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Supplementary Materials for the article

Influence of Prefabricated Rate on the Environmental Performance of Buildings Based on Life Cycle Assessment

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Supplementary Materials: The following are available online at www.mdpi.com/xxx/s,

S1: Data collection for the reference building

S2: Data for the scenarios with increasing prefabricated rates

S3: Data for sensitivity analysis

S4: Data for uncertainty analysis

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Supplementary Materials

S1: Data collection for the reference building

Table S1.1: Raw material consumption per m² floor area considering loss rates for the reference building

Work type	Material type	Raw material	Consumption	Reference
Precast concrete work	Precast concrete (loss rate: 4%)	Cement	20.75 kg/m²	[1, 2]
		Sand	132.8 kg/m²	
		Gravel	74.71 kg/m²	
	Reinforcement bars	Recycled steel	6.083 kg/m²	[3]
Conventional concrete work	Ready-mixed concrete (loss rate: 10%)	Cement	63.99 kg/m²	[1, 3]
		Sand	409.5 kg/m²	
		Gravel	230.3 kg/m²	
	Reinforcement bars	Recycled steel	17.58 kg/m²	[3]
Other material work	Metal	Steel, virgin	1.510 kg/m²	
		Stainless steel	0.582 kg/m²	
		Aluminium, virgin	0.549 kg/m²	
		Aluminium, recycled	0.549 kg/m²	
	Wood	Planed timber	9.780 kg/m²	
		Plywood	0.698 kg/m²	
		Plasterboard (loss rate: 4%)	4.646 kg/m²	
		Glued-laminated timber	11.83 kg/m²	
		Particle board	0.880 kg/m²	
	Mineral wool	Stone wool (loss rate: 7%)	6.796 kg/m²	
	Plastics	Polypropylene (loss rate: 7%)	2.118 kg/m²	
		Polystyrene	7.022 kg/m²	
	Glass	Glass	4.118 kg/m²	
		Insulated glass unit	4.340 kg/m²	

Table S1.2: Total material and energy consumption per m² floor area for the reference building during in-plant processing

Work type	Material/ energy	The reference building	Reference
Conventional concrete work	Electricity	1.728 kwh/m²	[4]
	Water	39.35 kg/m²	[5]
Precast concrete work	Electricity for concrete	0.561 kwh/m²	[4]
	Electricity for steel	0.270 kwh/m²	[6]
	Water	12.76 kg/m²	[5]
	Diesel	1.113 kwh/m²	[7]
	Steam	2.167 kwh/m²	[8]

Table S1.3: Transport information for sand and gravel of the reference building, from raw material suppliers to concrete plants

Work types	Concrete plants	Suppliers	Geographical distance	Average distance	Transport distance	Reference
Conventional concrete work	Täby	Sand & Grus AB Jehander - Ulvsunda	16.6 km	13.68 km	8753 kg × km	[3, 9]
	Värtan		10.5 km			
	Hammarby		10.2 km			
	Sollentuna		17.4 km			
Precast concrete work	Kvicksund	Abetong AB	0.8 km	8.867 km	1840 kg × km	
	Hallstahammar	Swerock AB	11.8 km			
	Nykvarn		14 km			

Table S1.4: Transport information for reinforcement bars of the reference building

Work types	Recycled steel processing plant	Construction site / Prefabrication plant	Average distance	Transport distance	Reference
Conventional concrete work	Factory in Latvia	Stockholm Royal Seaport	500 km by ship 8 km by truck	8790 kg × km by ship 140.6 kg × km by truck	[3]
Precast concrete work	Factory in Latvia	Kvicksund	500 km by ship 104.8 km by truck	3041.293 kg × km by ship 637.656 kg × km by truck	
		Hallstahammar			
		Nykvarn			

Table S1.5: Transport information for ready-mixed concrete and precast concrete components of the reference building, from concrete plants to construction site

Work types	Concrete plants	Construction site	Average distance	Transport distance	Reference
Conventional concrete work	Täby	Stockholm Royal Seaport	11 km	8478 kg × km	[3]
	Värtan				
	Hammarby				
	Sollentuna				
Precast concrete work	Kvicksund		90 km	23050 kg × km	
	Hallstahammar				
	Nykvarn				

Table S1.6: Transport distance between material processing factories to construction site for other building materials

Materials	Location	Geographical distance	Transport distance	Reference
Steel, virgin	Factory in Nora	230 km on road	Truck: 307.6 kg × km	[3]
	Factory in Bastad	540 km on road	Truck: 96.69 kg × km	
Stainless steel	Factory in Latvia	500 km on sea 8 km on road	Truck: 4.658 kg × km Ship: 291.1 kg × km	
Aluminium, virgin	Factory in Finstång	200 km on road	Truck: 109.8 kg × km	
Aluminium, recycled			Truck: 109.8 kg × km	
Planed timer	Factories in Töreboda and Bygdsiljum	500 km on road	Truck: 4890 kg × km	
Plywood			Truck: 349.0 kg × km	
Particle board			Truck: 440.0 kg × km	
Glulam			Truck: 5916 kg × km	
Plasterboard	Factory in Balsta	560 km on road	Truck: 232.3 kg × km	
Stone wool	Factories in Hällekis and Skövde	340 km on road	Truck: 2310 kg × km	
PP/PE	Factory in Spånga	15 km on road	Truck: 31.78 kg × km	
PS	Factory in Vårgårda	430 km on road	Truck: 3020 kg × km	
Glass	Factories in Jönköping and Edsbyn	315 km on road	Truck: 1297 kg × km	
IGU			Truck: 1367 kg × km	
Coating cement board	Factory in Muijala, Finland	300 km on sea 124 km on road	Truck: 87.35 kg × km Ship: 211.33 kg × km	

Table S1.7: Total material and energy consumption per m² floor area for the reference building during on-site work

Work type	Material/ energy	The reference building	Reference
Conventional concrete work	Electricity	0.831 kwh/m²	[4]
	Diesel	7.122 kg/m²	
Precast concrete work	Diesel	0.3489 kwh/m²	[4, 10, 11]

S2: Data for the scenarios with increasing prefabricated rates

Table S2.1: Total raw material consumption per m² floor area considering loss rates for the scenarios (kg/m²)

Work type	Materials	S1	S2	S3	S4	S5	S6	S7	S8	S9	Reference
Conventional concrete work	Cement	80.95	72.34	55.12	46.50	37.89	29.28	20.67	12.05	3.445	[1]
	Sand	518.1	463.0	352.8	297.6	242.5	187.4	132.3	77.15	22.05	
	Gravel	291.4	260.4	198.4	167.4	136.4	105.4	74.42	43.40	12.40	
	Recycled steel	22.24	19.88	15.15	12.78	10.41	8.046	5.679	3.313	0.947	[3]
Precast concrete work	Cement	4.844	12.92	29.07	37.14	45.21	53.28	61.36	69.44	77.5	[1]
	Sand	31.00	82.69	186.0	237.7	289.4	341.0	392.7	444.4	496.0	
	Gravel	17.44	46.51	104.6	133.7	162.8	191.8	220.9	250.0	279.0	
	Recycled steel	1.420	3.786	6.084	8.519	10.89	13.25	15.62	17.98	20.35	[3]

Table S2.2: Total material and energy consumption per m² floor area for the scenarios during in-plant processing

Work type	Material/ energy	S1	S2	S3	S4	S5	S6	S7	S8	S9	Reference
Conventional concrete work	Electricity (kwh/m²)	2.186	1.953	1.488	1.256	1.023	0.7906	0.5582	0.3255	0.093	[4]
	Water (kg/m²)	49.78	44.49	33.90	28.60	23.30	18.01	12.71	7.414	2.118	[5]
Precast concrete work	Electricity (kwh/m²)	0.1939	0.5171	1.163	1.487	1.810	2.133	2.456	2.779	3.103	[6]
	Water (kg/m²)	2.979	7.946	17.88	22.84	27.81	32.77	37.74	42.70	47.67	[5]
	Diesel (kWh/m²)	0.2596	0.6926	1.558	1.991	2.423	2.856	3.289	3.722	4.154	[7]
	Steam (kWh/m²)	0.5059	1.349	3.036	3.878	4.722	5.565	6.408	7.252	8.095	[8]

Table S2.3: Transport distance between sand and gravel processing plants and concrete plants for the scenarios (kg × km/m²)

Work types	S1	S2	S3	S4	S5	S6	S7	S8	S9	Reference
Conventional concrete work	11070	9896	7540	6361	5184	4006	2828	1649	471.2	[9]
Precast concrete work	429.5	1146	2577	3293	4009	4724	5441	6157	6872	

Table S2.4: Transport distance between concrete plants to construction site for the scenarios (kg × km/m²)

Work types	S1	S2	S3	S4	S5	S6	S7	S8	S9	Reference
Ready-mixed concrete in conventional concrete work	10730	9584	8478	7303	6161	5020	3880	2739	1597	[3]
Precast components in precast concrete work	5379	14350	23050	32280	41240	50210	59170	68130	77100	

Table S2.5: Transport distance for recycled steels of the scenarios (kg × km/m²)

Work types	Transport section	S1	S2	S3	S4	S5	S6	S7	S8	S9	Reference
Conventional concrete work	Supplier to Stockholm port	11120	9940	7575	6390	5205	4023	2840	1657	473.3	[3]
	Stockholm port to site	177.9	159.0	121.2	102.2	83.28	64.37	45.43	26.50	7.573	[9]
Precast concrete work	Supplier to Stockholm port	710.0	1893	3042	4260	5445	6625	7810	8990	10180	[3]
	Stockholm port to factory	148.8	396.8	637.6	892.8	1141	1389	1637	1884	2133	[9]

Table S2.6: Total energy consumption of conventional and precast concrete work for the scenarios during on-site work (kWh/m²)

Work types	Energy	S1	S2	S3	S4	S5	S6	S7	S8	S9	Reference
Conventional concrete work	Diesel	9.009	8.051	6.135	5.176	4.217	3.259	2.301	1.342	0.3834	[4]
	Electricity	1.023	0.915	0.697	0.588	0.479	0.370	0.261	0.152	0.0435	
Precast concrete work	Diesel	0.081	0.217	0.4886	0.6242	0.7599	0.8956	1.031	1.167	1.303	[10, 11]

Table S2.7: Datasets chosen for the LCA model in SimaPro

Materials/Energy/Process	Datasets
Gravel	Gravel, round {RoW} ∣ Cut-off, U
Sand	Sand {GLO} ∣ market for ∣ Cut-off, U
Cement	Cement, alternative constituents 6-20% {Europe without Switzerland} ∣ production ∣ Cut-off, U
Recycled steel	Steel, unalloyed {RoW}∣ recycled content ∣ Cut-off, U
Electricity	Electricity, medium voltage {SE} ∣ market for ∣ Cut-off, U
Water	Tap water {Europe without Switzerland}∣ market for ∣ Cut-off, U
Diesel	Diesel, burned in building machine {GLO} ∣ processing ∣ Cut-off, U
Steam	Steam, in chemical industry {RER} ∣ production ∣ Cut-off, U
Light-duty truck	Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RER} ∣ transport, freight, lorry 7.5-16 metric ton, EURO6 ∣ Cut-off, U
Heavy-duty truck	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} ∣ transport, freight, lorry 3.5-7.5 metric ton, EURO6 ∣ Cut-off, U
Ship	Transport, freight, sea, transoceanic ship {GLO} ∣ processing ∣ Cut-off, U
Steel, virgin	Steel, unalloyed {RoW}∣ steel production, converter, unalloyed ∣ Cut-off, U
Stainless steel	Reinforcing steel {RER}∣ production ∣ Cut-off, U
Aluminium, virgin	Aluminium, primary, cast alloy slab from continuous casting {RoW}∣ production ∣ Cut-off, U
Aluminium, recycled	Aluminium scrap, new {GLO}∣ recycled content ∣cut-off, U
Planed timer	Laminated timber element, transversally prestressed, for outdoor use {RER}∣ laminated timber element production, for outdoor use ∣ Cut-off, U
Plywood	Plywood, for outdoor use {RER}∣ production ∣ Cut-off, U
Plasterboard	Gypsum plasterboard {RoW}∣ production ∣ Cut-off, U
Glulam	Glued laminated timber, for outdoor use {RER}∣ production ∣ Cut-off, U
Particle board	Particle board, for outdoor use {RER}∣ production ∣ Cut-off, U
Stone wool	Stone wool {RoW}∣ stone wool production ∣ Cut-off, U
Polypropylene	Polypropylene, granulate {RER}∣ production ∣ Cut-off, U
Polystyrene	Polystyrene foam slab {RER}∣ production ∣ Cut-off, U
Glass	Flat glass, uncoated {RER}∣ production ∣ Cut-off, U
IGU	Foam glass {GLO}∣ production, without cullet ∣ Cut-off, U

S3: Data for sensitivity analysis

New supplier information and new geographical transport distance for raw materials, recycled steels and precast components:

(1) New raw material supplier: Sand & Grus AB Jehander – Ulvsunda. Distance between raw material supplier and prefabrication factory WAMA AB: 2.3 km

(2) Distance between recycled steel supplier and prefabrication factory: 500 km on sea and 10.6 km on road.

(3) Distance between prefabrication factory and construction site: 10.6 km (SeaRates, 2020).

Table S3.1: Transport distances for the reference building and scenarios (kg × km/m²) [9]

Suppliers	Transport types	S1	S2	RB	S3	S4	S5	S6	S7	S8	S9
Original suppliers	Raw material transport	429.5	1146	1840	2577	3293	4009	4724	5441	6157	6872
	Steel transport (truck)	148.8	396.8	637.6	892.8	1141	1389	1637	1884	2133	2381
	Precast component transport	5379	14350	23050	32280	41240	50210	59170	68130	77100	86060
New supplier	Raw material transport	111.4	297.2	477.4	668.5	854.1	1040	1225	1411	1597	1783
	Steel transport (truck)	15.05	40.13	64.49	90.3	115.4	140.5	165.6	190.6	215.7	240.8
	Precast component transport	633.5	1690	2714	3801	4857	5913	6968	8025	9081	10140

S4: Data for uncertainty analysis

Table S4.1: Environmental impact results with the minimum value of uncertain on-site material loss rate for precast concrete (Results from SimaPro version 9)

	S1	S2	RB	S3	S4	S5	S6	S7	S8	S9
Energy footprint (MJ/m²)	648.6	674.6	699.8	726.5	752.3	778.3	804.1	830.1	856.1	882
Energy footprint changing	-0.09%	-0.21%	-0.33%	-0.44%	-0.54%	-0.64%	-0.73%	-0.81%	-0.88%	-0.94%
Carbon footprint (kg CO2 eq/m²)	87.87	89.15	90.4	91.71	92.96	94.25	95.52	96.8	98.07	99.35
Carbon footprint changing	-0.07%	-0.18%	-0.29%	-0.39%	-0.51%	-0.60%	-0.70%	-0.80%	-0.89%	-0.95%
Water footprint (m³/m²)	1.502	1.496	1.491	1.485	1.479	1.473	1.467	1.461	1.455	1.449
Water footprint changing	-0.07%	-0.20%	-0.20%	-0.34%	-0.47%	-0.54%	-0.68%	-0.81%	-0.89%	-1.02%
Terrestrial ecotoxicity (kg 1,4-DCB/m²)	175.7	192.9	209.7	227.5	244.7	262	279.3	296.6	313.9	331.1
Terrestrial ecotoxicity changing	-0.11%	-0.31%	-0.43%	-0.52%	-0.65%	-0.72%	-0.78%	-0.84%	-0.92%	-0.96%

Table S4.2: Environmental impact results with the maximum value of uncertain on-site material loss rate for precast concrete (Results from SimaPro version 9)

	S1	S2	RB	S3	S4	S5	S6	S7	S8	S9
Energy footprint (MJ/m^2)	649.7	677.5	704.4	732.9	760.6	788.3	816	843.7	871.5	899.2
Energy footprint changing	+0.08%	+0.22%	+0.33%	+0.44%	+0.56%	+0.64%	+0.74%	+0.81%	+0.90%	+0.99%
Carbon footprint (kg CO2 eq/m^2)	87.99	89.48	90.92	92.44	93.92	95.4	96.88	98.36	99.85	101.3
Carbon footprint changing	+0.07%	+0.19%	+0.29%	+0.40%	+0.51%	+0.61%	+0.72%	+0.80%	+0.91%	+1.00%
Water footprint (m^3/m^2)	1.504	1.501	1.498	1.496	1.493	1.49	1.487	1.484	1.481	1.479
Water footprint changing	+0.07%	+0.13%	+0.27%	+0.40%	+0.47%	+0.61%	+0.68%	+0.75%	+0.89%	+1.02%
Terrestrial ecotoxicity (kg 1,4-DCB/m^2)	176.1	194	211.4	229.9	247.9	265.8	283.8	301.7	319.7	337.7
Terrestrial ecotoxicity changing	+0.11%	+0.26%	+0.38%	+0.52%	+0.65%	+0.72%	+0.82%	+0.87%	+0.92%	+1.02%

Table S4.3: Environmental impact results with the minimum value of uncertain on-site energy consumption for precast concrete (Results from SimaPro version 9)

	S1	S2	RB	S3	S4	S5	S6	S7	S8	S9
Energy footprint (MJ/m^2)	649.1	675.7	701.5	728.8	755.3	781.9	808.5	835.1	861.7	888.2
Energy footprint changing	-0.02%	-0.04%	-0.09%	-0.12%	-0.15%	-0.18%	-0.19%	-0.22%	-0.23%	-0.25%
Carbon footprint (kg CO2 eq/m^2)	87.93	89.29	90.62	92.02	93.37	94.73	96.09	97.46	98.82	100.2
Carbon footprint changing	0.00%	-0.02%	-0.04%	-0.05%	-0.07%	-0.09%	-0.10%	-0.12%	-0.13%	-0.10%
Water footprint (m^3/m^2)	1.503	1.499	1.494	1.49	1.485	1.481	1.477	1.472	1.468	1.463
Water footprint changing	0.00%	0.00%	0.00%	0.00%	-0.07%	0.00%	0.00%	-0.07%	0.00%	-0.07%
Terrestrial ecotoxicity (kg 1,4-DCB/m^2)	175.9	193.5	210.5	228.7	246.2	263.9	281.4	299	316.6	334.2
Terrestrial ecotoxicity changing	0.00%	0.00%	-0.05%	0.00%	-0.04%	0.00%	-0.04%	-0.03%	-0.06%	-0.03%

Table S4.4: Environmental impact results with the maximum value of uncertain on-site energy consumption for precast concrete (Results from SimaPro version 9)

	S1	S2	RB	S3	S4	S5	S6	S7	S8	S9
Energy footprint (MJ/m^2)	649.4	676.4	702.7	730.5	757.5	784.6	811.6	838.6	865.7	892.7
Energy footprint changing	+0.03%	+0.06%	+0.09%	+0.11%	+0.15%	+0.17%	+0.20%	+0.20%	+0.23%	+0.26%
Carbon footprint (kg CO2 eq/m^2)	87.94	89.34	90.7	92.13	93.51	94.9	96.29	97.69	99.08	100.5
Carbon footprint changing	+0.01%	+0.03%	+0.04%	+0.07%	+0.07%	+0.08%	+0.10%	+0.11%	+0.13%	+0.20%
Water footprint (m^3/m^2)	1.503	1.499	1.494	1.49	1.485	1.481	1.477	1.472	1.468	1.463
Water footprint changing	0.00%	0.00%	+0.07%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Terrestrial ecotoxicity (kg 1,4-DCB/m^2)	1.503	1.499	1.495	1.49	1.486	1.481	1.477	1.473	1.468	1.464
Terrestrial ecotoxicity changing	0.00%	0.00%	0.00%	+0.04%	+0.04%	+0.04%	+0.04%	+0.03%	+0.03%	+0.06%

References

1. Centre for environmental assessment of product and material systems, *Life cycle inventory data. (Online). .* Available at: http://www.cpmdatabase.cpm.chalmers.se/Start.asp (Accessed 5 February 2020). 1997.
2. Kim, D., *Preliminary Life Cycle Analysis of Modular and Conventional Housing in Benton Harbor, MI*. 2008.
3. Stockholmshem, *Markanvisningstävling plusenergihus i NDS etapp Brofästet. (Pdf). An internal report at the City of Stockholm.* 2012.
4. He, X., *The Research of Energy Consumption and Energy Conservation in Construction Technology. Master Thesis.* Chongqing University., 2013.
5. Weidema, B.P., et al., *Overview and methodology: Data quality guideline for the ecoinvent database version 3.* 2013.
6. Kim, N.-w. and J.-s. Bae, *A fundamental study on the characteristics of concrete with the substitution ratio of the rapidly cooled steel slag.* Journal of the Korea institute for structural maintenance and inspection, 2009. **13**(1): p. 78-87.
7. Kim, T. and C.U. Chae, *Evaluation analysis of the CO2 emission and absorption life cycle for precast concrete in Korea.* Sustainability, 2016. **8**(7): p. 663.
8. Xu, Z., S. Wang, and E. Wang, *Integration of BIM and energy consumption modelling for manufacturing prefabricated components: a case study in China.* Advances in Civil Engineering, 2019. **2019**.
9. SeaRates, *Route planner. (Online).* Available at: https://www.searates.com/route-planner/ (Accessed 8 February 2020). 2020.
10. Shen, L., *The environmental impact assessment of whole life cycle of the construction project based on BIM technology. MSc Thesis.* Nanjing Forestry University., 2015.
11. Wang, Y., *Whole life cycle carbon emissions research of industrialized precast construction.* Southeast University: Nanjing, China, 2016: p. 221.