

Article | Received 29 June 2026; Revised 10 September 2026; Accepted 22 September 2026; Published 29 September 2026
<https://doi.org/10.55092/sc20260019>

Supplementary data

Industry Foundation Classes (IFC)-enabled whole-building semantic optimisation and query-driven decision-support workflow for low-carbon and circular smart construction



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Supplementary tables

Tables S1–S6 provide the material database and detailed sensitivity, scalability, and uncertainty results supporting the manuscript.



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Table S1. Full prototype material database. Material properties used in the demonstrated workflow, including density, carbon factor, four circularity proxy dimensions, Building Circularity Score, source category, source reference or assumption, and notes.

material_id	component_type	material_family	density	density_unit	carbon_factor	carbon_factor_or_unit	C_rec	C_reu	C_dis	C_inf	BCS	source_type	source_reference_or_assumption	notes
concrete_block	wall	concrete_block	2200	kg/m ³	0.15	kgCO2e/kg	0.05	0.25	0.1	1.0	0.35	database/literature/EPD-derived	ICE_database; exact source reference to be verified before final submission	Value retained from prototype database; lifecycle scope recorded as A1–A3.
clt_panel	wall	clt_panel	470	kg/m ³	0.07	kgCO2e/kg	0.65	0.7	0.65	1.0	0.75	database/literature/EPD-derived	public_EPД; exact source reference to be verified before final submission	Value retained from prototype database; lifecycle scope recorded as A1–A5.
timber_frame	wall	timber_frame	500	kg/m ³	0.08	kgCO2e/kg	0.4	0.55	0.6	1.0	0.6375	database/literature/EPD-derived	One_Click_LCA_reference; exact source reference to be verified before final submission	Value retained from prototype database; lifecycle scope recorded as A1–A3.
steel_frame	wall	steel_frame	150	kg/m ³	0.85	kgCO2e/kg	0.85	0.9	0.9	1.0	0.9125	database/literature/EPD-derived	public_EPД; exact source reference to be verified before final submission	Value retained from prototype database; lifecycle scope recorded as A1–A3.
rammed_earth	wall	rammed_earth	2000	kg/m ³	0.03	kgCO2e/kg	0.9	0.1	0.05	0.8	0.4625	prototype assumption	prototype demonstration value; source to be verified before final submission	Illustrative prototype value; lifecycle scope recorded as A1–A3.

Table S1. *Cont.*

material_id	component_type	material_family	density	density_unit	carbon_factor	carbon_factor_unit	C_rec	C_reu	C_dis	C_inf	BCS	source_type	source_reference_or_assumption	notes
precast_concrete	wall	precast_concrete	2400	kg/m ³	0.18	kgCO2e/kg	0.15	0.35	0.25	1.0	0.4375	database/literature/EPD-derived	One_Click_LCA_reference; exact source reference to be verified before final submission	Value retained from prototype database; lifecycle scope recorded as A1–A3.
concrete_slab	floor	concrete_slab	2400	kg/m ³	0.15	kgCO2e/kg	0.2	0.5	0.2	1.0	0.475	database/literature/EPD-derived	ICE_database; exact source reference to be verified before final submission	Value retained from prototype database; lifecycle scope recorded as A1–A3.
clt_slab	floor	clt_slab	470	kg/m ³	0.07	kgCO2e/kg	0.7	0.8	0.7	1.0	0.8	database/literature/EPD-derived	public_EPd; exact source reference to be verified before final submission	Value retained from prototype database; lifecycle scope recorded as A1–A5.
steel_beam_deck	floor	steel_beam_deck	1200	kg/m ³	0.95	kgCO2e/kg	0.8	0.85	0.8	1.0	0.8625	database/literature/EPD-derived	public_EPd; exact source reference to be verified before final submission	Value retained from prototype database; lifecycle scope recorded as A1–A3.

Table S1. *Cont.*

material_id	component_type	material_family	density	density_unit	carbon_factor	carbon_factor_unit	C_rec	C_reu	C_dis	C_inf	BCS	source_type	source_reference_or_assumption	notes
timber_joist	floor	timber_joist	450	kg/m ³	0.06	kgCO ₂ e/kg	0.5	0.6	0.55	1.0	0.6625	database/literature/EPD-derived	One_Click_LCA_reference; exact source reference to be verified before final submission	Value retained from prototype database; lifecycle scope recorded as A1–A3.
hollowcore_slab	floor	hollowcore_slab	1800	kg/m ³	0.2	kgCO ₂ e/kg	0.1	0.3	0.15	1.0	0.3875	database/literature/EPD-derived	ICE_database; exact source reference to be verified before final submission	Value retained from prototype database; lifecycle scope recorded as A1–A3.
steel_roof	roof	steel_roof	7850	kg/m ³	0.4	kgCO ₂ e/kg	0.8	0.85	0.8	1.0	0.8625	database/literature/EPD-derived	public_EPD; exact source reference to be verified before final submission	Value retained from prototype database; lifecycle scope recorded as A1–A3.
timber_roof	roof	timber_roof	500	kg/m ³	0.08	kgCO ₂ e/kg	0.5	0.6	0.5	1.0	0.65	database/literature/EPD-derived	ICE_database; exact source reference to be verified before final submission	Value retained from prototype database; lifecycle scope recorded as A1–A3.

Table S1. *Cont.*

material_id	component_type	material_family	density	density_unit	carbon_factor	carbon_factor_unit	C_rec	C_reu	C_dis	C_inf	BCS	source_type	source_reference_or_assumption	notes
green_roof	roof	green_roof	1500	kg/m ³	0.1	kgCO2e/kg	0.75	0.4	0.3	0.85	0.575	prototype assumption	prototype demonstration value; source to be verified before final submission	Illustrative prototype value; lifecycle scope recorded as A–C.
aluminium_roof	roof	aluminium_roof	2700	kg/m ³	0.85	kgCO2e/kg	0.9	0.9	0.85	1.0	0.9125	database/literature/EPD-derived	One_Click_LCA_reference; exact source reference to be verified before final submission	Value retained from prototype database; lifecycle scope recorded as A1–A3.
concrete_roof	roof	concrete_roof	2400	kg/m ³	0.18	kgCO2e/kg	0.15	0.3	0.1	1.0	0.3875	database/literature/EPD-derived	ICE_database; exact source reference to be verified before final submission	Value retained from prototype database; lifecycle scope recorded as A1–A3.

Table S2. Building Circularity Score weighting sensitivity. Alternative weighting schemes and overlap with the equal-weight baseline non-dominated candidate set.

scenario	weights	pareto_set_size	overlap_with_baseline_pareto	balanced_count	low_carbon_oriented_count	circularity_oriented_count	two_cluster_structure_persists	changed_pareto_options	unchanged_pareto_options
equal_baseline	C_rec=0.25; C_reu=0.25; C_dis=0.25; C_inf=0.25	12	12	0	6	6	True	none	OPTION_032, OPTION_034, OPTION_037, OPTION_039, OPTION_042, OPTION_044, OPTION_082, OPTION_084, OPTION_087, OPTION_089, OPTION_092, OPTION_094
recycled_content_dominant	C_rec=0.40; C_reu=0.20; C_dis=0.20; C_inf=0.20	12	12	0	6	6	True	none	OPTION_032, OPTION_034, OPTION_037, OPTION_039, OPTION_042, OPTION_044, OPTION_082, OPTION_084, OPTION_087, OPTION_089, OPTION_092, OPTION_094
reuse_recyclability_dominant	C_rec=0.20; C_reu=0.40; C_dis=0.20; C_inf=0.20	12	12	0	6	6	True	none	OPTION_032, OPTION_034, OPTION_037, OPTION_039, OPTION_042, OPTION_044, OPTION_082, OPTION_084, OPTION_087, OPTION_089, OPTION_092, OPTION_094

Table S2. *Cont.*

scenario	weights	pareto_set_size	overlap_with_baseline_pareto	balanced_count	low_carbon_oriented_count	circularity_oriented_count	two_cluster_structure_persists	changed_pareto_options	unchanged_pareto_options
disassembly_dominant	C_rec=0.20; C_reu=0.20; C_dis=0.40; C_inf=0.20	12	12	0	6	6	True	none	OPTION_032, OPTION_034, OPTION_037, OPTION_039, OPTION_042, OPTION_044, OPTION_082, OPTION_084, OPTION_087, OPTION_089, OPTION_092, OPTION_094
information_completeness_dominant	C_rec=0.20; C_reu=0.20; C_dis=0.20; C_inf=0.40	12	12	0	6	6	True	none	OPTION_032, OPTION_034, OPTION_037, OPTION_039, OPTION_042, OPTION_044, OPTION_082, OPTION_084, OPTION_087, OPTION_089, OPTION_092, OPTION_094

Table S3. Semantic-classification threshold sensitivity. Classification outcomes for the nine tested norm_carbon and norm_circularity threshold combinations.

norm_carbon_threshold	norm_circularity_threshold	balanced_count	low_carbon_oriented_count	circularity_oriented_count	classification_changes_relative_to_baseline	short_interpretation
0.6	0.5	0	6	6	0	No classification changes relative to the baseline threshold setting.
0.6	0.6	0	6	6	0	No classification changes relative to the baseline threshold setting.
0.6	0.7	0	6	6	0	No classification changes relative to the baseline threshold setting.
0.7	0.5	0	6	6	0	No classification changes relative to the baseline threshold setting.
0.7	0.6	0	6	6	0	No classification changes relative to the baseline threshold setting.
0.7	0.7	0	6	6	0	No classification changes relative to the baseline threshold setting.
0.8	0.5	0	6	6	0	No classification changes relative to the baseline threshold setting.
0.8	0.6	0	6	6	0	No classification changes relative to the baseline threshold setting.
0.8	0.7	0	6	6	0	No classification changes relative to the baseline threshold setting.

Table S4. Runtime and scalability checks. Runtime measurements for the demonstrated 150-configuration case and synthetic larger design spaces. Runtime values are hardware-dependent.

scenario	configuration_count	combination_generation_time_s	objective_calculation_time_s	pareto_filtering_time_s	sorted_pareto_filtering_time_s	total_runtime_s	pareto_set_size	sorted_pareto_set_size	notes
current_150	150	0.006823	0.022505	0.00179	0.037988	0.031118	12.0	12	Existing $O(n^2)$ Pareto filter measured.
synthetic_1000	1000	0.004991	0.110621	0.044512	0.046172	0.160123	114.0	114	Existing $O(n^2)$ Pareto filter measured.
synthetic_10000	10000	0.085521	1.283113		0.561291	1.929925		75	Skipped existing $O(n^2)$ Pareto filter above 1000 configurations to avoid impractical runtime.
synthetic_100000	100000	0.453566	32.80307		11.261277	44.517913		94	Skipped existing $O(n^2)$ Pareto filter above 1000 configurations to avoid impractical runtime.

Table S5. Monte Carlo uncertainty and Pareto-stability results. Scenario-level Pareto-retention frequencies for all 150 configurations under combined, carbon-only, and BCS-only perturbations.

option_id	wall	floor	roof	total_embodied_carbon_kgco2e	building_circularity_core	is_pareto	combined_pareto_count	combined_pareto_frequency	carbon_only_pareto_count	carbon_only_pareto_frequency	bcs_only_pareto_count	bcs_only_pareto_frequency
OPTION_001	concrete_block	concrete_slab	steel_roof	31773.266753506916	0.7009700079623471	False	0	0.0	0	0.0	0	0.0
OPTION_002	concrete_block	concrete_slab	timber_roof	2746.3919 644440584	0.5763438275098987	False	0	0.0	0	0.0	0	0.0
OPTION_003	concrete_block	concrete_slab	green_roof	3776.3778440559663	0.5323581167619756	False	0	0.0	0	0.0	0	0.0
OPTION_004	concrete_block	concrete_slab	aluminium_roof	23861.10249648817	0.7302938151276289	False	0	0.0	0	0.0	0	0.0
OPTION_005	concrete_block	concrete_slab	concrete_roof	6416.887099061039	0.42239383989216817	False	0	0.0	0	0.0	0	0.0
OPTION_006	concrete_block	clt_slab	steel_roof	29667.560503506793	0.8320125677096845	False	0	0.0	0	0.0	0	0.0
OPTION_007	concrete_block	clt_slab	timber_roof	640.685714443935	0.7073863872572361	False	0	0.0	0	0.0	0	0.0
OPTION_008	concrete_block	clt_slab	green_roof	1670.671594055843	0.6634006765093131	False	0	0.0	0	0.0	0	0.0
OPTION_009	concrete_block	clt_slab	aluminium_roof	21755.396246488046	0.8613363748749665	False	0	0.0	0	0.0	0	0.0
OPTION_010	concrete_block	clt_slab	concrete_roof	4311.1808490609155	0.5534363996395057	False	0	0.0	0	0.0	0	0.0
OPTION_011	concrete_block	steel_beam_deck	steel_roof	36794.51675350721	0.8572130599687878	False	0	0.0	0	0.0	0	0.0
OPTION_012	concrete_block	steel_beam_deck	timber_roof	7767.641964444354	0.7325868795163394	False	0	0.0	0	0.0	0	0.0
OPTION_013	concrete_block	steel_beam_deck	green_roof	8797.627844056262	0.6886011687684164	False	0	0.0	0	0.0	0	0.0

Table S5. Cont.

option_id	wall	floor	roof	total_embodied_carbon_kgco2e	building_circularity_score	is_pareto	combined_pareto_count	combined_pareto_frequency	carbon_only_pareto_count	carbon_only_pareto_frequency	bcs_only_pareto_count	bcs_only_pareto_frequency
OPTION_014	concrete_block	steel_beam_deck	aluminium_roof	28882.352496488464	0.8865368671340698	False	0	0.0	0	0.0	0	0.0
OPTION_015	concrete_block	steel_beam_deck	concrete_roof	11438.137099061334	0.578636891898609	False	0	0.0	0	0.0	0	0.0
OPTION_016	concrete_block	timber_joynt	steel_roof	29629.579253506792	0.7765714847396571	False	0	0.0	0	0.0	0	0.0
OPTION_017	concrete_block	timber_joynt	timber_roof	602.7044644439328	0.6519453042872086	False	0	0.0	0	0.0	0	0.0
OPTION_018	concrete_block	timber_joynt	green_roof	1632.6903440558408	0.6079595935392857	False	0	0.0	0	0.0	0	0.0
OPTION_019	concrete_block	timber_joynt	aluminium_roof	21717.414996488045	0.805895291904939	False	0	0.0	0	0.0	0	0.0
OPTION_020	concrete_block	timber_joynt	concrete_roof	4273.199599060913	0.49799531666947827	False	0	0.0	0	0.0	0	0.0
OPTION_021	concrete_block	hollowcore_slab	steel_roof	31773.266753506916	0.6656893187996022	False	0	0.0	0	0.0	0	0.0
OPTION_022	concrete_block	hollowcore_slab	timber_roof	2746.3919644440584	0.5410631383471539	False	0	0.0	0	0.0	0	0.0
OPTION_023	concrete_block	hollowcore_slab	green_roof	3776.3778440559663	0.4970774275992309	False	0	0.0	0	0.0	0	0.0
OPTION_024	concrete_block	hollowcore_slab	aluminium_roof	23861.10249648817	0.6950131259648844	False	0	0.0	0	0.0	0	0.0
OPTION_025	concrete_block	hollowcore_slab	concrete_roof	6416.887099061039	0.3871131507294235	False	0	0.0	0	0.0	0	0.0
OPTION_026	clt_panel	concrete_slab	steel_roof	31724.333803185047	0.7050964001818297	False	0	0.0	0	0.0	0	0.0
OPTION_027	clt_panel	concrete_slab	timber_roof	2697.4590141221875	0.5804702197293813	False	0	0.0	0	0.0	0	0.0
OPTION_028	clt_panel	concrete_slab	green_roof	3727.4448937340953	0.5364845089814583	False	0	0.0	0	0.0	0	0.0
OPTION_029	clt_panel	concrete_slab	aluminium_roof	23812.1695461663	0.7344202073471118	False	0	0.0	0	0.0	0	0.0
OPTION_030	clt_panel	concrete_slab	concrete_roof	6367.954148739168	0.4265202321116509	False	0	0.0	0	0.0	0	0.0
OPTION_031	clt_panel	clt_slab	steel_roof	29618.62755318492	0.8361389599291671	False	8	0.008	2	0.002	0	0.0
OPTION_032	clt_panel	clt_slab	timber_roof	591.7527641220639	0.7115127794767189	True	1000	1.0	1000	1.0	1000	1.0
OPTION_033	clt_panel	clt_slab	green_roof	1621.738643733972	0.6675270687287957	False	6	0.006	0	0.0	7	0.007
OPTION_034	clt_panel	clt_slab	aluminium_roof	21706.463296166174	0.8654627670944492	True	1000	1.0	1000	1.0	1000	1.0
OPTION_035	clt_panel	clt_slab	concrete_roof	4262.247898739044	0.5575627918589884	False	0	0.0	0	0.0	0	0.0
OPTION_036	clt_panel	steel_beam_deck	steel_roof	36745.58380318534	0.8613394521882706	False	19	0.019	0	0.0	16	0.016
OPTION_037	clt_panel	steel_beam_deck	timber_roof	7718.709014122483	0.7367132717358221	True	990	0.99	1000	1.0	987	0.987
OPTION_039	clt_panel	steel_beam_deck	aluminium_roof	28833.419546166595	0.8906632593535525	True	990	0.99	1000	1.0	987	0.987
OPTION_040	clt_panel	steel_beam_deck	concrete_roof	11389.204148739464	0.5827632841180918	False	0	0.0	0	0.0	0	0.0
OPTION_041	clt_panel	timber_joynt	steel_roof	29580.64630318492	0.7806978769591398	False	1	0.001	2	0.002	0	0.0
OPTION_042	clt_panel	timber_joynt	timber_roof	553.7715141220617	0.6560716965066915	True	961	0.961	951	0.951	1000	1.0
OPTION_043	clt_panel	timber_joynt	green_roof	1583.7573937339696	0.6120859857587684	False	0	0.0	0	0.0	0	0.0
OPTION_044	clt_panel	timber_joynt	aluminium_roof	21668.482046166173	0.8100216841244218	True	960	0.96	949	0.949	1000	1.0
OPTION_045	clt_panel	timber_joynt	concrete_roof	4224.2666487390425	0.502121708888961	False	0	0.0	0	0.0	0	0.0
OPTION_046	clt_panel	hollowcore_slab	steel_roof	31724.333803185047	0.669815711019085	False	0	0.0	0	0.0	0	0.0

Table S5. Cont.

option_id	wall	floor	roof	total_embodied_carbon_kgco2e	building_circularity_score	is_pareto	combined_pareto_count	combined_pareto_frequency	carbon_only_pareto_count	carbon_only_pareto_frequency	bcs_only_pareto_count	bcs_only_pareto_frequency
OPTION_047	clt_panel	hollowcore_slab	timber_roof	2697.4590141221875	0.5451895305666365	False	0	0.0	0	0.0	0	0.0
OPTION_048	clt_panel	hollowcore_slab	green_roof	3727.4448937340953	0.5012038198187136	False	0	0.0	0	0.0	0	0.0
OPTION_049	clt_panel	hollowcore_slab	aluminium_roof	23812.1695461663	0.699139518184367	False	0	0.0	0	0.0	0	0.0
OPTION_050	clt_panel	hollowcore_slab	concrete_roof	6367.954148739168	0.3912395429489062	False	0	0.0	0	0.0	0	0.0
OPTION_051	timber_frame	concrete_slab	steel_roof	31725.50318705339	0.7039358523701001	False	0	0.0	0	0.0	0	0.0
OPTION_052	timber_frame	concrete_slab	timber_roof	2698.6283979905324	0.5793096719176518	False	0	0.0	0	0.0	0	0.0
OPTION_053	timber_frame	concrete_slab	green_roof	3728.6142776024403	0.5353239611697288	False	0	0.0	0	0.0	0	0.0
OPTION_054	timber_frame	concrete_slab	aluminium_roof	23813.338930034643	0.7332596595353822	False	0	0.0	0	0.0	0	0.0
OPTION_055	timber_frame	concrete_slab	concrete_roof	6369.123532607513	0.42535968429992144	False	0	0.0	0	0.0	0	0.0
OPTION_056	timber_frame	clt_slab	steel_roof	29619.796937053266	0.8349784121174377	False	1	0.001	0	0.0	0	0.0
OPTION_057	timber_frame	clt_slab	timber_roof	592.9221479904089	0.7103522316649893	False	49	0.049	45	0.045	0	0.0
OPTION_058	timber_frame	clt_slab	green_roof	1622.908027602317	0.6663665209170663	False	0	0.0	0	0.0	0	0.0
OPTION_059	timber_frame	clt_slab	aluminium_roof	21707.63268003452	0.8643022192827198	False	49	0.049	45	0.045	0	0.0
OPTION_060	timber_frame	clt_slab	concrete_roof	4263.417282607389	0.5564022440472589	False	0	0.0	0	0.0	0	0.0
OPTION_061	timber_frame	steel_beam_deck	steel_roof	36746.753187053684	0.860178904376541	False	1	0.001	0	0.0	0	0.0
OPTION_062	timber_frame	steel_beam_deck	timber_roof	7719.878397990828	0.7355527239240928	False	49	0.049	45	0.045	0	0.0
OPTION_063	timber_frame	steel_beam_deck	green_roof	8749.864277602735	0.6915670131761696	False	0	0.0	0	0.0	0	0.0
OPTION_064	timber_frame	steel_beam_deck	aluminium_roof	28834.588930034937	0.889502711541823	False	49	0.049	45	0.045	0	0.0
OPTION_065	timber_frame	steel_beam_deck	concrete_roof	11390.373532607808	0.5816027363063623	False	0	0.0	0	0.0	0	0.0
OPTION_066	timber_frame	timber_joyist	steel_roof	29581.815687053266	0.7795373291474103	False	0	0.0	0	0.0	0	0.0
OPTION_067	timber_frame	timber_joyist	timber_roof	554.9408979904067	0.6549111486949619	False	45	0.045	42	0.042	0	0.0
OPTION_068	timber_frame	timber_joyist	green_roof	1584.9267776023146	0.6109254379470389	False	0	0.0	0	0.0	0	0.0
OPTION_069	timber_frame	timber_joyist	aluminium_roof	21669.65143003452	0.8088611363126924	False	45	0.045	42	0.042	0	0.0
OPTION_070	timber_frame	timber_joyist	concrete_roof	4225.4360326073875	0.5009611610772315	False	0	0.0	0	0.0	0	0.0
OPTION_071	timber_frame	hollowcore_slab	steel_roof	31725.50318705339	0.6686551632073555	False	0	0.0	0	0.0	0	0.0
OPTION_072	timber_frame	hollowcore_slab	timber_roof	2698.6283979905324	0.5440289827549071	False	0	0.0	0	0.0	0	0.0
OPTION_073	timber_frame	hollowcore_slab	green_roof	3728.6142776024403	0.5000432720069841	False	0	0.0	0	0.0	0	0.0
OPTION_074	timber_frame	hollowcore_slab	aluminium_roof	23813.338930034643	0.6979789703726375	False	0	0.0	0	0.0	0	0.0
OPTION_075	timber_frame	hollowcore_slab	concrete_roof	6369.123532607513	0.3900789951371767	False	0	0.0	0	0.0	0	0.0
OPTION_076	steel_frame	concrete_slab	steel_roof	31739.914607966093	0.7067727470209946	False	0	0.0	0	0.0	0	0.0
OPTION_077	steel_frame	concrete_slab	timber_roof	2713.0398189032344	0.5821465665685462	False	0	0.0	0	0.0	0	0.0
OPTION_078	steel_frame	concrete_slab	green_roof	3743.0256985151423	0.5381608558206231	False	0	0.0	0	0.0	0	0.0

Table S5. Cont.

option_id	wall	floor	roof	total_embodied_carbon_kgco2e	building_circularity_score	is_pareto	combined_pareto_count	combined_pareto_frequency	carbon_only_pareto_count	carbon_only_pareto_frequency	bcs_only_pareto_count	bcs_only_pareto_frequency
OPTION_079	steel_frame	concrete_slab	aluminium_roof	23827.750350947346	0.7360965541862765	False	0	0.0	0	0.0	0	0.0
OPTION_080	steel_frame	concrete_slab	concrete_roof	6383.534953520215	0.42819657895081575	False	0	0.0	0	0.0	0	0.0
OPTION_081	steel_frame	clt_slab	steel_roof	29634.20835796597	0.8378153067683319	False	17	0.017	2	0.002	0	0.0
OPTION_082	steel_frame	clt_slab	timber_roof	607.3335689031107	0.7131891263158836	True	1000	1.0	1000	1.0	1000	1.0
OPTION_083	steel_frame	clt_slab	green_roof	1637.3194485150186	0.6692034155679606	False	7	0.007	0	0.0	9	0.009
OPTION_084	steel_frame	clt_slab	aluminium_roof	21722.044100947223	0.8671391139336141	True	1000	1.0	1000	1.0	1000	1.0
OPTION_085	steel_frame	clt_slab	concrete_roof	4277.828703520091	0.5592391386981532	False	0	0.0	0	0.0	0	0.0
OPTION_086	steel_frame	steel_beam_deck	steel_roof	36761.16460796639	0.8630157990274354	False	31	0.031	0	0.0	19	0.019
OPTION_087	steel_frame	steel_beam_deck	timber_roof	7734.2898189035295	0.738389618574987	True	994	0.994	1000	1.0	992	0.992
OPTION_088	steel_frame	steel_beam_deck	green_roof	8764.275698515437	0.694403907827064	False	7	0.007	0	0.0	9	0.009
OPTION_089	steel_frame	steel_beam_deck	aluminium_roof	28849.00035094764	0.8923396061927173	True	994	0.994	1000	1.0	992	0.992
OPTION_090	steel_frame	steel_beam_deck	concrete_roof	11404.78495352051	0.5844396309572565	False	0	0.0	0	0.0	0	0.0
OPTION_091	steel_frame	timber_joist	steel_roof	29596.227107965966	0.7823742237983047	False	1	0.001	0	0.0	0	0.0
OPTION_092	steel_frame	timber_joist	timber_roof	569.3523189031084	0.6577480433458563	True	833	0.833	846	0.846	1000	1.0
OPTION_093	steel_frame	timber_joist	green_roof	1599.3381985150163	0.6137623325979332	False	0	0.0	0	0.0	0	0.0
OPTION_094	steel_frame	timber_joist	aluminium_roof	21684.06285094722	0.8116980309635866	True	832	0.832	846	0.846	1000	1.0
OPTION_095	steel_frame	timber_joist	concrete_roof	4239.847453520089	0.5037980557281259	False	0	0.0	0	0.0	0	0.0
OPTION_096	steel_frame	hollowcore_slab	steel_roof	31739.914607966093	0.6714920578582498	False	0	0.0	0	0.0	0	0.0
OPTION_097	steel_frame	hollowcore_slab	timber_roof	2713.0398189032344	0.5468658774058014	False	0	0.0	0	0.0	0	0.0
OPTION_098	steel_frame	hollowcore_slab	green_roof	3743.0256985151423	0.5028801666578785	False	0	0.0	0	0.0	0	0.0
OPTION_099	steel_frame	hollowcore_slab	aluminium_roof	23827.750350947346	0.7008158650235319	False	0	0.0	0	0.0	0	0.0
OPTION_100	steel_frame	hollowcore_slab	concrete_roof	6383.534953520215	0.39291588978807107	False	0	0.0	0	0.0	0	0.0
OPTION_101	rammed_earth	concrete_slab	steel_roof	31728.79722611915	0.7021305557740765	False	0	0.0	0	0.0	0	0.0
OPTION_102	rammed_earth	concrete_slab	timber_roof	2701.922437056293	0.5775043753216281	False	0	0.0	0	0.0	0	0.0
OPTION_103	rammed_earth	concrete_slab	green_roof	3731.9083166682008	0.5335186645737051	False	0	0.0	0	0.0	0	0.0
OPTION_104	rammed_earth	concrete_slab	aluminium_roof	23816.632969100403	0.7314543629393585	False	0	0.0	0	0.0	0	0.0
OPTION_105	rammed_earth	concrete_slab	concrete_roof	6372.417571673273	0.4235543877038977	False	0	0.0	0	0.0	0	0.0
OPTION_106	rammed_earth	clt_slab	steel_roof	29623.090976119027	0.833173115521414	False	0	0.0	0	0.0	0	0.0

Table S5. Cont.

option_id	wall	floor	roof	total_embodied_carbon_kgco2e	building_circularity_score	is_pareto	combined_pareto_count	combined_pareto_frequency	carbon_only_pareto_count	carbon_only_pareto_frequency	bcs_only_pareto_count	bcs_only_pareto_frequency
OPTION_107	rammed_earth	clt_slab	timber_roof	596.2161870561694	0.7085469350689657	False	0	0.0	0	0.0	0	0.0
OPTION_108	rammed_earth	clt_slab	green_roof	1626.2020666680771	0.6645612243210426	False	0	0.0	0	0.0	0	0.0
OPTION_109	rammed_earth	clt_slab	aluminium_roof	21710.92671910028	0.862496922686696	False	0	0.0	0	0.0	0	0.0
OPTION_110	rammed_earth	clt_slab	concrete_roof	4266.7113216731495	0.5545969474512352	False	0	0.0	0	0.0	0	0.0
OPTION_111	rammed_earth	steel_beam_deck	steel_roof	36750.047226119445	0.8583736077805173	False	0	0.0	0	0.0	0	0.0
OPTION_112	rammed_earth	steel_beam_deck	timber_roof	7723.172437056588	0.7337474273280689	False	0	0.0	0	0.0	0	0.0
OPTION_113	rammed_earth	steel_beam_deck	green_roof	8753.158316668496	0.689761716580146	False	0	0.0	0	0.0	0	0.0
OPTION_114	rammed_earth	steel_beam_deck	aluminium_roof	28837.882969100698	0.8876974149457993	False	0	0.0	0	0.0	0	0.0
OPTION_115	rammed_earth	steel_beam_deck	concrete_roof	11393.667571673568	0.5797974397103386	False	0	0.0	0	0.0	0	0.0
OPTION_116	rammed_earth	timber_joist	steel_roof	29585.109726119026	0.7777320325513867	False	0	0.0	0	0.0	0	0.0
OPTION_117	rammed_earth	timber_joist	timber_roof	558.234937056167	0.6531058520989382	False	0	0.0	0	0.0	0	0.0
OPTION_118	rammed_earth	timber_joist	green_roof	1588.220816668075	0.6091201413510153	False	0	0.0	0	0.0	0	0.0
OPTION_119	rammed_earth	timber_joist	aluminium_roof	21672.94546910028	0.8070558397166686	False	0	0.0	0	0.0	0	0.0
OPTION_120	rammed_earth	timber_joist	concrete_roof	4228.730071673148	0.4991558644812078	False	0	0.0	0	0.0	0	0.0
OPTION_121	rammed_earth	hollowcore_slab	steel_roof	31728.79722611915	0.6668498666113318	False	0	0.0	0	0.0	0	0.0
OPTION_122	rammed_earth	hollowcore_slab	timber_roof	2701.922437056293	0.5422236861588835	False	0	0.0	0	0.0	0	0.0
OPTION_123	rammed_earth	hollowcore_slab	green_roof	3731.9083166682008	0.4982379754109604	False	0	0.0	0	0.0	0	0.0
OPTION_124	rammed_earth	hollowcore_slab	aluminium_roof	23816.632969100403	0.6961736737766138	False	0	0.0	0	0.0	0	0.0
OPTION_125	rammed_earth	hollowcore_slab	concrete_roof	6372.417571673273	0.388273698541153	False	0	0.0	0	0.0	0	0.0
OPTION_126	precast_concrete	concrete_slab	steel_roof	31790.066352742295	0.7018726562603589	False	0	0.0	0	0.0	0	0.0
OPTION_127	precast_concrete	concrete_slab	timber_roof	2763.1915636794365	0.5772464758079106	False	0	0.0	0	0.0	0	0.0
OPTION_128	precast_concrete	concrete_slab	green_roof	3793.1774432913444	0.5332607650599874	False	0	0.0	0	0.0	0	0.0
OPTION_129	precast_concrete	concrete_slab	aluminium_roof	23877.902095723548	0.7311964634256408	False	0	0.0	0	0.0	0	0.0
OPTION_130	precast_concrete	concrete_slab	concrete_roof	6433.686698296417	0.42329648819018006	False	0	0.0	0	0.0	0	0.0
OPTION_131	precast_concrete	clt_slab	steel_roof	29684.360102742172	0.8329152160076962	False	0	0.0	0	0.0	0	0.0
OPTION_132	precast_concrete	clt_slab	timber_roof	657.4853136793132	0.7082890355552479	False	0	0.0	0	0.0	0	0.0
OPTION_133	precast_concrete	clt_slab	green_roof	1687.471193291221	0.6643033248073249	False	0	0.0	0	0.0	0	0.0
OPTION_134	precast_concrete	clt_slab	aluminium_roof	21772.195845723425	0.8622390231729784	False	0	0.0	0	0.0	0	0.0

Table S5. Cont.

option_id	wall	floor	roof	total_embodied_carbon_kgco2e	building_circularity_score	is_pareto	combined_pareto_count	combined_pareto_frequency	carbon_only_pareto_count	carbon_only_pareto_frequency	bcs_only_pareto_count	bcs_only_pareto_frequency
OPTION_135	precast_concrete	clt_slab	concrete_roof	4327.980448296294	0.5543390479375175	False	0	0.0	0	0.0	0	0.0
OPTION_136	precast_concrete	steel_beam_deck	steel_roof	36811.31635274259	0.8581157082667997	False	0	0.0	0	0.0	0	0.0
OPTION_137	precast_concrete	steel_beam_deck	timber_roof	7784.441563679732	0.7334895278143513	False	0	0.0	0	0.0	0	0.0
OPTION_138	precast_concrete	steel_beam_deck	green_roof	8814.427443291639	0.6895038170664283	False	0	0.0	0	0.0	0	0.0
OPTION_139	precast_concrete	steel_beam_deck	aluminium_roof	28899.152095723843	0.8874395154320815	False	0	0.0	0	0.0	0	0.0
OPTION_140	precast_concrete	steel_beam_deck	concrete_roof	11454.936698296713	0.5795395401966208	False	0	0.0	0	0.0	0	0.0
OPTION_141	precast_concrete	timber_joyist	steel_roof	29646.378852742168	0.7774741330376689	False	0	0.0	0	0.0	0	0.0
OPTION_142	precast_concrete	timber_joyist	timber_roof	619.504063679311	0.6528479525852207	False	0	0.0	0	0.0	0	0.0
OPTION_143	precast_concrete	timber_joyist	green_roof	1649.4899432912189	0.6088622418372975	False	0	0.0	0	0.0	0	0.0
OPTION_144	precast_concrete	timber_joyist	aluminium_roof	21734.21459572342	0.8067979402029509	False	0	0.0	0	0.0	0	0.0
OPTION_145	precast_concrete	timber_joyist	concrete_roof	4289.999198296291	0.49889796496749017	False	0	0.0	0	0.0	0	0.0
OPTION_146	precast_concrete	hollowcore_slab	steel_roof	31790.066352742295	0.6665919670976141	False	0	0.0	0	0.0	0	0.0
OPTION_147	precast_concrete	hollowcore_slab	timber_roof	2763.1915636794365	0.5419657866451657	False	0	0.0	0	0.0	0	0.0
OPTION_148	precast_concrete	hollowcore_slab	green_roof	3793.1774432913444	0.49798007589724275	False	0	0.0	0	0.0	0	0.0
OPTION_149	precast_concrete	hollowcore_slab	aluminium_roof	23877.902095723548	0.6959157742628962	False	0	0.0	0	0.0	0	0.0
OPTION_150	precast_concrete	hollowcore_slab	concrete_roof	6433.686698296417	0.3880157990274354	False	0	0.0	0	0.0	0	0.0

Table S6. Aggregate Monte Carlo stability statistics. Aggregate non-dominated-set size, Jaccard similarity, and new-solution run-frequency statistics for the three uncertainty scenarios.

scenario	mean_pareto_set_size	std_pareto_set_size	min_pareto_set_size	max_pareto_set_size	new_solution_run_frequency	mean_jaccard_with_baseline	min_jaccard_with_baseline	max_jaccard_with_baseline
combined	11.945	1.727997395831371	4	24	0.087	0.9410633394383394	0.3333333333333333	1.0
carbon_only	11.862	1.587751869783185	8	18	0.047	0.9514777777777778	0.5	1.0
bcs_only	12.025	0.5782516753110188	8	16	0.028	0.9919478021978022	0.6666666666666666	1.0