

Environmental benefits arising from demountable steel-concrete composite floor systems in buildings

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Abstract

This paper presents an assessment and quantification of the environmental impacts arising from different steel-concrete composite floor systems. In particular, a demountable composite floor system using pretensioned high-strength friction grip bolts as shear connectors is compared with three conventional composite floor systems that use welded shear studs as shear connectors. The first type promotes the end-of-life scenario of disassembly and reuse of structural elements, while the conventional systems are related to the current practices of waste management for building materials, i.e. demolition and recycling. To analyse these different structural systems and relative scenarios, a comparative Life Cycle Assessment investigating two entire life cycles of the materials is developed. Based on the evaluation of several impact categories, the building with demountable composite floor system is identified as the most environmentally friendly solution among all the considered structural solutions, and the saving of emissions and resources is quantified for each impact category.

Keywords

Life Cycle Assessment

Circular Economy

Reuse

Steel-Concrete Composite Structures

Demountable Shear Connector

1. Introduction

The priorities of all European and world governments are continually evolving, and they are strictly related to the urgent environmental demands. The current concerns are about the increasing global consumption of finite non-renewable resources, progressive shortages of primary raw materials, the inefficient waste management, and the reduction of space available for final disposal of waste.

The source of these issues can be identified in the economic model which dominated the global economy's growth in the last decades/centuries. This model, denominated as "take-make-dispose", is purely linear because the products are fabricated from raw materials, sold, consumed and then disposed of as waste. The basic principle of this system is that natural resources are always available, accessible and disposable at low cost.

In contrast with this conventional model, the circular economy, denominated as "make-use-return", is aimed to maintain as long as possible the value of the materials/products and minimize the generation of waste [1].

One of the main sectors of the economy with the greatest business potential within the circular economy is the building sector due to its massive impact on the resource consumption, waste generation and environmental emissions [2]. Furthermore, the Waste Framework Directive 2008/98/EC [3] aims to have 70% of Construction and Demolition waste recycled by 2020. Hence, recycling is an increasingly widespread practice that is already well-established in the case of steel, thanks to both economic and environmental advantages. Nevertheless, a more sustainable construction sector can be achieved by developing demountable structural systems enabling the disassembly and the reuse of the structural elements at the end of life of the building [4].

This paper focuses on steel-concrete composite floor systems which represent the most efficient structural solution for buildings and bridges, as the composite action combines and optimizes the structural properties of the two most used and impactful building materials, i.e.

steel and concrete.

Nowadays, the deconstruction of a composite structure is problematic, if not impossible, due to the monolithic nature of the system offered by current shear connection practices. The most widely used shear connectors are the headed studs which are welded to the top flange of the steel beam and embedded into the concrete slab, as shown in different configurations of composite floor system in Fig. 1.

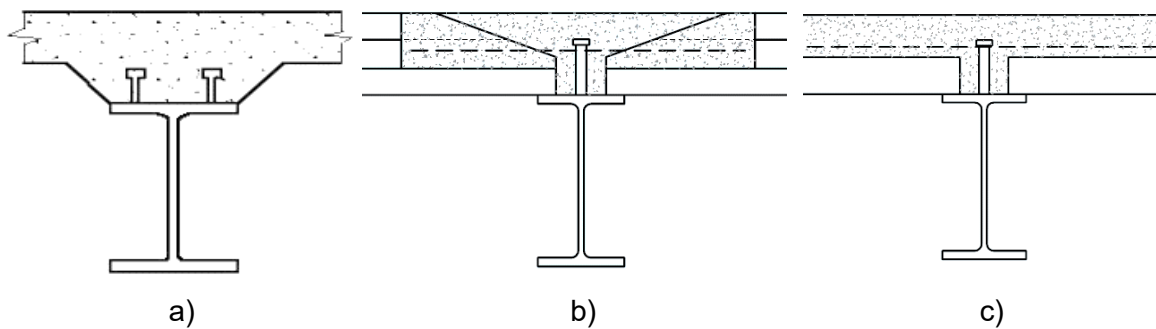


Fig. 1 Welded headed studs applied as shear connectors in profiled decking system (a), hollow core sections (b) and solid slab with topping (c) [5]

Demountable shear connection systems for steel-concrete composite beams promote the end-of-life scenario of disassembly and reuse of structural elements; therefore, they represent a potential solution to achieve more sustainable steel-concrete composite construction in full agreement with the principles of the circular economy. A number of recent research works proposed different demountable composite floor systems (Pavlovic et al. [6], Wang et al. [7], Moynihan and Allwood [8], Lam et al. [9], Feidaki and Vasdravellis [10], Suwaed and Karavasilis [11]); however, this paper focuses on the demountable steel-concrete beams made of precast concrete slabs and steel beams connected using pretensioned High-Strength Friction-Grip (HSFG) bolts (see Fig. 2).

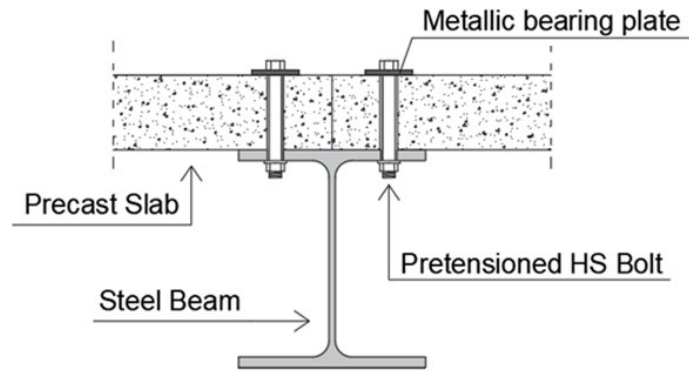


Fig. 2 Steel concrete composite beam with HSFG bolts

The structural behaviour of this technical solution was validated by extensive experimental tests and numerical modelling performed by Dallam [12], Marshall et al. [13], Kwon et al. [14], Bradford [15], Liu et al. [16], Ataei [17]. However, none of the above studies on demountable systems quantified the declared environmental benefits arising from the reuse of the structural elements.

In this paper, the life cycle impacts arising from demountable steel-concrete composite floor systems and the conventional monolithic ones are evaluated by means a comparative Life Cycle Assessment (LCA).

2. Methodology

The Life Cycle Assessment is developed in four phases according to EN ISO 14040/44 [18][19], i.e. goal and scope definition, inventory analysis, impact assessment and interpretation.

2.1. Goal and Scope Definition

This study is a comparative LCA between a demountable steel-concrete composite floor system and three conventional solutions, namely:

- ReuseStru: pre-tensioned High-Strength Friction-Grip Bolts (HSFGB) connect the steel beam to the solid precast concrete slabs promoting the reuse of all the structural elements at the end of the lifespan of the building (Fig. 2).

- Composite Slab: the most diffused structural system with profiled steel sheeting and cast in-situ concrete topping connected to the steel beam by means of embedded welded studs (Fig. 1a).
- Precast HCS: precast hollow core sections are connected to the steel beam through the conventional studs embedded in cast in-situ concrete infill between the precast units (Fig. 1b).
- Precast Solid: precast solid planks with in-situ reinforced concrete topping which embeds the headed studs welded to the top flange of the steel beam (Fig. 1c).

2.1.1. Functional Unit

The functional unit is a multi-story building intended for office use in a non-seismic area (e.g. UK). The case study is selected among the various configurations presented by Hicks et al. [20] and published by The Steel Construction Institute (SCI). It represents a typical layout of the broad range of modern office building. A rendering of the whole building is shown in Fig. 3.



Fig. 3 Rendering of the case study [20]

The shape of the building is rectangular and is 13.5 m wide by 48 m long (Fig. 4). The building has four storeys with an inter-storey height of 3.5 m, resulting in a total height of 14 m. The total floor area is approximately equal to 2600 m². The position of the columns, which subdivides the 13.5 m width in two separate bays of 6 m and 7.5 m, is conceived to facilitate the disposition of a corridor in cellular offices. The lifts and the stairways are placed at the

ends of the building.

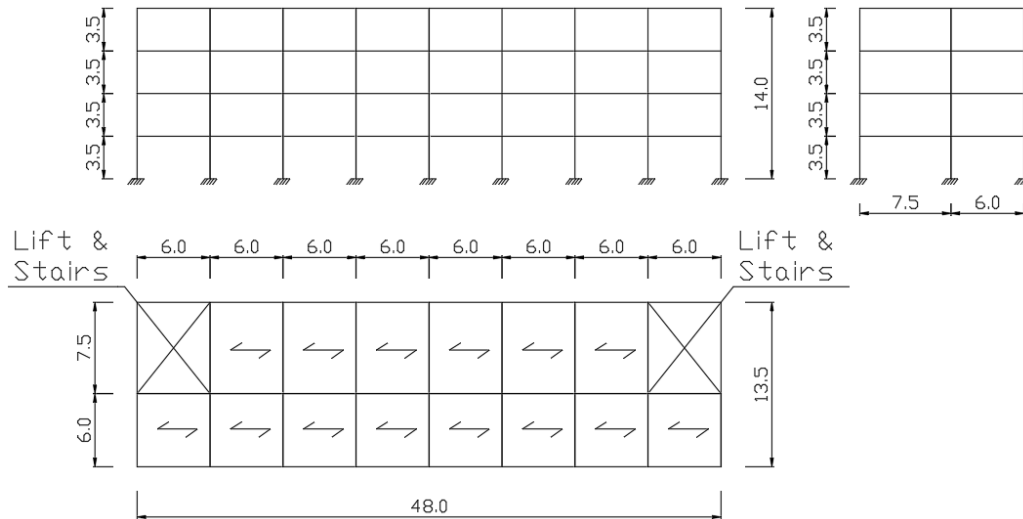


Fig. 4 Plan view and front views of case study, dimensions in meters

The analysis is focused on the frame superstructure of the building made of H-section steel columns, steel-concrete composite beams and floor slabs; while all the non-structural elements are not considered. In order to fulfil the same functional requirements regarding an imposed load, fire safety, and erection process characterised by unpropped constructions, different load bearing structures are needed for the investigated floor systems. While the prefabricated concrete slabs are capable to span the entire length of the column grid reported in Fig. 4, the composite slabs with profiled metal decking are supported also by secondary steel beams. Moreover, the different self-weight loads of floor systems significantly affect the sizes of H-section steel columns. For this reason, a whole building is defined as the functional unit, in accordance with methodology used by López-Mesa et al. [35].

Although the case study is focused on an office building, the information provided by this Life-Cycle-Analysis are not exclusive of this type of building because the investigated structural systems can be used in several other civil engineering applications (e.g. residential and commercial buildings, hotel, car parks).

2.1.2. System Boundaries and Allocation Procedures

To evaluate in a consistent way the environmental benefits related to the reuse of the structural elements, this study refers to the methodology proposed in Lavagna and Dotelli [21] defined

for the Expo 2015 in Milan. The objective of these guidelines is temporary buildings for mega-events, i.e. buildings characterized by a short lifespan corresponding to the mega-event duration and inevitable disassembly at the end of the event. Although the case study of this LCA does not represent a temporary building for mega events, these guidelines address the problem of evaluating the second use of construction materials. Unlike the typical end-of-life scenario of demolition and recycling, the possible “End-of-First-Use” scenarios presented by Lavagna and Dotelli [21] are associated to several types of reuse.

To focus the analysis on the direct comparison between recycling and reuse of structural elements, one scenario of reuse among the various alternatives is investigated, i.e. relocation without modification. The building with ReuseStru floor system is assumed to be entirely disassembled and reused elsewhere maintaining all the features of the original structure. The Reference Study Period (RSP) includes both the first use, assumed as 50 years (typical design lifespan of office building), and the second one, assumed equal to 50 years as well; resulting in RSP of 100 years. Since RSP should be the same for all the assessments in a comparative analysis, it is assumed that the buildings with conventional floor systems provide a lifespan of 50 years after which they are demolished, the structural elements are recycled and a new building with the same characteristics and service life (50 years) is constructed elsewhere with new structural elements.

The system boundaries of this LCA analysis include all the stages which compose the whole life cycle of the building (“cradle-to-cradle” approach). According to EN 15978 [22], the “modularity principle” is applied. Only the module B covering the use stage of the building is omitted by this LCA because the use phase conditions are considered identical in the cases compared: the structure does not affect the energy impacts of the building and does not require maintenance, as explained by Trabucco et al. [23] and Braedstrup [24].

The omission of the use phase (Modules B1-B7) from the analysis makes the results not exclusive for this specific RSP. For example, if the first structure is demolished or

disassembled after 20 years instead of the declared 50 years, only the usage period changes, 20 years instead of 50 years; but the impacts arising from the use of the structure are omitted from this comparative LCA.

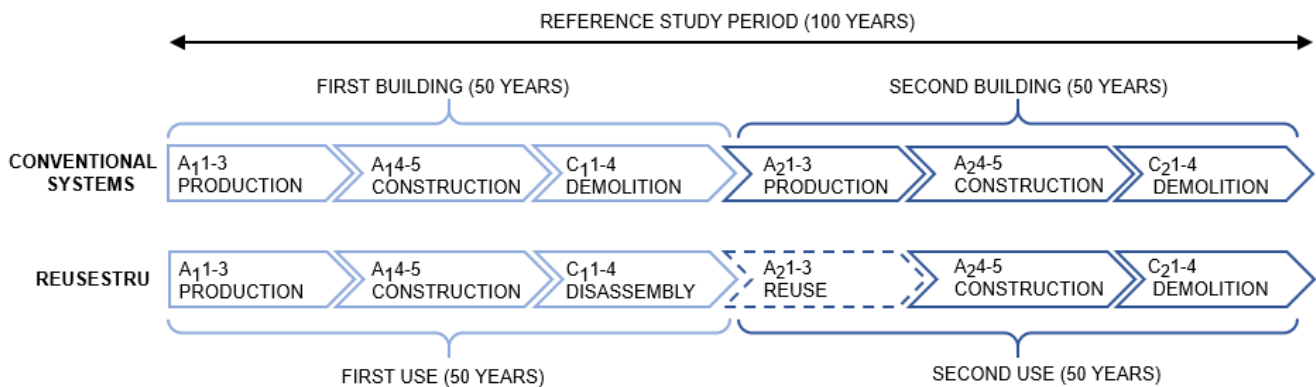


Fig. 5 Reference study period and system boundaries of LCA

The system boundaries are shown in Fig. 5. The module numbers are in compliance with the standard EN 15978:2011 [21], but doubled to be referred to the first building and the relocated one (first and second use of structural elements, respectively, in the case of demountable structures). So, the reference “1” means first building/use and the reference “2” means second building/use.

The main contraposition between the demolition of the conventional buildings and the deconstruction of the one made of demountable system is pointed out, as well as the production of new elements for the second service life opposed to the reuse of the overall superstructure.

Since the foundations of the first building could not be reused for the relocated one, the end-of-life scenario associated to the foundations is the same for the different superstructure systems. Therefore, in a comparative LCA addressing the differences between the solutions, the omission of the foundations is justified.

2.1.3. Assumptions

All the structural elements of the demountable frame system, including the steel columns connected to the steel beams by means of bolted connections, are assumed to be reused after

dismantling process, while all the elements of conventional structures are entirely recycled after demolition process. This latter assumption approximately reflects the current practices of Demolition & Waste management for the steel and the concrete. Whereas the steel can be recycled to the same or higher/lower quality of steel depending upon the processing of the recycling route (closed/semi-closed loop recycling), the crushed concrete can be used as aggregates or fill materials for several construction applications (downcycling) or as an aggregate for fresh concrete.

On the other side, the first assumption is finalized to evaluate the maximum possible benefits of the disassembly and the reuse practice. All the other scenarios that include the deconstruction phase can reasonably be considered as intermediate situations between these two extremes (100% Reuse vs 100% Recycling).

Complete reuse means that severe damages and deterioration, caused by extreme loading condition, are assumed to not occur during the first use of the building materials.

Due to these assumptions, the module C4 that represents the waste disposal stage has no impact because no materials are sent to the final disposal and landfill.

2.1.4. Impact Categories and Methodology

The methodology of impact assessment is in accordance with EN 15804 [25] and EN 15978 [22]. These standards identify the impact categories to be selected, as presented in Table 1.

Code	Impact Category	Unit
GWP	Global Warming Potential	Kg CO ₂ -equiv
ODP	Depletion Potential of The Stratospheric Ozone Layer	Kg CFC 11 equiv
AP	Acidification Potential of Land and Water	Kg SO ₂ equiv
EP	Eutrophication Potential	kg Phosphate equiv
POCP	Formation Potential of Tropospheric Ozone	Kg Ethene equiv
ADPE	Abiotic Depletion Potential for Non-Fossil Resources	Kg Sb equiv
ADPF	Abiotic Depletion Potential for Fossil Resources	MJ, net calorific value
PERT	Total use of renewable primary energy resources	MJ, net calorific value
PENRT	Total use of non-renewable primary energy resources	MJ, net calorific value

Table 1 Parameters describing environmental impacts and resource use

Due to lack of reliable data, the net use of fresh water and the environmental information describing waste categories are not considered. Compared to most of the research studies

and reports presented in literature that are concentrated and limited on two impact categories, i.e Global Warming Potential (GWP) and Embodied Energy (EE), the investigation of all these impact categories within the whole LCA study allows to obtain a significant and exhaustive comparison between the different structural systems and relative end-of-life scenarios.

2.2. Inventory Analysis

According to EN ISO 14040 [18], the inventory analysis is finalized to quantify relevant input and output of the product system by means of appropriate data collection and calculation procedures.

Module A₁₁-3 – Production stage

All the construction materials needed to realize the investigated superstructures are quantified through proper structural design performed by Brambilla [26], in accordance with EN1994-1-1 [27]. The design actions are represented by the structural self-weight (depending on the considered system), the additional gravitational loading due to ceiling and service equipment (0.5 kN/m²), raised floor and finishes (0.5 kN/m²), movable partitions (1 kN/m²) and accidental loading for office (3 kN/m²). According to the design outcomes, the composite slab with trapezoidal metal decking and in-situ reinforced concrete (Composite Slab) is made of a thickness of 130 mm, while the prefabricated units are defined according to the commercial profiles. Therefore, the design requirements can be fulfilled by either 150 mm thick prestressed hollow core sections with in-situ concrete infill in correspondence of welded shear connectors and no concrete topping (Precast HCS), or 75 mm thick precast solid plank with 75 mm reinforced in-situ concrete topping (Precast Solid), or 150 mm thick demountable prefabricated solid slab with cement mortar grouting between the units (ReuseStru). The amount of structural material is summarized in Table 2.

MATERIAL	UNIT	CONVENTIONAL SYSTEMS			REUSE STRU
		COMP. SLAB	PRECAST HCS	PRECAST SOLID	
STEEL COLUMN	[ton]	22.7	22.7	26	26
STEEL BEAM	[ton]	78.8	71.4	71.4	71.4

MATERIAL	UNIT	CONVENTIONAL SYSTEMS			REUSE STRU
		COMP. SLAB	PRECAST HCS	PRECAST SOLID	
STEEL BRACING	[ton]	2.8	2.8	2.8	2.8
SHEAR CONNECTORS	[ton]	2	0.75	1.1	1.5
METAL DECKING	[ton]	22.3	-	-	-
IN-SITU CONCRETE	[ton]	526.8	69.6	401.8	-
PRECAST SLAB	[ton]	-	535.7	401.8	803.5
REBAR	[ton]	10.9	1.9	10.5	-
CEMENT MORTAR	[ton]	-	-	-	19.4
TOTAL WEIGHT	[ton]	666.3	704.9	916.5	924.6

Table 2 Inventory of the construction materials

It is worth noting that the prefabricated units provide a reduction of total tonnage of steel beams in the frame system due to the lack of secondary beams. On other side, the composite floor with profiled metal decking is less heavy than the other options, resulting in reduced steel column cross-sections. This advantage is guaranteed by the Precast HCS system as well, where the hollow core slabs allow to optimize the self-weight of the structure conserving the same structural performance of solid slabs. Basically, the building with the ReuseStru system is the most onerous option in terms of the mass of the structural elements, but this drawback should be weighed within an overall LCA which takes into account the peculiar properties of complete demountability and reusability, as investigated in this paper. Finally, the incidence of the shear connectors on the overall weight of the structures is very limited, almost negligible. Regarding the data of all emissions and energy consumption associated to the production stage of each building material, specific EPDs [28] developed in accordance with EN 15804 [25] are collected. These EPDs report directly the results of the LCA “Cradle-to-gate”, in terms of environmental impacts and resource use, performed on the specific building product. When this type of information is not available, the data are collected by the database Ecoinvent version 3.4 [29] and processed with the software SimaPro [30] in accordance with the same methodology of impact assessment of EPD. Although the data presented in Ecoinvent could be more generic than a specific EPD, Ecoinvent is the most complete and accurate database on the building materials, as stated in a comparative study on commercial database performed

by Martinez-Racamora et al. [31].

The main information about the sources of the data are presented in Table 3.

Product	Source	Owner	Holder	Author LCA	Number	Issue Date
Steel Sections and Plates	EPD	Bauforumstahl e.V.	IBU	PE International	EPD-BFS-20130094-IBG1-EN	25.10.2013
Metal Decking	EPD	European Association for Panels & Profiles	IBU	PE International	EPD-EPQ-20130236-CBE1-EN	24.10.2013
Steel Rebar	EPD	ArcelorMittal Europe-Long Products	IBU	thinkstep Ltd.	EPD-ARM-20160051-IBD2-EN	09.20.2016
Precast Slab	EPD	British Precast Concrete Federation	IBU	thinkstep Ltd.	EPD-BPC-20160005-CCD1-EN	03.08.2017
Product	Source	Activity in database				
In-Situ Concrete	Ecoinvent	Concrete production 30-32 MPa {RoW} RNA only Alloc Def				
Cement Mortar	Ecoinvent	Cement mortar {RoW} production Alloc Def, U				

Table 3 EPD sources and database sources

The material properties, the dimensions, the geographical area and the industrial partners involved are deemed fully representative of the construction market under investigation for the case study, i.e. UK. Moreover, it is assumed that 1 kg of precast solid plank has the same impact of 1 kg of precast hollow core slab due to lack of data from relevant database or EPD. Despite slight differences during manufacturing of the two products, this assumption can be considered valid because both units are produced by the same UK factories and are made of identical materials.

Module A₁₄ – Transport from the gate to site

The transportation phase of the building materials “from gate to site” is accounted for the Module A₄ and it is modelled by means of weighted average data available for the UK construction sector. These values are published in a web tool “Carbon Footprint Tool for Buildings” [32] developed by Steel Construction Institute (SCI) which maintains continuously updated a free encyclopaedia for UK steel construction [33]. The information is reported in term of kgCO_{2e} per kg of material (kg CO_{2e}/kg). Subdividing it per the GWP impact of a heavy transport by truck expressed in “kg CO_{2e}/kg*ton” (obtained by Simapro), the average distance in km is fictitiously defined and presented in Appendix A. The distance related to the

prestressed precast slab is referred to the average value declared in the relative EPD, which covers only prefabrication companies settled in UK.

Module A₁₅ - Assembly

The on-site construction operations needed to realize the building are often neglected in many LCA presented in literature due to complexity of collection of relevant data. In this analysis, the case study investigated by Haney (2011) [34] is taken as reference for the erection process of the structural steel frame. It consisted of a three-storey mid-sized office building with a steel-framed bearing structure. On-site observations of the construction process were carried out to determine the equipment usage durations (primary data) associated to the erection activities. The construction activities for steel frame included unloading of building materials to the job site, the preparation and the placement of the structural elements and finally the connection operations. This detailed information is used for this LCA because the case studies are very similar from each other. Based on the type of machinery adopted, the relative activity is identified in Ecoinvent database v3.4 [29] and processed in Simapro [30] to obtain the environmental impacts. However, the placement of structural concrete is out of the scope of the work of Haney [34]. Therefore, these data are derived from the study presented by Lopez-Mesa et al. (2009) [35] where environmental impacts of building structures with cast in situ concrete floors and with precast concrete floors (hollow core section of 150 mm) were compared. Based on these two references, Appendix A summarizes all the information that are assumed to be representative for the construction process in UK.

Module C₁₁ – Deconstruction/Demolition

Very recently, a research study conducted by Yeung et al. (2017) [36] compared two distinct end-of-life scenarios for structural elements of a steel frame building, i.e. the current practices of demolition and recycling opposed to deconstruction and reuse. Therefore, all the sub-processes that distinguish reuse from recycling are identified and quantified. For this reason, Yeung investigated the gutting process, i.e. the systematic removal of interior finishes,

mechanical and electrical systems, and all non-structural components of the building. Although this process concerns the non-structural elements (not considered in this LCA), a comparative analysis which takes into account all peculiar aspects related to the different scenarios cannot neglect this phase, as it is essential to enable the disassembly of the structural elements. In spite of the study is referred to the construction sector in USA [37], the data are considered consistent and sufficiently representative of the actual processes of dismantling of a steel frame building in UK.

Once defined the demolition and deconstruction activities for the steel frame, the peculiar processes for the concrete floor system are to be identified. Two recent studies developed in the same university (TU Delft) respond to these needs. The first one presented by Naber (2012) [38] is focused on reuse of precast hollow core slabs from office buildings to residential buildings. The study compared the demolition & recycling end-of-life scenario with the dismantling & reuse for buildings equipped with precast hollow core section floor. In accordance with these contents, Glias (2013) [39] investigated the feasibility level of reusing existing structural precast concrete elements. Both the research studies are conducted with reference to the construction practices in Netherland. Nevertheless, these data are assumed to be extended to the actual disassembly processes performed in UK.

As reported in Appendix A, the removal of concrete between the precast units with electric machines depends on the thickness of the layer (expressed in cm).

Module C₁₂ – Transport in End of Life Stage

All the transports of the demolished structural building materials from site to sorting plant or landfill, until the end-of-waste status is achieved (i.e. recycling site), are to be accounted in this module. In 2012, PE International (now Thinkstep) conducted end-of-life studies on the building material for the construction sector in UK reported by the free encyclopaedia for UK steel construction [33]. The models and results were produced in accordance with EN 15804 [25]. The modelled building materials correspond to the structural elements investigated in this

LCA. Therefore, these end-of-life studies conducted by PE International are taken as benchmark in the calculation of impacts associated to Module C2. Data are reported in Appendix A.

Module C13 – Waste processing

Before the steel scrap is ready to be recycled (end-of-waste state), a waste processing characterized by shredding activities occur on it. The sub-processes of this stage were identified and quantified by Yeung et al. [36]. Instead, the impacts related to the concrete crushing are obtained by the above mentioned EoL studies [33] conducted by PE International. These data are considered fully representative of average treatment of crushed concrete in UK. Data are reported in Appendix A.

Module D1 – Benefits and loads of net scrap material

Generally, the system boundary is defined as a single service life of the building, hence the reuse and the recycling process are out of the boundary conditions. Since the boundary systems of this LCA consists of two successive life cycles (i.e. first building and relocated building), the benefits and loads associated to recycling and reuse at the end of first service life are included in the system boundaries. In particular, the analysis focuses on the relocation scenario assuming same structural scheme, geometry and occupancy, so the new relocated building is characterized by identical amount of material of the first building.

However, as previously explained, in case of recycling (conventional floor systems), not all demolished material closes the loop in the new product because the recycled content is under 100% according to the adopted EPD or in case of concrete material downcycling occurs. The end-of-life-scenarios declared in the adopted EPD or relevant documents are reported in Table

4.

Product	Recycled content [%]	Recycling output [%]	Sources for Module D
Steel sections	62	99	EPD
Metal decking	0	90	
Rebar	84	85	

Product		Recycled content [%]	Recycling output [%]	Sources for Module D
In situ concrete		0	90*	End-of-Life study
Precast slab	Concrete	0	90*	
	Rebar	70	98	

*Downcycling

Table 4 Inventory of end-of-life scenarios for Module D

All building materials provide almost 100% recycling output, but the recycled content is significantly different. In case of conventional floor systems, referring to the same EPDs for the production of new elements to be used in the second building is equivalent to state that the fraction of demolished construction material of first building is processed and recycled to become secondary material input in the new elements according to the current rate. For example, 62% of the demolished steel section can be considered recycled and included in the new produced steel sections for the second building, but the net scrap of 38% (i.e. the output of steel scrap at the end of first life cycle minus the input of secondary material into the production of the new element) goes out the system boundary.

Therefore, the production of the new structural elements of the second building is referred to the same Module A1-3 of the EPD used for first building subtracted of the benefits derived from Module D₁ calculated for net scrap. This is equivalent to assume that all demolished materials of the conventional systems are recycled even if not entirely included in the relocated building (100% Recycling). This is expressed by the following formula:

$$A_{21-3} = [(A_{11-3}) + D_1]$$

Where the value of the Module D₁ is negative if the benefits overcome the loads.

Second building – Conventional options

Apart the production stage just discussed, all the other life cycles stage associated to the second building can be considered equal to the ones of the first building, resulting in:

$$[A_4 + A_5 + C_1 + C_2 + C_3 + C_4]_2 \equiv [A_4 + A_5 + C_1 + C_2 + C_3 + C_4]_1$$

Second building – Demountable and reusable option

In compliance with the reference guidelines [21], all the operations and the processes needed to make the disassembled elements ready to be reused in the new frame are to be included within the production stage of the second use, i.e. Module A₂1-3. Since a relocation scenario with identical superstructure is investigated, the disassembled members, not damaged according to the assumptions, do not require any specific modification for reuse (e.g. the length of the precast units and all structural steel sections is the same).

The transport of all components of the building from the deconstruction site to the new site should be taken into account in the Module A₂4 [21]. In compliance with the above-mentioned End-of-Life studies the average transport distance in UK of reused steel and concrete elements/materials is 20 km. This distance is used as first option in the LCA. However, the incidence of this parameter on the overall environmental impact is evaluated by means of sensitivity analysis.

The assembly of the structural elements for the second use (Module A₂4) is the same as that of the first building.

Finally, the second building is assumed to be demolished, so the end-of-life stage of the second use (Modules C₂1-4) is in complete agreement with the processes declared for the conventional systems.

Summary of Inventory Analysis

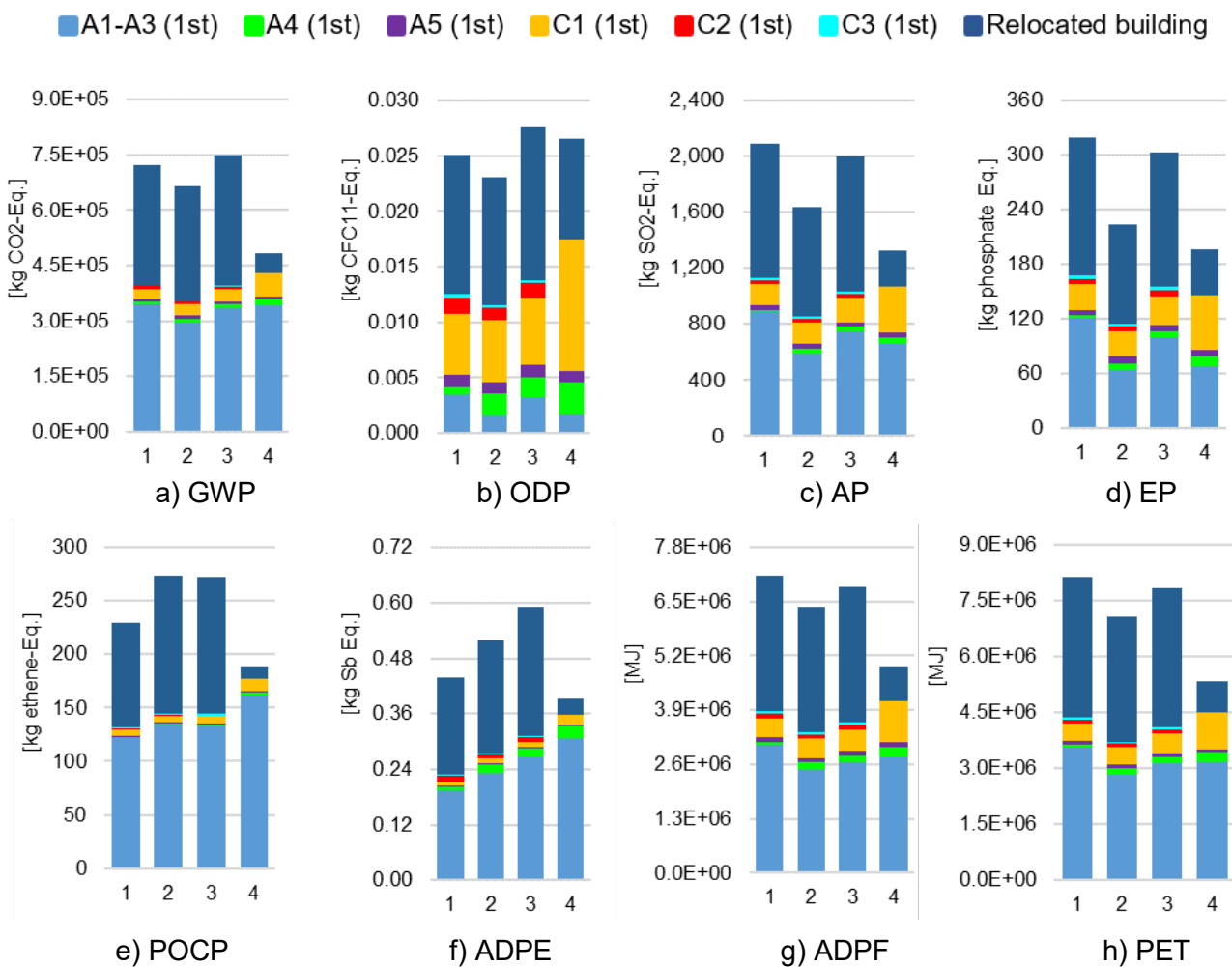
The inventory of all single processes considered in this LCA is summarized in Appendix B, specifying all quantities for the conventional systems and for the demountable steel concrete composite structure.

3. Impact Assessment Results and Interpretation

After defining the goal and the scope, performing the inventory analysis, the results of the whole life cycle assessment can be presented for all selected indicators. Firstly, the outcomes are represented according to the declared goal and scope. This means that the different structural options are compared including all the life cycle stages within the considered

boundary conditions. The total impact is obtained adding up all the contributions of both the first building and the relocated one, as well as the credit for net scrap is subtracted to the impact of the relocated conventional building (i.e. Full Recycling vs Full Reuse). Moreover, the results presented in Fig. 6 allow to compare the impacts related to each life cycle stage of the first building (indicated as “1st” in Fig. 6) for the different structural floor systems, as well as to verify the total impact produced once the first life cycle of materials is completed.

Secondly, the contributions of each construction material to environmental impacts of the production stage is evaluated.



Where:

1 = Composite Slab; 2 = Precast HCS; 3 = Precast Solid; 4 = ReuseStru

Fig. 6 Comparison of overall impacts for each impact category analysed

3.1. Global Warming Potential

The GWP impact results are shown in Fig. 6a. As expected, the ReuseStru system can

significantly reduce the global warming potential impact compared to the conventional structures. Among the conventional systems, the best environmental performance is provided by the composite structure with precast hollow core section (Precast HCS). Considering that the total surface effectively covered by the composite floor system in the building is equal to 2232 m² (according to Fig. 4), the saving of emissions arising from ReuseStru compared to Precast HCS is quantified in approximately 80 kg CO₂-eq/m². The increase of environmental impacts of the other two conventional systems, i.e. Composite Slab and Precast Solid, is quantified around 50% of whole GWP impact of ReuseStru.

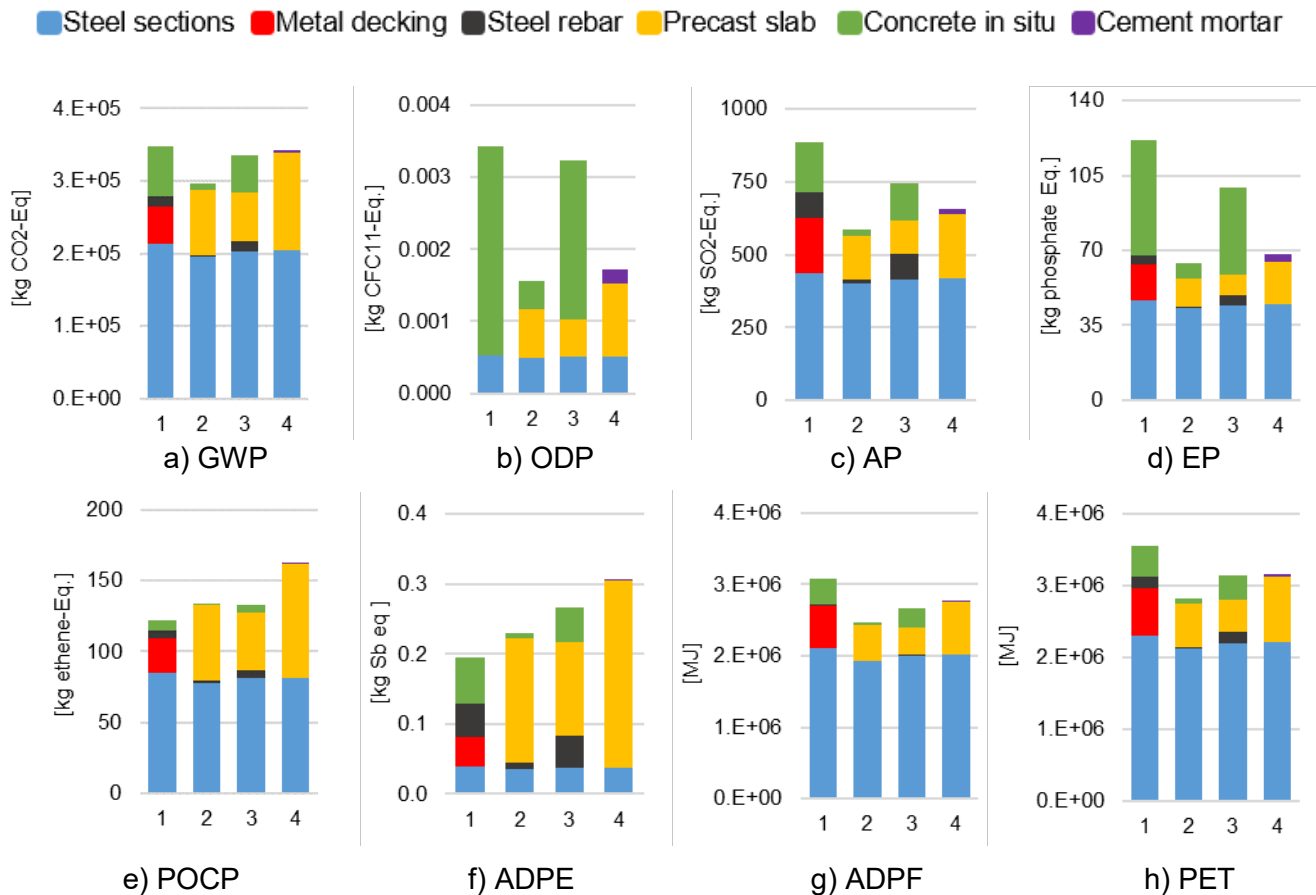
Since global warming potential is dominated by production stage, the benefit of the ReuseStru is determined by the lack of production and fabrication of new structural elements for the relocated building.

Besides the production phase, the impact of demolition and deconstruction stage is very significant. In Fig. 6a, it is evident that the deconstruction of the demountable structural frame produces more kg of CO₂eq compared to the conventional demolition. Basically, this is due to a different operative time of heavy equipment, because the demolition occurs more quickly than the complete deconstruction. The peculiar activity of gutting which distinguish the disassembly by the demolition is the main source of this increased time duration. Although the gutting activity is mainly labour intensive and requires considerable use of hand tools (minimal impact), it needs a dump truck for removing debris from site and a dust control unit (high impact) [36].

A further remark can be made on the transport of the products to the building site where the floor structural solutions with precast units are characterized by greater GWP score compared to cast in-situ concrete option, due to their high transport distance by lorry. However, this stage has a low relative contribution to the global GWP.

Since the GWP impact is dominated by the life cycle stage of production, the contributions of each material/product to this phase are investigated. In all the structural design options, the

main source of emissions is the production of steel sections and plates. Nevertheless, the building with Composite Slab systems is characterized by the lower total self-weight of the structure, the whole production of its building materials is the most impactful among all systems. In fact, the contribution from the corrugated steel decking is very significant compared to its limited self-weight, as shown in Fig. 7a.



Where:

1 = Composite Slab; 2 = Precast HCS; 3 = Precast Solid; 4 = ReuseStru

Fig. 7 Comparison of contributions of each product to environmental impacts of the production stage

3.2. Depletion Potential of The Stratospheric Ozone Layer

The ODP impact results are shown in Fig. 6b. As not expected, the overall ODP impact of Reusestru option is higher than the conventional structures. In fact, this impact category is dominated by the transport activity (Modules A4, C2), the on-site construction operations (A5) and the demolition process (C1). All these life cycle stages are affected by the same sources of emissions, i.e. the burning of diesel from the use of building machinery and the operation of

the lorry. As explained above, the deconstruction phase and the transport of precast units are unfavourable compared their alternatives due to the increased operative time and transport distance respectively. Therefore, the negative gap of total ODP between ReuseStru and conventional systems is justified. This negative gap is maximum with respect to hollow core slab system, which results the best design option for this impact category.

The production stage of the structure with cast in-situ concrete slab is associated to greater ODP score than the systems with precast concrete elements. In fact, the emissions during the production phase are dominated by cast in-situ concrete material (Fig. 7b). Therefore, the different environmental performance in terms of ODP between precast concrete and in-situ concrete is extended to the entire Module A1-3.

3.3. Acidification Potential of Land and Water

The AP impact results are summarized in Fig. 6c. The ReuseStru option provides lower environmental impact compared to all conventional solutions. However, the structural system with hollow core section units produces less emissions among the conventional systems, reducing the gap under 30% of whole AP of ReuseStru system. Also in this case, the impact category is dominated by production stage. Although the building with Composite Slab systems is made by the lower self-weight of the structure, the large scores associated to corrugated steel decking and reinforcing rebar make this building the most impactful option (Fig. 7c).

3.4. Eutrophication Potential

The EP impact results are illustrated in Fig. 6d. The trend of the results is similar to the previous impact categories. However, some distinctions can be made. The benefit arising from ReuseStru system compared to the Precast HCS structure is very limited, while it is very remarkable compared to all other options. The reduced environmental profit margin between ReuseStru and Precast HCS can be justified by the large contribution offered by the demolition and dismantling phase to the total impact. In fact, the disassembly stage affects 40% of the

total EP of the first use. When module C1 is relevant, the advantage from the demountable system which requires time consuming disassembly operations is reduced.

In the production phase, the major impact of cast in-situ concrete compared to the prefabricated concrete element (Fig. 7d) defines the gap between the floor solutions made mainly of cast in-situ concrete (Composite Slab and Precast Solid) and the other two equipped only with precast concrete units (Precast HCS and ReuseStru).

3.5. Formation Potential of Tropospheric Ozone Photochemical Oxidants

The POCP impact results are shown in Fig. 6e. ReuseStru is still identified as the most environmentally friendly solution. Unlike the previous categories, the lowest profit margin is with respect to Composite Slab, with a gap of 20% of whole POCP of ReuseStru system. This can be justified by the production phase, which is the dominant stage, where the contributions of cast in situ concrete are neglectable compared to precast concrete units, as reported in Fig. 7e.

3.6. Abiotic Depletion Potential for Non-Fossil Resources

The ADPE impact results are summarized in Fig. 6f. According to the previous categories, the building with demountable floor system is the most advantageous in terms of environmental impacts. However, the benefit of ReuseStru compared to Composite Slab is very limited in this category. It is around 10% of total ADPE of ReuseStru. The production represents the most impactful life cycle stage. The contribution arising from the production of steel sections is very restricted, while the stage is dominated by precast concrete slabs (if present). In case of ReuseStru, the contribution from precast units on Module A₁1-3 is dominant (see Fig. 7f), making the system as the most impactful of this phase.

3.7. Abiotic Depletion Potential for Fossil Resources

The ADPF impact results are shown in Fig. 6g. The global results in ADPF are in good agreement with the ones related to total use of primary energy resources. Therefore, the considerations provided for PET are valid in this impact category as well.

3.8. Total Use of Primary Energy Resources

The total use of primary energy resources (PET) are calculated as sum of total use of renewable primary energy resources (PERT) and total use of non-renewable primary energy resources (PENRT). They are summarized in Fig. 6h.

The results on primary energy resource usage reflect the trend of the ones associated to GWP Impact and ADPF. Hence, the observations made for GWP are still valid and are briefly summarized here.

In the whole LCA, the total use of primary energy resources is reduced by Reusestru system. The overall saving of MJ is minimum with respect to the Precast HCS system and it is quantified in almost 800 MJ/m². The production is the dominant stage, followed by the deconstruction and demolition (Fig. 7h). Within the production phase, the steel sections and plates are responsible of the main contributions.

4. Sensitivity Analysis

A key parameter to be investigated within the sensitivity analysis is the transport distance of the disassembled elements from the deconstruction site to the erection one for the relocated building. Considering the same type of transport made by heavy trucks on road, the distance is increased from the value assumed during the reference analysis, i.e. 20 km. Fig. 8 shows the effects of the variation of the relocation distance on the overall impact in Global Warming Potential (GWP) related to ReuseStru. In particular, the contribution arising from the transport stage aimed to reuse the structural elements (Module A4-Relocated Building) is pointed out.

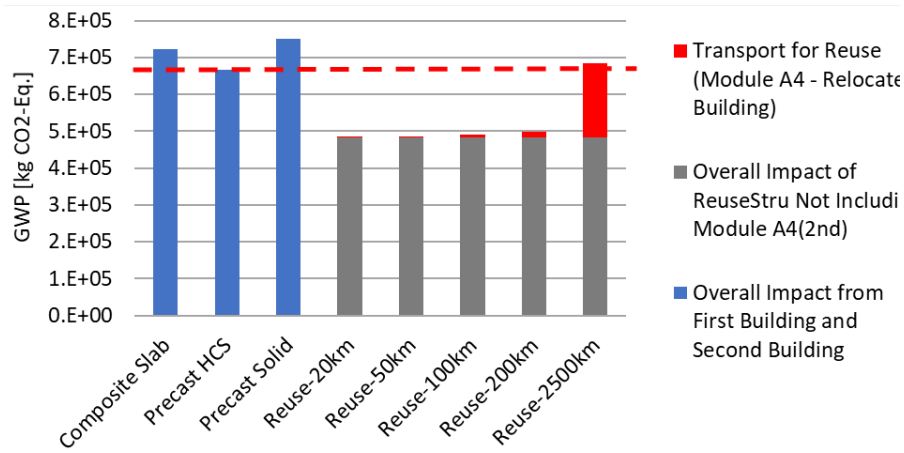


Fig. 8 Increment of GWP impact of ReuseStru with the increase of the transport distance

The most plausible values of transport distance are included between 20 km and 200 km. In this range of transport distance, the environmental benefits achieved with ReuseStru are confirmed, without substantial variations. The scenario of complete relocation becomes more impactful compared to the conventional options (with reference to the case of total recycling) when an unrealistic transport distance of 2500 km is required, as shown in Fig. 8.

The analysis that defines the threshold between benefit and load related to ReuseStru is carried out for all the considered impact categories. Once defined the impact from the transport of all structural elements for 1 km and the gap with the less impactful conventional solution, the distance limit for which the reuse has the same environmental impact of the conventional construction practices is calculated, as shown in Fig. 9.

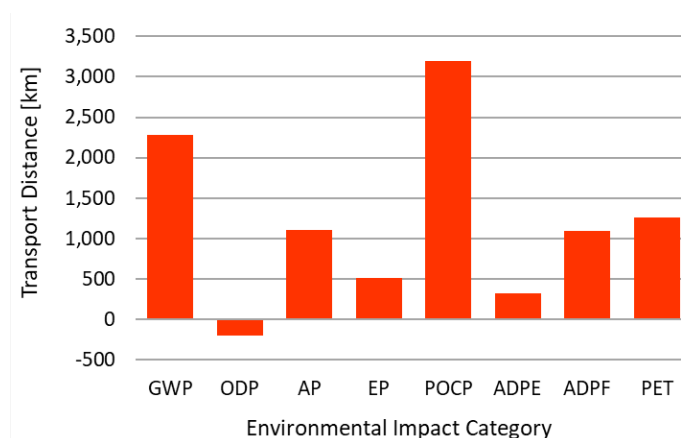


Fig. 9 Limit transport distance for all the considered impact categories

A huge distance, greater than 1000 km (more than London-Inverness), represents the limit between benefits and burdens in the main impact categories (GWP, AP, POCP, PET). The

distance threshold is reduced in a range of 300-500 km for impact categories of EP and ADPE. Finally, as shown in the impact assessment results, the ReuseStru option is disadvantageous in Depletion Potential of the stratospheric Ozone layer (ODP) category with a reference transport distance of 20 km.

5. Conclusions

The developed Life Cycle Assessment allowed to quantify the environmental benefits arising from demountable structural composite floor system, able to be disassembled and reused at the end of the service life of the building, compared to the conventional monolithic ones destined to the demolition and the recycling.

Considering an entire multi-story building erected in UK as functional unit, the analysis focused on the frame superstructure. The boundaries conditions and the reference study periods were defined by an entire service life of the case study followed by another one associated to the relocation of the building assumed with same geometry, destination and occupancy. In this way, all the structural elements of the demountable frame system were assumed to be completely reused after dismantling process, while full recycling of demolished material was considered for conventional systems.

Based on the obtained results, the following conclusions can be drawn:

- In almost all impact categories, the building with the demountable floor system (ReuseStru) was identified as the most environmentally friendly solution among all the options. The saving of emissions/resources was quantified for each impact category. For example, the saving of greenhouse gas emissions promoted by ReuseStru compared to the conventional systems was quantified in at least 80 kg CO₂-eq/m², as well as the saving of primary energy resources was estimated in at least 800 MJ/m². The only category where the building with ReuseStru is not beneficial is the depletion potential of the stratospheric ozone layer (ODP).

- Since many impact categories are dominated by production stage, the benefits from ReuseStru are determined by the lack of production and fabrication of new structural elements for the relocated building.
- The main source of emissions in the production phase is generally the production of steel sections and plates. However, the contributions from metal decking, cast in-situ concrete and precast concrete vary their incidence depending on the impact category under investigation.
- Besides the production phase, the impact of demolition and deconstruction stage is very significant. In particular, the deconstruction of the demountable structure is more impactful than the demolition of the conventional system. This is due to a different operating time of heavy equipment, because the demolition occurs more quickly than the complete deconstruction. The peculiar activity of gutting, which distinguishes the disassembly from the demolition, is the main cause of the increased impact.
- In the transport of the products to the building site, the floor structural solutions with precast units are characterized by longer transport distance by lorry (consequently major impact) compared to the cast in situ concrete. However, this stage generally has a low relative contribution to the overall results.
- Among the conventional systems, the best environmental performance is generally provided by the composite structure with precast hollow core sections.
- Finally, the sensitivity analysis demonstrated that the environmental benefits from ReuseStru are confirmed varying the transport distance for plausible values. In fact, the distance representing the threshold between benefits and loads is over 1000 km for many impact categories.

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Declarations of interest

None.

Figures

Colours should be used for Fig. 3, 6, 7 and 8.

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Appendix A - Supplementary data

Module	Product	Activity	Unit	Activity in Ecoinvent
A4	Steel Sections	Transport by truck	150 km	(1)*
	Metal Decking		275 km	(1)*
	Steel Rebar		275 km	(1)*
	Precast Slab		188 km	(1)*
	In-Situ Concrete		15 km	(2)*
	Cement Mortar		15 km	(2)*
A5	Steel columns	Unloading by forklift	7.6 min/memb.	(3)*
		Preparation by crane	2.9 min/memb.	(4)*
		Placing and connecting by crane	11.8 min/memb.	(4)*
		Placing and connecting by forklift	5.1 min/memb.	(3)*
	Steel beams	Unloading by forklift	3.3 min/memb.	(3)*
		Preparation by forklift	5.4 min/memb.	(3)*
		Placing and connecting by crane	6.0 min/memb.	(4)*
		Placing and connecting by forklift	1.8 min/memb.	(3)*
	Metal decking	Unloading by crane	2.8 min/ton	(4)*
		Placing by crane	3.0 min/ton	(4)*
	In-situ concrete	Pumping operation	1.0 l/m ³	(5)*
		Vibration operation	0.115 kWh/m ³	(6)*
	Precast slab	Placing by crane	1.31 kWh/m ²	(6)*
C1	Steel frame – Demolition	Hydraulic shears	76.1 m ³ /h	(4)*
		Dust control unit	76.1 m ³ /h	(3)*
		Sorting - Crawler loader	76.1 m ³ /h	(4)*
	Concrete floor – Demolition	Hydraulic excavator	12.5 ton/h	(4)*
		Dust control unit	12.5 ton/h	(3)*
		Sorting - Crawler loader	12.5 ton/h	(4)*
	Steel frame – Deconstruction	Gutting – Dump truck	23.0 m ³ /h	(4)*
		Gutting – Dust control unit	23.0 m ³ /h	(3)*
		Disassembly - Hydraulic crane	3.8 memb./h	(4)*
		Disassembly - Forklift	3.8 memb./h	(3)*
		Sorting – Lifting crane	4.5 memb./h	(4)*
		Sorting - Crawler loader	4.5 memb./h	(4)*
	Concrete floor – Deconstruction	Pneumatic hammer	0.20 (min/m)/cm	(3)*
Lifting crane		10 min/memb.	(4)*	

Module	Product	Activity	Unit	Activity in Ecoinvent
C2	Steel scrap	Transport by truck	463 km	(1)*
		Transport by barge	158 km	(7)*
	Crushed concrete	Transport by truck	20 km	(1)*
C3	Steel scrap	Hydraulic shears	0.022 h/ton	(4)*
		Grapple crane	0.022 h/ton	(4)*
		Shredder	0.004 h/ton	(5)*

*where:

- (1) = Transport, freight, lorry >32 metric ton, EURO5 (RER), Alloc Def, U
- (2) = Transport, freight, lorry 16-32 metric ton, EURO5 (RER), Alloc Def, U
- (3) = Machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state {GLO}| Alloc Def, U
- (4) = Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| Alloc Def, U
- (5) = Diesel per liter, burned in a building machine {GLO}| Alloc Def, U
- (6) = Electricity, low voltage, production GB, at grid/GB U
- (7) = Transport, freight, barge {RER}| processing | Alloc Def, U

Table A.1 Inventory analysis for the different life-cycle stages

Appendix B - Supplementary data

CONVENTIONAL SYSTEMS		COMPOS. SLAB	PRECAST HCS	PRECAST SOLID
PRODUCT STAGE (A1-A3)	Unit	Amount	Amount	Amount
Steel sections and plates	ton	106.2	97.6	101.3
Metal decking	ton	22.3	-	-
Reinforcing steel in bars	ton	10.9	1.9	10.5
Precast hollow core slab	ton	-	535.7	-
Precast solid slab	ton	-	-	401.8
Concrete 30 MPa	ton	526.8	69.6	401.8
TRANSPORT TO BUILDING SITE (A4)	Unit	Amount	Amount	Amount
Steel sections and plates	tkm	15930.7	14636.1	15188.6
Metal decking	tkm	6138.0	-	-
Reinforcing steel in bars	tkm	2997.8	516.6	2897.1
Precast slab	tkm	-	100707.8	75530.9
Concrete 30 MPa	tkm	7901.3	1044.6	6026.4
ASSEMBLY (A5)	Unit	Amount	Amount	Amount
Unloading - column -forklift	h	14.9	14.9	14.9
Unloading - beam -forklift	h	13.6	10.6	10.6
Unloading - decking - crane	h	1.0	-	-
Preparation Activities - column - crane	h	5.7	5.7	5.7
Preparation Activities - beam - forklift	h	22.3	17.3	17.3
Placing + Connection - column - crane	h	23.2	23.2	23.2
Placing + Connection - column - forklift	h	10.0	10.0	10.0
Placing + Connection - beam - crane	h	24.8	19.2	19.2
Placing + Connection - beam - forklift	h	7.4	5.8	5.8
Placing - decking - crane	h	1.1	-	-
Placing - precast slab	kWh	-	2923.8	2923.8
Pumping fuel in situ concrete/mortar	liter	219.5	29.0	167.4
Vibration electricity	kWh	25.2	3.3	19.3
DEMOLITION (C1)	Unit	Amount	Amount	Amount
Hydraulic Shears -steel frame	h	119.2	119.2	119.2
Hydraulic Excavator - floor system	h	44.8	48.6	65.1
Dust control unit	h	164.0	167.8	184.4
Sorting - Crawler loader	h	164.0	167.8	184.4
TRANSPORT (C2)	Unit	Amount	Amount	Amount
Transport barge - steel	tkm	22029.2	15713.5	17663.2
Transport road steel	tkm	64554.0	46046.6	51759.9
Transport road concrete	tkm	10535.0	12106.4	16070.4
WASTE PROCESSING (C3)	Unit	Amount	Amount	Amount
Hydraulic shears - steel	h	3.1	2.2	2.5
Grapple crane - steel	h	3.1	2.2	2.5
Shredder - steel	liter	299.8	213.8	240.3
Crushing concrete	ton	526.8	605.3	803.5
BENEFITS AND LOADS (D)	Unit	Amount	Amount	Amount
Steel sections and plates	ton	39.8	36.6	38.0
Metal decking	ton	22.3	-	-
Reinforcing steel in bars	ton	10.9	1.9	10.5
Precast slab	ton	-	535.7	401.8
Concrete	ton	526.8	-	401.8

Table B.1 Inventory of all process for conventional systems

REUSESTRU		
FIRST LIFE CYCLE		
PRODUCT STAGE (A1-A3)	Unit	Amount
Steel sections and plates	ton	101.7
Precast solid slab	ton	803.5
Cement mortar	ton	19.4
TRANSPORT TO BUILDING SITE (A4)	Unit	Amount
Steel sections and plates	tkm	15248.7
Precast slab	tkm	151061.8
Cement mortar	tkm	291.7
ASSEMBLY (A5)	Unit	Amount
Unloading - column -forklift	h	14.9
Unloading - beam -forklift	h	10.6
Preparation Activities - column - crane	h	5.7
Preparation Activities - beam - forklift	h	17.3
Placing + Connection - column - crane	h	23.2
Placing + Connection - column - forklift	h	10.0
Placing + Connection - beam - crane	h	19.2
Placing + Connection - beam - forklift	h	5.8
Placing - precast slab	kWh	2923.8
Pumping fuel in situ concrete/mortar	liter	8.1
DECONSTRUCTION (C1)	Unit	Amount
Gutting and removal - Dump truck	h	362.9
Gutting and removal - Dust control unit	h	362.9
Structural steel—Hydraulic crane	h	81.6
Structural steel—Fork lift	h	81.6
Sorting and loading - crane	h	96.0
Sorting and loading - crawler loader	h	96.0
Pneumatic hammer	kWh	160.1
Lifting crane	h	50.7
SECOND LIFE CYCLE		
PRODUCT STAGE (A1-A3)	Unit	Amount
Sandblasting	kWh	750.4
Adaptation - Sawing to size	kWh	192.9
TRANSPORT TO BUILDING SITE (A4)	Unit	Amount
Transport road -all elements	tkm	18492.5
ASSEMBLY (A5) as first life cycle		
DEMOLITION (C1)	Unit	Amount
Hydraulic Shears -steel frame	h	119.2
Hydraulic Excavator - floor system	h	65.8
Dust control unit	h	185.1
Sorting - Crawler loader	h	185.1
TRANSPORT (C2)	Unit	Amount
Transport barge - steel	tkm	17610.6
Transport road steel	tkm	51605.6
Transport road concrete	tkm	16070.4
WASTE PROCESSING (C3)	Unit	Amount
Hydraulic shears - steel	h	2.2
Grapple crane - steel	h	2.2
Shredder - steel	liter	218.6
Crushing concrete	ton	803.5

Table B.2 Inventory of all process for ReuseStru system