop an inventory, followed by an impact assessment, which includes calculating and presenting findings in a predefined way that supports comparison or further analysis. The ISO 14040 and 14044 standards of the International Organization for Standardisation (ISO) list the main four phases that must be carried out in any LCA study. The "14040 series" is within the broader ISO 14000 category on environmental management and most of the LCA studies adhere to the principles presented in it [53,54]. Fig. 3 illustrates the flowchart of the phases of LCA.

These phases are strongly related to each other, and it is a normal practice to go back and forth between phases. The main tasks in steps are as follows.

a) Defining goal and scope: includes the definition of the boundaries, timeframe and the limitations of the study. These definitions clarify the questions to be answered, and the reliability and precision of data needed to be used in the LCA. If LCA is to be used for comparing products or materials, then an appropriate functional unit must be defined that provides a level-playing field to compare the different products or services. Fig. 4 presents a flowchart of the general system boundaries for the whole life (Cradle to Grave) of construction projects with modules numbers. The life cycle stages included in the presented LCA study are delimited in the figure with a dashed line, clearly specifying the boundaries of this study.
b) Life Cycle Inventory (LCI) analysis: includes the collection of the required data and calculation for inventory analysis. This step is considered as the most important and most time-consuming step. It is common that this step leads to redefinition of some of the system boundaries and other methodological choices. In this phase, usually some available life cycle inventory databases for building materials are used.
c) Life Cycle Impact Assessment (LCIA): in this step, the environmental impacts are evaluated by converting the LCI to pre-defined impact categories based on a series of environmental indicators and selected characterisation models for each impact category. The common steps associated with this phase include the definition of impact categories by selecting a set of categories, classification factors and assigning of LCI results to each impact category, and the choice of a characterisation model to calculate indicator results within each impact category.
d) Interpretation and conclusions phase: in this step, outcomes from the previous steps are analysed to get conclusions about the environmental impact of the product under investigation within the defined boundaries and limitations towards providing recommendations. In general, LCA results are very useful in finding opportunities to improve the environmental performance of a product or process in the life cycle period, decision-making and marketing.

3. Comparative study

The scope of this case study is to evaluate the environmental impacts of PUSS flooring system with three types of concrete for a selection of live loads/spans scenarios (total of 16 scenarios, i.e. four slab spans (6, 8, 10 and 12m) times four live loads (2, 3, 4 and 5 kN/m^2), – Table 3) and compare the performance with hollow core precast slabs which are the current state-of-art long span precast flooring system. Fig. 5 depicts the flowchart of the structure for LCA model applied in this study.

3.1. Functional unit

The unit of comparison or the functional unit in this study is chosen to be one square meter (m^2) of flooring area for each live load/span scenario. Therefore, each of the 16 live loads/spans scenarios are evaluated separately and then the final outputs of each scenario are combined in a table to explore the pattern of change in environmental impacts with the increase of applied live load or span. All the emissions, energy consumption, and materials are then related to this functional unit, e.g. kg $CO_{2,e}/m^2$, kg/m^2, MJ/m^2, etc.

Table 1
Characteristics of the flooring systems.

Flooring system	Concrete material	Width of slab (mm)	Span of slab range (m)	Live load range (kN/m^2)	Depth of slab (mm)	Dead load range (kN/m^2)
Hollow core precast slab	NWC	1200	6 to 12	2 to 5	200 to 400	3.23 to 5.84
PUSS	NWC	2000			200 to 430	2.99 to 4.64
PUSS	LWC with Lytag	2000				2.09 to 3.36
PUSS	GPC	2000				2.78 to 4.35

Table 2
Details of concrete mix designs used in the studied flooring systems.

Flooring system	Concrete material	Cement (kg/m^3)	Water (kg/m^3)	Aggregates (kg/m^3)		Fly Ash (kg/m^3)	NaOH (kg/m^3)	Density (kg/m^3)	Concrete Grade
				Fine	Coarse				
Hollow core precast slab	NWC	454	213	660	1073			2400	C40/50
PUSS	NWC	343	175	621	1261			2400	C20/25
PUSS	LWC with Lytag Aggregates	250	197.5	625	520			1592.5	C20/25
PUSS	GPC		112	623	935	469	75	2214	C40/50

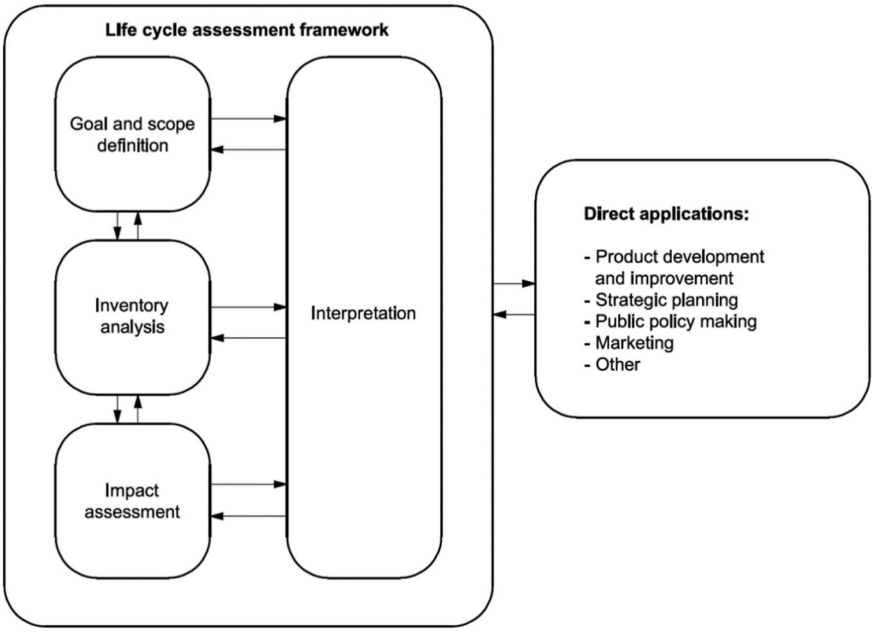

Fig. 3. LCA phases [53,54].

3.2. System boundaries

This research assesses the entire life of the flooring systems, from mining (A1) and manufacturing of flooring materials to production of slabs (A3), on-site construction (A5), end-of-life (EOL) demolition (C1) and disposal to landfill (C4) or recycling (C3). It also includes the transportations between each life cycle stage (A2, A4, C2), considering transportation distances relevant to the UK industry. However, the operation (use) and maintenance stage (B1-B5) is not included in the system boundary, as explained in section 5.1.2.d. This is displayed in Fig. 4 as well as a detailed flowchart in Fig. 6. The grid of each flooring system is chosen to be 12m wide X the span of the slab which is variable for each span scenario ranging between 6m and 12m (Fig. 7). The simplified general life cycle inventory calculation equation for each flooring system per functional unit is presented in Equation (1).

$$LCI_{Total} = \sum_{i=1}^{n} \left(M_{Material(i)} \times LCI_{Material(i)}\right) + \sum_{i=1}^{n} \left(T_{Construction(i)} \times LCI_{Construction(i)}\right) + \sum_{i=1}^{n} \left(M_{Demolition(i)} \times LCI_{Demolition(i)}\right) + \sum_{i=1}^{n} \left(M_{Recycling(i)} \times LCI_{Recycling(i)}\right) + \sum_{j=1}^{m} \left(\sum_{i=1}^{n} \left(M_{Transportation(i)} \times D_{Transportation(i)} \times LCI_{Transportation(i)}\right) \right) \tag{1}$$

Where: LCI_{Total} is the total LCI (carbon emissions or embodied carbon) of flooring system per functional unit ($CO_{2,e}/m^2$ of slab or MJ/m^2 of slab).

$M_{Material(i)}$ is the mass of each material used in production per functional unit (kg/m^2 of slab)
$LCI_{Material(i)}$ is the LCI of each material per kg of material ($CO_{2,e}$ or MJ per kg of material)
$T_{Construction(i)}$ is the operation time of each construction equipment per functional unit (hr/m^2 of slab)
$LCI_{Construction(i)}$ is the LCI of each equipment per hr of usage ($CO_{2,e}$ or MJ per hr of usage of equipment)
$M_{Demolition(i)}$ is the mass of each material demolished at EOL per functional unit (kg/m^2 of slab)

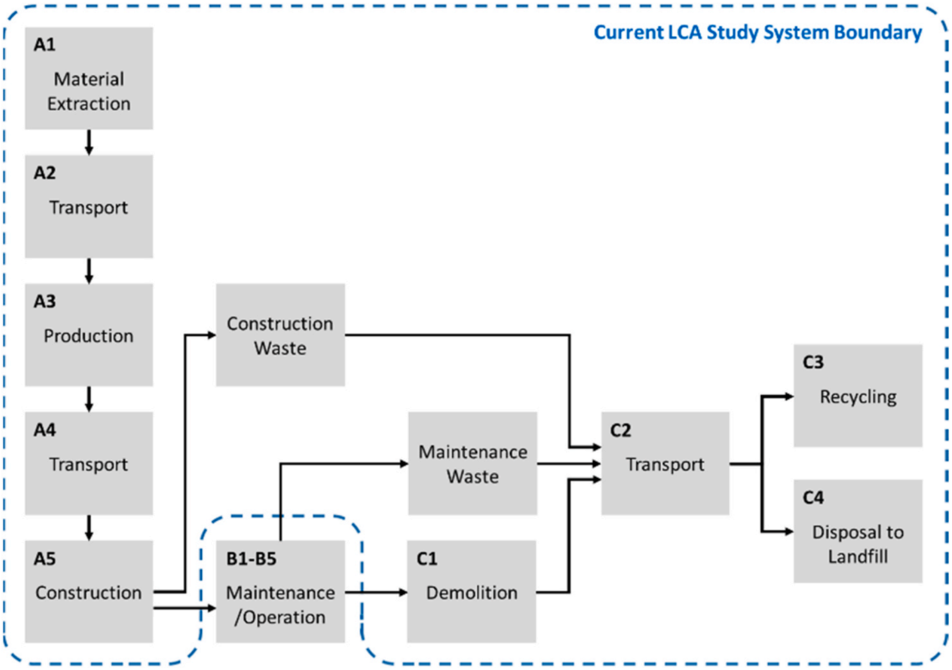

Fig. 4. LCA general life cycle stages of a structural product with LCA study boundaries.

Table 3
Live load/slab span scenarios of the LCA study.

		Live Load (kN/m^2)			
		2	3	4	5
Span (m)	6	LL 2 – Span 6	LL 3 – Span 6	LL 4 – Span 6	LL 5 – Span 6
	8	LL 2 – Span 8	LL 3 – Span 8	LL 4 – Span 8	LL 5 – Span 8
	10	LL 2 – Span 10	LL 3 – Span 10	LL 4 – Span 10	LL 5 – Span 10
	12	LL 2 – Span 12	LL 3 – Span 12	LL 4 – Span 12	LL 5 – Span 12

$LCI_{Demolition(i)}$ is the LCI of each demolished material per kg of material ($CO_{2,e}$ or MJ per kg of demolished material)
$M_{Recycling(i)}$ is the mass of each material recycled at EOL per functional unit (kg/m^2 of slab)
$LCI_{Recycling(i)}$ is the LCI of each recycled material per kg of material ($CO_{2,e}$ or MJ per kg of recycled material)
$M_{Transportation(i)}$ is the mass of each material/product being transpoted in each of the transportation stages per functional unit (tonne/m^2 of slab)
$D_{Transportation(i)}$ is the distance of each transportation stage in (km)
$LCI_{Transportation(i)}$ is the LCI of transportation trucks per tonne of materials per km ($CO_{2,e}$ or MJ per tonne. km)

3.3. Impact categories and calculation methodology

This paper is focused on the environmental impacts associated with these flooring systems during their entire life. The impact categories evaluated in the study are.

- Global Warming Potential (GWP), which is an indicator of the extent of global warming caused by GHGs over a period of time (usually 100 years). For CO_2, the characterisation factor is 1 for GWP [55]. The characterisation factors of other GHGs for GWP as $CO_{2,e}$ over 20, 100 and 500 years are provided in Table 4. The LCIA results for GWP are calculated at midpoint level using conversion factors from IPCC guidelines [1].
- Embodied Energy (EE), which is an indicator of the total energy consumption during the life cycle of the product. The calculation of EE does not differentiate between renewable from non-renewable energy sources.

4. Life cycle inventory (LCI)

The inventories of all the inputs flow such as materials and energy, and outputs flow, for example, air emissions and wastes are quantified for each product system. The gathered coefficients of carbon emissions and embodied energy for all the materials, equipment use, and transportation from a group of references from the UK where possible or nearby countries are given in Tables 5 and

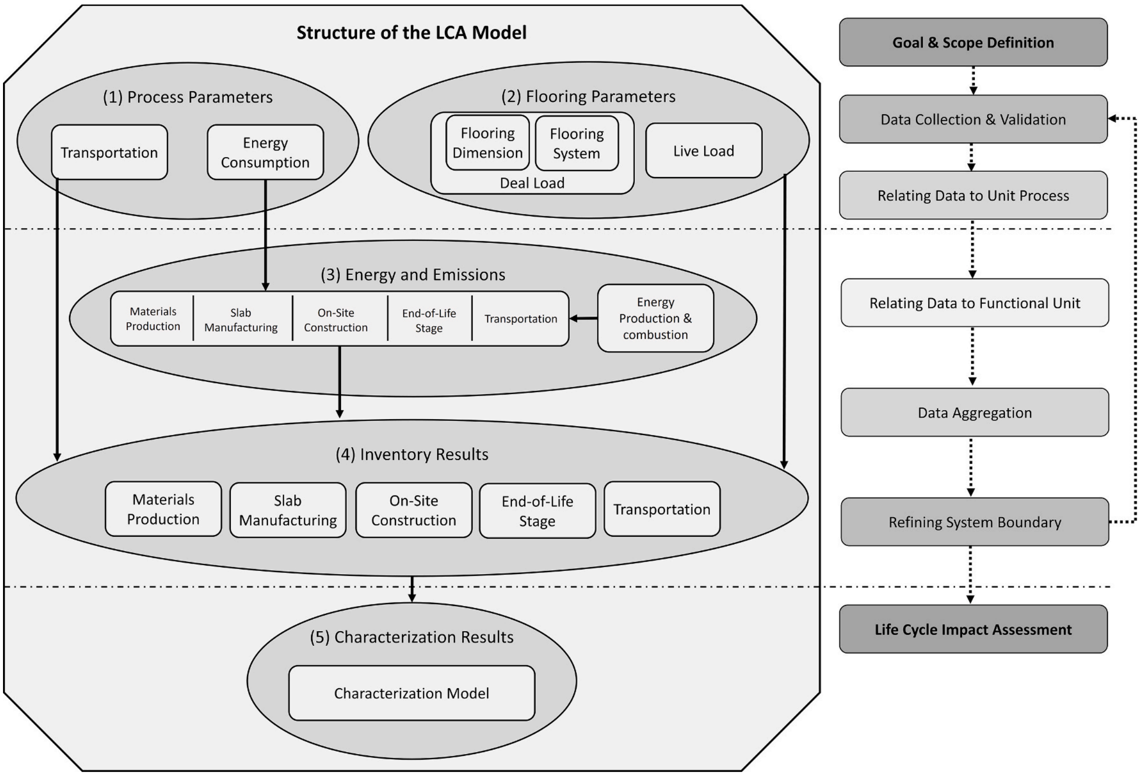

Fig. 5. Structure of the LCA model for this study.

6. In addition, the approximated waste factors of each of the production materials and the transportation distances are also gathered and presented in Tables 7 and 8. Waste factors are the additional material required to accommodate errors or mistakes, typically estimated as a percentage of material over the needed amounts of raw materials.

5. Inventory results

The inventory results for each flooring system over the range of the investigated live load/slab span scenarios are presented in this section. The calculation of these results for each scenario undertakes a series of steps. The first is the manual design of each flooring system based on the live loads and slab spans inputs, followed by quantifying the total amount of materials per flooring system. From these quantities, the inventory results are calculated at different life cycle stages of each flooring system, which are: manufacturing, transportation, on-site construction and end-of-life (demolition and recycling). A detailed example of these steps for one of the live load/slab span scenarios is provided in section 5.1 followed by overall outcomes for all the scenarios in section 5.2. These two sections detail the results using the approximate transportation distances listed in Table 8 and the coefficients of the "50:50" allocation approach for EOL recycling (Table 5). In addition, sensitivity analysis covering the transportation distance and EOL recycling allocation approaches is discussed in section 5.3.

5.1. Example of inventory results calculation methodology

This section outlines a detailed example of the calculation procedure for the inventory results of one of the analysed live load/slab span scenarios. Specifically, for slabs span = 8m undertaking 3 kN/m^2 live load.

5.1.1. Design optimisation of the flooring systems

In this step, the flooring systems are designed manually to carry a live load equal to 3 kN/m^2 for a span equal to 8m, considering Serviceability Limit State (SLS) and Ultimate Limit State (ULS), including design for deflection, flexure, and longitudinal shear.

a. Hollow core precast slab is designed in accordance with Eurocode 2 [56]. Initially, the slab depth is selected from the manufacturers' recommendations for this specific live load and span and designed to have this depth, which is 200 mm [57–59]. Furthermore, two additional slabs are designed with two larger depths (with 50 mm increment). The production materials for each of the three designs are quantified, and the inventory results are calculated for each design. The design with the lowest values is selected (Table 9). Note that an additional 50 mm finishing layer is needed, which adds to the total flooring depth and materials.
b. PUSS units (with NWC, LWC or GPC) are designed in accordance with Eurocode 4 [60], taking into consideration the findings of previous laboratory tests performed on PUSS units [48,50]. The depth of the slab depends on the available PFC steel sections in the

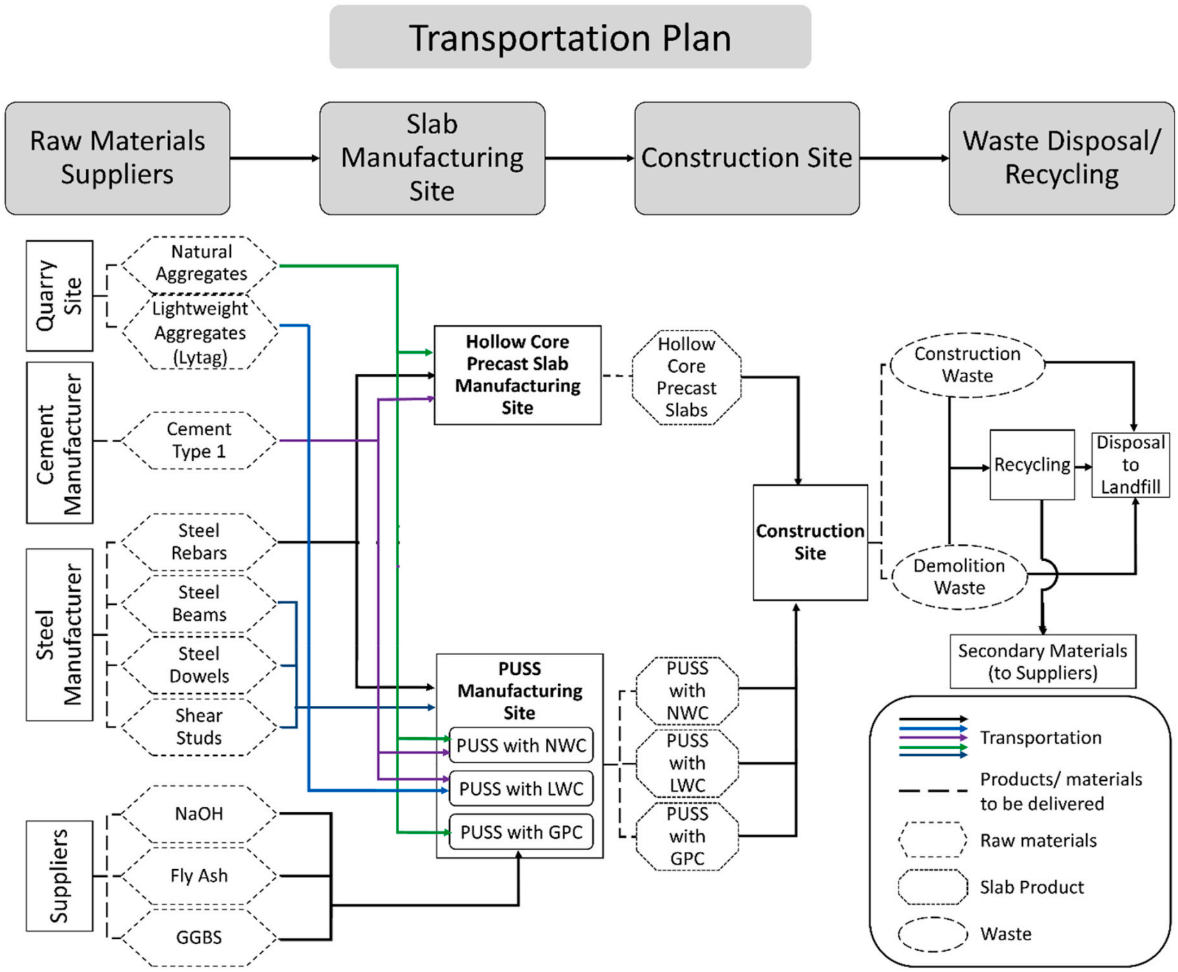

Fig. 6. System boundaries of the studied flooring systems.

UK market [61]. The initial steel section is selected to be equal to the designed depth of the one-step lower live load/slab span scenario. Therefore, the selected initial steel section for this design is 260x90x35 PCF. In addition, two more slabs are designed with the two larger steel sections (300x90x41 PCF and 300x100x46 P CS). As in the design process of hollow core slabs, the design that produces the lowest values is selected. For consistency, the same depth is selected for all the three PUSS systems (Table 9).

After evaluating the total inventory results for each of the three designs of each flooring system, the outcomes are compared to select the design with the lowest GWP and EE per functional unit. As shown in Table 9, the second designs (highlighted in green) for each flooring system exhibit the lowest values. Therefore, for this live load/span scenario, the design with 250 mm depth is selected for the hollow core slabs, while the design with 300 mm depth is selected for PUSS units (using 300x90x41 PCF).

The decision to select deeper slabs (the 2nd designs) for minimised environmental impacts contrasts with the expectation that shallower depths (1st designs) would have lower impacts. This can be attributed to the fact that shallower depths require denser reinforced concrete to meet structural requirements, which might potentially increase the overall environmental impact. Furthermore, in the case of PUSS system, shallower slabs may necessitate wider side concrete joists, which could lead to higher concrete usage. For instance, in the presented case, the 260 mm slabs have more concrete compared with the 300 mm slabs, as detailed in Table 10, which presents the individual material mass and total mass per square meter for each design of the flooring systems.

5.1.2. Detailed inventory results

The detailed inventory results for each life cycle stage are outlined in Tables 11 and 12 for GWP and EE, respectively. These outputs are also illustrated as bar charts in Figs. 8 and 9. Comparing the total GWP of PUSS flooring systems with hollow core slabs demonstrates that PUSS reduces the associated GWP by 27.24 %, 39.65 % and 44.15 %, respectively, when implementing NWC, LWC and GPC in PUSS. Similarly, PUSS flooring system consumes less total energy compared with hollow core slabs, saving 10.58 % when using NWC, 24.28 % with LWC and 21.71 % with GPC. The detailed life cycle stages inventory results provide a better understanding of the difference in environmental performance between the flooring systems at each life cycle stage.

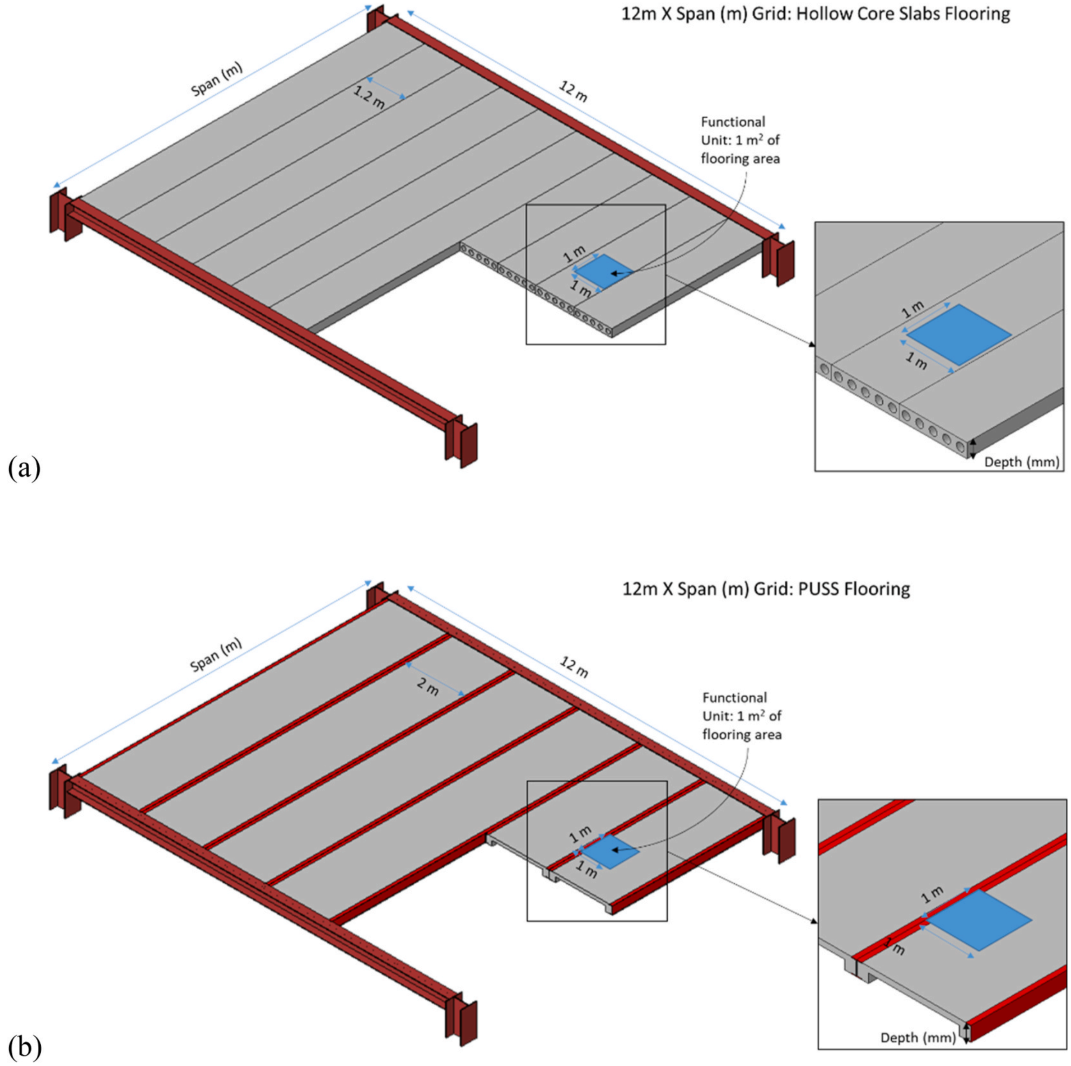

Fig. 7. Grids of (a) Hollow core flooring (b) PUSS flooring.

Table 4
GWP Characterisation factors of GHGs [1].

GHG	GWP indicator	GWP-20	GWP-100	GWP-500
CO_2	$CO_{2,e}$	1	1	1
CH_4-fossil		82.5 ± 25.8	29.8 ± 11	10 ± 3.8
CH_4-non fossil		79.7 ± 25.8	27 ± 11	7.2 ± 3.8
N_2O		273 ± 118	273 ± 130	130 ± 64

a. Manufacturing/production stage: This stage comprises the inventory results of all materials used in producing the flooring systems (A1, A3) as well as off-site slabs manufacturing process (A5). Material inventories cover all the emissions and embodied energy from the acquisition of raw materials (A1), processing them and transporting them to the slabs manufacturing sites (A2). The findings demonstrate that for all the flooring systems, this stage produces between 90 and 93 % of the total carbon emissions and consumes between 87 and 91 % of the total energy. During this stage, when compared with hollow core slabs, PUSS flooring produces 20.90 %, 31.63 % & 37.72 % less carbon emissions when NWC, LWC & GPC are used respectively. In terms of embodied energy, PUSS with NWC consumes only 1.7 % less energy than hollow core slabs, while PUSS with both LWC and GPC has about 13 % less embodied energy than hollow core slabs.

b. Transportation stage(s): The inventory results herein combine four main transportation stages, which are the transportation of slabs and construction materials to construction site (A4), transportation of manufacturing waste to landfill, transportation of construction waste to landfill and transportation of EOL demolition to final disposal (C2). The calculated GWP and EE are for fuel

Table 5
Embodied carbon and energy of the materials for production and EOL processes.

	Embodied Carbon Coefficient (kg $CO_{2,e}$/kg)	Embodied Energy Coefficient (MJ/kg)	Notes	Reference
Materials:				
Concrete mix 40/50 MPa (density: 2400 kg/m^3)	0.151	1	Using UK weighted average cement	[63]
Concrete mix 25/30 MPa (density: 2400 kg/m^3)	0.113	0.78		
Precast concrete	0.029	0.45	Added to the coefficient of the concrete mix	
Cement - general (UK weighted average)	0.74	4.5		
Fly ash	0.008	0.1		
GGBS	0.083	1.6		
NaOH	0.6329	3.505		[74]
Water	0.001	0.01		[63]
Fine aggregates (sand)	0.0048	0.081		
Coarse aggregates (gravel or crushed rock)	0.0052	0.083		
Steel reinforcement (density: 7850 kg/m^3)	0.077	1.04	For each 100 kg of rebar per m^3 of concrete, added to the coefficient of the concrete mix	
Shear studs & dowels	1.4	17.4	UK Typical - EU 59 %	
Steel sections	1.53	21.5	Recycled	
Prestressed reinforcement	1.81	20.3		[75]
End of life processes:				
Concrete demolition	0.00054	0.007		[76]
Recycling steel rebars, shear studs & dowels	−0.33	−3.2	using 50:50 method	[63]
Recycling steel sections	−0.39	−4.2	using 50:50 method	

Table 6
Embodied carbon and energy for construction equipment and transportation.

	Embodied Carbon Coefficient	Unit	Embodied Energy Coefficient	Unit	Reference
Construction equipment:					
Concrete compactor	0.2	kg $CO_{2,e}/m^3$	1.18	MJ/m^3	[62]
Tower crane of 100 ton	53.23	kg $CO_{2,e}$/hour	720	MJ/hour	
Concrete pump	46.12	kg $CO_{2,e}$/hour	540	MJ/hour	
Transportation:					
20ton diesel fuel truck	0.15	kg $CO_{2,e}$/tonne.km	2.4	MJ/tonne.km	[63]

Table 7
Approximate waste factors of each of the production materials.

Materials Waste	Waste Factor	Reference
Precast Concrete	0.01	[77]
In-Situ Concrete	0.053	
Steel Sections	0.01	
Steel Rebars	0.053	
Steel Deck	0.01	
Others	0.01	

Table 8
Approximate transportation distances at between different life cycle stages.

Transportation	Distance (km)	Reference
Cementitious materials to manufacturing site	100	[63]
Aggregates to manufacturing site	38	
Precast units to construction site	155	
Demolition to landfill	50	[77]

Table 9
Comparison of total inventory results for design optimisation.

Design \ Flooring system		Hollow core precast slab	PUSS with NWC	PUSS with LWC	PUSS with GPC
1st Design	Depth (mm)	200	260 (using 260x90x35 PCF)		
	GWP (kg CO_{2e}/m² of slab)	190.06	126.43	101.55	96.25
	EE (kg MJ/m² of slab)	2075.12	1594.03	1302.04	1383.45
2nd Design	Depth (mm)	250	300 (using 300x90x41 PCF)		
	GWP (kg CO_{2e}/m² of slab)	165.42	120.36	99.83	92.39
	EE (kg MJ/m² of slab)	1707.77	1527.08	1293.10	1336.98
3rd Design	Depth (mm)	300	300 (using 300x100x46 PCF)		
	GWP (kg CO_{2e}/m² of slab)	171.23	124.74	104.28	96.86
	EE (kg MJ/m² of slab)	1760.29	1594.52	1361.20	1404.97

Table 10
Comparison of material quantities in all design alternatives.

Material (kg per m² of slab)		Flooring system			
		Hollow Core Precast Slab	PUSS with NWC	PUSS with LWC	PUSS with GPC
1st Design	Concrete	292.74	311.01	206.37	286.92
	Steel/prestressed reinforcement	44.04	16.48	16.48	16.48
	Finishing Layer	126.36	0.00	0.00	0.00
	Steel section	0.00	53.08	53.08	53.08
	Shear connectors	0.00	2.43	2.43	2.43
	Total mass (kg per m² of slab)	463.14	383.01	278.36	358.91
2nd Design	Concrete	373.02	301.73	200.21	278.35
	Steel/prestressed reinforcement	28.61	9.74	9.74	9.74
	Finishing Layer	126.36	0.00	0.00	0.00
	Steel section	0.00	63.21	63.21	63.21
	Shear connectors	0.00	2.43	2.43	2.43
	Total mass (kg per m² of slab)	527.98	377.11	275.59	353.74
3rd Design	Concrete	402.16	300.85	199.63	277.54
	Steel/prestressed reinforcement	28.61	9.71	9.71	9.71
	Finishing Layer	126.36	0.00	0.00	0.00
	Steel section	0.00	69.18	69.18	69.18
	Shear connectors	0.00	2.43	2.43	2.43
	Total mass (kg per m² of slab)	557.13	382.17	280.95	358.87

Table 11
GWP results for LL = 3 kN/m² & span = 8 m (GWP - kg $CO_{2,e}$/m² of slab).

Life cycle stage	Flooring system			
	Hollow core precast slab	PUSS with NWC	PUSS with LWC	PUSS with GPC
Manufacturing	161.96	128.11	110.73	100.87
Transportation	13.18	10.81	7.71	10.10
On-site construction	1.47	0.83	0.83	0.83
Demolition	0.26	0.16	0.11	0.15
Recycling	−11.45	−19.55	−19.55	−19.55
Total	**165.42**	**120.36**	**99.83**	**92.39**

combustion from the transportation using 20-tonne payload diesel trucks. The assumed transportation distances are given in Table 8. The outputs show that for the studied flooring systems, transportation stage makes an average of around 8 % of the total GWP and 10 % of the total EE, which makes it the second highest proportion. The inventory results from transportation stages highly depend on the transportation distances. Therefore, a sensitivity analysis of the transportation distance variation is presented in section 5.3.1. Additionally, weight of the flooring system plays an important factor, thus, hollow core slabs have the largest values because they are the heaviest. In comparison to it, PUSS has 18 %, 41.5 % & 23.4 % lower GWP and EE with NWC, LWC & GPC respectively. It is clear that PUSS with LWC has the lowest outcomes in this stage due to its lighter weight.

Table 12
EE results for LL = 3 kN/m^2 & span = 8 m (EE – MJ/m^2 of slab).

Life cycle stage	Flooring system			
	Hollow core precast slab	PUSS with NWC	PUSS with LWC	PUSS with GPC
Manufacturing	1574.43	1547.47	1363.77	1368.95
Transportation	210.85	172.94	123.37	161.53
On-site construction	19.71	11.25	11.25	11.25
Demolition	3.43	2.09	1.39	1.93
Recycling	−100.64	−206.68	−206.68	−206.68
Total	**1707.77**	**1527.08**	**1293.10**	**1336.98**

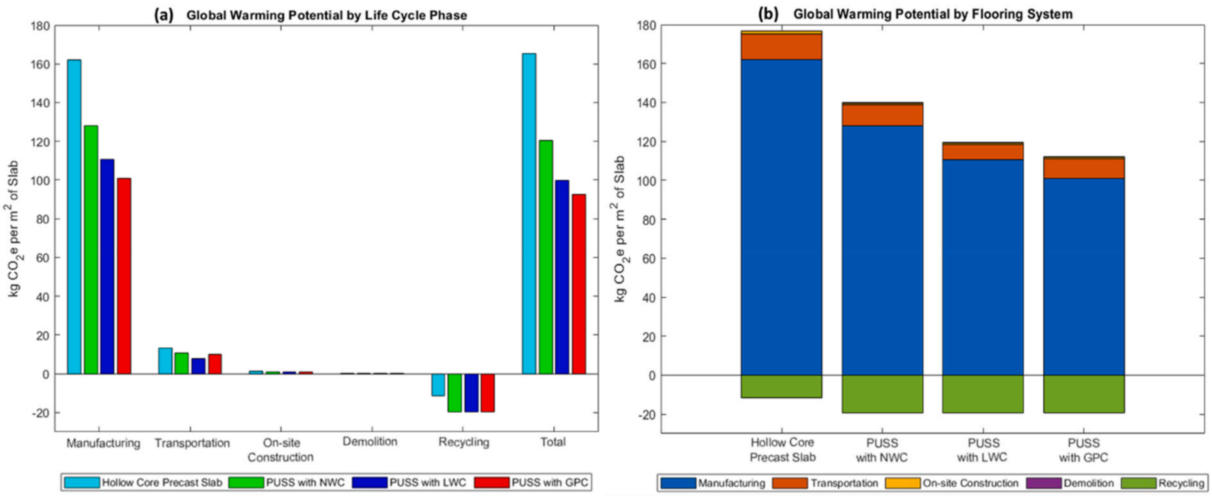

Fig. 8. GWP results for LL = 3 kN/m^2 & span = 8m (a) by life cycle stage (b) by flooring system.

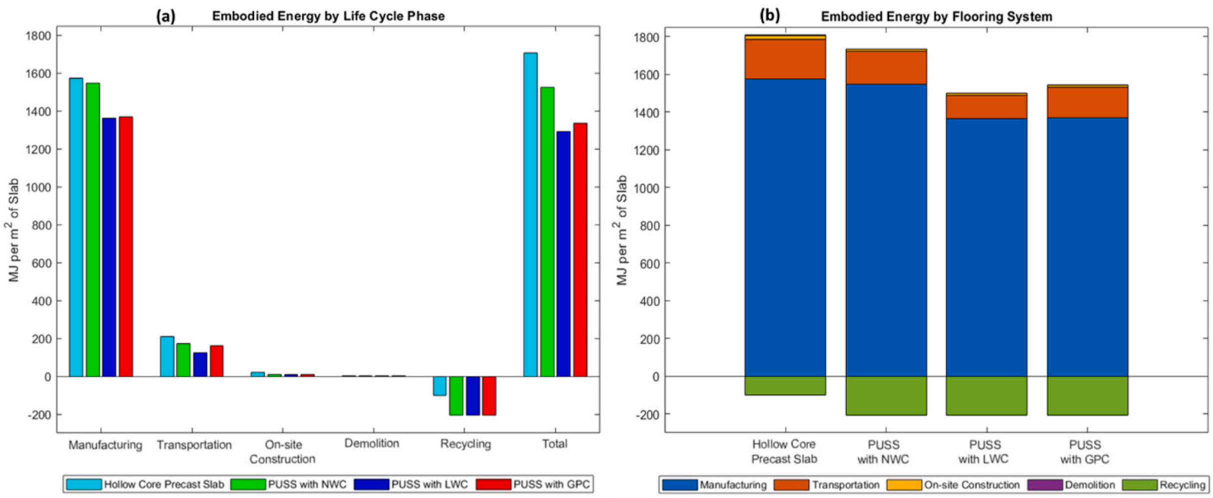

Fig. 9. EE results for LL = 3 kN/m^2 & span = 8m (a) by life cycle stage (b) by flooring system.

c. On-site construction stage: As the analysed flooring systems are prefabricated, on-site construction (A5) inventory results are mainly from the use of power operated tools and equipment such as cranes to install the slabs into their places. In addition, the installation of the finishing layer to hollow core slabs requires the use of concrete pumps, compactors and vibrators [62]. Off-site production mitigates the percentage of GWP and EE accompanying on-site construction stage and makes it only about 1 % or less. Consequently, this stage is marginal, having little effect on the overall outcomes. Findings also indicate that PUSS flooring reduces the on-site construction GWP and EE by about 44 % in comparison to hollow core slabs. This is because the wider 2m PUSS units decrease the overall required number of slabs when compared with hollow core slabs and thereafter reduce the needed operation time of tower cranes. In addition, PUSS flooring system does not require a finishing layer, which reduces the need of construction equipment on-site.

d. Operation (use) & maintenance stage (B1-B5): Floorings in buildings, along with structural elements in general, are designed to remain operational throughout the lifetime of the building with little or no maintenance required. In addition, in the event maintenance becomes necessary, impacts are expected to be almost equal across all flooring systems in various load/span scenarios. Therefore, the inventory results associated with this stage are assumed to have negligible effects on the overall outcomes.

e. End-of-life (EOL) stage: This stage reflects the impacts related to building demolition (C1) and materials reusability potential (recycling) (C3). The ICE inventory [63] provides the necessary information about the recyclability of steel elements, stating that about 95 % of steel sections and 75 % of the reinforcement bars can be recycled, while the remaining disposed to landfill (C4) [7]. For concrete, only its demolition and disposal to landfill are considered in this study. The inventory results from the demolition of the flooring systems are extremely insignificant, contributing to less than 0.2 % of the total GWP and EE. Conversely, recycling plays a noteworthy role in LCA outcomes, recovering a portion of the total GWP and EE, thereby presented as negative values. The larger amount of steel components used in PUSS flooring, in comparison to hollow core slabs, results in recovery values of GWP and EE that exceed those of hollow core slabs by over 170 %. In the recycling calculations of this example, the '50:50 allocation' approach is employed, assigning burdens from recycling processes equally to the flooring system and subsequent products in which the material is used. Using this approach for recycling, hollow core slabs recovers only about 6 % of the total GWP and EE, whereas for PUSS units with different concrete materials, the recycling-based recovery ranges from 12 % to 18 %. Note that there is a level of uncertainty associated with selecting the best allocation method for EOL recycling. The 'substitution method' involves assigning the environmental impacts associated with the recycled materials entirely to the product under assessment, enhancing its environmental advantages, which is expected to be supported by products manufacturers. On the other hand, the 'cutoff method' allocates the benefits of recycling entirely to the subsequent products. These two methods represent the extremes of distributing the benefits, and the selection of other methods such as the '50:50 allocation' approach leads to results between the two extremes [63–65]. While the application of different allocation approaches definitely leads to pronounced disparity in the final outcomes [66], the sensitivity analysis by Cherubini et al. [67] showed that, in most cases, it has no impact on the relative ranking in comparative LCA studies. A sensitivity analysis of the allocation methods is presented in section 5.3.2 and its outcomes agrees with Cherubini et al. [67].

5.2. Assessment of all live load/slab span scenarios

The methodology for calculating inventory results, as outlined in Section 5.1, is similarly applied for the remaining 15 live load/slab span scenarios. The results for all the scenarios are then compiled and compared, providing a comprehensive perspective to the LCA results associated with varying live loads and spans in flooring systems.

5.2.1. Global warming potential (GWP)

The cumulative GWP of all the analysed flooring systems across the examined scenarios are gathered and compared in Table 13. Each GWP result for the three PUSS floorings is followed by a percentage that indicates the extent to which it deviates from the hollow core slabs (benchmark) with identical spans and live loads. Green shades demonstrate that all calculated GWPs for PUSS floorings are lower than those of hollow core slabs, with darker shades representing higher deviation. Upon a comprehensive analysis, it is evident that PUSS with GPC stands out as the option with lowest GWP, followed by PUSS with LWC, and then PUSS with NWC. Moreover, it is noteworthy that PUSS flooring exhibits slightly greater benefits at lower spans, with the percentage difference from hollow core slabs decreasing a little as spans increase, though still yielding favourable results. These results are visually presented as 3D surfaces in

Table 13
Comparison of GWP results for all live load/slab span scenarios (kg $CO_{2,e}/m^2$ of slab).

Span (m)	LL (kN/m²)	Hollow core precast slab	PUSS with NWC	% of HC	PUSS with LWC	% of HC	PUSS with GPC	% of HC
6	2	119.5	89.5	74.9%	72.1	60.3%	64.4	53.9%
6	3	137.8	92.0	66.7%	73.7	53.5%	66.6	48.3%
6	4	153.0	107.4	70.2%	85.3	55.7%	77.5	50.6%
6	5	163.3	111.1	68.0%	87.8	53.8%	80.6	49.4%
8	2	152.6	105.4	69.1%	87.1	57.1%	78.9	51.7%
8	3	165.4	120.4	72.8%	99.8	60.3%	92.4	55.9%
8	4	173.6	127.1	73.2%	104.6	60.3%	95.8	55.2%
8	5	190.0	133.5	70.3%	109.0	57.3%	101.3	53.3%
10	2	181.1	138.2	76.3%	113.6	62.7%	107.7	59.5%
10	3	195.7	138.9	70.9%	117.1	59.8%	109.0	55.7%
10	4	203.8	148.0	72.6%	123.5	60.6%	114.6	56.3%
10	5	220.3	152.3	69.1%	126.5	57.4%	118.1	53.6%
12	2	229.5	158.1	68.9%	130.3	56.8%	124.5	54.3%
12	3	234.1	160.8	68.7%	136.0	58.1%	128.5	54.9%
12	4	243.3	173.7	71.4%	145.0	59.6%	137.1	56.3%
12	5	271.1	184.1	67.9%	152.2	56.2%	146.0	53.9%

Fig. 10 (a) which illustrates distinct variations in results across the investigated live loads and spans without any overlap. The same results are also depicted in a 2D plot for GWP versus span in Fig. 10 (b). Both figures reveal a clear linear relationship between the total GWP and the live load and span. To precisely capture this relationship, the results for each flooring system are fitted into linear equations of the form presented in Equation (2). The derived linear equations are evaluated using the coefficient of determination (R-squared) which is most appropriate to examine how linear equations fit to the data [68,69]. All the derived equations for GWP agreed with the analysis outcomes, yielding R^2 values higher than 0.977. The high R^2 values (close to 1) indicate that the model explains a large proportion of the variance in the data, confirming the suitability of using R-squared for this analysis. The flooring system-dependent coefficients and corresponding R^2 values for each flooring system are provided in Table 14.

$$\text{GWP (kg CO}_{2,e}\text{/m}^2\text{ of slab)} = a_1\, S + b_1\, LL \tag{2}$$

Where: a_1 & b_1 are flooring system-dependent coefficient.

S & LL are the slab span and live load variables respectively

5.2.2. Embodied energy (EE)

The cumulative EE of flooring systems are outlined in Table 15. As with the GWP analysis previously discussed, each EE outcome is accompanied by a color-coded percentage, indicating its deviation from the hollow core slabs (benchmark) with comparable spans and live loads. Following an inclusive evaluation, the analysis reveals that PUSS with LWC stands out as option with the lowest associated EE, succeeded by PUSS with GPC, and then PUSS with NWC. This order differs from the observed GWP outcomes. Furthermore, as indicated by the GWP results, a noticeable trend emerges, in which the difference in EE between PUSS and hollow core slabs is more pronounced at lower spans and live loads, but diminishes as these variables increase. The visual representation of the results is illustrated as 3D surfaces in Fig. 11 (a). Also, Fig. 11 (b) presents a 2D plot depicting EE versus span, offering a graphical representation. Similar to GWP graphs, a clear linear relationship between the total EE and the live load and span is noticed from the figures. Employing curve fitting, the results for each flooring system are expressed through linear equations, as outlined in Equation (3), which closely align with the results of the LCA, achieving R^2 values surpassing 0.957. The flooring system-dependent coefficients as well as R^2 values for each flooring system are presented in Table 14. The impact of the slab span on the total inventory results (GWP and EE) appears more pronounced than that of the live load, signified by its higher coefficients within Equation (2) & Equation (3).

$$\text{EE (MJ/m}^2\text{ of slab)} = a_2\, S + b_2\, LL \tag{3}$$

Where: a_2 & b_2 are flooring system-dependent coefficient.

S & LL are the slab span and live load variables respectively

5.2.3. Floor weight and depth

The inventory results previously outlined do not solely assess the environmental performance of the flooring system. Additional measures contribute to reduced environmental impacts by enabling the downsizing of other structural elements, leading to a reduction in overall material consumption within a building. Utilising lighter floorings, for instance, reduces the dead loads imposed on other structural elements like beams, columns, and foundations. Furthermore, a shallower slab depth diminishes the necessary beam size, subsequently lowering the overall building height and reducing material usage.

The densities of the flooring systems, expressed as mass per square meter of the flooring area, are compared side by side in Fig. 12 for direct assessment. The figure notably displays PUSS with LWC as the lightest option among the studied systems, followed by PUSS with GPC. In contrast, hollow core slabs exhibit significantly greater weight, nearly doubling that of PUSS with LWC. Furthermore, all

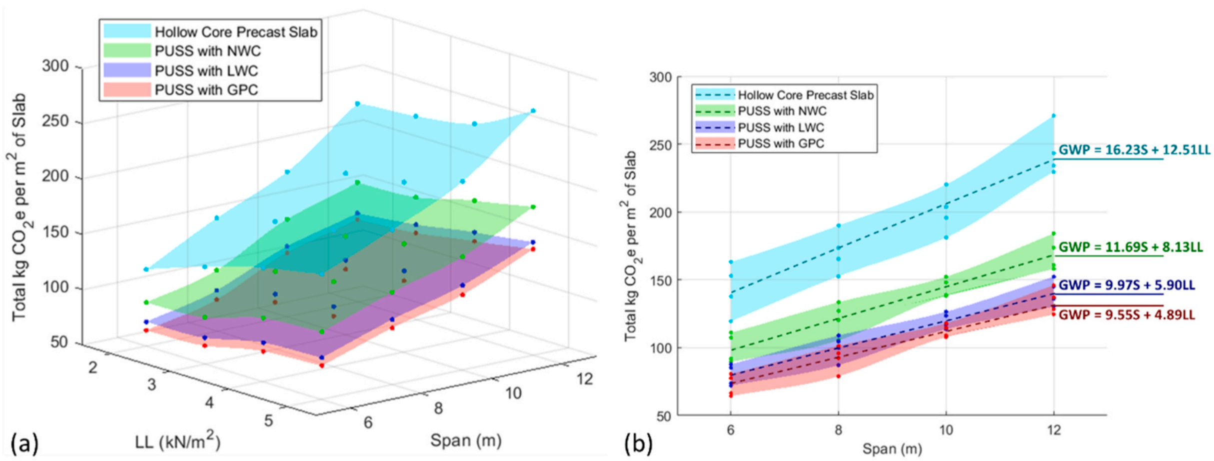

Fig. 10. (a) 3D plot of GWP results (b) 2D plot of GWP results with curve fitting equations.

Table 14
Constants of curve fitting equations for GWP and EE.

Flooring system	GWP (kg $CO_{2,e}/m^2$ of slab)			EE (MJ/m^2 of slab)		
	a_1	b_1	R^2	a_2	b_2	R^2
Hollow Core Precast Slab	16.23	12.51	0.9773	172.14	125.39	0.9578
PUSS with NWC	11.69	8.13	0.9873	154.56	88.64	0.9852
PUSS with LWC	9.97	5.90	0.9913	134.42	63.70	0.9815
PUSS with GPC	9.55	4.89	0.9793	139.92	65.96	0.9717
	$GWP = a_1 *S + b_1 * LL$			$EE = a_2 *S + b_2 * LL$		
	S = span (m) & LL = live load (kN/m^2)					

Table 15
Comparison of EE results for all live load/slab span scenarios (MJ/m^2 of slab).

Span (m)	LL (kN/m^2)	Hollow core precast slab	PUSS with NWC	% of HC	PUSS with LWC	% of HC	PUSS with GPC	% of HC
6	2	1182.8	1088.3	92.0%	892.6	75.5%	919.4	77.7%
6	3	1414.1	1122.5	79.4%	915.7	64.8%	950.6	67.2%
6	4	1551.9	1309.3	84.4%	1056.6	68.1%	1105.6	71.2%
6	5	1681.3	1358.9	80.8%	1090.5	64.9%	1150.0	68.4%
8	2	1545.7	1316.0	85.1%	1111.8	71.9%	1138.5	73.7%
8	3	1707.8	1527.1	89.4%	1293.1	75.7%	1337.0	78.3%
8	4	1792.3	1594.8	89.0%	1340.0	74.8%	1383.4	77.2%
8	5	1999.8	1681.9	84.1%	1399.4	70.0%	1461.3	73.1%
10	2	1887.4	1768.8	93.7%	1481.3	78.5%	1558.2	82.6%
10	3	2068.6	1788.4	86.5%	1541.1	74.5%	1585.7	76.7%
10	4	2122.2	1890.4	89.1%	1611.3	75.9%	1663.6	78.4%
10	5	2330.5	1946.1	83.5%	1649.4	70.8%	1712.1	73.5%
12	2	2445.7	2039.2	83.4%	1712.7	70.0%	1804.8	73.8%
12	3	2453.6	2095.2	85.4%	1810.1	73.8%	1873.7	76.4%
12	4	2568.7	2244.9	87.4%	1913.0	74.5%	1992.5	77.6%
12	5	2917.7	2385.7	81.8%	2010.1	68.9%	2118.4	72.6%

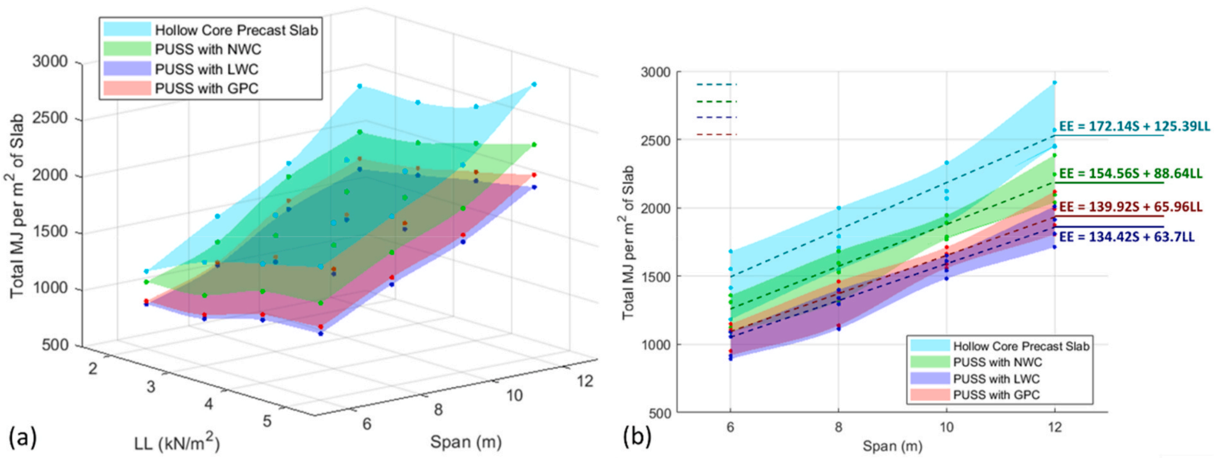

Fig. 11. (a) 3D plot of EE results (b) 2D plot of EE results with curve fitting equations.

three PUSS flooring options demonstrate nearly identical slope increments with increasing spans, however, the slope associated with hollow core slabs is steeper, indicating a more substantial disparity, especially at higher spans. It is also evident from the figure that changes in live load have a relatively minor impact on the flooring weight compared with the changes in span which have more significant influence.

As illustrated in Fig. 13, the depths of hollow core slabs and PUSS units closely align at smaller spans. However, as spans increase, hollow core slabs exhibit smaller depths compared with PUSS. While this might initially appear as an advantage to hollow core slabs, they require an additional 50 mm finishing layer, a requirement not needed for PUSS flooring. Consequently, it can be concluded that

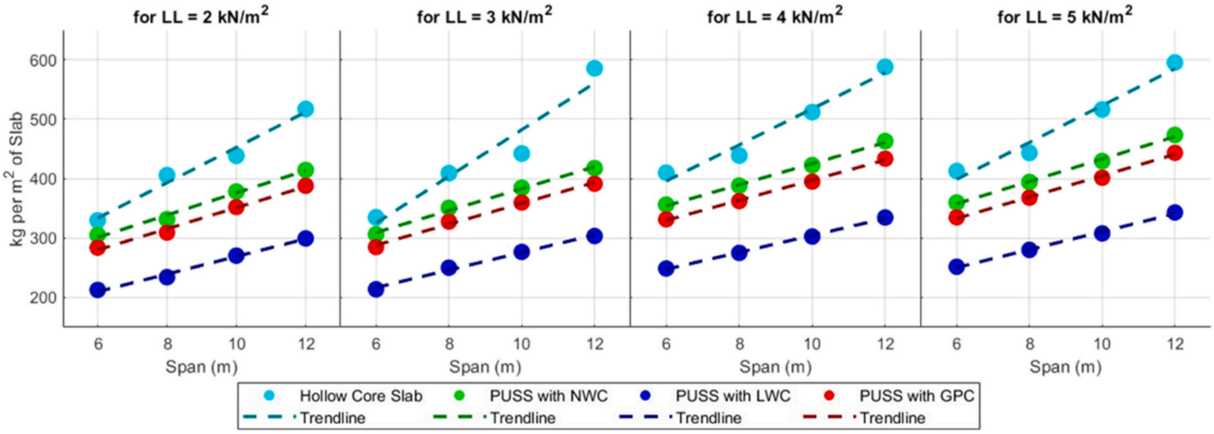

Fig. 12. Floor weight change pattern with increasing spans and live loads.

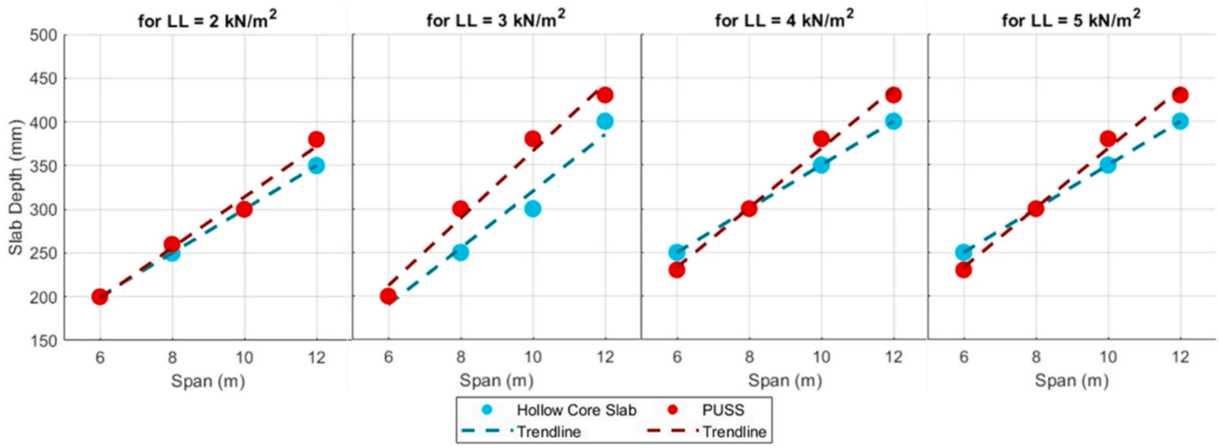

Fig. 13. Floor depth change pattern with increasing spans and live loads.

the depth is of less significance in comparing the environmental performance of the two flooring systems.

Based on the densities and depths of the slabs under examination, linear equations were derived through curve fitting. The derived equations are useful to roughly estimate the densities (Equation (4)) and depths (Equation (5)) of the slabs by substituting the magnitude of the live loads and spans. The flooring system-dependent coefficients for these equations as well as R^2 values for each flooring system are presented in Table 16.

$$\text{Density (kg per m}^2\text{ of slab)} = a_3\, S + b_3\, LL \tag{4}$$

$$\text{Depth (mm)} = a_4\, S + b_4\, LL \tag{5}$$

Where: a_3, a_4, b_3 & b_4 are flooring system-dependent coefficient.

S & LL are the slab span and live load variables respectively

5.3. Sensitivity analysis

A sensitivity analysis is applied to explore the impacts of uncertainties in transportation distance and EOL recycling allocation methods on the LCA outputs. These parameters are selected due to their significant influence on the results, ranking second and third after the off-site construction phase, and the level of uncertainty associated with them. The analysis aims to assess the effects of varying transportation distances and the recycling allocation methods on the final GWP and EE outcomes of the LCA study.

5.3.1. Transportation distance

The previously presented LCA results utilise the approximate transportation distances listed in Table 8. For the sensitivity analysis, these distances are adjusted by factors of 1/3, 2/3, 2, and 3 times the original values to account for uncertainty. The results of this analysis are illustrated in Fig. 14 (GWP) and Fig. 15 (EE).

The general conclusion from this sensitivity analysis is that varying the transportation distance does not alter the ranking of the

Table 16
Constants of curve fitting equations for densities and depths of slabs.

Flooring System	Density (kg per m^2 of slab)			Mass (mm)		
	a_3	b_3	R^2	a_4	b_4	R^2
Hollow Core Precast Slab	37.90	33.40	0.9273	29.98	14.25	0.8990
PUSS with NWC	28.11	36.38	0.8483	31.25	11.67	0.9376
PUSS with LWC	20.64	24.58	0.8873			
PUSS with GPC	26.35	33.73	0.8562			
	Density = a_3 *S + b_3 * LL S = span (m) & LL = live load (kN/m^2)			Depth = a_4 *S + b_4 * LL		

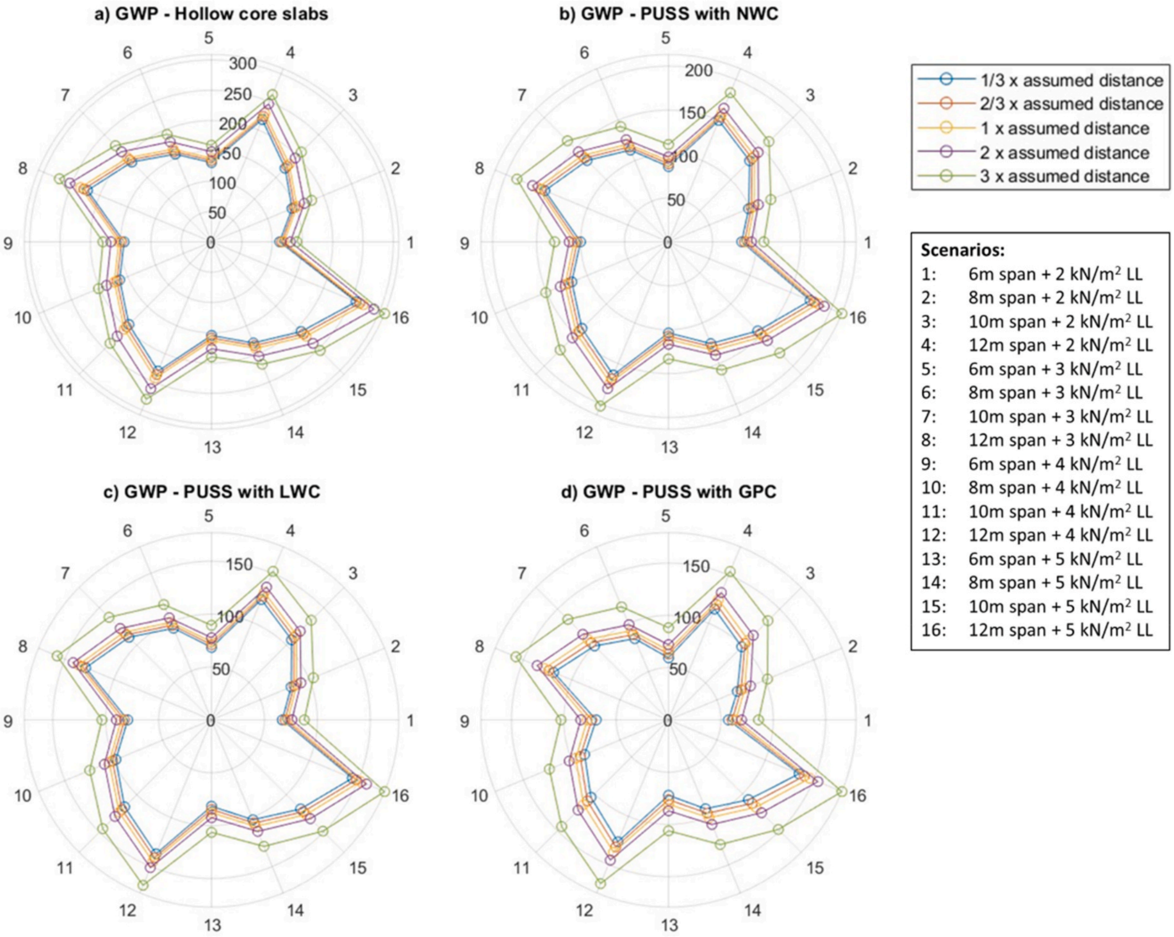

Fig. 14. Sensitivity analysis of transportation distance effect on GWP outcomes.

environmental performance of the studied flooring systems. PUSS with GPC consistently remains the best performer in terms of GWP, while PUSS with LWC is the best in terms of EE. Hollow core slabs, on the other hand, consistently exhibit the worst performance across all 16 scenarios analysed.

However, the sensitivity analysis reveals that the impact of transportation distance on the final GWP and EE outcomes (as a percentage compared with the previously presented results) varies between the flooring systems. For GWP, the transportation distance has the least effect on hollow core slabs and the greatest effect on PUSS with GPC. Specifically, reducing the distances to 1/3 of the original values decreases the total GWP of hollow core slabs by an average of approximately 5 %, and by 6 % for both PUSS with NWC and PUSS with LWC, while it reduces the GWP of PUSS with GPC by an average of 9 %. Conversely, increasing the distances to three times the original values raises the total GWP by about 16 % for hollow core slabs, 18 % for both PUSS with NWC and PUSS with LWC, and 27 % for PUSS with GPC.

In terms of EE, the transportation distance affects PUSS with both NWC and LWC the least, while PUSS with GPC is the most affected. Calculations with 1/3 distances reduce the total EE by around 8 % for hollow core slabs, 7.7 % for both PUSS with NWC and

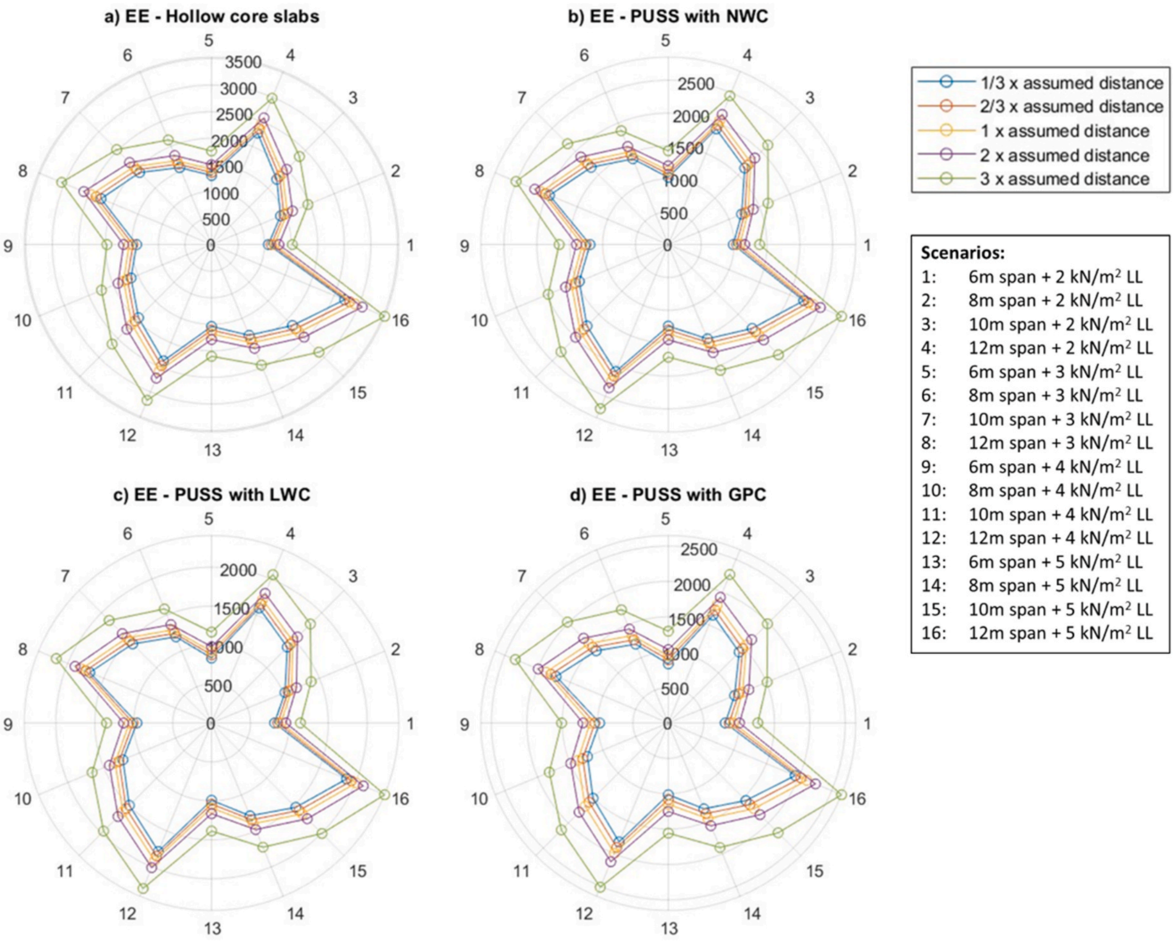

Fig. 15. Sensitivity analysis of transportation distance effect on EE outcomes.

PUSS with LWC, and 10 % for PUSS with GPC. Conversely, using three times the original distances increases the total EE by approximately 24 % for hollow core slabs, 23 % for both PUSS with NWC and PUSS with LWC, and 30 % for PUSS with GPC. These findings underscore that while transportation contributes 5.75 %–11.5 % of the total GWP and 7 %–14.5 % of the total EE in the initial LCA, these contributions can vary significantly with actual transportation distances.

5.3.2. EOL recycling allocation approach

The LCA study in sections 5.1 and 5.2 employs the "50:50" allocation approach for EOL recycling as outlined in section 5.1.2.e., wherein 50 % of the recycling benefits are attributed to the studied flooring systems. To evaluate the sensitivity of this assumption, two additional approaches are considered: the "cutoff" approach, which excludes any recycling benefits from the studied floorings, and the "substitution" approach, which allocates 100 % of the recycling benefits to the studied floorings. The results of this analysis are presented in Fig. 16.

Similar to the transportation distance, the sensitivity analysis for recycling allocation methods indicates that altering the allocation approach does not change the ranking of the environmental performance of the studied flooring systems across all the 16 scenarios analysed. However, the impact of changing allocation approaches is most pronounced for both PUSS with GPC and PUSS with LWC. Adopting the cutoff approach increases the GWP and EE associated with these floorings by an average of approximately 20 % and 15 %, respectively, compared with the 50:50 approach. Conversely, utilising the substitution approach decreases the GWP and EE by similar percentages. For hollow core slabs, the changes are the least significant, having an average of about 7 % in GWP and 6 % in EE. For PUSS with NWC, the average percentages are about 15 % and 13 %, respectively.

Overall, using the substitution approach decreases the GWP and EE outcomes for all flooring systems, but as a percentage, the difference between PUSS flooring and hollow core slabs increases, further favouring PUSS flooring. Conversely, the cutoff approach increases the GWP and EE outcomes for all flooring systems, but as a percentage, the difference between PUSS flooring and hollow core slabs decreases, though PUSS flooring still has less associated environmental impacts.

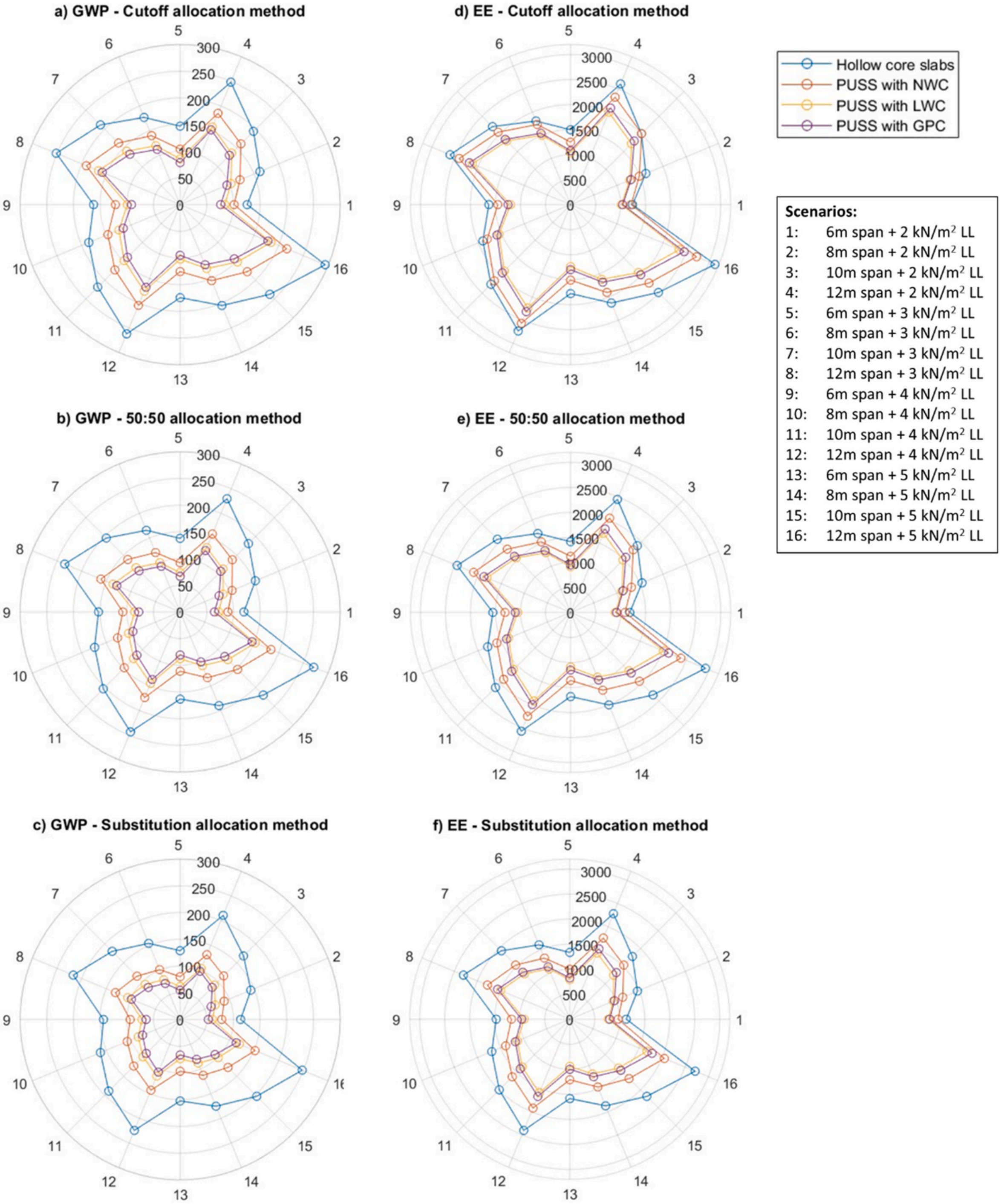

Fig. 16. Sensitivity analysis of recycling allocation method effect on GWP and EE outcomes.

6. Results discussion

Building upon the detailed analysis of the results, this section explores the broader implications of the case study findings by having an overall look at the life cycle stages of all the explored scenarios, and discussing the key factors influencing the environmental impacts of the studied flooring systems in the context of UK geographical conditions. The following key points highlight the main takeaways from the analysis.

a. The manufacturing phase of the analysed flooring systems constitutes a significant portion, ranging from 86 % to 94 %, of the total calculated GWP for all flooring systems and between 83 % and 93 % of the total EE. These high proportions are consistent with findings from previous research on precast floorings, where the manufacturing phase often accounts for up to over 90 % of the total environmental impacts [70]. These percentages are lower for smaller live loads and slabs' spans and gradually increase as these variables increase. This is primarily attributed to the inclusion of materials inventories in this phase. Moreover, a substantial portion of the impacts comes from the construction process, leaving minimal share from on-site construction work.
b. The inventory results from all transportation phases throughout the life cycle of the flooring systems accounts for a relatively small but significant share of the environmental impacts. For the investigated live load/slab span scenarios, when using the approximate average transportation distances within UK (Table 8), transportation contributes to between 5.75 % and 11.5 % of the total GWP and 7 %–14.5 % of the total EE, which is consistent with previous research stating that transportation on average contributes to between 7 % and 10 % of total GWP and EE [70,71]. These percentages can vary significantly due to the uncertainties in transportation distances, as highlighted in the sensitivity analysis. Although the transportation-related impacts increase with larger live loads and spans -due to the heavier slabs requiring more transportation trips-it is found that their proportional contribution to the total inventory results decreases. This inverse relationship is a result of the transportation phase's relatively lower impact compared to the manufacturing phase.
c. The on-site construction phase contributes only between 0.25 % and 1.25 %, respectively, of the total GWP and EE for the PUSS flooring system with the three concrete alternatives, whereas it is responsible for a range of 0.35 %–2.2 % of the total GWP and EE for the hollow core slabs flooring system, in agreement with the case study presented by Balasbaneh et al. [70] stating that on-site construction is responsible for around 2 % of the total GWP and EE of hollow core slabs. These percentages are inversely proportional to the live load and span. The elevated results and percentages accompanying hollow core slabs is attributed to the necessity of adding a finishing layer.
d. The end-of-life (EOL) phase comprises two sections: demolition to landfill, mainly considered for demolished concrete, and the recycling of steel elements in the flooring system. The demolition of concrete in the flooring systems appears negligible, responsible for less than 0.25 % of the total inventory results for all floorings across all live load/span scenarios. Conversely, recycling is a major contributor to the difference between the two flooring systems in the final results. Under the "50:50" allocation approach, steel recycling recovers between 4 % and 7 % of the total inventory results for hollow core slabs and between 10 % and 18 % for PUSS floorings. These percentages are directly proportional to the live load and span. However, the sensitivity analysis in section 5.3.2 demonstrates that the recovery percentage can vary significantly depending on the selected EOL recycling allocation approach.
e. The inventory results across all live load/span scenarios reveal an overall better environmental performance of the PUSS flooring system with all three concrete alternatives compared with hollow core slabs, considering both GWP and EE. PUSS with GPC emerges as the option with the lowest overall GWP, reducing it by 40 %–50 % in comparison to hollow core slabs. It is followed by PUSS with LWC, which achieves savings between 37 % and 46 % of the total GWP generated by hollow core slabs, and finally, PUSS with NWC, which demonstrates reductions between 24 % and 33 % of the total GWP generated by hollow core slabs. Regarding EE, PUSS with LWC is identified as the option with the lowest overall EE, conserving between 21 % and 35 % of the total EE generated by hollow core slabs. It is followed by PUSS with GPC, achieving savings between 17 % and 32 % of the total EE generated by hollow core slabs, and finally, PUSS with NWC, which shows reductions of only between 6 % and 20 % of the total EE generated by hollow core slabs.
f. The reduction in the total inventory results for PUSS flooring compared with hollow core slabs is a cumulative effect derived from all life cycle phases. For the manufacturing phase, the reduction results from the use of less materials and the incorporation of concretes with less environmental impacts in PUSS with LWC and PUSS with GPC floorings. In transportation phase, savings are attributed to the lighter weights of PUSS slabs, enabling the transportation of larger number of slabs per truck loading. For the on-site construction phase, the wider PUSS units reduce the required number of slabs, subsequently minimising the number of lifts needed by tower cranes for slab placement. Hollow core slabs necessitate the use of additional on-site equipment, such as concrete pumps and compactors, for finishing layer placement. For concrete demolishing phase, there is negligible difference; however, the higher steel content in PUSS flooring allows for a greater recovery percentage during recycling.

7. Conclusions and recommendations

Construction sector stands as a major contributor to environmental degradation, responsible for significant GHGs emissions and consuming considerable amounts of energy. Addressing the worldwide demand and in the meantime reducing these harmful effects can be achieved only by restricting the impacts of construction, given the economic growth and the escalating demand for new buildings to accommodate a growing population. A more viable approach involves the widespread adoption of sustainable and environmentally friendly construction practices. Several construction techniques are recognised as environmentally friendly alternatives to traditional construction methods. Notably, opting for prefabrication instead of on-site concrete casting, substituting cement in concrete with more sustainable materials, the use of lighter construction materials, and deploying optimisationed composite structural elements contribute significantly in reducing the environmental impacts and resource consumption.

This paper evaluates the environmental performance of two flooring systems —PUSS and hollow core slabs— through a comparative life cycle assessment (LCA) study. Both flooring systems demonstrate comparable functional behaviours in terms of fire resistance, thermal insulation, and the presence of voids for the passage of building services. To ensure similar structural performance, both systems were designed to withstand equivalent loads and compared across 16 live load/slab span scenarios. The PUSS flooring system is assessed utilising three concrete alternatives: normal weight concrete (NWC), lightweight concrete (LWC), and geopolymer concrete (GPC). The LCA includes evaluating the embodied energy (EE) and global warming potential (GWP) of the flooring systems from cradle to grave. The case study highlights the environmental advantages of the fully prefabricated composite flooring systems (PUSS) and its benefits over the widely used hollow core precast flooring system.

The assessment outcomes reveal that, regardless of the flooring span and applied live loads, PUSS with GPC exhibits the most favourable performance in terms of GWP, closely followed by PUSS with LWC. However, in terms of EE, PUSS with LWC emerges as the top performer, with PUSS with GPC closely trailing. The marginal difference in the two impacts makes selecting the best option challenging. Nevertheless, the lighter weight of PUSS with LWC implies additional savings in inventory results through design modifications to the underlying structure, from beams to foundations. This characteristic makes it the flooring option with the best environmental performance in this study. Following these two floorings, PUSS with NWC ranks third, while hollow core slabs exhibits the least favourable environmental performance. Furthermore, the sensitivity analysis results confirm that variations in transportation distance and recycling allocation methods do not alter the relative ranking of the flooring systems. This robustness in ranking underscores the reliability of the findings despite potential uncertainties in these parameters.

The findings of this research indicate that various manufacturing approaches significantly influence the GHGs emissions and EE, ranked from most to least impactful, these approaches are: reduction of material consumption, off-site production, optimisation of the transportation distance and increasing slab unit width.

It is essential to note that the design of the analysed PUSS and hollow core units is in accordance with EC2 and EC4. The use of alternative design codes may yield different designs, consequently affecting the total inventory results and accordingly the derived curve-fitting equations. Nevertheless, the difference should remain within the acceptable limits and follow the same overall trend. In addition, while this research has yielded valuable outcomes, there is room for enhancement in future research to provide even more comprehensive outcomes. The design of PUSS units is constrained by the utilisation of existing British steel parallel flange channel (PFC) sections. Incorporating custom-made sections into the study has the potential to yield even more versatile designs. This expansion would facilitate the investigation of the impact of larger slab spans, given that the currently available sections can achieve a maximum span of 12m in PUSS units. Future studies could also involve exploring new calculation methodologies or generating new materials and equipment inventories instead of relying on published databases.

Moreover, for enhanced precision, future investigation could incorporate sensitivity analysis of different parameters, such materials production process. In addition, detailed inventory results from operation and maintenance stage of the flooring systems can be considered, as well as end-of-life (EOL) concrete recycling. While these factors might not lead to significant changes in outcomes or substantial differences between flooring systems, their inclusion would contribute to the overall accuracy of the outputs. Lastly, examining the impact of flooring systems on underlying structural elements and quantifying the resultant material savings, when added to the total inventory results of the floorings, has the potential to significantly enhance the environmental performance of lighter flooring systems.

Data availability

No data was used for the research described in the article.

CRediT authorship contribution statement

Ahmed Abdulla Alali: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Yue Huang:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Konstantinos Daniel Tsavdaridis:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Pean, S. Berger, B. Zhou, IPCC, 2021: Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the, Intergovernmental Panel on Climate Change, 2021.
[2] X. Li, Y. Zhu, Z. Zhang, An LCA-based environmental impact assessment model for construction processes, Build. Environ. 45 (3) (2010) 766–775.
[3] R. Mateus, L. Bragança, Sustainability assessment and rating of buildings: developing the methodology SBToolPT–H, Build. Environ. 46 (10) (2011) 1962–1971.
[4] P. Van den Heede, N. De Belie, Environmental impact and life cycle assessment (LCA) of traditional and 'green'concretes: literature review and theoretical calculations, Cement Concr. Compos. 34 (4) (2012) 431–442.
[5] H.J. Jang, Y.H. Ahn, S.H. Tae, Proposal of major environmental impact categories of construction materials based on life cycle impact assessments, Materials 15 (14) (2022) 5047.
[6] B. Rey-Álvarez, B. Sanchez-Montanes, A. García-Martínez, Building material toxicity and life cycle assessment: a systematic critical review, J. Clean. Prod. 341 (2022) 130838.
[7] I.M. Ahmed, K.D. Tsavdaridis, Life cycle assessment (LCA) and cost (LCC) studies of lightweight composite flooring systems, J. Build. Eng. 20 (2018) 624–633.

[8] Y.H. Dong, L. Jaillon, P. Chu, C.S. Poon, Comparing carbon emissions of precast and cast-in-situ construction methods–A case study of high-rise private building, Construct. Build. Mater. 99 (2015) 39–53.
[9] V.M. Malhotra, Role of supplementary cementing materials in reducing greenhouse gas emissions, Concrete technology for a sustainable development in the 21st century 5 (2000) 6.
[10] İ.B. Topçu, M.U. Toprak, T. Uygunoğlu, Durability and microstructure characteristics of alkali activated coal bottom ash geopolymer cement, J. Clean. Prod. 81 (2014) 211–217.
[11] C. Meyer, The greening of the concrete industry, Cement Concr. Compos. 31 (8) (2009) 601–605.
[12] P. Nath, P.K. Sarker, Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition, Construct. Build. Mater. 66 (2014) 163–171.
[13] K. Neupane, Fly ash and GGBFS based powder-activated geopolymer binders : a viable sustainable alternative of portland cement in concrete industry, Mech. Mater. 103 (2016) 110–122.
[14] T. Suwan, Development of Self-Cured Geopolymer Cement, Doctoral dissertation, Brunel University London, 2016.
[15] T. Bakharev, Thermal behaviour of geopolymers prepared using class F fly ash and elevated temperature curing, Cement Concr. Res. 36 (6) (2006) 1134–1147.
[16] P. Duxson, A. Fernández-Jiménez, J.L. Provis, G.C. Lukey, A. Palomo, J.S. van Deventer, Geopolymer technology: the current state of the art, J. Mater. Sci. 42 (9) (2007) 2917–2933.
[17] K. Komnitsas, D. Zaharaki, V. Perdikatsis, Geopolymerisation of low calcium ferronickel slags, J. Mater. Sci. 42 (9) (2007) 3073–3082.
[18] D. Hardjito, C.C. Cheak, C.H.L. Ing, Strength and setting times of low calcium fly ash-based geopolymer mortar, Mod. Appl. Sci. 2 (4) (2008) 3–11.
[19] A.M.M. Al Bakri, H. Kamarudin, I.K. Nizar, A.V. Sandu, M. Binhussain, Y. Zarina, A.R. Rafiza, Design, processing and characterization of fly ash-based geopolymers for lightweight concrete application, Rev. Chem. 64 (4) (2013) 382–387.
[20] G.S. Ryu, Y.B. Lee, K.T. Koh, Y.S. Chung, The mechanical properties of fly ash-based geopolymer concrete with alkaline activators, Construct. Build. Mater. 47 (2013) 409–418.
[21] D.A. Salas, A.D. Ramirez, N. Ulloa, H. Baykara, A.J. Boero, Life cycle assessment of geopolymer concrete, Construct. Build. Mater. 190 (2018) 170–177.
[22] R. Mateus, S. Neiva, L. Bragança, P. Mendonça, M. Macieira, Sustainability assessment of an innovative lightweight building technology for partition walls–comparison with conventional technologies, Build. Environ. 67 (2013) 147–159.
[23] B. López-Mesa, Á. Pitarch, A. Tomás, T. Gallego, Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors, Build. Environ. 44 (4) (2009) 699–712.
[24] L. Jaillon, C.S. Poon, Sustainable construction aspects of using prefabrication in dense urban environment: a Hong Kong case study, Construct. Manag. Econ. 26 (9) (2008) 953–966.
[25] F. Wong, Y.T. Tang, Comparative embodied carbon analysis of the prefabrication elements compared with in-situ elements in residential building development of Hong Kong, Int. J. Civ. Environ. Eng. 6 (2) (2012) 89–94.
[26] J. Anderson, A. Moncaster, Embodied carbon of concrete in buildings, Part 1: analysis of published EPD, Buildings & Cities 1 (1) (2020) 198–217.
[27] C. Hill, A. Norton, J. Dibdiakova, A comparison of the environmental impacts of different categories of insulation materials, Energy Build. 162 (2018) 12–20.
[28] G. Grazieschi, F. Asdrubali, G. Thomas, Embodied energy and carbon of building insulating materials: a critical review, Cleaner Environmental Systems 2 (2021) 100032.
[29] F. Asdrubali, G. Grazieschi, M. Roncone, F. Thiebat, C. Carbonaro, Sustainability of building materials: embodied energy and embodied carbon of masonry, Energies 16 (4) (2023) 1846.
[30] G. Hahnel, A. Whyte, W.K. Biswas, A comparative life cycle assessment of structural flooring systems in Western Australia, J. Build. Eng. 35 (2021) 102109.
[31] I.M. Ahmed, K.D. Tsavdaridis, The evolution of composite flooring systems: applications, testing, modelling and eurocode design approaches, J. Constr. Steel Res. 155 (2019) 286–300.
[32] K.D. Tsavdaridis, C. D Mello, M. Hawes, Experimental study of ultra shallow floor beams (USFB) with perforated steel sections, in: Nordic Steel 09, Nordic Steel, 2009, September, pp. 312–319.
[33] K.D. Tsavdaridis, C. D'Mello, B.Y. Huo, Experimental and computational study of the vertical shear behaviour of partially encased perforated steel beams, Eng. Struct. 56 (2013) 805–822.
[34] K.D. Tsavdaridis, A. Giaralis, Derivation of dynamic properties of steel perforated Ultra Shallow Floor Beams (USFBTD) via Finite Element modal analysis and experimental verification, in: Proceedings of the 7th National Conference on Steel Structures, vol. 2, 2011, pp. 321–329.
[35] R. Kansinally, K.D. Tsavdaridis, Vibration response of USFB composite floors, in: Nordic Steel Construction Conference 2015, 2015, September.
[36] C. Maraveas, Z. Fasoulakis, K.D. Tsavdaridis, Fire resistance of axially restrained and partially unprotected Ultra Shallow Floor Beams (USFB®) and DELTABEAM® composite beams, in: Applications of Fire Engineering, Taylor Francis, 2017, September, pp. 81–90.
[37] C. Maraveas, K.D. Tsavdaridis, A. Nadjai, Fire resistance of unprotected ultra shallow floor beams (USFB): a numerical investigation, Fire Technol. 53 (2017) 609–627.
[38] N. Alam, A. Nadjai, F. Ali, W. Nadjai, Structural response of unprotected and protected slim floors in fire, J. Constr. Steel Res. 142 (2018) 44–54.
[39] O. Hechler, M. Braun, New structural concepts in high-rise building, Highrise towers and tall buildings 2010. Design and construction of safe and sustainable highrise structures, in: International Conference at the Technische Universität München, Overseas Publishers Association, 2010.
[40] J.B. Yan, J.Y. Wang, J.R. Liew, X. Qian, Applications of ultra-lightweight cement composite in flat slabs and double skin composite structures, Construct. Build. Mater. 111 (2016) 774–793.
[41] O. Hechler, M. Braun, R. Obiala, U. Kuhlmann, F. Eggert, G. Hauf, CoSFB—composite slim-floor beam: experimental test campaign and evaluation, in: Composite Construction in Steel and Concrete VII, 28-31 July 2013, Palm Cove, American Society of Civil Engineers, North Queensland, Australia, 2013.
[42] M. Lawson, P. Beguin, R. Obiala, M. Braun, Slim-floor construction using hollow-core and composite decking systems, Steel Construction 8 (2) (2015) 85–89.
[43] S. Hicks, Current trends in modern floor construction, New Steel Construct. 11 (1) (2003) 32–33.
[44] D.L. Mullett, Slim Floor Design and Construction, The Steel Construction Institute, 1992.
[45] M.K. Rahman, M.H. Baluch, M.K. Said, M.A. Shazali, Flexural and shear strength of prestressed precast hollow-core slabs, Arabian J. Sci. Eng. 37 (2012) 443–455.
[46] Z.M. Hussein, W.I. Khalil, H.K. Ahmed, Structural behavior of sustainable Hollow Core Slabs reinforced with hybrid fibers, ARPN J. Eng. Appl. Sci. 13 (24) (2018) 9328–9334.
[47] F.P.V. Ferreira, K.D. Tsavdaridis, C.H. Martins, S. De Nardin, Steel-concrete composite beams with precast hollow-core slabs: a sustainable solution, Sustainability 13 (2021) 4230, 2021.
[48] I.M. Ahmed, K.D. Tsavdaridis, Shear connection of prefabricated slabs with LWC - part1: experimental and analytical studies, J. Constr. Steel Res. 169 (2020) p106016.
[49] I.M. Ahmed, Shear connection of a prefabricated lightweight steel-concrete composite flooring system. Doctor of Philosophy Thesis, The University of Leeds, 2019.
[50] A.A. Alali, K.D. Tsavdaridis, Flexural behaviour of prefabricated ultra-shallow composite slabs with horizontally oriented shear connectors, in: Proceedings of 10th National Conference on Steel Structures. EEME, 2023, October.
[51] K.H. Yang, J.K. Song, K.I. Song, Assessment of CO_2 reduction of alkali-activated concrete, J. Clean. Prod. 39 (2013) 265–272.
[52] British Standards Institution, BS EN 15978:2011 - Sustainability of Construction Works — Assessment of Environmental Performance of Buildings — Calculation Method, BSI Standards Limited, London, 2011.
[53] BS EN ISO 14040, Environmental Management - Life Cycle Assessment - Principles and Framework, European Committee for Standardization, Brussels, 2006.
[54] BS EN ISO 14044, +A1-2018 Environmental Management - Life Cycle Assessment - Requirements and Guidelines, European Committee for Standardization, Brussels, 2006.
[55] M. Brander, G. Davis, Greenhouse gases, CO_2, CO_{2e}, and carbon: What do all these terms mean, Ecometrica, White Papers (2012), 1–3.

[56] BS EN 1992-1-1, Eurocode 2: Design of Concrete Structures, Part 1-1: General Rules and Rules for Buildings, European Committee for Standardization, Brussels, 2004.
[57] Longley, Hollowcore precast flooring [Online]. Available from: https://www.longley.uk.com/wp-content/uploads/2014/09/4pp-Hollowcore-Precast-Flooring-Leaflet-NOV-2019-WEB-1.pdf, 2019.
[58] Forterra, Hollowcore load-span tables [Online]. Available from: https://www.forterra.co.uk/wp-content/uploads/2020/12/Hollowcore-Loadspan-Tables-V3-3.pdf, 2020.
[59] FP McCann, Precast flooring solutions [Online]. Available from: https://fpmccann.co.uk/wp-content/uploads/2021/06/Flooring_2022_v5.1.pdf, 2021.
[60] BS EN 1994-1-1, Eurocode 4: Design of Composite Steel and Concrete Structures, Part 1-1: General Rules and Rules for Buildings, Euro-pean Committee for Standardization, Brussels, 2004.
[61] British Steel, Steel sections [Online]. Available from: https://britishsteel.co.uk/media/vv2la1v1/uk-sections-datasheets-100723.pdf, 2018.
[62] C.V. Gorkum, CO_2 Emissions and Energy Consumption during the Construction of Concrete Structures, Delft University of Technology, Holland, pg, 2010, pp. 1–143.
[63] G. Hammond, C.A. Jones, BSRIA Guide: Embodied Carbon the Inventory of Carbon and, BSRIA, Bracknell, 2011.
[64] Y. Huang, A. Spray, T. Parry, Sensitivity analysis of methodological choices in road pavement LCA, Int. J. Life Cycle Assess. 18 (2013) 93–101.
[65] K. Allacker, F. Mathieux, S. Manfredi, N. Pelletier, C. De Camillis, F. Ardente, R. Pant, Allocation solutions for secondary material production and end of life recovery: proposals for product policy initiatives, Resour. Conserv. Recycl. 88 (2014) 1–12.
[66] A.L. Nicholson, E.A. Olivetti, J.R. Gregory, F.R. Field, R.E. Kirchain, End-of-life LCA allocation methods: open loop recycling impacts on robustness of material selection decisions, in: 2009 IEEE International Symposium on Sustainable Systems and Technology, IEEE, 2009, May, pp. 1–6.
[67] E. Cherubini, D. Franco, G.M. Zanghelini, S.R. Soares, Uncertainty in LCA case study due to allocation approaches and life cycle impact assessment methods, Int. J. Life Cycle Assess. 23 (2018) 2055–2070.
[68] D.B. Figueiredo Filho, J.A.S. Júnior, E.C. Rocha, What is R^2 all about? Leviathan (3) (2011) 60–68.
[69] D. Chicco, M.J. Warrens, G. Jurman, The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation, PeerJ Computer Science 7 (2021) e623.
[70] A.T. Balasbaneh, W. Sher, D. Yeoh, K. Koushfar, LCA & LCC analysis of hybrid glued laminated Timber–Concrete composite floor slab system, J. Build. Eng. 49 (2022) 104005.
[71] L. Vukotic, R.A. Fenner, K. Symons, Assessing embodied energy of building structural elements, in: Proceedings of the Institution of Civil Engineers-Engineering Sustainability, vol. 163, Thomas Telford Ltd, 2010, September, pp. 147–158. No. 3.
[72] A.G.J. Way, T.C. Cosgrove, M.E. Brettle, Precast Concrete Floors in Steel Framed Buildings, The Steel Construction Institute, 2007.
[73] A.A. Alali, K.D. Tsavdaridis, Flexural behaviour of prefabricated ultra-shallow steel-concrete composite slabs, ce/papers 4 (2–4) (2021) 787–794.
[74] L. Thannimalay, S. Yusoff, N.Z. Zawawi, Life cycle assessment of sodium hydroxide, Aust. J. Basic Appl. Sci 7 (2) (2013) 421–431.
[75] Steel AB. Hjulsbro, Environmental product declaration for PC-strand – prestressed steel for reinforcement of concrete, in: In Accordance with ISO 14025 and EN 15804:2012+A2:2019. EPD-IES-0002400:002 (S-P-02400), 2020. Retrieved from, https://www.hjulsbrosteel.com/.
[76] J. Sjunnesson, Life cycle assessment of concrete. Department of Technology and Society, Environmental and Energy Systems Studies, Lund University, Lund, Sweden, 2005.
[77] J. Orr, O. Gibbons, W. Arnold, How to Calculate Embodied Carbon v1.0. IStructE, 2020.

Glossary

EE: Embodied energy
EOL: End of life
FA: Fly ash
GGBS: Ground granulated blast furnace slag
GHGs: Greenhouse gases
GPC: Geopolymer concrete
GWP: Global warming potential
LCA: Life cycle assessment
LCI: Life cycle inventory
LCIA: Life cycle impact assessment
LWC: Lightweight aggregates concrete
NWC: Normal weight concrete
PFC: Parallel flange channel steel section
PUSS: Prefabricated ultra-shallow slabs flooring system
WWSS: Web-welded shear stud