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Determining the carbon footprint reduction of reusing lightweight exterior infill walls: A case study of a school building in the United Kingdom

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ABSTRACT

The global construction sector consumes 40 billion tonnes of raw materials and is responsible for considerable CO_2 emissions. With growing awareness of its environmental impact, the construction sector is looking to transition from a linear economy “take-make-waste” scenario towards more circular economy principles. Lightweight exterior infill walls are built between floors of primary structural frames to provide building façades. The design of these components is usually based on the current linear economic model. While lightweight exterior infill walls are becoming increasingly common in building construction in the UK, no studies have investigated the potential environmental benefits of designing them with circularity in mind. This means there’s a lack of research on both the carbon footprint of these walls and the potential environmental benefits of reusing them. Thus, this article assesses the significance of the carbon emissions from lightweight exterior infill walls and examines whether there is any carbon reduction when lightweight exterior infill walls are demounted from the building frames and reused. This paper first examines the construction process of lightweight exterior infill walls and explores the opportunity to demount and reuse them. Then, the environmental impacts of the lightweight exterior infill walls are analysed using a lifecycle assessment framework. Sensitivity and uncertainty analyses are also conducted. The results demonstrate that (i) the embodied carbon of the lightweight exterior infill walls over their lifecycle represents approximately 22% of the embodied carbon of the entire building, and (ii) the disassembly and reuse of infill walls can reduce a building’s embodied carbon over its typical lifetime by about 6% compared to the linear scenario where the walls were not reused.

1. Introduction

1.1. Background

The construction sector is one of the largest contributors to mineral-based material resource extraction, waste production and carbon emissions (Adams et al., 2017). Such activities affect the Earth’s climate and can have a negative environmental impact (Stott, 2016). Equally, however, modern infrastructure underpins modern life. As such, it is beholden on society to deliver efficient infrastructure while minimising environmental impacts. Current construction paradigms based on the “take-make-waste” linear economy will continue to impact our environment negatively (LETI, 2020; Guerra and Leite, 2021). Several government bodies and industries thus have recently incorporated the principles of the circular economy into their policymaking to support the use of virgin materials and products, protect material resources and reduce carbon footprints (McDowall et al; Turcu and Gillie, 2020). In the construction sector, this will involve actions such as reducing material extraction, minimising waste during the construction and end-of-life phases, reducing interventions by extending lifetimes and reusing and/or recycling products, components and materials at the end of their lives (Minunno et al., 2020; Joensuu et al., 2020; Eberhardt et al., 2022).

This study is part of a larger UK program investigating circular economy principles for mineral-based construction materials and focuses on “Design for Deconstruction and Reuse” (Kitayama and Iuorio, 2022, 2024). It focuses on lightweight exterior infill walls due to their

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growing popularity as external walls for both concrete and steel framed buildings, but also because their current design and application typify a linear economy approach to construction. Therefore, understanding and quantifying any potential carbon benefit in advancing the circularity of these façade systems could be beneficial. This study specifically examines a case of a school building in the UK. The choice of case study, the design of the infill panels, and potential routes for reuse were based on extensive discussions and workshops with various industrial and societal stakeholders.

1.2. Lightweight exterior infill walls

Lightweight exterior infill walls are increasingly being used on a range of building types and are an economical and efficient method of providing façade walls (SCI, 2019). The infill walls are built between the floors of steel or concrete frames and are designed to resist wind load and support the weight of the cladding (see Fig. 1). They do not carry load from the surrounding primary structural frames thus they are non-load bearing. The steel frame members of infill walls typically comprise cold-formed steel (CFS) C-sections of various depths (typically 70–300 mm) (SCI, 2019; Iuorio and Kitayama, 2024).

To date, researchers have investigated the environmental performance of building façades made from different materials (Kim, 2011; Radhi and Sharples, 2013; Han et al., 2015; Pomponi and D'Amico, 2017; Hay and Ostertag, 2018; Kvocka et al., 2020; Chafer et al., 2021; O'Neill et al., 2021; Gao et al; Iuorio et al., 2023), with a focus on the façade's embodied carbon emissions. These studies were motivated by the recognition that: (i) embodied carbon had been insufficiently investigated in the past, (ii) efforts to reduce the operational carbon emissions of buildings have led to the use of thicker walls and have thus increased embodied carbon emissions, and (iii) the ratio of embodied to operational carbon emissions will increase as technological advances reduce operational carbon emissions. Other researchers identified that windows were the critical component in determining the environmental performance of building façades and focused on the environmental performance assessment of window frames and glasses (Citherlet et al., 2000; Asif et al., 2005; Sinha and Kutnar, 2012; Carlisle and Friedlander, 2016).

However, no study has investigated the embodied carbon emissions with a focus on infill walls of the type described above, and certainly, no studies have quantified the carbon impacts of reusing such elements to reduce emissions and virgin material extraction.

1.3. Research questions and novelty

Based on the discussions above, there is a pressing need to:

- evaluate the embodied carbon of lightweight exterior infill walls, accounting for current adopted linear economy principles, and
- analyse the effectiveness of incorporating circular economy principles into the lifecycle of lightweight exterior infill walls.

Thus, this article aims to answer the following specific research questions.

- How significant are the carbon emissions from lightweight exterior infill walls based on the current "take-make-waste" linear economic model?
- Is there any carbon reduction when the lightweight exterior infill walls are demounted from the building frames and reused?

In an attempt to answer these questions, a school building constructed in 2022 in Northwest England was taken as a reference. Specifically, this paper first summarises the information about the construction of lightweight exterior infill walls adopted in the case study, it then proposes a deconstruction process and discusses the potential of lightweight exterior infill walls for reuse. The paper subsequently assesses the life cycle performance of a building with lightweight exterior infill walls in terms of embodied carbon emissions for the current linear economic model. It discusses how to consider a reuse scenario within the lifecycle assessment framework and analyses the potential benefits in terms of carbon emissions by reusing the lightweight exterior infill walls. To ensure the reliability of the results, both a sensitivity and an uncertainty analysis are performed. The findings of this paper can pave the way for considering the reuse of components in the early stage of design. Indeed, this study can serve as a reference for evaluating carbon reductions resulting from the reuse of infill wall components, thereby influencing the development of future circular facade systems.

2. Construction of lightweight exterior infill walls

2.1. Circularity of materials used in lightweight exterior infill walls

As shown in Fig. 2, lightweight exterior infill walls are made of CFS frames, internal and external insulation panels, internal and external plasterboards, cladding, and windows (glasses and frames). Some of the typical infill wall components either use a highly recycled material content (such as CFS and aluminium window frames) or have relatively low carbon footprints (such as plasterboards) – we will present a detailed analysis of data in Section 3.3.

However, recycling alone should not be considered as circularity (Gharfalkar et al., 2015), and the overall circularity of these components is minimal. Indeed, while CFS, aluminium window frames and cladding are made with a high percentage of recycled material, the recycling

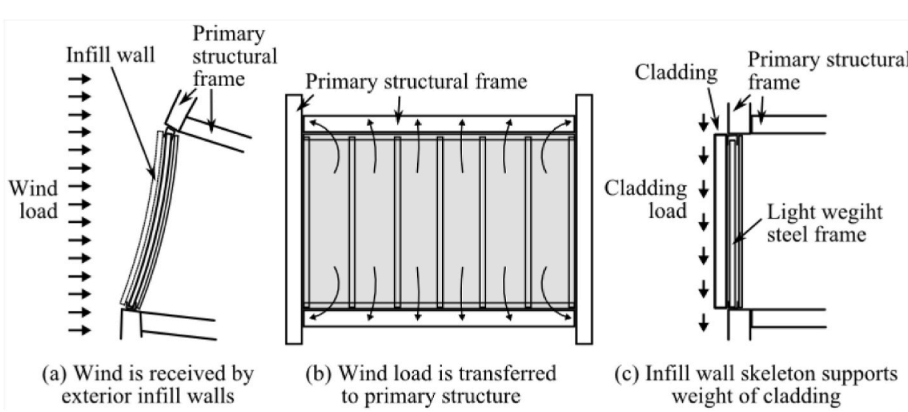

Fig. 1. Functionality of lightweight exterior infill walls.

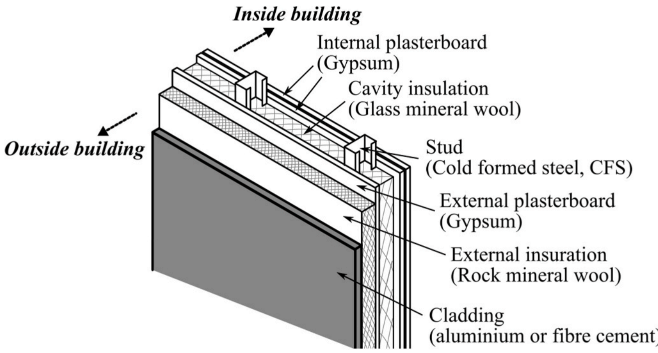

Fig. 2. Components of lightweight exterior infill walls.

processes require energy-intensive operations, which lead to high embodied carbon emissions (Dunant et al., 2018).

Plasterboards are light and their production processes have been improved to make them energy efficient, so generally have low embodied carbon (Papailiopoulou et al., 2017; Etex, 2022a). However, the incorporation of recycled plasterboard when manufacturing new plasterboard is low (only about 5% of the total mass of new plasterboard is from recycled plasterboard – Kitayama and Iuorio, 2023b), and manufacturing new plasterboard requires extraction of virgin gypsum (BRE, 2018). Also, at end-of-life, most plasterboards are downcycled (Papailiopoulou et al., 2017; BRE, 2018).

The manufacturers of internal insulation (glass mineral wool) and external insulation (rock mineral wool) in the UK have increased their recycled contents and reduced the percentage of end-of-life insulation sent to the landfill, although the overall amount sent to landfill is still high (International EPD System, 2019; Rockwool, 2024; Knauf, 2022).

Fibre cement claddings have high cement contents, the production of which results in large carbon emissions (Schneider et al., 2011). The circular treatment of fibre cement cladding at end-of-life has not been established yet, and many used products are sent to landfills or downcycled (IBU, 2019, Etex, 2022b).

End-of-life window glass, although fully recyclable, is seldom recycled into new glass products, and instead, it is usually crushed together with other building materials and either sent into landfills or recovered to low-grade fill applications (Hestin et al., 2016).

In summary, the components within lightweight exterior infill walls could be circular but are not at present. Problems exist since they (i) need considerable quantities of virgin materials for production, (ii) are sent to landfills or downcycled at the end of their lives, or (iii) need energy-intensive recycling processes.

2.2. Construction of lightweight exterior infill walls and their deconstruction and reuse potential

In the UK, lightweight exterior infill walls are either entirely site-assembled or partly prefabricated and then constructed on-site (SCI, 2012a; SCI, 2021). The site-assembled infill walls are made from CFS members with C-sections (SCI, 2012b) which are delivered from the factory and cut to length on-site. Alternatively, the pre-assembled walls are factory-assembled using a CFS frame and external plasterboard, before being delivered to the site, and craned into the primary structural frame. When the pre-assembled walls are panelised into small portions of a wall, they can be manually installed without a crane (see Figs. 3 and 4). There are several advantages of using the pre-assembled, panelised infill walls, such as: (a) enhanced safety of installation workers (installation from inside the structure, reducing external working at height), (b) reduced costs (reduced mast climber and scaffolding requirements), and (c) reduced site waste.

The installation process of pre-assembled, panelised infill walls to the primary structural frame is illustrated schematically in Fig. 5 and is based on the client's documentation and the authors' observations during the construction process. The deconstruction of infill walls can be considered as a reverse of the construction process shown in Fig. 5, based on the reversible mechanical connections between the pre-assembled infill walls and the frame members (Iacovidou and Purnell, 2016; SCI, 2019; Kitayama and Iuorio, 2023a,b). Note that all

Fig. 4. Pre-assembled lightweight exterior infill wall panels installed in the primary structural frames.

Fig. 3. Pre-assembled lightweight exterior infill wall panels.

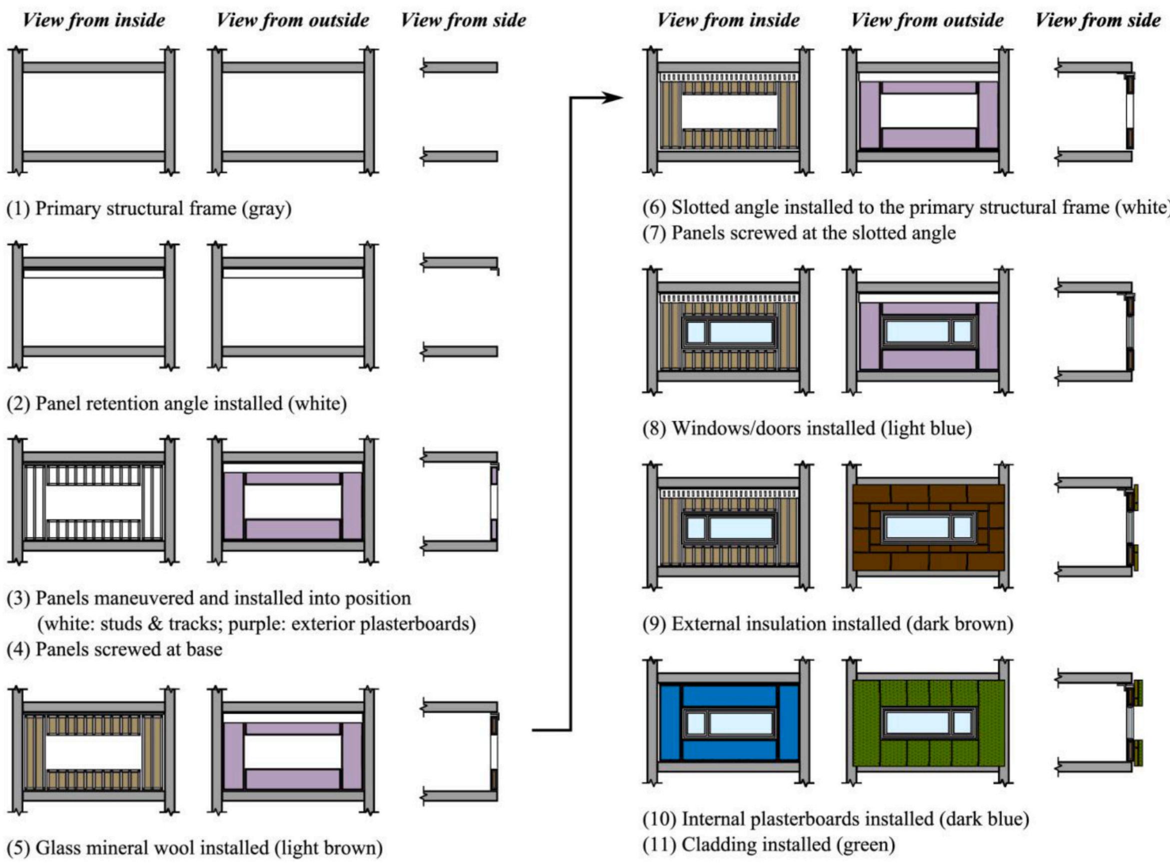

Fig. 5. The construction process of pre-assembled panelised lightweight exterior infill wall (deconstruction is assumed to be a reverse of the construction process).

components of the infill walls except cladding panels could be constructed and deconstructed from the inside of the building, allowing rapid process and safe operation. The construction and deconstruction of the cladding panels must be done from the exterior of the structure, using a mobile elevated working platform or scaffolding.

3. Life cycle embodied carbon assessment

This work presents an embodied carbon Life Cycle Assessment (LCA) study of a case study school building, carried out in accordance with ISO 14040 (ISO, 2006) and ISO 14044 (ISO, 2020), and articulated in the four prescribed phases: a) goal and scope definition, b) inventory analysis, c) impact assessment, and d) interpretation phase.

Embodied carbon assessment, a subset of LCA, evaluates the total greenhouse gas emissions emitted throughout the entire lifecycle of a product or service, such as a building. This includes carbon emissions in terms of CO_2e from raw material extraction, manufacturing, transportation, construction, maintenance, and eventual demolition or deconstruction (Hammond and Jones, 2008). The specific building considered in this paper is detailed in Section 3.1, with the analysed life cycle modules outlined in Section 3.2. Additionally, Section 3.3 defines the building components included in the LCA, followed by the assessment method in Section 3.4 and the interpretation of results in Section 3.5. Embodied carbon is a contributing factor to global warming (BSI, 2011), which in turn drives major changes in the Earth's climate (McCulloch et al., 2024). In response, many countries, including the UK, have set ambitious net-zero carbon emission targets for 2050 (LETI, 2020; Johnson et al., 2023). Calculating the embodied carbon was motivated by these contexts combined with the authors' hypothesis that reusing durable infill wall components (circular scenario) may reduce embodied carbon compared to the non-reused case (linear scenario).

This section first describes the information of the case study building, and describes the four phases in ISO 14040 (ISO, 2006) for the embodied carbon LCA.

3.1. Case study building

The case study presented here is based on a school constructed in 2022 in Greater Manchester, UK. It consists of a teaching block and the dining/main hall. Fig. 6 illustrates the geometry and dimensions of the school building. The teaching block has three floors (ground, first and second floors) and a roof. The dining/main hall is a one-storey atrium space. The total area of the building excluding the roof area is 5741 m^2. The building frames are steel with some braces in the building perimeter. Prefabricated reinforced concrete slabs were used to construct the floor systems on the first, and second floors and the roof. Fig. 7 shows views of the building under construction (photos taken by the first author of this article in December 2022). The main components, excluding window glasses and frames, of the lightweight exterior infill walls are shown in Fig. 2. Figs. 3 and 4 show the pre-assembled components of the lightweight exterior infill walls for the case study building, while Fig. 5 illustrates the construction process of these walls. As seen in these photographs and a figure, the entire building uses lightweight exterior infill walls.

3.2. Goal and scope definition

The goal of this lifecycle assessment is to quantify the embodied carbon emissions of the lightweight exterior infill walls assuming a current "take-make-waste" linear economic model, and to identify the extent to which embodied carbon savings could be delivered by reusing the components of the infill walls for the construction of a future façade (circular scenario).

Following BS EN 15978 (2011), the lifecycle of the building has been

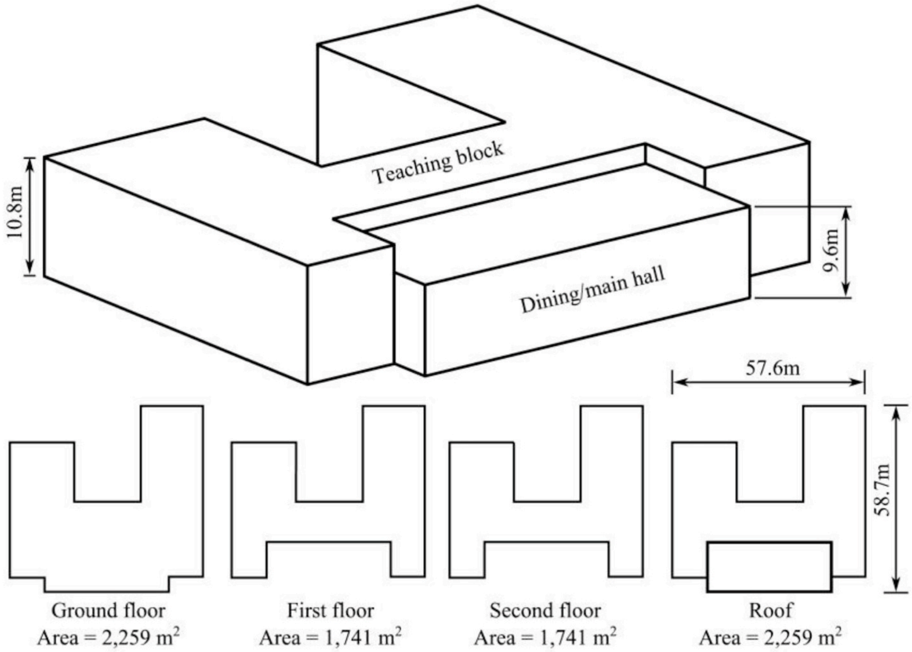

Fig. 6. Schematic of case study building.

(i) Inside view of the building
(On the second floor of the teaching block)

(ii) Outside view of the building
(Dining/main hall and teaching block)

Fig. 7. Views of the school building.

broken into five stages: (i) product stage (module A1-3), (ii) construction process stage (module A4,5), (iii) use stage (module B1-7), (iv) end of life stage (module C1-4), and (v) benefits and loads beyond the system boundary (module D). The LCA system boundaries considered in this study are cradle-to-grave (module A-C), as shown in Fig. 8. This study focused on structural members in the building's substructure and

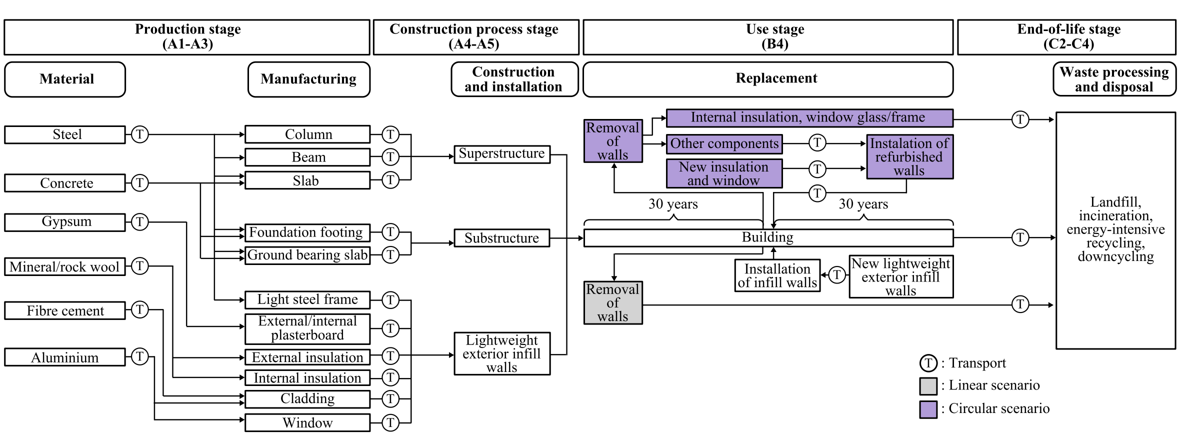

Fig. 8. Scope and system boundary of the case study, including the linear and circular scenarios.

superstructure, including lightweight exterior infill walls. These elements were chosen because they represent the minimum building components required for lifecycle embodied carbon assessment according to RICS (2017) and Gibbons and Orr (2022). Data for other building elements, such as internal finishes, furnishings, or mechanical equipment, was unavailable for inclusion in this analysis. Moreover, as demonstrated in Iuorio et al. (2023), the structural members have higher impacts in terms of carbon footprint in comparison to other components, such as internal finishes and furnishings. In Fig. 8, specific considerations for the linear scenario are coloured in grey, while those for the circular scenario are coloured in purple. The linear scenario involves replacing infill walls every 30 years, whereas the circular scenario involves reusing durable infill wall components during 30-year replacements, as elaborated in sub-sections 3.2.1 and 3.2.2.

Note that this paper assesses the environmental performance of the building with infill walls exclusively in terms of embodied carbon emissions. Therefore, carbon emissions related to the operation and water use required to run the building (modules B6 and B7) are outside of the scope of this study.

3.2.1. Linear scenario

The lifecycle of the lightweight exterior infill walls follows the current construction practice, as part of a linear economic model of "take-make-waste", where the infill walls are made from scratch (A1-A3), transported and installed in the building (A4-A5), and used for 30 years (B4). After 30 years, according to current practice in the UK (Loussos et al., 2015; ARUP, 2022), all infill wall components are sent to landfill or recycled (C2–C4), and newly manufactured infill walls are installed and used for another 30 years.

In this study, the product stage consists of raw material supply (module A1), transport (module A2) and manufacture (module A3) for the different components shown in Fig. 8.

The construction process stage consists of the transport of the components to the construction site (module A4) and the construction installation process (module A5). The lightweight exterior infill walls were prefabricated and brought to site, for installation in the primary structural frame (see Figs. 3–5).

Regarding the use stage (modules B1 to B5), this study only considers module B4 (Replacement) during the use stage, as the impacts of other modules in this stage on the total embodied carbon are generally insignificant or very little data exists (Gibbons and Orr, 2022).

Finally, the end-of-life stage consists of deconstruction or demolition (module C1), transport (module C2), waste processing (module C3) and disposal (module C4). This study did not explicitly consider module C1 due to the lack of data, and given the assumption that it usually has a minor influence, as demonstrated also by RICS and IStructE (RICS, 2017; Gibbons and Orr, 2022).

3.2.2. Circular scenario

The previous subsection described the system boundaries for the linear scenario where all lightweight exterior infill wall components are assumed to have a 30-year lifespan, whereupon they are replaced. However, based on the EPDs, manufacturer's documents and other research results, there is a potential for some infill wall components to be used for longer than 30 years (see the discussions in Section 2.1). Also, the components of the infill wall are connected by screws, which are the suitable connectors for the disassembly and reuse of components (see the discussions in Section 2.2). The prefabricated panelised infill wall construction enables speedy construction and deconstruction of infill walls, mostly from inside the building. Thus, disassembly and reuse of the infill walls' components for other wall constructions is feasible.

In light of this, the scenario of reusing the infill wall components at the replacement stage (i.e., 30 years after the construction of the building) is now considered. Specifically, if the components have remaining lifespans at the replacement stage, i.e., after 30 years (B4 in Fig. 8), that are longer than the remaining lifespan of the building (a further 30 years), those components can be reused at the replacement stage to become components of new infill walls. Later in this paper, Table 3 presents the expected component lifespans for each infill wall component. From Table 3, all of the components apart from the "window glass" and the "window frame" are "reusable" at the 30-year replacement point. It is considered that the internal (cavity) insulations are also replaced after 30 years of initial façade construction, as it is likely that there will be an outside environment change and/or compliance with stricter energy efficiency regulation that necessitates the retrofit of the building façade (Loussos et al., 2015; BBC, 2022). All the other things in the circular scenario at stage B4 are same as the linear scenario as described in Section 3.2.1. The considered scenario is illustrated in Fig. 8.

3.3. Inventory analysis

Building information and embodied carbon factors were derived as described in the following two sub-sections.

3.3.1. Building information

The material inventory was determined based on information obtained from the various parties involved in the school's construction, i.e., the material suppliers, the contractors and the local authority clients. Where precise dimensions were unknown, for example with some of the structural member sections, best-guess estimates were based on the architectural drawings and the common steel structural sections used in the UK (SCI, 2013, 2014, 2015). Table 1 presents the inventory of masses for each member in the superstructure and substructure of the building. The lifespans of the members (CL_i) in Table 1 are all assumed to be 60 years, i.e., the expected lifespan of the school building.

Table 2 presents the data for the infill wall components, including the mass, component lifespans (CL_i; considering linear scenario) and either geometries, number of layers, or typology of the component. The CL_i were determined based on the common practice that whole façades are replaced every 30 years (Loussos et al., 2015; ARUP, 2022).

Table 3 presents information for the infill wall components considering the circular scenario. The expected component lifetimes for each infill wall component were determined based on the manufacturer's documents, EPDs, technical reports and journal articles. Note that the component lifespans of steel frames (250 years) and aluminium cladding (120 years) greatly exceed the 30-year design life assumed in Table 2. This may be because the typical replacement period is determined partly based on the warranties issued by manufacturers, which are often much shorter than their serviceable life (Hartwell et al., 2021).

3.3.2. Embodied carbon factors

Embodied carbon factors (ECFs) for the considered lifecycle modules (discussed in Section 3.2) were obtained for representative values of UK constructions. The sources and databases used include RICS (2017), Gibbons and Orr (2022), Hammond and Jones (2008) as well as EPDs.

Table 1
Inventory of masses and lifespans for each member in the building structure (Gross Internal Area, GIA = 5,741 m^2).

	Components	Mass (kg)	Lifespan, CL_i (years)
Superstructure	Column	63,079	60
	Beam	149,549	
	Slab (concrete)	2,106,908	
	Slab (reinforcement steel)	99,038	
Substructure	Foundation footing (concrete)	40,954	
	Foundation footing (steel)	1507	
	Ground-bearing slab (concrete)	663,242	
	Ground bearing slab (steel)	31,177	

Table 2
Inventory of masses and lifespans for each infill wall component for linear scenario (Gross Internal Area, GIA = 5,741 m^2).

Components	Mass (kg)	Lifespan, CL_i (years)	Notes
Cold-formed steel	21,991	30	The dimensions of the lightweight steel members for infill walls are estimated as follows (unit: mm): Head track: WL = 200, FL = 76, LL = 0, T = 1.2. W = 3.39. Base track: WL = 200, FL = 76, LL = 0, T = 1.2. W = 3.39. Jambs: WL = 196, FL = 65, LL = 15, T = 1.2. W = 3.39. Lintels: WL = 200, FL = 76, LL = 0, T = 1.2. W = 3.39. Sills: WL = 200, FL = 76, LL = 0, T = 1.2. W = 3.39. Where WL: web length, FL: flange length, LL: lip length, W: weight (kg/m), T: thickness. (EOS Framing, 2022; Framing, 2023).
Internal plasterboards	24,672		Two layers of 12.5 mm thickness boards.
External plasterboards	16,827		One layer of 12.5 mm thickness board.
Internal insulation	9,252		Glass mineral wool. 200 mm thickness. One layer.
External insulation	7,710		Rock mineral wool. 100 mm thickness. One layer.
Cladding (aluminium)	2,503		Between the first floor and the roof. 0.9 mm thickness.
Cladding (fibre cement)	10,134		Between the ground floor and the first floor. 12 mm thickness. (EQUITONE, 2022a,b).
Window glass	17,467		4 mm thickness. Two layers (SAS, 2023).
Window aluminium frame	2,615		PURe window systems and SF52 curtain wall (SAS, 2023).

Table 3
Inventory of masses and lifespans for each infill wall component for circular scenario (Gross Internal Area, GIA = 5,741 m^2).

Components	Mass (kg)	Lifespan, CL_i (Years)	Notes
Cold-formed steel	21,991	250 years	SCI (2009), Lawson et al. (2010), AISI (2004), CFSEI (2013)
Internal plasterboards	24,672	60 years	BRE (2018)
External plasterboards	16,827	60 years	Framing, 2023
Internal insulation	9252	30 years	Knauf (2022), Rockwool (2024)
External insulation	7710	60 years	Rockwool
Cladding (aluminium)	2503	120 years	Stacey and Bayliss (2015), Lawson et al. (2010)
Cladding (fibre cement)	10,134	60 years	EQUITONE (2022a,b)
Window glass (for both framed window and curtain walls)	17,467	30 years	SAS (2023)
Window aluminium frame (for both framed window and curtain walls)	2615	30 years	SAS (2023)

The procedure in Gibbons and Orr (2022) is based on the RICS (2017) but with additional information on default values and assumptions for embodied carbon calculations for building constructions in the UK.

As a summary of this information, Tables 4 and 5 present the embodied carbon factors for structural members and lightweight exterior infill walls, respectively, evaluated based on the procedures in Sections 3.3.2.1-3.3.2.4 in this article. The embodied carbon factors for the superstructure and substructure in module B4 are zero due to the assumption that the lifespans of structural components other than infill walls are all 60 years based on RICS (2017), which is the same as the reference study period of the building.

The subsections hereafter explain the details of the embodied carbon calculations for modules A1-3, A4-5, B4, and C1-4 (see Fig. 8). When the components are reused for another infill wall construction, the differences in embodied carbon calculation must be considered between the linear and circular scenarios for each infill wall component that is not reused. Such considerations are also described below for module B4 in Section 3.3.2.3.

3.3.2.1. Product stage (module A1-A3). The embodied carbon factors for each component in the lightweight exterior infill walls for modules A1-A3, $ECF_{A13,i}$, were obtained from Table 2.3 in Gibbons and Orr (2022). When such information was missing, either the database of the Inventory of Carbon and Energy (The ICE Database; Hammond and Jones, 2008) or Environmental Product Declarations (EPDs) were used.

3.3.2.2. Construction process stage (modules A4, A5). Information on the precise delivery operations of the infill wall components from the manufacturing facilities to the construction site is limited. However, from discussions with manufacturers and contractors, it was deduced that the exterior plasterboards were manufactured and transported to where the light steel frame members are manufactured. The pre-assembled wall panels were factory-manufactured and transported to site. The total distance travelled is approximately 300 km (determined based on the discussion with manufacturers, and the information on typical transportation distance for “Nationally manufactured” construction products per Gibbons and Orr, 2022). For other wall components (except light steel), the assumption of national manufacture was made and thus a distance of 300 km by average load was considered. For the light steel in infill walls, the assumed distance was 323 km by lorry based on the manufacturer’s EPD (The International EPD System). Finally, other components (i.e., beams, columns, braces, slabs) were assumed to be produced locally and, therefore, a distance of 50 km by average load was considered (Gibbons and Orr, 2022).

When 300 km road transport by average laden vehicles is assumed, the embodied carbon factors for transportation of each component in the lightweight exterior infill wall, except CFS members, for modules A4, $ECF_{A4,i}$, are obtained from Table 2.5 in Gibbons and Orr (2022), which is 0.032kgCO_2e/kg. 0.057kgCO_2e/kg is used for ECF_{A4} for CFS members based on the manufacturer’s EPD (The International EPD System, 2022).

Module A5 (Construction installation process) is divided into two processes: A5w (Material wastage on site) and A5a (Site activities) (Gibbons and Orr, 2022). Note that the $ECF_{A5w,i}$ is calculated for each infill wall component while the ECF_{A5a} is calculated for the entire building. The $ECF_{A5w,i}$ is computed as follows:

$$ECF_{A5w,i} = WF_i \cdot \left(ECF_{A13,i} + ECF_{A4,i} + ECF_{C2,i} + ECF_{C34,i}\right) \tag{1}$$

where $ECF_{C2,i}$ and $ECF_{C34,i}$ are the embodied carbon factors for module C2 (Transport) and modules C3 (Waste processing) and C4 (Disposal), respectively. These factors are discussed in the following sub-sections. WF_i is a waste factor, which is calculated from the waste rate, WR_i, as follows:

$$WF_i = \frac{1}{1 - WR_i} - 1 \tag{2}$$

Some of the waste rates are summarised in Table 2.6 of Gibbons and Orr (2022). The larger data set for WR_i is available in the original data source from WRAP (2008).

The following equation is provided by Gibbons and Orr (2022) to calculate the site activity embodied carbon factor (ECF_{A5a}) in the absence of project-specific data:

$$ECF_{A5a} = CAEF \cdot PC \tag{3}$$

Table 4
Embodied carbon factors (ECFs) for super- and sub-structures.

	Components	Embodied carbon factors ($kgCO_2e/kg$)					
		A1-3[a]	A4[a]	A5w[a]	B4[a]	C2[a]	C3,4[a]
Superstructure	Column	2.5	0.005	0.025	0	0.005	0.013
	Beam	2.5	0.005	0.025	0	0.005	0.013
	Slab (concrete)	50.2 $kgCO_2e/m^2$[b]	0.005	0.502 $kgCO_2e/m^2$ + 0.00023 $kgCO_2e/kg$	0	0.005	0.013
	Slab (reinforcement steel)		0.005		0	0.005	0.013
Substructure	Foundation footing (concrete)	0.12	0.005	0.008	0	0.005	0.013
	Foundation footing (steel)	0.76	0.005	0.041	0	0.005	0.013
	Ground-bearing slab (concrete)	0.12	0.005	0.008	0	0.005	0.013
	Ground bearing slab (steel)	0.76	0.005	0.041	0	0.005	0.013

[a] All embodied carbon factors are based on Gibbons and Orr (2022).
[b] Floor areas: 2259 m^2 (Ground floor), 1741 m^2 (1st floor), 1741 m^2 (2nd floor), 2259 m^2 (Roof).

Table 5
Embodied carbon factors (ECFs) for lightweight exterior infill walls.

Components	Embodied carbon factors ($kgCO_2e/kg$)					
	A1-3	A4	A5w	B4	C2	C3,4
Steel frame	1.29[g]	0.057[g]	0.028[d]	1.39[d,e]	0.005[g]	0.026[g]
Internal plasterboards	0.16[b]	0.032[d]	0.011[d]	0.22[d,e]	0.005[d]	0.013[d]
External plasterboards	0.14[h]	0.032[d]	0.0044[d]	0.18[d,e]	0.005[d]	0.013[d]
External insulation	1.28[a]	0.032[d]	0.235[d]	1.56[d,e]	0.005[d]	0.013[d]
Internal insulation	1.28[a]	0.032[d]	0.235[d]	1.56[d,e]	0.005[d]	0.013[d]
Cladding (aluminium)[f]	6.83[a]	0.032[d]	0.069[d]	6.95[d,e]	0.005[d]	0.013[d]
Cladding (fibre cement) [f]	0.57[c]	0.032[d]	0.019[d]	0.64[d,e]	0.005[d]	0.013[d]
Window	1.67[a]	0.032[d]	0.091[d]	1.81[d]	0.005[d]	0.013[d]
Frame	6.58[a]	0.032[d]	0.349[d]	6.98[d]	0.005[d]	0.013[d]

[a] Hammond and Jones (2008).
[b] Etex (2022a).
[c] Etex (2022b).
[d] Gibbons and Orr (2022).
[e] Table 3 in this article.
[f] Wates (2022).
[g] EOS Framing Ltd (2023).
[h] Etex France Building Performance (2022).

where *CAEF* is the factor that accounts for the carbon emission from the construction activity, which is suggested to be 700$kgCO_2e$/£100,000 for the carbon assessment for the superstructure and substructure only, and 1,400$kgCO_2e$/£100,000 be used for the whole building. In this study, only superstructure and substructure are considered as listed in Tables 1–5, thus, the lower value of 700$kgCO_2e$/£100,000 is used. If elements other than the superstructure and substructure were considered, such as internal finishes, furnishings, or mechanical equipment (as detailed in RICS, 2017), the upper bound of 1,400$kgCO_2e$/£100,000 would be used. *PC* is the project cost (in £), which is £17 m based on the information on the contractor's website (Wates, 2022).

3.3.2.3. Replacement stage (module b4). The embodied carbon factor for the module B4 (Replacement) for component *i*, $ECF_{B4,i}$, is computed as follows (Gibbons and Orr, 2022):

$$ECF_{B4,j} = \left\lceil \frac{RSP}{CL_i} - 1 \right\rceil \cdot (ECF_{A13,i} + ECF_{A4,i} + ECF_{A5w,i} + ECF_{C2,i} + ECF_{C34,i}) \tag{4}$$

where *RSP* is the reference study period of the building ($RSP = 60$ years in this study per RICS, 2017), CL_i is the lifespan for *i*th infill wall components or structural members, and ⌈ ⌉ is the parenthesis that rounds up the value inside it (0 if the calculation inside the parenthesis becomes less than 0). The factors, $ECF_{A13,i}$, $ECF_{A4,i}$, $ECF_{A5w,i}$, $ECF_{C2,i}$, and $ECF_{C34,i}$ are explained previously. Table 1 presents the CL_i of the primary structural members and Tables 2 and 3 present the CL_i of the infill wall components for linear and circular scenarios, respectively.

For the circular scenario, the calculation of $ECF_{B4,i}$ needs adjustment considering the scenario presented in Fig. 8 and described as follows.

i. $ECF_{A13,i} = 0$ for the infill wall components that are reused after the first 30 years of use. For other components that are not reused (i.e., window glass, window frame, and internal insulation), $ECF_{A13,i}$ for linear scenario is used.
ii. $ECF_{A4,i} = 0.005$ for the infill wall components that are reused following the first 30 years of use considering that the used products are disassembled and reassembled into a new wall at a facility that needs a total journey of 50 km and are transported on road with average loading. For other components that are not reused, $ECF_{A13,i}$ for linear scenario is used.
iii. $ECF_{A5w,i} = 0$ for the infill wall components that are reused following the first 30 years of use. For other components that are not reused, $ECF_{A13,i}$ for linear scenario is used.

3.3.2.4. End-of-life stage (module C1–C4). RICS (2017) suggests an embodied carbon factor of 3.4 $kgCO_2e/m^2$ GIA (GIA: Gross Internal Area — RICS, 2018) for module C1 (Deconstruction or demolition) in the absence of specific information, and so is used in this study. Note that the ECF_{C1} is calculated for the entire building. In this study, a GIA of 5, 741 m^2 was estimated for the studied building based on the architectural drawings (see Fig. 6).

The embodied carbon factor for module C2 (Transport) depends on the end-of-life scenario. The end-of-life scenario for each infill wall component can be established based on the EPDs and information in RICS (2017). Considering the assumptions from the system boundaries, $ECF_{C2} = 0.005$ $kgCO_2e/kg$ is used for both landfill, incineration and recycling cases based on the recommendations in RICS (2017) and Gibbons and Orr (2022).

Embodied carbon factors for waste processing for recovery or recycling emissions (module C3) were not available for the considered infill wall components. RICS (2017) and Gibbons and Orr (2022) suggest that in the absence of specific information for module C3, module C3 and the disposal (module C4) are grouped and the default emissions for disposal to landfill (module C4) should be applied. Herein the embodied carbon factor for modules C3 and C4, $ECF_{C34} = 0.013$ $kgCO_2e/kg$ is used.

3.4. Impact assessment

The embodied carbon was obtained by multiplying the quantities of each component of infill wall or primary structures (masses or volumes – see Tables 1–3) by the corresponding embodied carbon factors (see Tables 4 and 5). The embodied carbon evaluated for each component is totalled to obtain embodied carbon for the entire building including lightweight exterior infill walls.

3.5. Interpretation

The next section discusses the obtained results through diagrams that summarise the computed embodied carbon. Analysis of sensitivity and uncertainty of the LCA results are also conducted and their results are presented.

4. Results and discussion

4.1. Life-cycle embodied carbon of the linear and circular scenarios

Based on the previous section, the embodied carbon for A1-A5 (inclusive of A5a) is 1128 tonnes CO_2e for the entire building including lightweight exterior infill walls. Normalising this by the total floor area (gross internal area) of 5,741 m^2 gives a normalised embodied carbon of 196 $kgCO_2e/m^2$. Given a typical embodied carbon range of 150–400$kgCO_2e/m^2$ for construction to practical completion (Modules A1-A5) for the substructure and superstructure (Gibbons and Orr, 2022), the calculated embodied carbon is deemed reasonable. As discussed above, there is no component-specific information available for computing embodied carbon emissions for modules A5a (Site activities) and C1 (Deconstruction/demolition), thus they were excluded from the considerations below.

Fig. 9 presents the embodied carbon of the entire building for the linear and circular scenarios. For linear scenario, the exterior walls contribute 22% of the entire building's embodied carbon emissions. This is significant and warrants efforts to reduce embodied carbon emissions. On the other hand, the circular scenario reduces embodied carbon emissions by 75 tonnesCO_2e (from 1294 to 1219 tonnesCO_2e). This adoption of reuse therefore reduces the embodied carbon by about 6%, and reduces the contribution of the infill walls to embodied carbon from 22% to 17%.

These observations imply that reusing durable infill wall components contributes to a non-negligible reduction in embodied carbon. Also, the results indicate that if the lifespans of other infill wall components, with high carbon footprints (e.g., window glass, window frames) could be extended (i.e., $CL_i \geq 60$ years) and reused, then the beneficial effect of reusing lightweight exterior infill walls will be enhanced.

The embodied carbon of the lightweight exterior infill walls for the lifecycle stages A-C was calculated to be 280 and 204 tonnes CO_2e, for linear and circular scenarios, respectively. This indicates a 27% reduction in embodied carbon when durable components of infill walls were reused. The contribution of each component to this total is shown in Fig. 10. In the linear scenario, the CFS members (61 tonnesCO_2e) and window glass (63 tonnesCO_2e) dominate, while those from the internal (11 tonnesCO_2e) and external (6 tonnesCO_2e) plasterboards are minor. This trend may be strengthened if there will be an increasing recycling practice of gypsum plasterboards (Papailiopoulou et al., 2017; Weimann et al., 2021). Despite the widely reported contribution of cement and concrete to global CO_2 emissions, the fibre cement cladding only makes a small contribution to the overall embodied carbon of the infill walls.

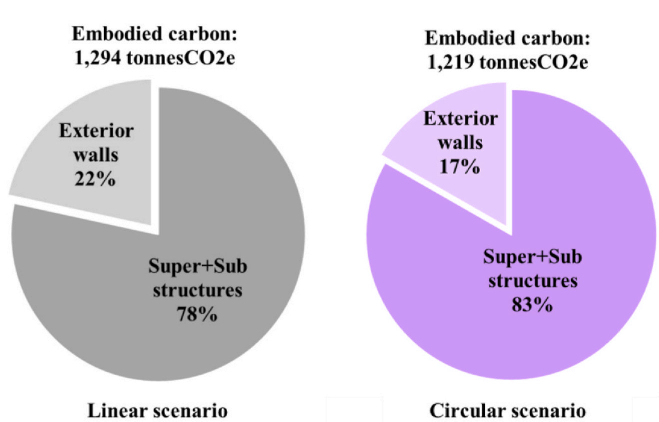

Fig. 9. Embodied carbon emission of the entire building for the linear (left) and circular (right) scenarios, modules A1-A5w, B4, C2–C4.

By reusing the steel frames in the reuse scenario, a substantial reduction in carbon emissions was achieved (49% reduction), highlighting their significant contribution. Thus, in the circular scenario, it is window glass (63 tonnesCO_2e), and to a lesser extent the window frame (37 tonnesCO_2e), that contributes most to the carbon footprint.

Fig. 11 presents the embodied carbon emitted from different lifecycle stages for linear and circular scenarios. The results indicate that, for the linear scenario, the greatest embodied carbon was from the use stage (stage B; 140 tonnesCO_2e). Replacement of infill walls after 30 years has a significant effect on the total embodied carbon emissions in the infill wall lifecycle. The contributions towards embodied carbon emissions from the construction process stage (A4, A5w; 12 tonnesCO_2e) and the end-of-life stage (C2–C4; 2 tonnesCO_2e) were minor. This indicates that the embodied carbon emission may be reduced if the infill walls are used for a longer period than usually replaced (every 30 years), or their components are reused to make new infill walls. For the circular scenario, reusing infill wall components greatly reduced emissions from the use stage (64 tonnesCO_2e; 54% reduction when compared with the linear scenario). The contributions towards embodied carbon emissions from the construction process stage (A4, A5w; 12 tonnesCO_2e) and the end-of-life stage (C2–C4; 2 tonnesCO_2e) remain minor.

4.2. Sensitivity and uncertainty analyses

While the supplementary document presents the full descriptions concerning the sensitivity and uncertainty analyses, this section introduces the reader to the main results and conclusions obtained from them.

The sensitivity of the embodied carbon for modules A1-A5w, B4, C2–C4 and for the entire building including the infill walls towards the following variations were evaluated: (i) wall replacement period (10, 15, 20 and 30 years; for both linear and circular scenarios), (ii) transportation distance of infill walls from the manufacturing facilities to construction site (50, 150, 300, and 400 km; for both linear and circular scenarios), (iii) transportation distance of infill walls from the construction site to reuse facility (10, 25, 50, 100, 300 km; for the circular scenario), and (iv) transportation distance of infill walls from the construction site to end-of-life treatment location (10, 25, 50, 100, 300 km; for both linear and circular scenarios). Note that we capped the wall replacement period ("i" above) at 30 years because a period longer than that would result in wall replacements occurring only once within the building's 60-year lifespan. Therefore, the results of the embodied carbon values are the same as those obtained for a 30-year period. The results are presented in Fig. 12.

Regarding the sensitivity of the replacement period of infill walls ("i" above), the results showed that the circular scenario is particularly beneficial when the walls are replaced at a shorter period (e.g., 10 years compared to 30 years) in reducing the embodied carbon. Regarding the sensitivities in transportation distances ("ii" - "iv" above), the results of these changes did not have a significant impact, is due to the lightness (i.e. reduced weight) of the nationally-manufactured infill wall components.

Uncertainty analysis was conducted to understand how uncertainties in embodied carbon factors for the various infill wall components and primary structural members may affect the computed embodied carbon for the entire building. Monte-Carlo simulation was employed using the minimum, maximum and average embodied carbon factors in Gibbons and Orr (2022) and Hammond and Jones (2008), and using the triangular uncertainty distribution with the minimum, maximum and average embodied carbon factors. When considering minimum and maximum distribution range, the embodied carbon for the entire building for modules A1-A5w, B4, C2–C4 was (a) between 1209 and

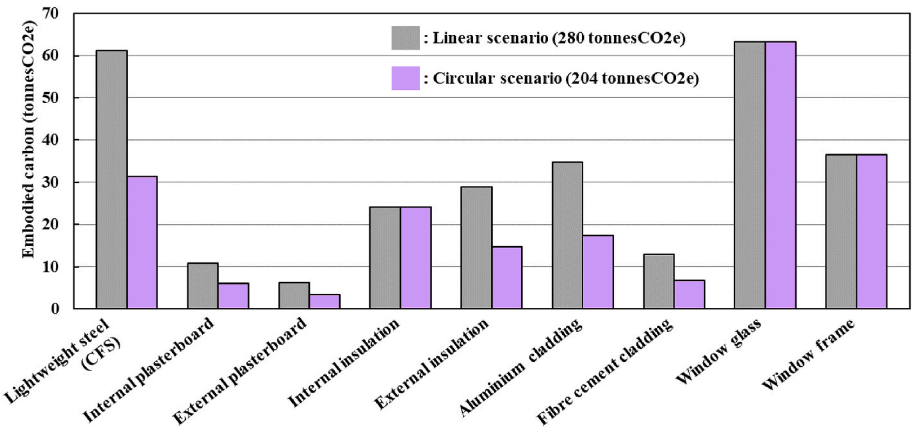

Fig. 10. Embodied carbon from infill wall components in the linear and circular scenarios (modules A1-A5w, B4, C2–C4).

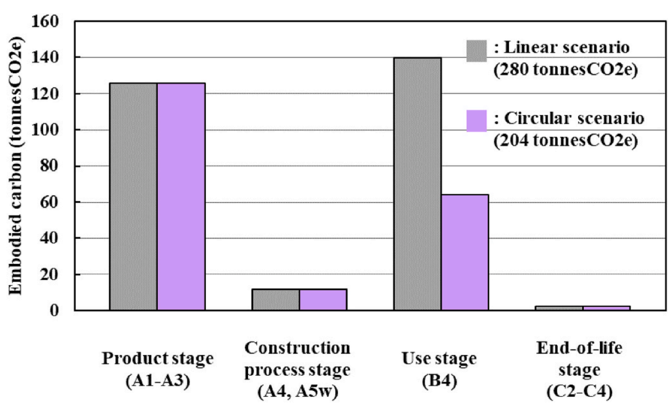

Fig. 11. Embodied carbon from different lifecycle stages for the infill walls in the linear and circular scenarios (modules A1-5w, B4, C2-4).

1406 tonnesCO_2e for the linear scenario and (b) between 1149 and 1312 tonnesCO_2e for the circular reuse scenario. The results are shown in Fig. 13. These results indicated the possible deviations from the analysis results shown in the previous sections. Nonetheless, the observations and findings from the previous subsection were deemed valid in terms of the total embodied carbon emissions from the entire buildings even when the uncertainties in the embodied carbon factors were considered as there are only limited areas covering up each other in the probability distributions from linear and circular scenarios.

4.3. Comparison of results with other studies

Although there are no studies that investigated the embodied carbon emissions with a focus on lightweight exterior infill walls of the type described in this paper, and no studies have quantified the carbon impacts of reusing such elements to reduce emissions, there are some studies that reported embodied carbon values for other types of walls or reported embodied carbon values for exterior walls, albeit without specifying wall designs.

A report by Cundall (2013) presented embodied carbon data for office buildings from various industry case studies. Among these, the data from Davis Langdon (now AECOM) on thirty newly built steel-framed office buildings, ranging from 2 to 36 storeys, reveals that exterior walls represent between 5% and 25% of the buildings' embodied carbon over their lifecycle (considering modules A1-A5). The data indicates no correlation between the percentage of embodied carbon from exterior walls and the number of storeys.

WBCSD (2021) presented six industry case studies on building embodied carbon, with five from UK constructions. These buildings, ranging from 6 to 21 storeys and with GIAs ranging from 14,544 m^2 to 47,264 m^2, show that exterior walls contribute between 9% and 25% (modules A1-A5) and between 10% and 31% (modules A-C) of the buildings' embodied carbon. The study also showed that there is no correlation between the percentage of embodied carbon from exterior walls and the number of storeys nor the GIAs.

The UK's Low Energy Transformation Initiative (LETI, 2020) published a report presenting representative embodied carbon percentages for four archetype buildings: "small-scale residential", "medium and large-scale residential", "commercial offices", and "schools". The report indicates that, considering modules A-C, the percentage of embodied carbon from exterior walls for the four archetype buildings are 17%, 13%, 16%, and 16%, respectively.

Table 6 summarises the embodied carbon percentages from the three studies and the results from this paper. Though there may be some discrepancies in the methods of evaluation of embodied carbon values, such as the inclusion or exclusion of particular building elements, overall, the numbers are consistent, with this paper's results for the linear and circular scenarios falling within the range of carbon percentages from other studies.

5. Limitations of this study

This study focused on embodied carbon emissions from cradle to grave lifecycle (BSI, 2011) to investigate the carbon footprint reduction of reusing lightweight exterior infill walls. However, the analysis did not account for carbon emissions resulting from operational energy and water use, and scenarios beyond the reference study period of 60 years. Given that exterior walls influence carbon emissions from operational energy use (Rivera et al., 2021), the consideration of operational carbon emissions may alter the findings presented in this paper. Moreover, certain infill wall components are durable and may be reused for periods exceeding 60 years. Considering scenarios extending beyond this reference period could further highlight the benefits of reusing these durable components in terms of reducing carbon emissions. Furthermore, while this study focused on a single building for the case study, analysing additional buildings could enhance the robustness of the findings presented in this paper. These are the limitations of this study that may be worthy of future investigation.

6. Conclusions

Although lightweight exterior infill walls are becoming increasingly popular in UK building façade construction, no research has explored the environmental benefits of designing them with circularity in mind. This is a significant gap, as the world faces a shortage of fresh materials for construction and needs to drastically reduce carbon emissions to

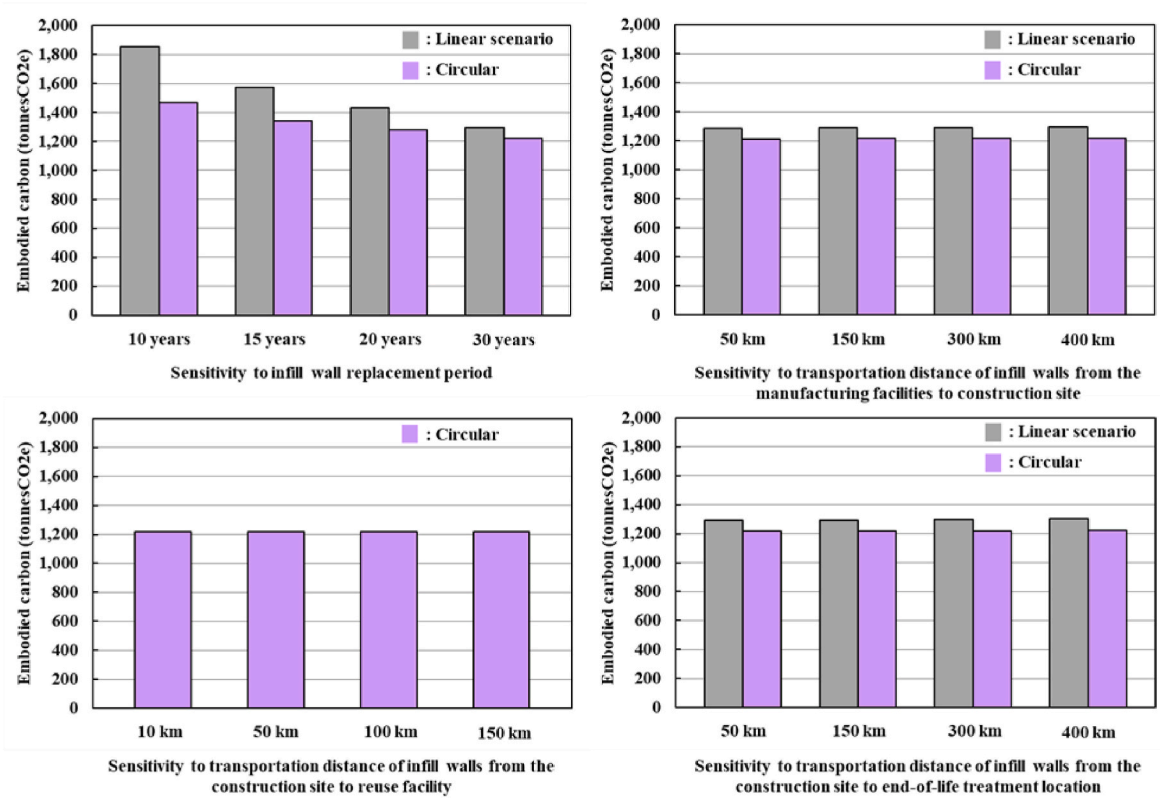

Fig. 12. Sensitivity analysis results showing the embodied carbon for the entire building including the infill walls, modules A1-5w, B4, C2-4.

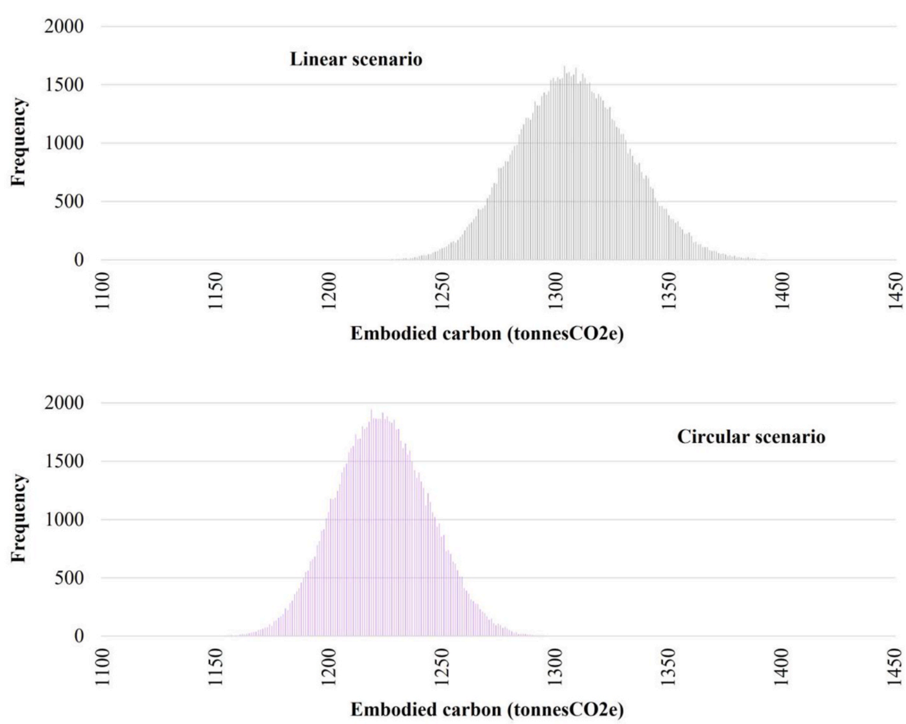

Fig. 13. Uncertainty analysis results showing the embodied carbon emissions of the entire building for the linear (above) and circular (below) scenarios, modules A1-5w, B4, C2-4.

combat climate change. To address this, this paper investigated the potential for incorporating circular economy principles into the lifecycle of lightweight exterior infill walls, and evaluated the carbon impacts.

This article first presented how the pre-assembled panelised lightweight exterior infill walls are constructed using information from a school building in Greater Manchester, UK. Based on these, the work discussed the potential and feasibility of deconstruction and reuse of infill walls and their components.

Table 6
Proportions of exterior walls in the total building carbon footprint from other sources and in this paper.

Data sources	Proportion of exterior walls in the total building carbon footprint
Cundall (2013)	5–25% (A1-A5)
WBCSD (2021)	9–25% (A1-A5), 10–31% (A-C)
LETI (2020)	13–17% (A-C)
This study (Linear scenario)	12% (A1-A5)[a], 22% (A-C)
This study (Circular scenario)	12% (A1-A5)[a], 17% (A-C)

[a] The proportions of exterior walls in the total building carbon footprint from linear and circular scenarios in this study are identical as the difference of carbon calculation between different scenarios arise from module B4, see Section 3.3.2.3 in this paper.

This article then presented the lifecycle embodied carbon assessment for the case study building, considering two scenarios. The first lifecycle scenario considered the current "take-make-waste" linear economy practise which sees the replacement of the infill walls every 30 years, to, then, install new walls, that can respond to new energy and aesthetic requirements. For this linear scenario, it was found that the embodied carbon of the lightweight exterior infill walls over their lifecycle amounts to about 22% of the embodied carbon of the entire building.

A second lifecycle scenario, instead, assessed the embodied carbon emissions assuming a circular economy scenario, to evaluate the potential benefits of reusing infill wall components. This study demonstrated that reusing the durable infill wall components at the 30-year replacement stage in constructing new infill walls can reduce carbon emissions by about 6% compared to the linear scenario. The study also found that if other carbon-intensive infill wall components (i.e., window glass) were reused, then the reduction in embodied carbon by reusing the infill walls could be enhanced. Sensitivity analysis showed that the time between installation of the infill walls and their replacement could be significant, while variations in transport distances were insignificant. Meanwhile, sensitivity and uncertainty analysis provided information on possible deviations of results from the lifecycle analysis. Notably, the sensitivity analysis found that the transportation distances of infill walls using nationally manufactured construction components did not affect total carbon emissions to a significant extent. The uncertainty analysis found that the proportions of exterior walls in the total building carbon footprint and the significance of reusing the lightweight exterior infill walls were deemed valid even when the uncertainties in the embodied carbon values were considered.

In addition to the technical aspects discussed in this article, there is an urgent need for policy recommendations to promote the utilisation of second-hand lightweight exterior infill walls in building construction. This could be achieved through governmental initiatives aimed at enhancing the value of materials during the replacement period of infill walls or by offering tax incentives to companies that adopt demountable and second-hand infill walls.

Future work should examine how to prolong the lifespan of the high emitters such that they can be reused. This being said, not only technological but also a cultural shift is required within the construction sector for more sustainable approaches. While the processes of demounting and reusing the lightweight exterior infill walls are practices that are not common in conventional construction settings, fostering a shift towards more environmentally conscious and resource-efficient approaches is crucial for the long-term sustainability of the construction industry.

CRediT authorship contribution statement

Shoma Kitayama: Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Ornella Iuorio:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition. **Irene Josa:** Writing – review & editing, Visualization, Validation, Software, Investigation, Formal analysis, Data curation. **Aiduan Borrion:** Supervision, Project administration, Funding acquisition. **Leon Black:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

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

Data will be made available on request.

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