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INVESTIGATE THE CARBON FOOTPRINTS OF THREE INTERMEDIATE FLOORING SYSTEMS: CROSS-LAMINATED TIMBER, SOLID CONCRETE, AND HOLLOW-CORE PRECAST CONCRET

Jenan Abu Qadourah
Department of Architecture and Building Technology,
Faculty of Engineering,
Mutah University,
P.O. Box 7, Al-Karak,
61710 Jordan

Ala'a M. Al-Falahat
Mechanical Engineering Department,
Faculty of Engineering,
Mutah University,
P.O Box 7, Al-Karak,
61710 Jordan

Saad S. Alrwashdeh
Mechanical Engineering Department,
Faculty of Engineering,
Mutah University,
P.O Box 7, Al-Karak,
61710 Jordan

Key words: *sustainable materials, cross-laminated timber, life-cycle assessment, environmental impact, cradle-to-gate, embodied energy, greenhouse gas emissions*

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INVESTIGATE THE CARBON FOOTPRINTS OF THREE INTERMEDIATE FLOORING SYSTEMS: CROSS-LAMINATED TIMBER, SOLID CONCRETE, AND HOLLOW-CORE PRECAST CONCRETE

***Jenan Abu Qadourah*[1]*, Ala'a M. Al-Falahat*[2]*, Saad S. Alrwashdeh*[2]**

[1]Department of Architecture and Building Technology, Faculty of Engineering, Mutah University,
P.O. Box 7, Al-Karak, 61710 Jordan
[2]Mechanical Engineering Department, Faculty of Engineering, Mutah University, P.O Box 7, Al-Karak 61710 Jordan

This paper evaluates and compares the embodied energy and embodied carbon using a Life Cycle Assessment (LCA) approach for three different intermediate floor structures, all of which use prefabricated materials—cross-laminated timber (CLT), precast hollow-core concrete, and solid concrete—to decide which floor construction materials have less environmental impact for use in the construction of a semi-detached house in the UK. The Inventory of Carbon & Energy (ICE) and the Carbon Calculator tool were used to calculate the carbon footprint from "cradle to grave" to determine whether the use of a CLT solution provides improved environmental performance over the traditional concrete solutions. The carbon footprint results indicate that the use of a hollow-core precast concrete floor system emits less carbon than the other two systems, although the concrete requires more fossil fuel input than the timber during the manufacturing process, so based on this, the footprint from cradle to gate for the timber was expected to be the less than that of the concrete. However, the results show the opposite; this is because of the differences in the material quantities needed in each system.

Key words: sustainable materials, cross-laminated timber, life-cycle assessment, environmental impact, cradle-to-gate, embodied energy, greenhouse gas emissions

INTRODUCTION

Over the past few years, there has been growing concern in the world about the increase of greenhouse gas (GHG) emissions, including those of CO_2 [1-5]. The building construction sector is the main source of CO2 emissions, as more than 40 % of the global GHG outputs and energy consumption are produced through building construction and operation [6-9]. Overall, more than half of the embodied carbon in construction is connected to the materials consumption [10-13], as it uses 40 % of the total gravel, sand, and raw stone consumed worldwide [14-18]. Moreover, these materials must be transported long distances, which leads to increased fuel consumption and produces a lot of greenhouse gases [11]. Accordingly, a wide range of embodied carbon mitigation solutions focus on reducing the use of materials from carbon-intensive supply chains [6, 19-22]. These include solutions that aim to reduce excessive material usage through "light weighting" to reduce waste material on site; solutions to optimize the usable life of materials by increasing the life of existing structures and constructing new ones to be adaptable and simple to dismantle (enabling materials and components to be reused); or replacement of materials and building products with alternatives that have low-carbon supply chains [20, 23]. In the UK, this has been addressed by the Building Regulations Part L with standards to reduce household energy use [17]. Although in-use energy is significant, a building has a much wider range of associated energy or carbon. Materials, for example, require energy for their manufacturing, transport to site, disposal, and end-of-life demolition (see Figure1). This is known as the embodied energy of material from cradle to grave [24, 25].

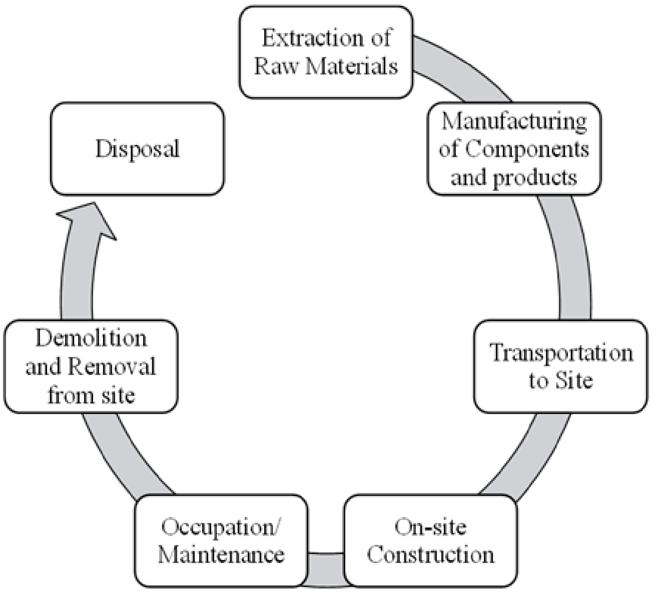

Figure 1: Building construction life cycle process from cradle to grave

Although this standard gives a comprehensive overview of the associated GHG emissions for a material, making it easy to compare and identify an area where the

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*Jenan.abuqadourah@mutah.edu.jo

impacts could be reduced, it is relatively complex to calculate. Hammond and Jones [26] collated public source data on the embodied energy and carbon of many common construction materials, publishing them in the Inventory of Carbon & Energy (ICE). The figures used in ICE are from cradle to gate for most of the materials. The Environmental Agency has used this to develop a Carbon Calculator and make some improvements to calculating the carbon footprint from cradle to grave; for example, it considers transport of materials and workers to the site, site energy use, and the disposal of construction waste (cradle to grave) [27]. Using these tools, the cradle-to-grave GHG emissions for three different sound insulation prefabricated floor structures for a semi-detached house in the UK were investigated to determine whether the use of a cross-laminated timber (CLT) solution provides improved environmental performance over the traditional concrete solutions. Past construction has heavily involved concrete and steel, both of which are highly energy-intensive when combining the materials, production, transport, and construction stages. However, timber has the potential to avoid the majority of fossil fuel consumption and CO_2 release related to these conventional materials [28]. In the United Kingdom, the usage of timber in construction is increasing. Timber frame systems accounted for nearly a quarter of all UK housing starts in 2016, up nearly 9 % from the previous year, according to the Structural Timber Association, compared to 3.6 percent growth in non-timber frame systems [29]. Besides, engineered wood products, such as CLT and glulam, are now facilitating a new generation of larger timber buildings in the UK and many other countries around the world, including industrial and commercial buildings [28, 29].

METHODOLOGY AND KEY ASSUMPTION

This paper evaluates and compares the embodied energy (EE) and embodied carbon (EC) using an LCA approach for three different intermediate floor structures, all of which use prefabricated materials—CLT, precast hollow-core concrete, and solid concrete—to decide which floor construction materials have less environmental impact for use in the construction of a semi-detached house. The components of each floor system are illustrated in Figure 2, and more details can be accessed in Appendices 1, 2, and 3. Full life cycle, from ‘cradle to grave’ system boundary has been applied in this study, which includes material extraction, manufacturing, transportation, on-site construction and installation, and the demolition phase [27]. The operation and maintenance stage of the LCA has not been considered, as it is assumed the energy required when the floor is in use will be similar for all materials. A full life cycle assessment from cradle to grave gives a more realistic and reliable environmental impact than consideration of embodied energy and carbon from cradle to gate alone [32-34]. Cradle to gate assessment does not give a complete picture of a product that can be compared to other materials in a meaningful way, because other features of the various material alternatives' use-phase and end-of-life are not included [35]. As mentioned earlier, the Environmental Agency Carbon Calculator has been used to calculate the embodied energy and embodied carbon. Inventory data has been collected from the Carbon & Energy (ICE) database to determine emissions factors for other materials and for end of life scenarios [26]. To allow a simple assessment, the floor outline is assumed to be rectangular and have a total area of approximately 150 m2, with dimensions of 10 m wide by 15m long. The site is assumed to be located in Cardiff, CF24 4BZ. For each system, the components have been defined, and the required tonnage, distance and travel mode from the manufacturer, tonnage wasted, disposal mechanisms, and distance and travel mode to the waste processing site of each component have been specified (see Appendices 1-2). This information is then input into the Environmental Agency Carbon Calculator to calculate the tons of CO_2 emitted for each system from cradle to grave. The precast hollow-core concrete floor structure comprises a pre-cast hollow-core concrete slab, a leveling screed, a resistance layer like rubber, and a vapor control layer. The slab should be tightly abutted; all joints should be filled with grout, assumed to be a mortar; and the thickness should be 0.15 m. The hollow segments of the precast slab should be distributed over a minimum of 80 % of the slab. According to the manufacturing company, the hollow-core concrete slabs are available in a range of widths for spans up to 15 m [31]. The precast solid concrete floor is assumed to have the same components used in the hollow-core concrete floor system, except

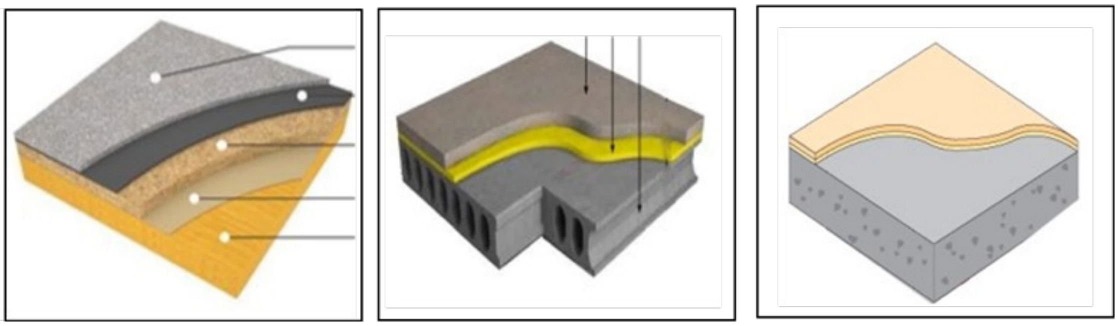

Figure 2: (A) The components of a CLT floor [30]; (B) The components of a hollow-core concrete floor system [31]; (C) The components of a solid concrete floor system [31]

that the thickness of the concrete layer must be 0.10 m instead of 0.15 m, and each slab can be prefabricated with a size of up to 6×3 m. For this site, the slabs' dimensions are assumed to be 5×5 m; accordingly, six slabs are needed to cover the floor area; the joint between the slabs should be filled with in-situ mortar [31]. The studied floor systems are assumed to be installed by hand; however, the energy use of heavy equipment like a crane is need-ed. The crane is hired from Gullivers Company, which is 5.5 km from the construction site. Moreover, the hollow-core concrete floor and the solid concrete floor need a mortar mixer in addition to the crane. Regarding the project duration and site accommodation, the same assumptions are made for the three systems: that the project duration is three weeks; eight people are permanently on site, as this is a small project; and the main used elements are prefabricated. Accordingly, accommodation is needed for three weeks. For the waste in the three systems, recycling is prioritized, and the closest processing plants to the site have been selected for use in the analysis. Waste figures are assumed to be 5 % or 10 % according to average figures for each material unless the material is supplied in specified amounts for which the waste can be calculated exactly.

RESULTS

Overall, as illustrated in Table 1, the cradle-to-grave CO2 emissions of the hollow concrete floor are the lowest, while the solid concrete floor has the highest carbon footprint. The CO_2 emissions of the solid precast concrete floor are 25 % higher than those of the hollow-core concrete and 6 % higher than those of the CLT floor, and the highest carbon footprint among all these floor systems is during the manufacturing process, which is from cradle to gate. From gate to site, the carbon emissions are the lowest, while from site to grave, the carbon footprint is the same for all the studied floor systems; this is because the three types are prefabricated locally, and the site accommodation and project duration are the same (see Figure 3).

DISCUSSION

The carbon footprint results indicate that the use of a hollow-core precast concrete floor system emits less carbon than the other two systems. Based on the fact that concrete requires more fossil fuel input than timber during the manufacturing process, the footprint from cradle to gate for the timber was expected to be the less than that of the concrete. However, the results show the opposite; this is because of the differences in the material quantities needed in each system. And this is clear through comparing the hollow-core system with the solid-core one, as the same material is used with the same embodied energy, yet different amounts of CO_2 are emitted: hollow-core concrete produces 4 tons, and solid concrete produces 6.6 tons (see Table 2). Another factor that affects the carbon footprint in these three systems is the use of miscellaneous materials. In all three systems, a rubber insulation layer is used, while the CLT floor additionally uses wood fiber insulation to increase the efficiency of sound insulation, which increases the carbon footprint. On the other hand, most of the carbon footprint resulted from the finishing layer in the concrete (solid and hollow-core concrete) systems. However, from gate to site, there are no big differences between the three systems. This is because all the material was manufactured locally, so the amount of fossil fuel consumed to transport the material to the site is relatively low. Also, from site to grave, the carbon footprint is low because all the systems are prefabricated, which leads to a significant decrease in the construction time and the on-site waste compared to in-situ systems; moreover, there are many disposal sites near the construction site.

Overall, as the main function for these floors is to isolate the sound, this leads to the use of more layers with more thickness and different materials in the CLT floor, which causes an in-crease in the carbon footprint of this system, although the timber has less embodied energy than the concrete.

Table 1: Cradle to grave carbon footprint for the CLT, hollow-core concrete, and solid concrete floors

FLOOR TYPE	CRADLE TO GATE ($TON\ CO_2$)	GATE TO SITE ($TON\ CO_2$)	SITE TO GRAVE ($TON\ CO_2$)	CRADLE TO GRAVE ($TON\ CO_2$)
CLT FLOOR	16.9	0.021	2.5	19.4
HOLLOW-CORE CONCRETE FLOOR	13.2	0.023	2.5	15.7
SOLID CONCRETE FLOOR	18.3	0.023	2.5	20.8

Table 2: Embodied CO2 by energy consumption and material quantities needed for the main material in each floor system

	TIMBER	CONCRETE HOLLOW-CORE SLAB	SOLID CONCRETE SLAB
EMBODIED ENERGY (TCO$_2$/TON MATERIAL)	0.31	0.33	0.33
QUANTITY NEEDED (TONS)	10.2	4	6.6

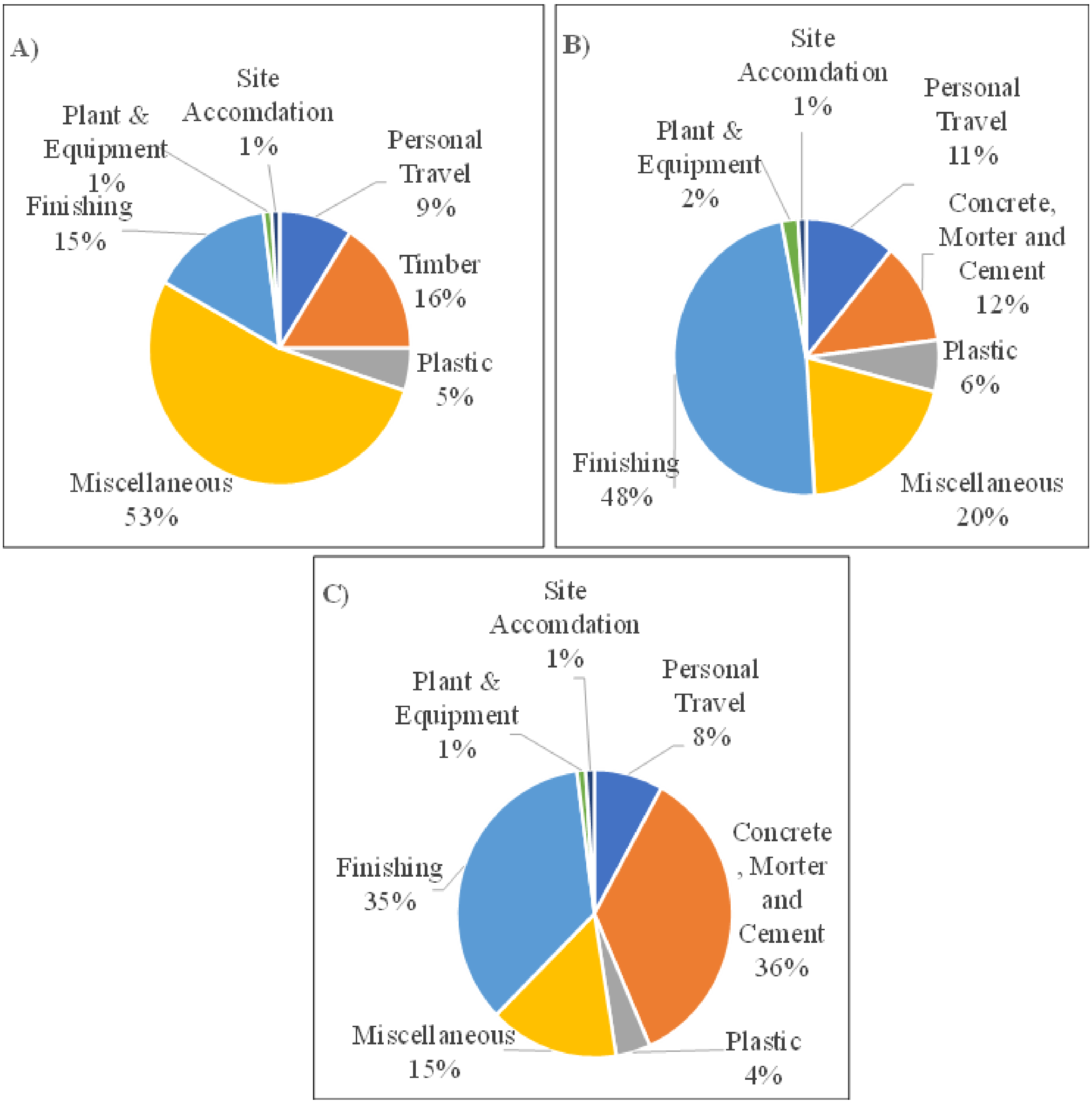

Figure 3: (A) Carbon emissions by process and material for the CLT floor, (B) Hollow-core concrete floor, (C) Solid concrete floor

CONCLUSION

Although the carbon footprint of the hollow-core floor concrete systems is lowest, it is difficult to conclude which type of flooring has the lowest environmental impacts. This is due to the other factors involved in the life cycle of the element, such as the life expectancy of these systems, their need for maintenance, and the effect of each floor on in-use energy. However, different aspects can be controlled to decrease the carbon footprint, such as using local materials with less embodied energy and with less material needed without affecting the efficiency of the structure, as well as using recyclable material. In general, the prefabricated systems can be very efficient in decreasing the carbon footprint on the site by decreasing the duration of construction and de-creasing the amount of on-site waste, as well as the use of equipment. Overall, it is important to understand the GHG emissions associated with the various parts of the building process; however, the techniques for doing this are still in their infancy. While these are being developed, cradle-to-site analysis is still a useful tool to identify key areas of improvement when considering potential element systems.

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APPENDIXES

Appendix 1: summary of assumptions and calculations used to estimate the carbon footprint from cradle to grave for the CLT Floor system

Component	Screed (cement and sand)	Rubber	Wood fiber insulation	Vapor control layer (polyethylene)	5-layer Crosslam timber
Volume required	0.025*10*15 =3.75 m^3	0.012*10*15= 1.8 m^3	0.01*10*15= 1.5 m^3	0.003*10*15= 0.45 m^3	0.13*10*15= 19.5 m^3
Density (tons/ m^3)	1.2	1.5	0.05	0.92	0.5
Wastage rate	5%	5%	1%	10%	5%
Quantity tones (with wastage rate)	1.2*3.75+ (1.2*3.75*5%) = 4.75	1.5*1.8+ (1.5*1.8* 5%) = 2.835	0.05*1.5+ (0.05*9* 1%) = 0.12	0.45*0.92+ (0.45*0.92*10%) =0.45	19.5*0.54+ (19.5*0.5 *5%) = 10.2
Embodied energy tCO2/ton material	0.6	2.85	0.93	1.93	0.31
Footprint (tons fossil CO2e (embodied)	2.85	8.123	1.95	0.9	3.1
Embodied CO2	16.90 tons CO2, (Cradle to gate) (material +waste)				
Manufacturing site	Roath Dock Road. Cardiff. C F10 4ED	Penarth. CF64 2LA	Wellwood, Cardiff. CF23 9JR	Leighton Buzzard, LU7 4TZ	London SE12NL
Distance (gate to site)	6.9 km	7.4	4.16	223.2	247.8
Mode of travel	Road	Road	Road	Road	Road
Footprint (tons fossil CO2e (transport)	0.004	0.003	0.004	0.007	0.003
Total	0.021 tons CO2 by Transport of Materials (gate to site) Cradle to site = 16.92 tons CO2				

Disposal method	Reuse / recycled CF24 2QS	recycled CF14 1DO	Reuse /recycled CF10 4LY	Landfill CF11 6EU	Recycling /reuse CF10 4LY
Distance to disposal (km)	3.8	4.3	4	3.2	4
Mode of travel	Road	Road	Road	Road	Road
Tons wasted	0.39	0.135	0.75	0.0414	0.49
total	1.8 tons wasted				
Waste	0.00				tons CO2
Equipment	Power source	Hours in use	Equipment plant location	Distance to equipment hire plant	Came travel I/day
Crane	Diesel	Working For 5 hours Each day Need 10l/day for 10 days. (50 litters)	Gullivers hire, CF118TX	5.5	For 2 days (One to travel to the site one travel from the site) (10 litters for 11 km travel distance)
One crane is needed in the site construction which travel from and to the site we time and stay in the site during the 7-working day consumed 51/day for travailing and for working (5.5*2)					
Plant Emissions tons CO2	0.3 tons CO2				
Personnel Travel			Work duration		
Small (fewer than 8 people permanently on site)			three weeks		
Personal travel tons CO,			2 tons CO2		
Site accommodations					
5I/day for 12 days, 100km			0.156		
Electricity 30 kwh			0.013		
Site accommodation tons CO,			0.2 tons CO,		
Site to grave tons CO2. Waste tons CO_2+ Plant Emissions tons CO2 + Personal travel tons CO2, Site accommodation tons CO2			0.2+21%3+0= 2.5 tons CO_2		
Cradle to grave tons CO2.			19.4 tons CO_2		

Appendix 2: summary of assumptions and calculations used to estimate the carbon footprint from cradle to grave for the precast hollow core concrete floor system

Component	Screed (sand and cement)	Rubber	Vapor control layer	Hollow-core Concert Slabs	Mortar
Volume required	10*15*0.065= 9.75	0.006*10*15= 0.9	0.004*10*15 = 0.45 m^3	The hollow segments should be distributed over a minimum of 80% of the slab. Volume required =10*15*0.15= 22.5*(20%) =4.5 5 slabs needed	Volume required between the 5 slabs is: 0.1*0.25*15*5 =1.1
Density (tons/m^3)	1.2	1.5	0.92	0.80	1.9
Wastage rate	5%	5%	10%	10%	10%
Quantity tones (with wastage rate)	1.2*9.75+(12*9.75*0.05) = 12.3	1.2*0.9+(1.2*0.9*.05) = 1.1	0.45 *0.92+(0.45*0.92*10%) =0.45	0.8* 7.5+(0.8*7.5*0.1) = 4	1.1*1.9+(1.1*1.9*0.1) = 2.2
Embodied energy tCO2/ton material	0.6	2.85	0.9	0.33	0.18
Footprint (tons fossil CO2e)	7.4	3.1	0.9	2.28	0.88
Embodied CO2+ material	13.20 tons CO2				(Cradle to gate)
Manufacturing site	Roath Dock Road, Cardiff,	Penarth. C F64 21A	Leighton Buzzard, LU7	Hope construction material,	Hope construction material,
Distance from (gate to site)	6.9 km	7.4	223.2	7.0	7.0
Mode of travel	Road	Road	Road	Road	Road
Footprint (tons fossil CO2e	0.004	0.003	0.007	0.006	0.003
Total	0.023 tons CO2 by Transport of Materials (gate to site) Cradle to site :(13.2+0.021) = 13.22 tons CO2				

Distance to disposal (km)	3.8	4.3	3.2	3.8	3.8
Mode of travel	Road	Road	Road	Road	Road
Tons wasted	0.39	0.135	0.0414	0.36	0 *2*
total Tons wasted	1.1				
Waste tons CO2	0.00				
Equipment	Power source	Hours in use	Equipment plant location	Distance to equipment hire place	Carne travel I/day
Crane	As mentioned in appendix 1		(0.3		tons CO2)
Mortar mixture	Power source	Hours in use			kWh
	Electric 500 W	Mixed 50 liters per minutes. 3.1 148m3 (3114.8l is needed) 3114.8/50 =62 min Around one hour			1*500= 500 Wh = 0.500 kWh (0.0 tons CO2)
Plant Emissions tons CO2	0.3				tons CO2
Personal travel	(the same as appendix 1)				2 tons CO2
Site accommodation tons CO2	(the same as appendix 1)				0.2 tons CO2
Site to grave tons CO2. Waste tons CO2 + Plant Emissions tons CO2 + Personal travel tons CO2 + Site accommodation tons CO2					0.2+2+3+0= 2.5 tons CO2
Cradle to grave tons CO_2					15.7 tons CO2

Appendix 3: summary of assumptions and calculations used to estimate the carbon footprint from cradle to grave for the precast solid slabs) concrete floor system

Component	Screed (sand and cement)	Rubber	Vapor control layer (polyethylene)	Concrete precast concrete solid floor slabs	Mortar
Volume required	The same as appendix 2			Volume required = 10*15*0.15= 22.5*(20%) =4.5 volume of slab 10*3*0.15*(20%) =0. 4.5 6 slabs needed	Volume required between the 6 slabs is: (0.1*10*0.1*4) +(0.1*0.1*15*3) = 0.85
Density	The same as appendix 2			0.80(tons/m^3)	1.9(tons/m^3)
Wastage rate	The same as appendix 2			10%	10%
Quantity tones (with wastage rate)	The same as appendix 2			0.8*22.5+(0.13*22.5*0.1) = 6.6	0.85*1.9+(0.135*1.9*0.1) = 1.77
Embodied energy tCO2/tons material	The same as appendix 2			0.33	0.18
Footprint (tons fossil CO2e (transport)	7.4	3.1	0.9	6.51	0.39
Disposal method	The same as appendix 2				
Distance to disposal	The same as appendix 2				
Mode of travel	The same as appendix 2				
Tons wasted	0.39	0.135	10.0414	`1.8	0.1615
total	15 Tons wasted				
Waste	0.00				
Embodied CO2 material +waste	18.3 tons CO2 (Cradle to gate)				
Manufacturing site	The same as appendix 2				
Distance from (gate to site)	The same as appendix 2				
Mode of travel	The same as appendix 2				
Footprint (tons fossil CO2e (transport)	0.004	0.003	0.007	0.006	0.003
Total	0.023 tons CO2 by Transport of Materials (gate to site) Cradle to site:(18.3+0.021) = 18.32 tons CO2				
Equipment					
Crane	As mentioned in appendix 2			(0.3 tons CO2)	
Mortar mixture	Power source	Hours in use		kWh	
	Electric 500 W	Mixed 50 liters per minutes. 1.77m3 (1770.1 is needed) 3114.8/50 =35 min Around 0.52		0.5*500= 250 Wh = 0.250 kWh (0.0tons CO2)	
Plant Emissions	0.3 tons CO2				
Personal travel (the same as appendix 2)				2 tons CO2	
Site accommodation tons CO2, (the same as appendix 2)				0.2 tons CO2	
Site to grave tons CO2. Waste tons CO2. Plant Emissions tons CO2 + Personal travel tons CO2, Site accommodation tons CO2				0.2+24%3+0= 2.5 tons CO2	

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