Supplementary Information
Carbon vs. cost option mapping: A tool for improving early-stage design decisions

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1. Cost model coefficients

The cost model reflects current practice in early-stage cost estimates produced by quantity surveyors. The rates for materials include the costs for transport to the site and the construction itself. The values were obtained through conversations with civil engineering practitioners and quantity surveyors in the UK. The values are therefore most suitable for the UK and can be expected to vary for other countries. The cost rates were normalised by the cost for a cubic meter of concrete due to their proprietary nature. The values used in both test cases are given in Table 1.

Material/ Operation	Element	Cost type	Cost rate	Cost rate unit	Multipliers
Steel	Beams, Columns	Steel	15.2	£/t	m_{beams}, m_{columns}
	Connections, Plates	Steel	15.2	£/t	m_{conns}, m_{plates}
	Beams, Columns	Paint	2.73	£/t	m_{beams}, m_{columns}
	Column	Base plates	3.03	£/plate	$n_{\text{baseplates}}$
	Shear studs	Steel	15.2	£/t	$m_{\text{shearstuds}}$
	Frame	Cladding connection	0.394	£/m	$l_{\text{perimeter}}$
	Beams, Columns, Connections, Plates	Sundries	5.0	%	steel costs
Reinforced Concrete	Slab, Columns, Foundations	Concrete	1.0	£/m^3	V_{conc}
	Slab, Columns, Foundations	Rebar	6.67	£/t	m_{rebar}
	Steel decking	Steel deck	0.273	£/m^2	A_{floor}
	Slab, Foundations	Side formwork	0.121	£/m^2	$A_{\text{fw,side}}$
	Slab	Soffit formwork	0.303	£/m^2	$A_{\text{fw,soffit}}$
	Slab	Cladding connection	0.394	£/m	$l_{\text{perimeter}}$
	Slab	Surface finishing	0.0152	£/m^2	A_{floor}
	Precast decking	Precast Concrete	0.303	£/m^2	A_{floor}
	Columns	Formwork	0.424	£/m^2	$A_{\text{fw,col}}$
	Slab, Columns, Foundations	Sundries	5.0	%	RC costs
Timber	Beams, Columns	Glulam	9.09	£/m^3	V_{beams},V_{columns}
	CLT decking	CLT	0.833	£/m^2	A_{floor}
	Frame	Cladding connection	0.606	£/m	$l_{\text{perimeter}}$
Excavation	Substructure	Excavation & Disposal	0.303	£/m^3	V_{exc}
Piling	Pile Foundation	D<600 mm	0.606	£/m	l_{piles}
	Pile Foundation	$D\geq$600 mm, D<800 mm	1.06	£/m	l_{piles}
	Pile Foundation	$D\geq$800 mm	1.52	£/m	l_{piles}
	Foundation	Pile mat	0.152	£/m^2	A_{floor}

Table 1: Coefficients of the cost model used for both case studies. The cost rates are normalised due to their proprietary nature.

2. Embodied carbon model coefficients

The embodied carbon coefficients used for the test cases cover the life-cycle stages A1–A5 (cradle-to-completion) and reflect current industrial practise [1]. The life-cycle stages B–D are not considered here, as their influence on embodied carbon is very low (B), low (C), or uncertain and in the distant future (C,D) [1]. Obviously, other sets of coefficients can be provided as input to include more life-cycle stages, to adapt to regional differences, or to make use of new or higher quality data. The embodied carbon coefficients for the life-cycle stages A1–A3 (cradle-to-gate) were taken from the open-access ICE database [2]. In accordance with EN 15804 [3], any permanent storage of biogenic carbon is not included. This is achieved by using the A1–A3 carbon coefficients given in Jones and Hammond [2] which neglect sequestration.

The further carbon arising from transport of materials to the construction site and the construction itself were estimated using a current IStructE guidance document [1]. In order to calculate emissions from transport to site, average distances and transport mode splits need to be assumed for every material. These are given in Tables 2 and 3. The contribution of A4 emissions then results from multiplying the assumed distances per mode with the transport emissions factors given by the UK Government [4], assuming average loading of HGVs. Emissions caused by construction activities (A5) are calculated by accounting for material wastage on site and by estimating the emissions caused by site activities, i.e. on-site electricity consumption and fuel use. Both waste factors and the site activity emission factor are taken from Gibbons and Orr [1] and are given in Table 2 and 4, respectively.

The embodied carbon coefficients used in the test cases are given in Table 4.

Material/product	Transport category	Waste rate [%]
Steel reinforcement	UK	5
Steel frame	UK	1
Steel deck	UK	10
Concrete in situ	Local	5
Concrete precast	UK	1
Glulam frame	Europe (Road)	1
CLT deck	Europe (Road)	10
Formwork	Global (Ship)	10

Table 2: Assumed transport categories and waste rates per material.

Transport category	Road distance [km]	Sea distance [km]	A4 carbon factor [kg CO_2e/kg]
Local	50	0	0.00533
UK	300	0	0.0320
Europe (Road)	1500	50	0.161
Global (Ship)	200	10000	0.183

Table 3: Distances by mode and total emissions per transport category.

Material/ Operation	Element	Emissions Type	Emissions Rate	Emission Rate Unit	Multipliers
Steel	Beams, Columns	Steel	1.60	kg CO_2e/kg	m_{beams}, m_{columns}
	Connections, Plates	Steel	3.10	kg CO_2e/kg	m_{conns}, m_{plates}
	Beams, Columns	Paint	13.5	kg CO_2e/m^2	A_{beams}, A_{columns}
	Shear studs	Steel	2.30	kg CO_2e/kg	$m_{\text{shear studs}}$
Reinforced Concrete	Piles	Concrete C30/37	0.127	kg CO_2e/kg	$m_{\text{conc},30/37}$
	Slabs, Columns, Pads	Concrete C32/40	0.127	kg CO_2e/kg	$m_{\text{conc},32/40}$
	Pile caps	Concrete C35/45	0.134	kg CO_2e/kg	$m_{\text{conc},35/45}$
	Slab, Columns, Foundations	Rebar	2.13	kg CO_2e/kg	m_{rebar}
	Steel decking	Steel Deck	3.10	kg CO_2e/kg	$m_{\text{comp,deck}}$
	Slab, Columns, Foundations	Formwork	0.980	kg CO_2e/kg	m_{fw}
	Precast decking	Precast concrete	0.209	kg CO_2e/kg	m_{floor}
Timber	Beams, Columns	Glulam	0.681	kg CO_2e/kg	m_{beams}, m_{columns}
	CLT decking	CLT	0.605	kg CO_2e/kg	m_{deck}
Construction	Whole Structure	Plant	0.007	kg CO_2e/£	total project cost

Table 4: Coefficients of the embodied carbon model used for both case studies. The modelled life cycle stages are A1-5 (cradle to completion).

3. Input parameters for the test cases

The parameters defining the examined test cases are given in Tables 5-7. We note that except for geometry and soil properties the used input parameters for both test cases were identical. The span tables used to design deckings are provided as a collection of text files together with the output data on the data repository [insert link].

		test case 1	test case 2
geometry	layout	Fig. 2a	Fig. 2b
	number of storeys	5	4
	column spacing range	$4 - 12\,\mathrm{m}$	
	storey height	4 m	
	max. structural zone	1500 mm	
loads	permanent loads floors	$2.5\,\mathrm{kN/m^2}$	
	variable loads floors	$2.5\,\mathrm{kN/m^2}$	
	permanent loads roof	$2.5\,\mathrm{kN/m^2}$	
	variable loads roof	$0.75\,\mathrm{kN/m^2}$	
	facade load	$2.5\,\mathrm{kN/m^2}$	
	parapet load	$0.75\,\mathrm{kN/m}$	
utilisation & serviceability limits	max. utilisation ratio	1.0	
	min. fire rating	60 minutes	
	steel beam total load deflection	$l/250$	
	steel beam dead load deflection	$l/200$	
	steel beam imposed load deflection	$l/360$	
	composite beam construction deflection	$l/250$	
	composite beam total deflection	$l/250$	
	steel beam natural frequency limit	4.0 Hz	
	timber beam instantaneous imposed load deflection	$l/300$	
	timber beam final imposed load deflection	$l/200$	
	timber beam final total load deflection	$l/250$	
	timber beam natural frequency limit	8.0 Hz	
	reinforced concrete deflection (enforced via span-to-depth ratio method)	$l/250$	

Table 5: Geometry, loading, and serviceability limits used for the test cases.

		test case 1	test case 2
Materials	concrete grade: slabs, columns, pads, raft	C32/40	
	concrete grade: piles	C30/37	
	concrete grade: pile caps	C35/45	
	concrete density (reinforced, hardened)	2548 kg/m^3	
	concrete density (reinforced, unhardened)	2650 kg/m^3	
	steel grade: beams, columns	S355	
	steel rebar yield strength	500 MPa	
	steel density	7850 kg/m^3	
	glulam grades: beams, columns	GL24h	
	glulam density	420 kg/m^3	
	CLT density	475 kg/m^3	
	formwork density	700 kg/m^3	
	formwork thickness	18 mm	
Design space	concrete slab thickness range	100–800 mm	
	concrete slab thickness increment	25 mm	
	ground-bearing slab thickness	150 mm	
	ground-bearing slab steel reinforcement rate	5 kg/m^2	
	concrete column width range	150–1000 mm	
	concrete column width increment	25 mm	
	base mat rebar sizes [mm]	{8,10,12,16,20,25,32}	
	base mat rebar spacing	100–250 mm	
	base mat rebar spacing increments	25 mm	
	additional rebar sizes [mm]	{6,8,10,12,16,20,25,32,40}	
	steel beam sizes	all UB sections	
	steel column sizes	all UC sections	
	max. glulam beam depth	2560 mm	
	max. glulam beam width	560 mm	
	glulam beam depth,width increment	20 mm	
	max. glulam column width	560 mm	
	glulam column width increment	20 mm	
	deckings	see collection of span tables	

Table 6: Material grades and design space definitions for the test cases.

	test case 1	test case 2 soil 1	test case 2 soil 2	test case 2 soil 3	test case 2 soil 4
depth of made ground [m]	0.4	0.4	0.4	0.4	0.4
depth of ground water table [m]	2.0	2.0	20.0	2.0	20.0
weight density γ' [kN/m^3]	19.0	19.0	19.0	19.0	19.0
soil type	cohesive	cohesive	cohesive	granular	granular
friction angle φ' [°]	-	-	-	28.0	35.0
undrained shear strength at top of stratum c_u [kN/m^2]	75.0	60.0	120.0	-	-
undrained shear strength gradient dc_u/dz [kN/m^3]	0.0	0.0	0.0	-	-

Table 7: Soil properties used in the test cases.

References

[1] O. Gibbons, J. Orr, How to calculate embodied carbon, 1.0 ed., The Institution of Structural Engineers, 2020. ISBN: 978-1-906335-47-2.

[2] C. Jones, G. Hammond, ICE Database V3.0, 2019. URL: https://circularecology.com/embodied-carbon-footprint-database.html (last accessed: 2022-01-11).

[3] British Standards Institution, BS EN 15804:2019: Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products., BSI, London, 2019. ISBN: 978-0-539-19042-7.

[4] UK Government, Greenhouse gas reporting: conversion factors 2020, 2020. URL: https://carbon.tips/cf2020 (last accessed: 2022-01-12).