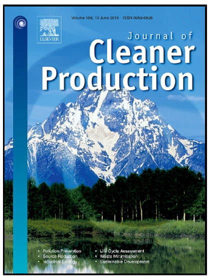
Article:

Wang, J., Densley Tingley, D.O. orcid.org/0000-0002-2477-7629, Mayfield, M. et al. (1 more author) (2018) Life cycle impact comparison of different concrete floor slabs considering uncertainty and sensitivity analysis. Journal of Cleaner Production, 189. pp. 374-385. ISSN 0959-6526

https://doi.org/10.1016/j.jclepro.2018.04.094



Life cycle impact comparison of different concrete floor slabs considering uncertainty and sensitivity analysis

JingJing Wang, Danielle Densley Tingley, Martin Mayfield, YuanFeng Wang

PII:	S0959-6526(18)31114-4
DOI:	10.1016/j.jclepro.2018.04.094
Reference:	JCLP 12675
To appear in:	*Journal of Cleaner Production*
Received Date:	14 October 2017
Revised Date:	06 April 2018
Accepted Date:	10 April 2018

Please cite this article as: JingJing Wang, Danielle Densley Tingley, Martin Mayfield, YuanFeng Wang, Life cycle impact comparison of different concrete floor slabs considering uncertainty and sensitivity analysis, *Journal of Cleaner Production* (2018), doi: 10.1016/j.jclepro.2018.04.094

Life cycle impact comparison of different concrete floor slabs considering uncertainty and sensitivity analysis

JingJing Wang[a,b], Danielle Densley Tingley[b], Martin Mayfield[b], YuanFengWang[a,*]

[a,*]School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, PR China.

[b] Department of Civil and Structural Engineering, The University of Sheffield,S1 3JD, United Kingdom.

E-mail: cyfwang@bjtu.edu.cn. Tel: 86-10-51685552. Fax: 86-10-51685552.

Highlights:

Environmental impacts of precast, composite and cast-in-situ slabs are conducted.

All life cycle stages from cradle-to-grave (including end-of-life stage) are included.

Both midpoint and endpoint of LCA results are analyzed.

The floor slabs are designed based on two functional units.

Uncertainty analysis and sensitivity analysis are carried out.

Abstract:

The traditional construction industry is characterized as a labor-intensive, wasteful, and inefficient sector. Currently, prefabrication has become a common practice in residential development and has reduced energy consumption and waste generation compared to traditional on-site practices. This study investigates the differences in life cycle environmental impacts among three different floor systems (precast slab, composite slab (semi-precast slab) and cast-in-situ slab) based on two functional units (delivering the same carrying capacity and maintaining consistent floor depth) using both LCA midpoint and endpoint methods using the software tool SimaPro. This study sets a calculation boundary for the construction process: raw material production, slab production, transportation, construction activities on-site, demolition and recycling of buildings at the end-of-life stage. Moreover, uncertainty and sensitivity analysis are carried out to help decision-makers identify major environmental impact factors and develop eco-friendly plans to facilitate housing industrialization. The results indicate that (1) the environmental impact of precast slab outperforms those of cast-in-situ and composite floors regardless of different design functional units and evaluation methods. (2) While under different functional units, the environmental performance of composite and cast-in-situ floors varies considerably. (3) From the perspective of life cycle stages, the transportation sector and its supply chain make up a significant portion of the final environmental impact and are responsible for 45.2%, 50.1% and 53.6% of the total impact for the precast, composite and cast-in-situ slabs, respectively. Slab production of precast slab (it is raw material production of cast-in-situ and composite slabs) is the second largest contributor to the environmental impact.

Keywords: LCA, Precast slab, Cast-in-situ slab, Composite slab, Uncertainty analysis, Sensitivity analysis

1. Introduction

Due to its conventional on-site construction approach the construction industry is often considered to be labor-intensive, wasteful, and inefficient (Mao et al., 2013; Liao et al., 2011). It has been reported that the construction sector consumes about 40% of the total global energy (WBCSD, 2009), uses 40% of the global materials (Horvath, 2004) and produces 50% of global waste (De Schepper et al., 2014). It is estimated that in the UK alone, approximately 109 million tons of construction waste are produced each year (Paschoalin et al., 2008).

Many strategies have been adopted to improve the efficiency of building construction to reduce material and energy consumption as well as carbon emissions. Such strategies generally involve innovative methods such as design for disassembly, lean construction and waste management (Ji et al., 2016). Prefabrication is also considered a new way to improve the sustainability of construction activities (Zhang et al., 2014). The first step of prefabricated construction is to produce construction components in precast yards, then the complete or semi-complete components are transported to construction sites, and finally these components are assembled to construct buildings (Hong et al., 2016).

According to Lopez-Mesa et al. (2009), the environmental impact of a building with precast concrete slabs is approximately 12.2% lower than that made with cast-in-situ slabs. However, the evaluation of environmental impacts from prefabrication is a complex problem, from one perspective, prefabrication reduces construction wastage as only installation occurs on the construction site, but from another perspective, prefabrication might generate more greenhouse gas emissions during transportation and manufacturing. Moreover, the higher potential recycling and re-use rates of precast products will deliver more environmental benefits than in-situ concrete construction systems at the end-of-life stage. Study of the environmental impact of prefabricated structures or buildings is to date relatively limited, it is therefore necessary to fully assess the whole life cycle environmental impacts of a prefabricated system.

The key aim of this paper is to compare the life cycle environmental impacts of prefabricated and cast-in-situ floor systems. The following investigations are conducted: (i) this study builds a whole life cycle assessment (LCA) model with all processes from cradle-to-grave being considered. (ii) In order to verify the validity of the presented model, and ascertain the best environmental design alternative, a comparison of three different construction floor slabs (precast slab, composite slab and cast-in-situ slab) is conducted, based on two functional units. (iii) Uncertainty analysis, including model and data uncertainties, is carried out to evaluate how these sources of uncertainty may effect environmental impact results. (iv) Finally, sensitivity analysis is conducted to help decision-makers identify major causes of environmental impact and develop lower impact construction solutions.

2. Literature review

Prefabrication is a construction method that could improve quality control, environmental performance, and site safety, whilst reducing labor demand and construction time (Jaillon and Poon, 2008). Currently, research on the environmental impact of precast/prefabrication can be divided into the following aspects:

(1) Through comparison of environmental impacts (such as GHG emissions, energy consumption) of prefabricated and cast-in-situ construction methods to ascertain which construction system is more environmentally beneficial. Dong et al. (2015) compared the carbon emissions of two construction systems at four different levels, i.e. concrete, element, group of elements, and building, finding that with prefabrication, carbon emissions are 10% less than that in-situ cast concrete, for one cubic meter. Other scholars also considered GHG reduction as a benefit of implementing precast concrete (Cao et al., 2015; Mao et al., 2013; Ji et al., 2016). Beyond GHG emissions, prefabrication is also environmentally beneficial for energy and material consumption (Pons and Aguado, 2012; Jeong et al., 2017; Pittau et al., 2017; Aye et al., 2012). For example, Jeong et al. (2017) conducted an integrated evaluation of productivity, cost and carbon dioxide emissions between prefabricated and conventional columns and estimated that the carbon

dioxide emissions of the prefabricated column is 72.18% higher than that of the conventional column.

(2) Some research focuses upon the evaluation of environmental impacts caused by prefabrication in different life cycle stages to find out which stage produces larger environment impacts (Bonamente et al., 2014). Mao et al. (2013) investigated the difference in GHG emissions between precast and cast-in-situ methods. In their study, five processes were included: raw materials production, transportation of building materials, waste and soil as well as prefabricated components, and construction activities on site. Results show that raw material production took the largest proportion of total GHG emissions, accounting for about 85%. Ingrao et al. (2014) made an assessment on the life cycle environmental impact of precast concrete using basalt aggregates, indicating the highest impact phase is the production of the basalt aggregates. Wong and Tang (2012) reviewed the "cradle to site" GHG emissions of prefabricated elements for residential buildings, finding that most of the carbon savings come from raw-material extraction and this is because less material is used.

(3) The factors affecting the use of precast concrete systems are discussed in several studies. Hong et al. (2016) put forward an input–output-based hybrid model to investigate the relationship of energy use of prefabricated components and the corresponding effect on final embodied energy. Their study concluded that the final energy consumption and prefabrication rate was linearly correlated. Chen et al. (2010) identified 33 sustainable performance criteria (SPC) including seven dimensions namely, economic factors: 'long-term cost', 'constructability', 'quality', and 'first cost'; social factors: 'impact on health and community', 'architectural impact' and environmental factor: 'environmental impact' for construction method selection in prefabricated buildings. The results show that social awareness and environmental concerns were considered as increasingly important in choice of construction method. Pons and Wadel (2011), Pasquire et al. (2005) as well as Idrus and Newman (2002) did similar research, identifying five factors as being the most important ones, namely 'appropriateness of use', 'cost', 'constructability', 'speed' and 'health and safety' in Idrus and Newman (2002) study.

(4) There are also some studies focusing on the reduction of construction waste resulting from prefabrication (Jaillon et al., 2009; Tam et al., 2007) and the corresponding waste treatment

method (Wu et al., 2015; Li et al., 2014; Ding et al., 2016; Baldwin et al., 2009; Lu and Yuan, 2013). Jaillon et al. (2009) studied the application of prefabrication and corresponding impact on waste reduction in Hong Kong, concluding prefabrication results in a 52% reduction in waste. Both Ding et al. (2016) and Baldwin et al. (2009) suggest that implementing design for deconstruction (DfD) would reduce demolition waste. Prefabrication is one potential method to achieve this. The increased reuse potential is likely to decrease end of life waste. Lu and Yuan (2013) investigated waste reduction potential in the upstream processes including manufacturing and transportation of components, finding that waste generation rate in the upstream processes is approximately 2% lower with prefabrication compared to traditional cast in-situ concrete construction.

(5) Work has also been carried out on different implementation mechanisms for prefabricated construction. Four key areas include: 1) Financial incentives: Hong et al. (2018) analyzed barriers to promote prefabricated construction in China and indicated that the future focus should lie in providing financial support to promote the development of prefabrication technology, optimizing the structural integrity of prefabricated buildings, and improving the maturity of the precast market. 2) Feasibility: In work by Tam et al. (2007), Li et al. (2016) and Jaillon and Poon (2014), feasibility analysis is conducted, exploring advantages, hindrances and future developments in adopting prefabrication in construction activities. 3) Strategic: Zhai and Huang (2017) developed a mechanism to coordinate two independent entities (i.e. building company and a prefab factory. 4) Technological: In Chen et al's. (2010) study, they presented a Construction Method Selection Model (CMSM) to aid building team members during early project stages to apply prefabrication in concrete buildings.

From the literature review, the following gaps in research have been identified: although some studies have compared the environmental burdens between prefabrication and cast-in-situ methods, most of them didn't consider the demolition, recycling and re-use at the end-of-life stage. In addition, there are few studies that also compare the environment benefits/impacts of a composite slab (semi-precast slab) with other pre-cast concrete systems. Moreover, decisions often are taken based on deterministic analysis, without explicit evaluation of the uncertainties involved and consideration of the potential variation in result. A comprehensive research effort, which not only investigates the environmental burden of precast construction method, but also takes into account the uncertainty and sensitivity of the evaluation process is still lacking. Existing research also lacks exploration of the relationships between assembly rate, structural system, construction process and final environmental impacts.

3. Methods

3.1 Methodology

In order to compare the environmental impacts of precast, composite and cast-in-situ construction methods, an LCA approach is adopted. Borghi (2013) suggested that LCA has developed into a key tool to estimate the overall environmental performance of products from cradle to grave. In general, LCAs include the following four steps: (1) goal and scope definition; (2) life cycle inventory (LCI); (3) life cycle environmental impact assessment; (4) interpretation (ISO-14040, 2006; ISO-14044, 2006). In accordance with the research aim of this study, the following subsections give a detailed description of this methodology.

3.2 Environmental impact assessment

In the life cycle environmental impact assessment (LCIA) process, all the inventory data is aggregated into specific environmental impact categories. In general, the LCIA process has three steps: characterization, normalization and weighting (ISO-14042, 2000). In the classification step, the contribution of each burden to each impact category is calculated by multiplying it by a characterization factor (Oliver-Solà et al., 2009). In the normalization and weighting process, the magnitude of LCIA results can be further calculated relative to reference information (a common scale to all impact categories, normally representing the background impact from society’s total activities). The aim of normalization and weighting is to better understand the relative significance of each indicator result and to facilitate the interpretation of results (Monteiro and Freire, 2012).

As to the selection of LCIA method, there are many LCIA methods that are available, such as ‘Eco-indicator 99’, ‘CML 2001’, ‘EDIP 2003’, ‘IMPACT 2002+’, ‘EPD’, ‘International reference Life Cycle Data system (ILCD)’ and ‘ReCiPe’(Dreyer et al., 2003). These methods vary across areas which may lead to different LCIA results. These methods can be classified into midpoint and endpoint two categories. Midpoint methods are considered problem-oriented methods, they have midpoints impact categories such as climate change, ozone depletion, human toxicity and particulate matter etc. (see Table 4). They model problems at an early stage in the cause-effect chain with characteristic values, allowing a more transparent assessment, limiting the uncertainties, and enable the results to be more objective. Endpoint methods can be regarded as damage-oriented methods, they have a narrowed set of categories, such as damage to human health, ecosystem and resources. Aside from characterization, the results of endpoint often need to be normalized and weighted (Monteiro and Freire, 2012). In this paper, the environmental impact assessment of the three floor systems were performed using the software tool SimaPro and ILCD and ReCiPe 2008 were used to assess the midpoint and endpoint results respectively.

3.3 Functional unit and system boundaries

3.3.1 System boundaries

In terms of the inclusion of life cycle stages, the full LCA, i.e. cradle-to-grave is adopted in this paper, including the material production, transportation, construction process and end-of-life stages. The floors studied internal floors, thus, they have minimal impact on the in-use energy of the building. The main purpose of this paper is to compare the LCA results caused by different construction methods, thus, any possible thermal mass benefits from different solutions during the use stage are considered out of the scope of this study, see Fig.1 in (BS EN, 2011).

Process maps for the precast, composite and cast-in-situ scenarios are shown in Fig.1. It can be seen from the figures that manufacturing prefabrication elements in a precast yard is a more complex process than casting in construction site. Nonetheless, the procedures to be carried out on construction site can be simplified when using the precast units as some works have already been transferred to the precast yard.

3.3.2 Functional unit

The functional unit (FU) is seen as the reference unit of the product system for which the environmental impact will be calculated (De Schepper et al., 2014). Within this study, the floor system is the focus. Two different functional units are adopted, FU_1 means that all the three floor systems are designed to deliver the same carrying capacity for a given load, meaning that the minimal amount of material can be used. Under FU_2, the floor slabs are designed to maintain a consistent floor depth (e.g. 200 mm depth), which could be of benefit if this was a limiting factor in design. It is worth noting that no matter under which FU, all the floor systems need to be designed according to Eurocode (BS EN, 2005; BS EN, 2004) to meet the minimum load requirements. Fig.2 shows the cross-sectional views of the floor systems.

FU_1: Deliver the basic carrying capacity;

FU_2: Maintain a consistent floor depth.

3.4 Description of the case study

In order to verify the LCA model, a precast school building is chosen as a case study. The school is located in Leeds in the UK and the precast yard is located in Belfast in Northern Ireland. Fig.3 is the schematic diagram of the school. The total floor area of this school is 11600 m^2. In the original alternative, excepting the dead-weight, the slabs need to support live loads (5 kN/m^2) and additional dead loads (screed, ceiling & service and finishes with 1.8, 0.55 and 0.2 kN/m^2, respectively). The concrete mix and corresponding transportation distance of raw materials (by referring to the Google Maps) is shown in Table 1.

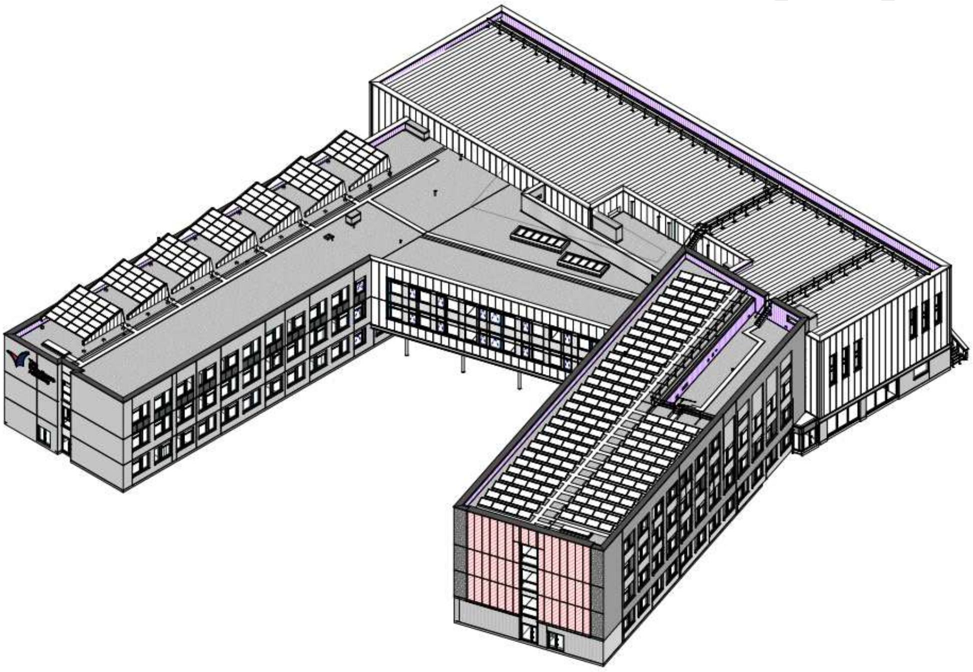


Fig. 3. The schematic diagram of the school

Table 1

Material weights to produce 1 m^3 of concrete and corresponding transport distance

Type	Quantity	Transport		
		Departure	Destination	Distance (km)
CEM |42.5R	365 kg	Ballyconnell	Ardboe	131.48
6/14 mm Aggregate	525 kg	Magheraglass	Ardboe	0
6/14 mm Aggregate	490 kg	Draperstown	Ardboe	23.5
0/4 mm Concrete Sand	305 kg	Magheraglass	Ardboe	0
0/4 mm Concrete Sand	405 kg	Draperstown	Ardboe	23.5
0/2 mm Building Sand	255 kg	Lough Neagh	Ardboe	68.1
Added Water	72 L	-	-	0
Total Free Water	149 L	-	-	0
HC1 Paver	0.75 L	Belfast(Sika UK)	Ardboe	50.1

3.5 Data collection

One of the most critical steps in LCA is data collection. Generally, site-specific data and existing databases are the two main sources of data in LCA research. Some data can be obtained from the case study directly, such as the theoretical concrete and steel use, concrete mix and transportation distance. Other data such as the waste recycling rate and material losses, which cannot be obtained from the case study directly can be calculated by parameters from existing literature.

(1) Element fabrication/ construction stage

Since the process of element fabrication stage and construction stage are very similar and the only difference is that they happen in different places, in this paper, we discuss the two stages together. Five main aspects are considered across the precast yard and construction site: material, equipment, energy, labor and waste (Dong, 2014).

Firstly, both materials in the precast yard and construction site can be classified into four types: the theoretical demand for material, raw material loss, surplus material and waste. Fig.4 shows the material flow in precast yard. The theoretical demand for material can be calculated according to the given load and Eurocode (BS EN, 2005; BS EN, 2004). Raw material loss is the loss of material during handling, storage or manufacturing (Aziz, 2015), these lost materials likely end up as miscellaneous waste. The surplus materials generated during the manufacturing and construction processes mainly consist of hardened concrete with or without reinforcement, steel reinforcement and pieces of structural steel and fresh concrete (from production and washing of equipment) (Sven et al., 2003). In the precast yard, the surplus materials can be recycled and reused because they are relatively easy to collect. Formulas (1) and (2) describes how to calculate material loss and surplus material respectively. Table 2 shows the rates of material loss and surplus material of steel and concrete. Moreover, on construction sites, aside from the permanent construction material such as concrete and rebar, there are also some temporary materials, such as formwork and scaffolding. Since the temporary materials are normally reused across many projects, their environmental impacts are not considered in this study.

$$\text{Material}_{loss} = \text{Theoretical amount} \times \text{Rate}_{loss} \qquad (1)$$

$$\text{Material}_{surplus} = \text{Theoretical amount} \times \text{Rate}_{surplus} \qquad (2)$$

Equipment adopted in the precast yard and construction site may be different across different plants and construction sites, but the common character is that once the machines are introduced to the plant (construction site), they can be repeated to produce a large number of products, the abrasion loss to produce one unit product can be ignored. In addition, the environmental impact caused by machine abrasion belongs to machine production stage but not the building construction stage. Thus, in this paper, only the energy consumed by equipment is considered. As to the manpower, the transport method to transfer the workers to site are included in the study.

Waste treatment is considered as follows: (1) for precast slab, on the construction site there is minimal waste, since the slabs are already manufactured and only need to be installed. Previous research indicates that per m^2 hollow core slab installation, 1 kg of concrete waste is produced (SPC, 2017). (2) The waste caused by traditional cast-in-situ and composite slabs in the construction site is higher. Unlike the surplus materials in precast yard, most of these materials can't be recycled or reused, they would be disposed of at landfill. Fig.5 compares the difference of solid waste treatment in precast yard and construction site. It is worth noting that recycling of ferro metals (steel and rebar) can decrease environmental impact caused by a construction project significantly. If the ferro metals are recycled, 70% of the environmental burden can be counteracted (Sven et al., 2003). As to wastewater, it is estimated that typically 45 kg of wastewater per m^3 of concrete is produced (Sven et al., 2003).

(2) Transportation

In pre-cast yards, the transport refers to internal transportation (Sven et al., 2003). It means that cement, aggregates, reinforcement must be brought to the plant. The internal transport consists of three stages, bringing the supplies into the plant from their storage areas, the transportation of the fresh concrete in the plant and the transportation of the finished product to the stockyard. Since the transportation distance of the fresh concrete in the plant and the finished product to the stockyard is relatively small compared to the distance of bringing the supplies into the plant and is difficult to estimate without detailed information, in this paper, only the latter is considered. The transport distance between the precast yard and the construction site is estimated using Google Maps, for example, the transport distance from Belfast (the location of precast yard and raw materials) to Leeds is 514.5 km.

(3) End of life stage

Construction and demolition (C&D) waste generated from demolition of buildings at the end-of-life stage is one of the largest solid waste streams in the world. Recycling these wastes into useful materials can minimize the C&D waste volume significantly. It is stipulated that 70% of non-hazardous C&D waste should be reused or recycled by 2020 in the EU (Hu et al., 2013). End of life concrete can be divided into four alternatives. (1) Re-use, this refers to elements which still have good mechanical properties which can be directly reused in other new buildings or refurbishment projects (BRE, 2017). (2) Aggregate recycling, concrete can be recycled into new aggregates for asphalt/concrete production (CEDD, 2016). (3) Fill recycling, granular waste concrete is used as hardcore in road construction or substructure works (Hu et al., 2013). (4) Disposal, waste concrete that cannot be re-used or recycled is likely to end up in landfill. It is estimated by Building Research Establishment Green Guide that 50% of concrete is crushed and recycled as new aggregate, 40% is down cycled for use such as road sub-base and drainage layers, and the remainder goes to landfill (Weight, 2006).

Steel rebar and sheet, are easily sorted from waste streams due their magnetism, more than 85% of steel in the world is recycled at EOL stage. In UK construction, the recycling rates of various steel products have been estimated at 98% for rebar, 89% for profile steel cladding, the re-use rate is 10% for profile steel cladding (Sansom and Avery, 2014).

Table 3 summarizes the life cycle inventory data for the different slab options in the case project.

Table 3

Life cycle inventory data of the case study

			Input	Unit	Precast slab	Composite		Cast-in-situ	
						FU_1	FU_2	FU_1	FU_2
Production stage	Raw material production	Concrete	Theoretical amount	m^3	1438.40	1624.00	2204.00	2900.00	2320.00
			Material loss	m^3	57.54	64.96	88.16	116.00	92.80
			Surplus material	m^3	23.01	81.20	110.20	171.10	136.88
		steel	Theoretical amount	t	109.18	200.97	200.97	86.63	105.85
			Material loss	t	0.00	14.07	14.07	6.06	7.41
			Surplus material	t	-	2.81	2.81	2.25	2.75
		Zn (Tata Steel, 2013)		t	-	3.19	3.19	-	-
	Inter-transportation	Concrete		tkm	261259.47	-	-	-	-
		steel		tkm	6550.85	-	-	-	-
	Element manufacture (Dong, 2014; Sven et al.,2003)			GJ	580.00	-	-	-	-
	Waste	Wastewater		t	68.35	-	-	-	-
		Waste concrete landfill		t	143.84	-	-	-	-
		Waste concrete as new aggregate		t	57.54	-	-	-	-
Transportation	Raw material			tkm	3797810.37	4767755.96	6386187.96	8261899.28	6652934.04
	Supplementary material			tkm	72338.28	58418.28	58418.28	55680.00	55680.00
	Manpower			personkm	3480.00	6960.00	6960.00	13920.00	13920.00
Construction	Supplementary material	Structural Steel/steel		t	10.61	10.61	10.61	-	-
		Screed/Mortar		t	1160.00	928.00	928.00	928.00	928.00
		Fabric Reinforcement (Mesh) (CR, 2017)		t	35.03	35.03	35.03	-	-
	Energy	Diesel (Dong, 2014; Sven et al., 2003)		GJ	348.00	1126.87	1405.03	1750.32	1469.86

Table 3 (Continued)

Life cycle inventory data of the case study

Construction	Waste	Concrete	t	-	365.40	495.90	717.75	574.20
		Steel	t	-	-	-	8.15	9.96
		Wastewater	t	-	79.66	108.11	143.42	114.74
End of life	Concrete	Crushed and recycled	t	2523.00	2610.00	3335.00	4205.00	3480.00
		Down-cycled	t	2018.40	2088.00	2668.00	3364.00	2784.00
		Landfill	t	504.60	522.00	667.00	841.00	696.00
	Steel	Recycled	t	151.72	219.48	219.48	84.90	103.73
		Lost	t	3.10	2.47	2.47	1.73	2.12

Note:

In this table, for precast slab, the production stage means slab production stage, for cast-in-situ and composite slab, it means raw material production stage.

3.6 Interpretation

3.6.1 Uncertainty analysis

According to the description of Eco-indicator 99-manual (Goedkoop, 1999), uncertainty factors are distinguished into two types: uncertainties about the correctness of the models used and data uncertainties.

(1) Uncertainties about the correctness of the models

The building of different evaluation models not only has something to do with differences in knowledge levels, but also fundamental differences in attitude and perspective play an important role. According to Eco-indicator 99-manual, there are three "Archetypes" of perspective, H (Hierarchist), E (Egalitatain) and I (Individualist). For the three perspectives, the characterization, normalization and weighting factors are different (Goedkoop, 1999), and thus, there will be a series of ReCiPe methods, ReCiPe H/A, H/H, E/A, E/E, I/A and I/I where A is the abbreviation of average weighting set. For example, "ReCiPe H/A" refers to the normalization values of the Hierarchist version with the average weighting set. "ReCiPe H/H" refers to the normalization values with the weighting set belonging to the Hierarchist perspective, see Table 5 and 6. The default ReCiPe method is ReCiPe H/A in SimaPro.

(2) Data uncertainties

The data uncertainties refer to difficulties in measuring or predicting effects caused by the input data. Most of the input data used in this case study are obtained from practical experience and literature. There are some unavoidable limitations of the available input data, additional assumptions are needed during analysis. For example, different waste recycling rates will result in different environmental impacts. For this case study, only one recycling rate is considered.

3.6.2 Sensitivity analysis

In order to assess the robustness of the evaluation model and account for the variability of critical input variables, a sensitivity analysis was performed (Roy, 2005). The use of sensitivity analysis contains two aspects: (1) find the critical input variables, namely, find the parameters that have a largest influence on the final impacts. A hotspot assessment provides information on where the issues of concern may be the most significant in the product's life cycle. (2) Estimate the variability of environmental scores associated with these key variable parameters, as different values of the key parameters may lead to significant changes in the outcome.

4. Results and discussion

4.1 Comparison of LCA results

4.1.1 LCA results between different functional units

Table 4 shows the midpoint impact results of the three alternative slabs using ILCD method in LCA software tool SimaPro. The method is generally accepted and commonly used for demonstrating environmental profiles. The results of the environmental categories have different units because they are the raw characterization values without normalization and weighting. It is clear that the precast slab has the lowest impact irrespective of the functional unit selected, with 13 damage categories (marked in bold in Table 4) showing the lowest value. When the floor slabs are designed to meet the minimum load requirements (FU_1), the composite slab has higher environmental impacts compared to that of the precast, but constantly displays an environmental performance better than that of the cast-in-situ slab. This pattern is reversed when the floor systems are designed under fixed depth, e.g. 200 mm depth (FU_2).

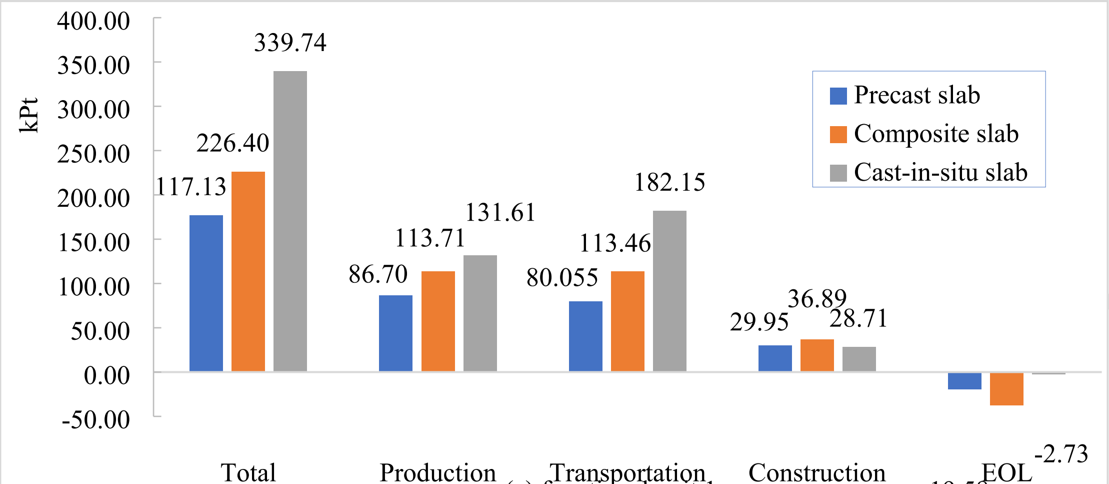
Table 4

ILCD impact assessment: characterization

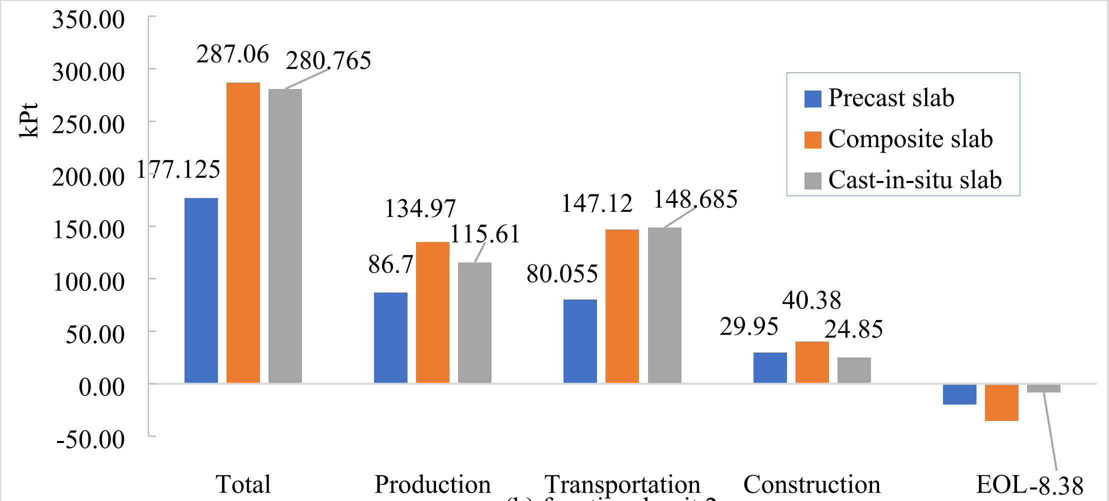
Damage category (Unit)	Precast	Composite		Cast-in-situ	
		FU_1	FU_2	FU_1	FU_2
Climate change(kg CO2 eq)	**$2.34\cdot10^{6}$**	$3.11\cdot10^{6}$	$3.77\cdot10^{6}$	$4.67\cdot10^{6}$	$3.83\cdot10^{6}$
Ozone depletion (kg CFC-11 eq)	**$2.98\cdot10^{-1}$**	$6.24\cdot10^{-1}$	$7.44\cdot10^{-1}$	$7.98\cdot10^{-1}$	$6.87\cdot10^{-1}$
Human toxicity, cancer effects (CTUh)	**$9.58\cdot10^{-2}$**	$4.80\cdot10^{-2}$	$6.27\cdot10^{-2}$	$1.13\cdot10^{-1}$	$1.07\cdot10^{-1}$
Human toxicity, non-cancer effects (CTUh)	**3.77**	4.62	6.16	8.03	6.51
Particulate matter (kg PM2.5 eq)	**$1.46\cdot10^{3}$**	$1.62\cdot10^{3}$	$2.13\cdot10^{3}$	$2.76\cdot10^{3}$	$2.26\cdot10^{3}$
Ionizing radiation HH (kg U235 eq)	**$1.38\cdot10^{5}$**	$1.51\cdot10^{5}$	$1.99\cdot10^{5}$	$2.58\cdot10^{5}$	$2.13\cdot10^{5}$
Ionizing radiation E (interim) (CTUe)	**1.18**	1.30	1.71	2.22	1.84
Photochemical ozone formation (kg NMVOC eq)	**$1.48\cdot10^{4}$**	$2.07\cdot10^{4}$	$2.65\cdot10^{4}$	$3.21\cdot10^{4}$	$2.64\cdot10^{4}$
Acidification (molc H+ eq)	**$1.29\cdot10^{4}$**	$1.82\cdot10^{4}$	$2.33\cdot10^{4}$	$2.77\cdot10^{4}$	$2.28\cdot10^{4}$
Terrestrial eutrophication (molc N eq)	**$5.16\cdot10^{4}$**	$6.94\cdot10^{4}$	$8.98\cdot10^{4}$	$1.11\cdot10^{5}$	$9.11\cdot10^{4}$
Freshwater eutrophication (kg P eq)	$5.79\cdot10^{1}$	**$5.05\cdot10^{1}$**	$7.31\cdot10^{1}$	$1.18\cdot10^{2}$	$9.60\cdot10^{1}$
Marine eutrophication (kg N eq)	$4.66\cdot10^{3}$	**$4.39\cdot10^{3}$**	$6.24\cdot10^{3}$	$1.00\cdot10^{4}$	$8.24\cdot10^{3}$
Freshwater ecotoxicity (CTUe)	**$2.89\cdot10^{6}$**	$2.99\cdot10^{6}$	$3.94\cdot10^{6}$	$5.35\cdot10^{6}$	$4.49\cdot10^{6}$
Land use (kg C deficit)	**$9.58\cdot10^{6}$**	$1.14\cdot10^{7}$	$1.53\cdot10^{7}$	$2.00\cdot10^{7}$	$1.62\cdot10^{7}$
Water resource depletion (m3 water eq)	**$2.64\cdot10^{3}$**	$2.65\cdot10^{3}$	$3.56\cdot10^{3}$	$4.86\cdot10^{3}$	$4.05\cdot10^{3}$
Mineral, fossil & ren resource depletion	**$5.98\cdot10^{1}$**	$7.81\cdot10^{1}$	$1.03\cdot10^{2}$	$1.32\cdot10^{2}$	$1.07\cdot10^{2}$

(kg Sb eq)

Fig.6 illustrates the LCA endpoint results under different functional units. According to Consultants (2000), the LCA result values can be regarded as dimensionless figures. As a name we use point (Pt). The absolute value of the points is not very relevant as the main purpose is to compare relative differences between products or components. The scale is chosen in such a way that the value of 1 Pt is representative for one thousandth of the yearly environmental load of one average European inhabitant. Thus, this value is calculated by dividing the total environmental load in Europe by the number of inhabitants and multiplying it with 1000 (scale factor). It indicates that, at level 1 the cast-in-situ has the highest score with 339.74 kPt. The composite slab shows a reduction (-33%) by having a value of 226.4 kPt whilst the precast shows an even further reduction (-48%) with a value of 117.13 kPt. It can also be seen that production and transportation phases are the most two influential components among the environmental impact categories and life cycle phases of the three floor systems. Transportation sector and its supply chain are responsible for 45.2%, 50.1% and 53.6% of the total impact for precast, composite and cast-in-situ slabs, respectively. The environmental impact caused by production stage accounts for 48.9%, 50.2% and 53.6% of the final impacts for the three floor systems. During the end-of-life (EOL) stage, even though the demolition of the building will consume some resources and energy, considering concrete and steel can be recycled after demolition, the EOL stage will bring environmental benefits. While for FU_2, when the composite and cast-in-situ slabs maintain a consistent depth with the precast slab (200 mm), the situation is a little different. It is easy to see that the precast slab still has the lowest environmental impact, while the composite slab replacing the cast-in-situ slab becomes the highest among the three systems.



(a) functional unit 1



(b) functional unit 2

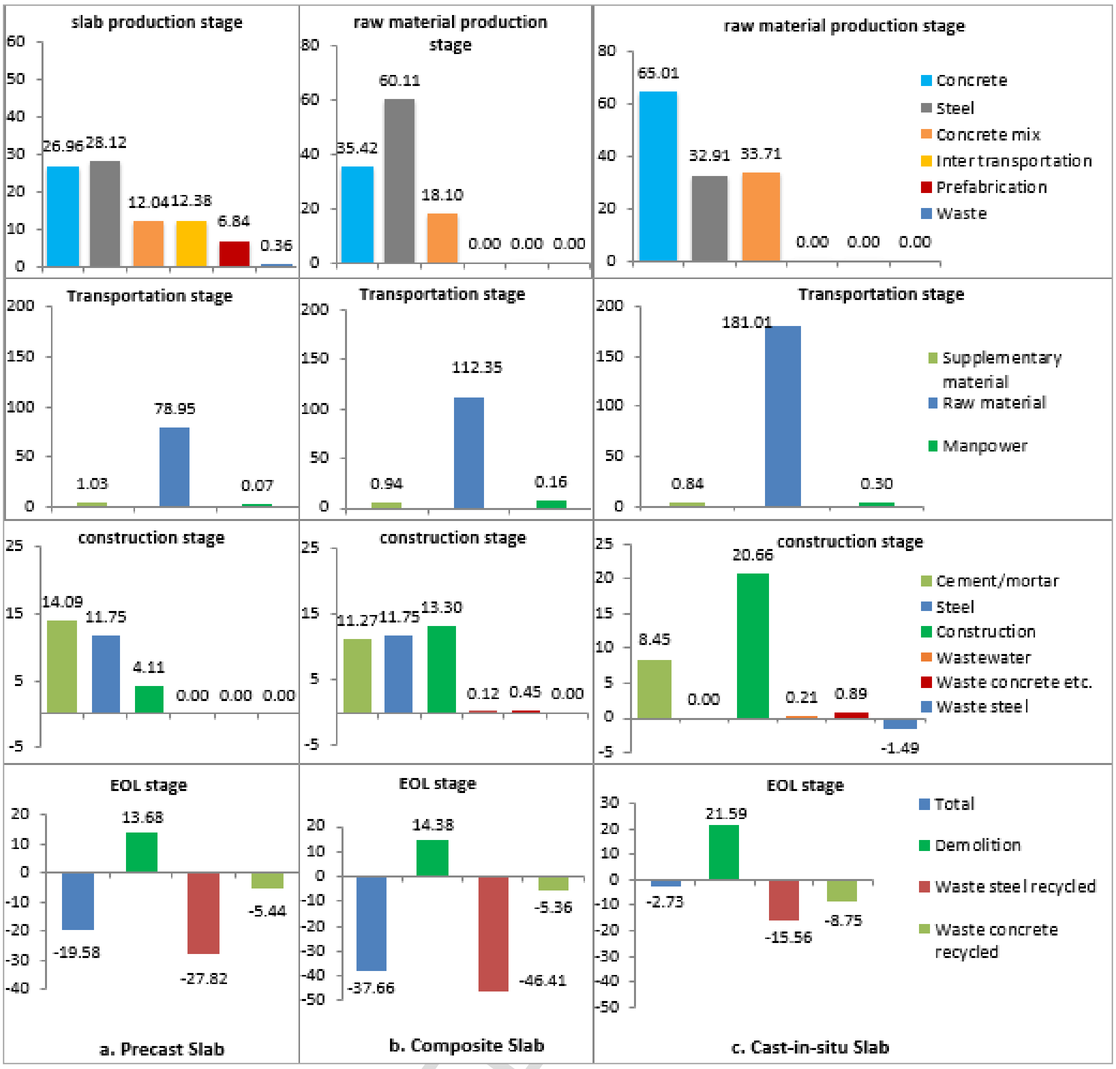
Note: In this figure, for precast slab, the production stage means slab production stage, for cast-in-situ and composite slab, it means raw material production stage.

Fig. 6. Comparison of LCA endpoint results between different functional units

It can be seen from Table 4 and Figure 6 that no matter with which evaluation method (midpoint or endpoint) and functional unit, precast slab always shows the best environmental performance. There are three reasons for this: 1) in terms of productivity, the prefabrication elements in precast yard are considerably better than that cast in site and semi-prefabrication because they need shorter fabrication times (Jeong et al., 2017). 2) Waste generation and treatment, production process of prefabrication elements are also better than the other two (Wu et al., 2015; Li et al., 2014; Ding et al., 2016; Baldwin et al., 2009; Lu and Yuan, 2013). 3) In terms of material consumption, since precast slabs are hollow slabs, they can save concrete and steel as much as possible. When the three floor systems are designed with FU_1: delivering the basic carrying capacity, most of the loading are supported by steel plate for composite slab, less concrete are needed than that for cast-in-situ slab, thus, the final environmental impact of the former is better than that of the latter. While, when the floor systems are designed with FU_2: maintaining a consistent floor depth, composite slab with high environmental impact steel plate plus 200 mm of concrete performance will produce bigger environmental impact than that of cast-in-situ slab.

4.1.2 LCA results between different stages

Comparison of environmental impacts of the three floor systems during different stages (FU_1) is shown in Fig.7. In the production stage, six processes are included, concrete production, steel production, concrete mix, inter-transportation, prefabrication and waste. From the perspective of production process, the environmental impacts caused by production of concrete and steel are the two most dominant components of the environmental impacts. The two categories account for approximately 63.5%, 84.1% and 74.4% of the total environmental impacts during the production stage. This is because the production of raw materials such as cement and steel are carbon intensive, with high energy and resource consumption. From the perspective of construction method, it can also be seen from Fig.7 that the precast slab has less concrete and steel than the composite and cast-in-situ slabs. By reducing the amount of concrete and steel, the environment impact caused by the corresponding concrete mix and related transportation will also reduce. The construction of composite and in-situ slabs occurs on-site, with no prefabrication and inter-transportation in precast yard. Similarly, we assume that there are no wastes generated off-site for these two floor systems.



a. Precast Slab

b. Composite Slab

c. Cast-in-situ Slab

Fig. 7. Comparison of environmental impacts of the three floor systems during different stages (kPt)

In the transportation stage, all the supplementary materials (such as steel used to make steel mesh, U-shape steel that is used to combine the elements for the precast and composite slabs, screed materials), raw materials and manpower need to be transported to the construction site. When considering the environmental impacts from transport, the majority of impacts arise from the transport of raw materials, with only a small proportion from the transport of supplementary materials and construction labor. There are three reasons behind this: (1) large volume and mass of the raw materials which require transport from the raw material production site to the construction site; (2) the corresponding transport distance is very long; (3) lorries used to deliver raw materials have a higher carbon intensity per km/kg compared to cars used to transfer people.

In the construction stage: six processes are included: cement production, steel production, energy consumption of construction activities, wastewater, and waste concrete and steel. The processes can be classified into three categories. (1) Supplementary steel for the precast and composite slabs is needed, but for the cast-in-situ slab, there is no such supplementary steel beyond typical rebar. Similarly, for the precast and composite slabs, more structural screed is required as it needs to cover the steel mesh, see Fig.2. (2) The cast-in-situ construction method is more complex than that of the prefabricated and composite construction methods. Thus, the energy consumption of construction activities for cast-in-situ method is larger than that of the other two. (3) Wastewater, waste concrete and waste steel are the waste sources in the cast-in-situ construction site, since the precast slabs are already manufactured and only need to be installed in the construction site, we assume that there is no waste. For the composite slab, since sheet is prefabricated in a steel factory, we assume that there is no waste steel in the construction stage.

At the end-of-life stage, three processes are included: (1) Demolition process, (the environmental impact caused by energy consumption to demolish buildings); (2) waste steel recycling processes; (3) waste concrete recycling processes. In the latter, the waste concrete can be reused as new aggregates for asphalt/concrete production, as well as hardcore in road construction or fill material. It is worth noting that even though the consumption of energy such as petroleum and diesel to demolish buildings will produce negative environmental impacts, the recycling and reuse of waste concrete and steel can compensate these impacts to some extent. With a higher recycling rate of sheet and steel, composite and precast slabs bring bigger environmental benefits.

4.2 Uncertainty analysis

In section 2, three types of uncertainty were defined: uncertainty in perspectives and weightings, uncertainty in the waste treatment method in the production and construction stage, as well as EOL stage.

4.2.1 Uncertainty analysis of LCA model

As discussed before, there are three perspectives of the evaluation model ReCiPe 2008, Hierarchist, Egalitarian and Individualist.

It can be seen from Table 5 and 6, the relative importance of the impact categories does have a minor effect on the results. Under FU_1, in all cases, the ranking of alternatives does not change, although the distance between the scores obtained by each alternative changes slightly. Precast slabs are always the best environmental alternative and the environmental damage caused by cast-in-situ slabs is the biggest among the three floor systems. Under most cases with FU_2, composite slabs have the largest environmental impact, while using the weighting factors in the individualist perspective would make the decision about the composite and cast-in-situ slabs very difficult. The figures marked in bold in Table 5 and 6 show the highest environmental damage value. Compared to average weighting factors, the weighting set belonging to the hierarchist perspective places a higher importance on resource consumption. The scenario of egalitarian considers higher values on the ecosystem impact in the daily practice and individualist puts more focus on human health. The uncertainty analyses performed in this section highlights the difficulty in dealing with different weighting parameters of the adopted decision-making approach.

Table 5

Uncertainty analysis considering different perspectives and weights (FU_1)

Perspective	Method	Weighting values	Precast (kPt)	Composite (kPt)	Cast-in-situ(kPt)
Hierarchist	ReCiPe H/A	Eco=0.40;Hum=0.40;Res=0.2	177.13	226.41	**339.74**
	ReCiPe H/H	Eco=0.40;Hum=0.30;Res=0.3	165.88	208.01	**318.77**
Egalitarian	ReCiPe E/A	Eco=0.40;Hum=0.40;Res=0.2	223.82	292.73	**438.14**
	ReCiPe E/E	Eco=0.50;Hum=0.30;Res=0.2	175.49	227.65	**340.10**
Individualist	ReCiPe I/A	Eco=0.40;Hum=0.40;Res=0.2	143.15	177.91	**276.34**
	ReCiPe I/I	Eco=0.25;Hum=0.55;Res=0.2	184.34	229.02	**359.11**

Table 6

Uncertainty analysis considering different perspectives and weights (FU_2)

Perspective	Method	Weighting values	Precast (kPt)	Composite (kPt)	Cast-in-situ(kPt)
Hierarchist	ReCiPe H/A	Eco=0.40;Hum=0.40;Res=0.2	177.13	**287.06**	280.76
	ReCiPe H/H	Eco=0.40;Hum=0.30;Res=0.3	165.88	**265.22**	262.65
Egalitarian	ReCiPe E/A	Eco=0.40;Hum=0.40;Res=0.2	223.82	**370.11**	362.50
	ReCiPe E/E	Eco=0.50;Hum=0.30;Res=0.2	175.49	**287.65**	281.49
Individualist	ReCiPe I/A	Eco=0.40;Hum=0.40;Res=0.2	143.15	**228.02**	227.01
	ReCiPe I/I	Eco=0.25;Hum=0.55;Res=0.2	184.34	294.11	**295.02**

4.2.2 Different waste treatment methods in the production stage

The use of recycled fine aggregates can result in a minor reduction of compressive strength (SPB, 2017). Since the collection of steel is easily carried out during the precast yard, it is assumed that all the steel is recycled. Thus, in this section, only the recycling of waste concrete is considered. Fig.8 shows how the final environmental impact changes with different waste treatment methods of concrete in the production stage. It can be seen from Fig.8, that compared to landfill directly, an average combined method (which is the usually method adopted by precast yard) can reduce the final environmental burden by 53%. If the waste concrete can be reused or recycled, e.g. as road base filling material or new aggregate, 119% and 186% of the final impact can be reduced.

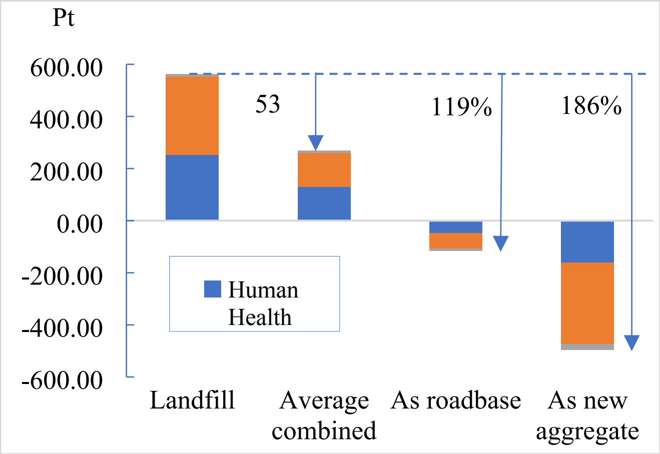


Fig. 8. he environmental impacts caused by different waste treat methods of concrete in precast yard (the arrows represent the reduction percentage of environmental impact of other waste treatment methods compared to landfill)

4.2.3 Different waste treatment methods in the EOL stage

Usually, waste material from the demolition of buildings is recycled or landfilled directly. However, precast products have the potential to be different since many precast elements could be reused or recycled at the end of their first use, such as concrete pipes and railway sleepers which have a long service life. Some companies now offer a take back service on precast concrete units so that they may be repaired and reused (BRE, 2017). According to a study by Tingley and Davison study (2012), if an element can be reused one time, the environmental impact could be shared across the two uses (see Fig. 6 in (Tingley and Davison, 2012)). Fig.9 describes how the final EOL environmental impact of precast slab changes with different waste treatment methods.

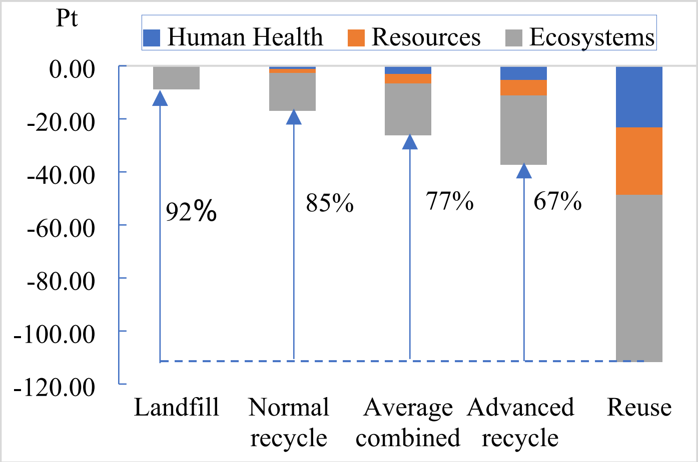


Fig. 9. The EOL environmental impact of precast slab with different waste concrete treat methods

It is easy to obtain the conclusion that reuse of the elements can reduce the environmental impact significantly and this is the main reason that precast products should be promoted. Fig.9 also shows that advanced and normal recycling can reduce the environmental impacts by 28.60 Pt and 8.33 Pt respectively compared to landfill for the case floor system. Moreover, it is estimated that construction industry produces approximately 109 million tonnes of construction waste each year (24% of total waste) in the UK, and concrete contributed 59% of this (CRWP, 2008). If all the waste concrete can be recycled as aggregate, it will reduce 599 million Pt environmental impact. That is to say, 152 million Pt on human health, 12.4 million Pt on ecosystem and 335 million Pt on natural resources.

4.3 Sensitivity analysis

In this case, the precast slab is kept constant as the preferred alternative. Hence, a sensitivity analysis is performed for the precast slab designed to meet the minimum load requirement. A hotspot analysis result is presented in Fig.10. There are three rings in Fig.10, the inner ring represents the basic classification of life cycle stages, the values are the corresponding rates of environmental impacts produced by the slab production stage, the transportation stage and the end-of-life stage. Similarly, the second and third rings are more specific classifications of the life cycle stages. It can be seen from this figure that the transportation stage accounts for a significant proportion (about 41%) of the final score. During the transportation stage, the transportation of precast slab takes the largest ratio. This is because when a building uses precast elements, large parts of the building need to be brought to the site directly, consuming more fuel.

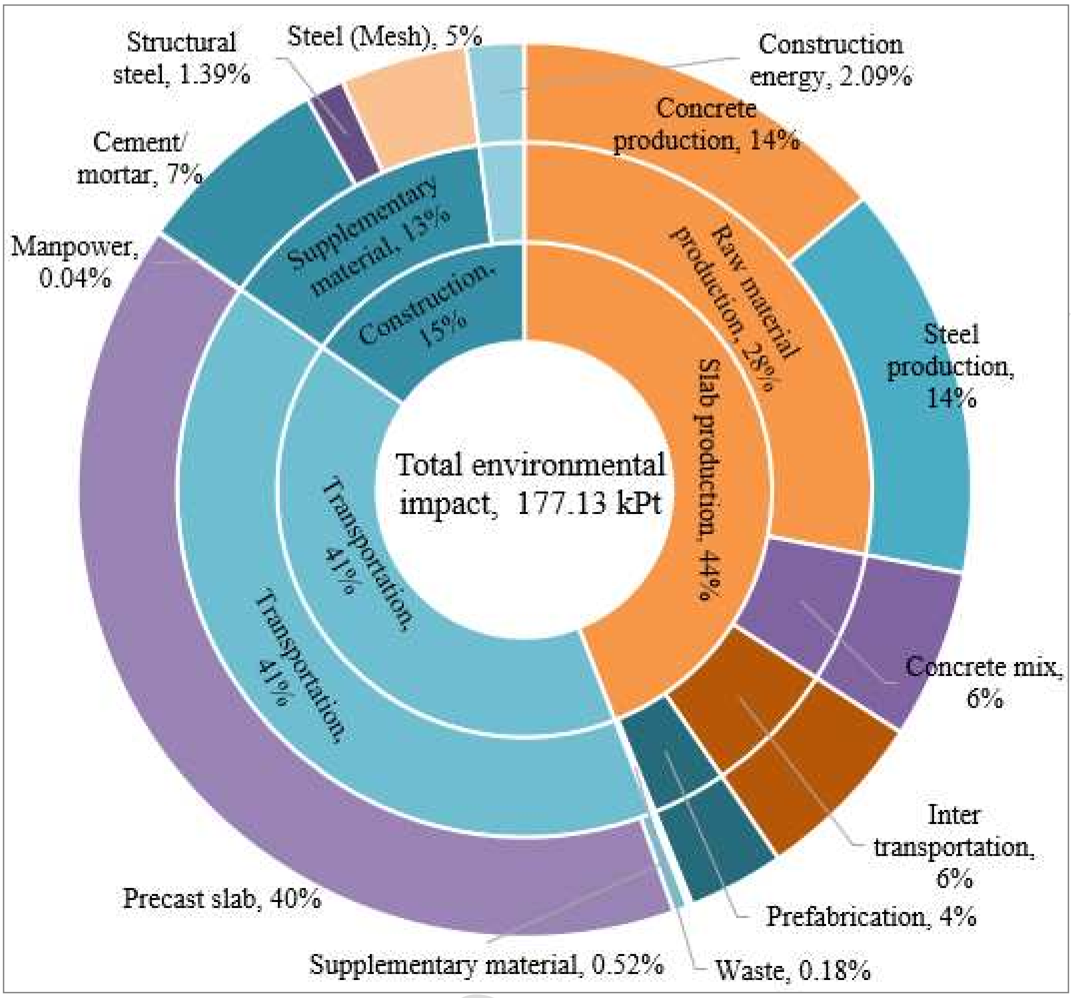


Fig. 10. Hotspots analysis of precast slab (FU_1)

From google maps, we can estimate the original transport distance at 514.5km, which is a significant distance. If all the other parameters are kept the same, reducing the transportation distance is the most direct and effective measure to reduce the environmental impact. Fig.11 shows how the environmental score changes with the alteration of transport distance. It is possible to observe that the minimum, average, and maximum total environmental scores are 143, 177, and 222 kPt respectively when the transport distance varies from 300km to 800km. Indeed, the results shown in this figure would allow the conclusion that the variation of the transport distance has the potential to change the values of the three damage categories (human health, resource, and ecosystem) significantly but not equally compared to Fig.6 (precast slab, FU_1). According to the probabilistic results, the coefficient of variation of resources is the largest, from the lowest value 122 Pt to the highest value 141 Pt. Following resources, human health also sees a relatively higher variation, from 20 Pt to 49 Pt, while damage to ecosystem is the least variable, with 2 Pt and 5 Pt for lowest and highest values. Thus, the general conclusion can be obtained that damage to resources is the most sensitive to the variation of transport distance, while damage to ecosystem sees little variation.

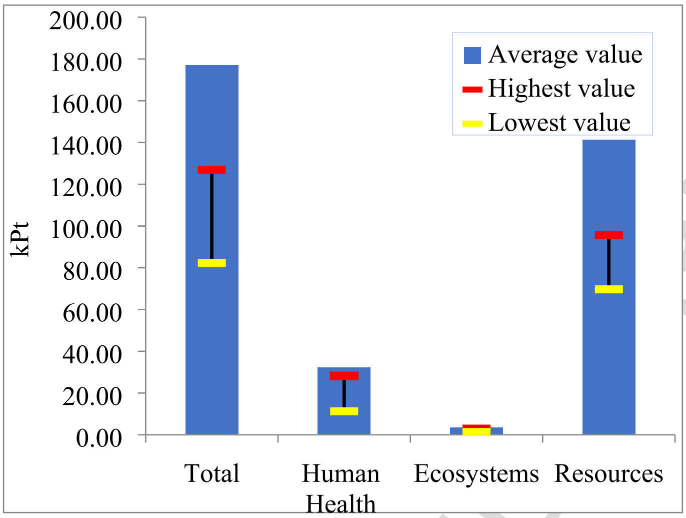


Fig. 11. Sensitivity analysis of transport distance of precast slab (FU$_1$) (from 300 km to 800 km)

5. Conclusions and recommendations

This study investigates the difference in environmental burden between the three construction methods with the life cycle boundary from cradle to grave. The outcome of this work is to make recommendations for optimum floor systems, with increased sustainability and reduced environmental impacts. Firstly, it is necessary for clients, designers, and construction managers to assess environmental impacts during the whole life cycle, since recycling and re-use at the demolition stage can reduce the whole life impacts by reducing the need for new raw materials in the future. Secondly, this study indicates that environmental burdens depend much on functional unit, thus, key stakeholders should consider both aspects when making decisions. Thirdly, through uncertainty and sensitivity analysis, the critical input parameters which have a larger influence on the final score can be established and corresponding measures can be adopted. Finally, in this paper, both midpoint and endpoint results are analyzed since they can provide reliable and interpreted assessment respectively.

There are still some deficiencies of this study, although the benefit is apparent as the hot-spots can be easily detected, encompassing the detailed information of the whole construction process consumes large amount of time to collect data and design different alternatives.

Consequently, the LCA model studies the environmental burden of the floor system rather than the entire building, and a complete building system could be studied in the future. To further explore the potential benefits and impacts of prefabrication, the study could also be extended to include economic and social impacts in addition to environmental impacts.

Acknowledgements

This work was supported by the National Key Research and Development Plan of China with grant number 2016YFC0701806.

Thanks to BAM construction for providing the case study and supporting information on material sourcing for this work.

References

Anderson, J., & Shiers, D., 2009. Green Guide to Specification. John Wiley & Sons, Oxford.

Asumnaa, O. A., 1999. Optimising Environmental Effects of Prefabricated Concrete Building Frames. Helsinki University of Technology.

Aye, L., Ngo, T., Crawford, R. H., Gammampila, R., & Mendis, P., 2012. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. Energ Buildings, 47, 159-168.

Aziz, K., 2015. Material Losses in Cost Accounting, Linkedin. https://www.linkedin.com/pulse/material-losses-cost-accounting-khalid-aziz. Accessed 4 February 2017 (accessed 07 October 2017).

Baldwin, A., Poon, C. S., Shen, L. Y., Austin, S., & Wong, I., 2009. Designing out waste in high-rise residential buildings: Analysis of precasting methods and traditional construction. Renew energ, 34(9), 2067-2073.

Bonamente, E., Merico, M. C., Rinaldi, S., Pignatta, G., Pisello, A. L., Cotana, F., & Nicolini, A., 2014. Environmental impact of industrial prefabricated buildings: Carbon and energy footprint analysis based on an LCA approach. Energ Procedia, 61, 2841-2844.

Borghi, D. A., 2013. LCA and communication: environmental product declaration. Int J Life Cycle Assess, 18(2):293–295.

BRE (Building Research Establishment), 2017. Be Aware Supply Chain Resource Efficiency Sector Report: Precast Concrete.

https://www.bre.co.uk/filelibrary/pdf/rpts/BeAware_Precast_Concrete_Sector_Report_02Mar09.pdf (accessed 07 October 2017).

BS EN 15978, 2011. Sustainability of Construction Works, Assessment of Environmental Performance of Buildings, Calculation Mmethod. British Standards Institution, UK.

BS EN 1993-1-1, 2005. Eurocode 3: Design of Steel Structures-Part 1-1: General Rules and Rules for buildings. British Standards Institution, UK.

BS EN 1994-1-1, 2004. Eurocode 4: Design of Composite Steel and Concrete Structures-Part 1-1: General Rules and Rules for Buildings. British Standards Institution, UK.

Cao, X., Li, X., Zhu, Y., & Zhang, Z., 2015. A comparative study of environmental performance between prefabricated and traditional residential buildings in China. J Clean Prod, 109, 131-143.

CEDD (Civil Engineering and Development Department), 2016. Management of public filling. http://www.cedd.gov.hk/eng/services/licences/ (accessed 07 October 2017).

Chen, Y., Okudan, G. E., & Riley, D. R., 2010. Sustainable performance criteria for construction method selection in concrete buildings. Automat constr, 19(2), 235-244.

Consultants, P., 2000. Eco-indicator 99 Manual for designers. Ministry of Housing, Spatial Planning and the Environment.

CR (Collins Reinforcements), 2017. Mesh or fabric reinforcement to BS 4483. http://rebar.co.uk/mesh-reinforcement/ (accessed 07 October 2017).

CRWP (Construction Resources and Waste Platform), 2008. Overview of demolition waste in the UK. http://www.wrap.org.uk/sites/files/wrap/CRWP-Demolition-Report-2009.pdf (accessed 07 October 2017).

DCC (Devon County Council), 2011. Environmental statement: 15 construction waste. http://www.devon.gov.uk/dcc3242_150.pdf (accessed 07 October 2017).

De Schepper, M., Van den Heede, P., Van Driessche, I., & De Belie, N., 2014. Life cycle assessment of completely recyclable concrete. Mater, 7(8), 6010-6027.

Ding, Z., Wang, Y., & Zou, P. X., 2016. An agent based environmental impact assessment of building demolition waste management: conventional versus green management. J Clean Prod, 133, 1136-1153.

Dong, Y. H., Jaillon, L., Chu, P., & Poon, C. S., 2015. Comparing carbon emissions of precast and cast-in-situ construction methods–A case study of high-rise private building. Constr Build Mater, 99, 39-53.

Dong, Y. H., 2014. Life Cycle Sustainability Aassessment Modeling of Building Construction. University of Hong Kong.

Dreyer, L. C., Niemann, A. L., Hauschild, M. Z., 2003. Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-indicator 99. Int J Life Cycle Ass, 8(4), 191-200.

Goedkoop, M., 1999. A Damage Oriented Method for Life Cycle Impact Assessment. The Eco-indicator 99.

Hong, J., Shen, G. Q., Li, Z., Zhang, B., & Zhang, W., 2018. Barriers to promoting prefabricated construction in China: A cost–benefit analysis. J Clean Prod, 172, 649-660.

Hong, J., Shen, G. Q., Mao, C., Li, Z., & Li, K., 2016. Life-cycle energy analysis of prefabricated building components: an input–output-based hybrid model. J Clean Prod, 112, 2198-2207.

Horvath, A., 2004. Construction materials and the environment. Annu. Rev. Environ. Resour, 29, 181-204.

Hu, M., Kleijn, R., Bozhilova-Kisheva, K. P., & Di Maio, F., 2013. An approach to LCSA: the case of concrete recycling. Int J Life Cycle Ass, 18(9), 1793-1803.

Idrus, A. B., & Newman, J. B., 2002. Construction related factors influencing the choice of concrete floor systems. Constr Manage & Econ, 20(1), 13-19.

Ingrao, C., Giudice, A. L., Tricase, C., Mbohwa, C., & Rana, R., 2014. The use of basalt aggregates in the production of concrete for the prefabrication industry: Environmental impact assessment, interpretation and improvement. J Clean Prod, 75, 195-204.

ISO-14040, 2006. Environmental Management-Life Cycle Assessment-Principle and Framework, 2006.

ISO-14042, 2000. Environmental Management-Life Cycle Assessment-Life Cycle Impact Assessment. Geneva, Switzerland.

ISO-14044, 2006. Environmental Management-Life Cycle Assessment-Requirement and Guidelines, 2006.

Jaillon, L., & Poon, C. S., 2008. Sustainable construction aspects of using prefabrication in dense urban environment: a Hong Kong case study. Constr M Econ, 26(9), 953-966.

Jaillon, L., & Poon, C. S., 2014. Life cycle design and prefabrication in buildings: A review and case studies in Hong Kong. Automat constr, 39, 195-202.

Jaillon, L., Poon, C. S., & Chiang, Y. H., 2009. Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. Waste manage, 29(1), 309-320.

Jeong, J., Hong, T., Ji, C., Kim, J., Lee, M., Jeong, K., & Lee, S., 2017. An integrated evaluation of productivity, cost and CO_2 emission between prefabricated and conventional columns. J Clean Prod, 142, 2393-2406.

Ji, Y. B., Li, K., Liu, G., Shrestha, A., & Jing, J., 2016. Comparing greenhouse gas emissions of precast in-situ and conventional construction methods. J Clean Prod, 173, 124-134.

Li, C. Z., Hong, J., Xue, F., Shen, G. Q., Xu, X., & Luo, L., 2016. SWOT analysis and Internet of Things-enabled platform for prefabrication housing production in Hong Kong. Habitat Int, 57, 74-87.

Li, Z., Shen, G. Q., & Alshawi, M., 2014. Measuring the impact of prefabrication on construction waste reduction: an empirical study in China. Resour Conserv Recy, 91, 27-39.

Liao, P. C., O'Brien, W. J., Thomas, S. R., Dai, J., & Mulva, S. P., 2011. Factors affecting engineering productivity. J Manage Eng, 27(4), 229-235.

Lopez-Mesa, B., Pitarch, A., Tomas, A., & Gallego, T., 2009. Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors. Build Environ, 44(4), 699-712.

Lu, W., & Yuan, H., 2013. Investigating waste reduction potential in the upstream processes of offshore prefabrication construction. Renew Sust Energ Rev, 28, 804-811.

Mao, C., Shen, Q., Shen, L., & Tang, L., 2013. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects. Energ Buildings, 66, 165-176.

Monteiro, H., & Freire, F., 2012. Life-cycle assessment of a house with alternative exterior walls: comparison of three impact assessment methods. Energ Build, 47, 572-583.

Oliver-Solà, J., Josa, A., Rieradevall, J., & Gabarrell, X., 2009. Environmental optimization of concrete sidewalks in urban areas. Int J Life Cycle Assess, 14(4), 302-312.

Paschoalin, R.F., De Carvalho, A.C., Alberto, J., Castanon, B., 2008. Construction and Sustainable Development. Constructing Excellence, 6:1.

Pasquire, C., Gibb, A., & Blismas, N., 2005. What Should You Really Measure If You Want to Compare Pre-fabrication with Traditional Construction? In 13th International Group for Lean Construction Conference: Proceedings (p. 481). International Group on Lean Construction.

Pittau, F., Malighetti, L. E., Iannaccone, G., & Masera, G., 2017. Prefabrication as large-scale efficient strategy for the energy retrofit of the housing stock: An Italian case study. Procedia Eng, 180, 1160-1169.

Pons, O., & Aguado, A., 2012. Integrated value model for sustainable assessment applied to technologies used to build schools in Catalonia, Spain. Build Environ, 53, 49-58.

Pons, O., & Wadel, G., 2011. Environmental impacts of prefabricated school buildings in Catalonia. Habitat Int, 35(4), 553-563.

Roy, B., 2005. Paradigms and challenges, in: Greco, S., Figueira, J., & Ehrgott, M. Multiple Criteria Decision Analysis. Springer's International Series. Springer, New York, USA.

Sansom, M., & Avery, N., 2014. Briefing: Reuse and recycling rates of UK steel demolition arisings. In Proceedings of the Institution of Civil Engineers-Engineering Sustainability. Thomas Telford Ltd.

Sansom, M., & Meijer, J., 2002. Life-cycle assessment (LCA) for steel construction. Eur, 20570, 1-160.

SPB (Sustainable Precast Concrete), 2017. Building Reuse. http://www.sustainableprecast.ca/en/precast_sustainability/building_reuse/(accessed 7 October 2017).

SPC (Sustainable Precast Concrete), 2017. Transportation and Erection.Canadian Precast/Prestressed Concrete Institute. http://www.sustainableprecast.ca/en/precast_sustainability/transportation_erection/ (accessed 07 October 2017).

Sven, A., Arne, S., Arto, S., & Jan, A. V., 2003. Environmental issues in prefabrication: State-of-theart report. International federation for structural concrete, Fib F d ration Internationale Du B ton, (21), 8-11.

Tam, V. W., Tam, C. M., Zeng, S. X., & Ng, W. C., 2007. Towards adoption of prefabrication in construction. Build Environ, 42(10), 3642-3654.

Tata Steel, 2013. Durability of composite metal decking. https://blog.tatasteelconstruction.com/durability-of-composite-metal-decking/(accessed 07 October 2017).

Tingley, D. D., & Davison, B., 2012. Developing an LCA methodology to account for the environmental benefits of design for deconstruction. Build Environ, 57, 387-395.

WBCSD, 2009. Energy Efficiency in Buildings. World Business Council for Sustainable Development.

Weight, D., 2006. Whole-life costs: concrete vs steel. http://www.building.co.uk/whole-life-costs-concrete-vs-steel/3069406.article (accessed 07 October 2017).

Wong, F., & Tang, Y. T., 2012. Comparative embodied carbon analysis of the prefabrication elements compared with in-situ elements in residential building development of Hong Kong. World Acad of Sci, 62(1), 161-166.

Wu, H., Wang, J., & Huang, W., 2015. Causal Relationship Analysis of the Impact of Prefabrication on Construction Waste Reduction. In Proceedings of the 19th International Symposium on Advancement of Construction Management and Real Estate. Springer, Berlin, Heidelberg.

Zhai, Y., & Huang, G. Q., 2017. Operational Hedging and Coordination in Prefabrication Construction Industry. Procedia Manuf, 11, 1178-1183.

Zhang, X., Skitmore, M., & Peng, Y., 2014. Exploring the challenges to industrialized residential building in China. Habitat Int, 41, 176-184.