

Supplementary Materials

A goal programming approach for balancing life-cycle carbon burden and lean value in Industry 4.0 portfolio selection

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Supplementary Table 1. Technology-attributable carbon burden components of the technology alternatives (CFU). Components correspond to the production-stage, operational, maintenance-related, and end-of-life categories defined in Section 3.3 and are reported on the common illustrative CFU basis used in the numerical application.

Technology	Production	Operational	Maintenance	End-of-life	Total C_i
T1 — IoT-based machine monitoring	18	12	9	6	45
T2 — AI-based quality inspection	26	23	12	7	68
T3 — Predictive maintenance	20	13	9	6	48
T4 — Collaborative robots	36	18	13	8	75
T5 — AGV/AMR internal logistics	34	17	12	7	70
T6 — Digital twin	20	25	10	7	62
T7 — Cloud manufacturing analytics	12	32	9	7	60
T8 — Edge computing	22	10	6	4	42
T9 — RFID/RTLS tracking	14	9	8	5	36
T10 — Additive manufacturing	42	23	10	7	82

Supplementary Table 2. Lean value sub-scores, composite lean value, investment cost and implementation difficulty. Sub-scores q_{im} are on a 1–10 scale. The composite lean value is $L_i = 10 \cdot \sum_m \alpha_m q_{im}$ with equal dimension weights $\alpha_m = 0.20$.

Technology	Lead time	Quality	WIP/invent ory	Resource eff.	Flexibility	L_i	K_i (CU)	H_i
T1 — IoT-based machine monitoring	8	5	6	8	7	68	60	3
T2 — AI-based quality inspection	6	10	5	7	10	76	85	5
T3 — Predictive maintenance	7	7	5	9	8	72	70	4
T4 — Collaborative robots	8	7	6	5	9	70	95	6
T5 — AGV/AMR internal logistics	9	4	8	5	7	66	90	5
T6 — Digital twin	9	7	7	8	10	82	80	5
T7 — Cloud manufacturing analytics	8	6	7	8	8	74	75	4
T8 — Edge computing	5	5	4	8	7	58	65	3
T9 — RFID/RTLS tracking	6	4	8	5	4	54	45	2
T10 — Additive manufacturing	7	7	6	7	10	74	100	6

Supplementary Table 3. Preference-weight sensitivity: optimal portfolio and goal deviations as the lean weight w_l is varied from 0 to 1 in steps of 0.1, with all other settings at their baseline values. Numerical data underlying Figure 5.

w_C	w_L	Selected portfolio	Carbon (CFU)	Lean value	Cost (CU)	Difficulty	d_C^+	d_L^-
1.0	0.0	(empty)	0	0	0	0	0	350
0.9	0.1	T1+T3+T6+T7	215	296	285	16	0	54
0.8	0.2	T1+T3+T6+T7	215	296	285	16	0	54
0.7	0.3	T1+T3+T6+T7	215	296	285	16	0	54
0.6	0.4	T1+T3+T6+T8+T9	233	334	320	17	13	16
0.5	0.5	T1+T3+T6+T8+T9	233	334	320	17	13	16
0.4	0.6	T1+T3+T6+T8+T9	233	334	320	17	13	16
0.3	0.7	T1+T3+T6+T7+T9	251	350	330	18	31	0
0.2	0.8	T1+T3+T6+T7+T9	251	350	330	18	31	0
0.1	0.9	T1+T3+T6+T7+T9	251	350	330	18	31	0
0.0	1.0	T1+T3+T6+T7+T9	251	350	330	18	31	0

At $w_l = 0$ only carbon excess is penalized and 83 feasible portfolios attain zero deviation; the empty portfolio is shown as one representative zero-deviation solution.

Supplementary Table 4. Carbon-target sensitivity: optimal portfolio and goal deviations as the carbon target is varied from 180 to 300 CFU in steps of 10, for each preference scenario. Numerical data underlying Figure 6.

Scenario	C target (CFU)	Selected portfolio	Carbon (CFU)	Lean value	d_C^+	d_L^-
S1	180	T1+T3+T8+T9	171	252	0	98
S1	190	T1+T3+T6+T9	191	276	1	74
S1	200	T1+T3+T6+T8	197	280	0	70
S1	210	T1+T6+T7+T8	209	282	0	68
S1	220	T1+T3+T6+T7	215	296	0	54
S1	230	T1+T3+T6+T8+T9	233	334	3	16
S1	240	T1+T3+T6+T8+T9	233	334	0	16
S1	250	T1+T3+T6+T7+T9	251	350	1	0
S1	260	T1+T3+T6+T7+T9	251	350	0	0
S1	270	T1+T3+T6+T7+T9	251	350	0	0
S1	280	T1+T3+T6+T7+T9	251	350	0	0
S1	290	T1+T3+T6+T7+T9	251	350	0	0
S1	300	T1+T3+T6+T7+T9	251	350	0	0

S2	180	T1+T3+T6+T9	191	276	11	74
S2	190	T1+T3+T6+T9	191	276	1	74
S2	200	T1+T3+T6+T8	197	280	0	70
S2	210	T1+T3+T6+T8+T9	233	334	23	16
S2	220	T1+T3+T6+T8+T9	233	334	13	16
S2	230	T1+T3+T6+T8+T9	233	334	3	16
S2	240	T1+T3+T6+T8+T9	233	334	0	16
S2	250	T1+T3+T6+T7+T9	251	350	1	0
S2	260	T1+T3+T6+T7+T9	251	350	0	0
S2	270	T1+T3+T6+T7+T9	251	350	0	0
S2	280	T1+T3+T6+T7+T9	251	350	0	0
S2	290	T1+T3+T6+T7+T9	251	350	0	0
S2	300	T1+T3+T6+T7+T9	251	350	0	0
S3	180	T1+T3+T6+T7+T9	251	350	71	0
S3	190	T1+T3+T6+T7+T9	251	350	61	0
S3	200	T1+T3+T6+T7+T9	251	350	51	0
S3	210	T1+T3+T6+T7+T9	251	350	41	0
S3	220	T1+T3+T6+T7+T9	251	350	31	0
S3	230	T1+T3+T6+T7+T9	251	350	21	0
S3	240	T1+T3+T6+T7+T9	251	350	11	0
S3	250	T1+T3+T6+T7+T9	251	350	1	0
S3	260	T1+T3+T6+T7+T9	251	350	0	0
S3	270	T1+T3+T6+T7+T9	251	350	0	0
S3	280	T1+T3+T6+T7+T9	251	350	0	0
S3	290	T1+T3+T6+T7+T9	251	350	0	0
S3	300	T1+T3+T6+T7+T9	251	350	0	0

Supplementary Table 5. Budget sensitivity: optimal portfolio and goal deviations as the investment budget is varied from 200 to 460 CU in steps of 5, for each preference scenario. Numerical data underlying Figure 7.

Scenario	Budget (CU)	Selected portfolio	Carbon (CFU)	Lean value	Cost used (CU)	d_C ⁺	d_L ⁻
S1	200	T1+T6+T9	143	204	185	0	146
S1	205	T1+T3+T7	153	214	205	0	136
S1	210	T1+T3+T6	155	222	210	0	128
S1	215	T1+T6+T7	167	224	215	0	126
S1	220	T1+T6+T7	167	224	215	0	126
S1	225	T1+T6+T7	167	224	215	0	126
S1	230	T1+T6+T7	167	224	215	0	126
S1	235	T1+T6+T7	167	224	215	0	126
S1	240	T1+T3+T8+T9	171	252	240	0	98
S1	245	T1+T7+T8+T9	183	254	245	0	96
S1	250	T1+T3+T7+T9	189	268	250	0	82
S1	255	T1+T3+T6+T9	191	276	255	0	74
S1	260	T1+T6+T7+T9	203	278	260	0	72
S1	265	T1+T6+T7+T9	203	278	260	0	72
S1	270	T1+T6+T7+T9	203	278	260	0	72
S1	275	T1+T3+T6+T8	197	280	275	0	70
S1	280	T1+T6+T7+T8	209	282	280	0	68
S1	285	T1+T3+T6+T7	215	296	285	0	54
S1	290	T1+T3+T6+T7	215	296	285	0	54
S1	295	T1+T3+T6+T7	215	296	285	0	54
S1	300	T1+T3+T6+T7	215	296	285	0	54
S1	305	T1+T3+T6+T7	215	296	285	0	54
S1	310	T1+T3+T6+T7	215	296	285	0	54
S1	315	T1+T3+T6+T7	215	296	285	0	54
S1	320	T1+T3+T6+T7	215	296	285	0	54
S1	325	T1+T3+T6+T7	215	296	285	0	54
S1	330	T1+T3+T6+T7	215	296	285	0	54
S1	335	T1+T3+T6+T7	215	296	285	0	54
S1	340	T1+T3+T6+T7	215	296	285	0	54
S1	345	T1+T3+T6+T7	215	296	285	0	54
S1	350	T1+T3+T6+T7	215	296	285	0	54
S1	355	T1+T3+T6+T7	215	296	285	0	54
S1	360	T1+T3+T6+T7	215	296	285	0	54
S1	365	T1+T3+T6+T7	215	296	285	0	54
S1	370	T1+T3+T6+T7	215	296	285	0	54
S1	375	T1+T3+T6+T7	215	296	285	0	54
S1	380	T1+T3+T6+T7	215	296	285	0	54
S1	385	T1+T3+T6+T7	215	296	285	0	54
S1	390	T1+T3+T6+T7	215	296	285	0	54
S1	395	T1+T3+T6+T7	215	296	285	0	54

S1	400	T1+T3+T6+T7	215	296	285	0	54
S1	405	T1+T3+T6+T7	215	296	285	0	54
S1	410	T1+T3+T6+T7	215	296	285	0	54
S1	415	T1+T3+T6+T7	215	296	285	0	54
S1	420	T1+T3+T6+T7	215	296	285	0	54
S1	425	T1+T3+T6+T7	215	296	285	0	54
S1	430	T1+T3+T6+T7	215	296	285	0	54
S1	435	T1+T3+T6+T7	215	296	285	0	54
S1	440	T1+T3+T6+T7	215	296	285	0	54
S1	445	T1+T3+T6+T7	215	296	285	0	54
S1	450	T1+T3+T6+T7	215	296	285	0	54
S1	455	T1+T3+T6+T7	215	296	285	0	54
S1	460	T1+T3+T6+T7	215	296	285	0	54
S2	200	T1+T6+T9	143	204	185	0	146
S2	205	T1+T3+T7	153	214	205	0	136
S2	210	T1+T3+T6	155	222	210	0	128
S2	215	T1+T6+T7	167	224	215	0	126
S2	220	T1+T6+T7	167	224	215	0	126
S2	225	T1+T6+T7	167	224	215	0	126
S2	230	T1+T6+T7	167	224	215	0	126
S2	235	T1+T6+T7	167	224	215	0	126
S2	240	T1+T3+T8+T9	171	252	240	0	98
S2	245	T1+T7+T8+T9	183	254	245	0	96
S2	250	T1+T3+T7+T9	189	268	250	0	82
S2	255	T1+T3+T6+T9	191	276	255	0	74
S2	260	T1+T6+T7+T9	203	278	260	0	72
S2	265	T1+T6+T7+T9	203	278	260	0	72
S2	270	T1+T6+T7+T9	203	278	260	0	72
S2	275	T1+T3+T6+T8	197	280	275	0	70
S2	280	T1+T6+T7+T8	209	282	280	0	68
S2	285	T1+T3+T6+T7	215	296	285	0	54
S2	290	T1+T3+T6+T7	215	296	285	0	54
S2	295	T1+T3+T6+T7	215	296	285	0	54
S2	300	T1+T3+T6+T7	215	296	285	0	54
S2	305	T1+T3+T6+T7	215	296	285	0	54
S2	310	T1+T3+T6+T7	215	296	285	0	54
S2	315	T1+T3+T7+T8+T9	231	326	315	11	24
S2	320	T1+T3+T6+T8+T9	233	334	320	13	16
S2	325	T1+T3+T6+T8+T9	233	334	320	13	16
S2	330	T1+T3+T6+T8+T9	233	334	320	13	16
S2	335	T1+T3+T6+T8+T9	233	334	320	13	16
S2	340	T1+T3+T6+T8+T9	233	334	320	13	16
S2	345	T1+T3+T6+T8+T9	233	334	320	13	16
S2	350	T1+T3+T6+T8+T9	233	334	320	13	16
S2	355	T1+T3+T6+T8+T9	233	334	320	13	16
S2	360	T1+T3+T6+T8+T9	233	334	320	13	16
S2	365	T1+T3+T6+T8+T9	233	334	320	13	16
S2	370	T1+T3+T6+T8+T9	233	334	320	13	16
S2	375	T1+T3+T6+T8+T9	233	334	320	13	16
S2	380	T1+T3+T6+T8+T9	233	334	320	13	16
S2	385	T1+T3+T6+T8+T9	233	334	320	13	16
S2	390	T1+T3+T6+T8+T9	233	334	320	13	16
S2	395	T1+T3+T6+T8+T9	233	334	320	13	16
S2	400	T1+T3+T6+T8+T9	233	334	320	13	16
S2	405	T1+T3+T6+T8+T9	233	334	320	13	16
S2	410	T1+T3+T6+T8+T9	233	334	320	13	16
S2	415	T1+T3+T6+T8+T9	233	334	320	13	16
S2	420	T1+T3+T6+T8+T9	233	334	320	13	16
S2	425	T1+T3+T6+T8+T9	233	334	320	13	16
S2	430	T1+T3+T6+T8+T9	233	334	320	13	16
S2	435	T1+T3+T6+T8+T9	233	334	320	13	16
S2	440	T1+T3+T6+T8+T9	233	334	320	13	16
S2	445	T1+T3+T6+T8+T9	233	334	320	13	16
S2	450	T1+T3+T6+T8+T9	233	334	320	13	16
S2	455	T1+T3+T6+T8+T9	233	334	320	13	16
S2	460	T1+T3+T6+T8+T9	233	334	320	13	16
S3	200	T1+T6+T9	143	204	185	0	146
S3	205	T1+T3+T7	153	214	205	0	136
S3	210	T1+T3+T6	155	222	210	0	128
S3	215	T1+T6+T7	167	224	215	0	126
S3	220	T1+T6+T7	167	224	215	0	126
S3	225	T1+T6+T7	167	224	215	0	126
S3	230	T1+T6+T7	167	224	215	0	126
S3	235	T1+T6+T7	167	224	215	0	126
S3	240	T1+T3+T8+T9	171	252	240	0	98

S3	245	T1+T7+T8+T9	183	254	245	0	96
S3	250	T1+T3+T7+T9	189	268	250	0	82
S3	255	T1+T3+T6+T9	191	276	255	0	74
S3	260	T1+T6+T7+T9	203	278	260	0	72
S3	265	T1+T6+T7+T9	203	278	260	0	72
S3	270	T1+T6+T7+T9	203	278	260	0	72
S3	275	T1+T3+T6+T8	197	280	275	0	70
S3	280	T1+T6+T7+T8	209	282	280	0	68
S3	285	T1+T3+T6+T7	215	296	285	0	54
S3	290	T1+T3+T6+T7	215	296	285	0	54
S3	295	T1+T3+T6+T7	215	296	285	0	54
S3	300	T1+T3+T6+T7	215	296	285	0	54
S3	305	T1+T3+T6+T7	215	296	285	0	54
S3	310	T1+T3+T6+T7	215	296	285	0	54
S3	315	T1+T3+T7+T8+T9	231	326	315	11	24
S3	320	T1+T3+T6+T8+T9	233	334	320	13	16
S3	325	T1+T3+T6+T8+T9	233	334	320	13	16
S3	330	T1+T3+T6+T7+T9	251	350	330	31	0
S3	335	T1+T3+T6+T7+T9	251	350	330	31	0
S3	340	T1+T3+T6+T7+T9	251	350	330	31	0
S3	345	T1+T3+T6+T7+T9	251	350	330	31	0
S3	350	T1+T3+T6+T7+T9	251	350	330	31	0
S3	355	T1+T3+T6+T7+T9	251	350	330	31	0
S3	360	T1+T3+T6+T7+T9	251	350	330	31	0
S3	365	T1+T3+T6+T7+T9	251	350	330	31	0
S3	370	T1+T3+T6+T7+T9	251	350	330	31	0
S3	375	T1+T3+T6+T7+T9	251	350	330	31	0
S3	380	T1+T3+T6+T7+T9	251	350	330	31	0
S3	385	T1+T3+T6+T7+T9	251	350	330	31	0
S3	390	T1+T3+T6+T7+T9	251	350	330	31	0
S3	395	T1+T3+T6+T7+T9	251	350	330	31	0
S3	400	T1+T3+T6+T7+T9	251	350	330	31	0
S3	405	T1+T3+T6+T7+T9	251	350	330	31	0
S3	410	T1+T3+T6+T7+T9	251	350	330	31	0
S3	415	T1+T3+T6+T7+T9	251	350	330	31	0
S3	420	T1+T3+T6+T7+T9	251	350	330	31	0
S3	425	T1+T3+T6+T7+T9	251	350	330	31	0
S3	430	T1+T3+T6+T7+T9	251	350	330	31	0
S3	435	T1+T3+T6+T7+T9	251	350	330	31	0
S3	440	T1+T3+T6+T7+T9	251	350	330	31	0
S3	445	T1+T3+T6+T7+T9	251	350	330	31	0
S3	450	T1+T3+T6+T7+T9	251	350	330	31	0
S3	455	T1+T3+T6+T7+T9	251	350	330	31	0
S3	460	T1+T3+T6+T7+T9	251	350	330	31	0

Supplementary Table 6. Budget saturation diagnosis. For each preference scenario the table reports the budget beyond which the optimal portfolio no longer changes on a 5 CU grid between 200 and 460 CU, the resources actually used by that portfolio, and, where feasible, the objective value associated with the best remaining single-technology addition.

Scen.	Saturation budget (CU)	Portfolio beyond saturation	Cost used (CU)	Capacity used	d_C ⁺	d_L ⁻	Relaxing H _{max} changes it?	Best single addition	Objective after addition	Objective at optimum
S1	285	T1+T3+T6+T7	285	16 / 18	0	54	No	T9	0.0986	0.0463
S2	320	T1+T3+T6+T8+T9	320	17 / 18	13	16	No	—	—	0.0524
S3	330	T1+T3+T6+T7+T9	330	18 / 18	31	0	No	—	—	0.0423

Supplementary Table 7. Combined budget and carbon-target sensitivity: full results underlying Table 8. The lean value target is fixed at 350 and the preference weights at the balanced setting.

Budget (CU)	C target (CFU)	Selected portfolio	Carbon (CFU)	Lean value	Cost used (CU)	d_C ⁺	d_L ⁻
280	200	T1+T3+T6+T8	197	280	275	0	70
280	220	T1+T6+T7+T8	209	282	280	0	68
280	240	T1+T6+T7+T8	209	282	280	0	68
280	260	T1+T6+T7+T8	209	282	280	0	68
310	200	T1+T3+T6+T8	197	280	275	0	70
310	220	T1+T3+T6+T7	215	296	285	0	54
310	240	T1+T2+T6+T7	235	300	300	0	50
310	260	T1+T2+T6+T7	235	300	300	0	50
320	200	T1+T3+T6+T8	197	280	275	0	70
320	220	T1+T3+T6+T8+T9	233	334	320	13	16
320	240	T1+T3+T6+T8+T9	233	334	320	0	16
320	260	T1+T3+T6+T8+T9	233	334	320	0	16
330	200	T1+T3+T6+T8	197	280	275	0	70
330	220	T1+T3+T6+T8+T9	233	334	320	13	16
330	240	T1+T3+T6+T8+T9	233	334	320	0	16
330	260	T1+T3+T6+T7+T9	251	350	330	0	0
340	200	T1+T3+T6+T8	197	280	275	0	70
340	220	T1+T3+T6+T8+T9	233	334	320	13	16
340	240	T1+T3+T6+T8+T9	233	334	320	0	16
340	260	T1+T3+T6+T7+T9	251	350	330	0	0
370	200	T1+T3+T6+T8	197	280	275	0	70
370	220	T1+T3+T6+T8+T9	233	334	320	13	16
370	240	T1+T3+T6+T8+T9	233	334	320	0	16
370	260	T1+T3+T6+T7+T9	251	350	330	0	0
400	200	T1+T3+T6+T8	197	280	275	0	70
400	220	T1+T3+T6+T8+T9	233	334	320	13	16
400	240	T1+T3+T6+T8+T9	233	334	320	0	16
400	260	T1+T3+T6+T7+T9	251	350	330	0	0

Supplementary Table 8. Definition of the three dependency configurations used in the robustness analysis.

Configuration	Prerequisite constraints	Count
baseline	The five prerequisites of Table 5: $x_3 \leq x_1$, $x_6 \leq x_1$, $x_7 \leq x_1$, $x_2 \leq x_7 + x_8$, $x_5 \leq x_9$.	5
relaxed	The plant is assumed already to operate a condition-monitoring layer, so the three prerequisites on T1 are inactive. Remaining: $x_2 \leq x_7 + x_8$, $x_5 \leq x_9$.	2
strengthened	The digital twin additionally requires a computing substrate ($x_6 \leq x_7 + x_8$), and the disjunctive requirement for AI-based quality inspection is narrowed to edge computing alone ($x_2 \leq x_8$), on the ground that the illustrative strengthened configuration assumes edge-only processing for latency-sensitive quality inspection. The remaining baseline prerequisites are unchanged: $x_3 \leq x_1$, $x_6 \leq x_1$, $x_7 \leq x_1$, $x_5 \leq x_9$.	6

Supplementary Table 9. Technology selection frequencies (%) for all 18 experimental cells of the Monte Carlo design. Each cell is based on 10,000 replications. Table 9 of the manuscript reports the mean of the three dependency configurations for each perturbation level and preference scenario.

Level	Dependency	Scen.	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
±10%	baseline	S1	100.0	1.3	98.0	0.0	0.0	81.5	87.0	32.2	29.9	0.0
±10%	baseline	S2	100.0	0.5	99.2	0.0	0.0	63.0	38.8	98.4	97.4	0.0
±10%	baseline	S3	100.0	1.3	96.7	0.0	0.0	79.4	57.9	65.0	97.2	0.0
±10%	relaxed	S1	97.5	1.3	99.1	0.0	0.0	81.5	87.3	32.5	30.4	0.0
±10%	relaxed	S2	99.5	0.4	99.5	0.0	0.0	63.0	39.1	98.0	97.8	0.0
±10%	relaxed	S3	99.0	1.3	97.1	0.0	0.0	79.5	58.4	64.9	97.5	0.0
±10%	strengthened	S1	100.0	0.8	97.7	0.0	0.0	82.0	86.8	32.6	30.0	0.0
±10%	strengthened	S2	100.0	0.4	98.9	0.0	0.0	63.3	38.7	98.7	97.4	0.0
±10%	strengthened	S3	100.0	0.7	96.4	0.0	0.0	80.1	57.5	65.7	97.2	0.0
±20%	baseline	S1	100.0	9.2	82.3	0.9	0.4	70.6	72.4	52.9	46.4	0.8
±20%	baseline	S2	100.0	6.1	88.2	0.4	0.6	58.2	55.5	82.6	81.9	0.5
±20%	baseline	S3	100.0	9.1	83.3	0.5	0.9	70.3	62.2	67.5	83.0	0.7
±20%	relaxed	S1	87.2	11.0	87.1	1.0	0.5	71.4	74.6	52.4	49.2	0.7
±20%	relaxed	S2	94.5	6.7	90.5	0.3	0.6	58.5	57.0	81.7	83.5	0.4
±20%	relaxed	S3	92.8	10.0	85.6	0.5	0.9	70.7	64.4	67.2	84.6	0.6
±20%	strengthened	S1	100.0	5.7	80.7	0.6	0.3	72.6	73.8	56.2	45.7	0.7
±20%	strengthened	S2	100.0	4.6	86.9	0.4	0.5	58.6	56.8	84.6	81.3	0.5
±20%	strengthened	S3	100.0	6.2	82.1	0.5	0.8	71.4	63.0	70.6	82.2	0.6

Supplementary Table 10. Portfolio-level stability for all 18 experimental cells. “Reproduced” is the percentage of replications in which the optimal portfolio is identical to the nominal portfolio of that preference scenario. No replication produced an empty feasible set.

Level	Dependency	Scen.	Nominal portfolio	Reproduced (%)	Distinct portfolios	Mean size	Infeasible
±10%	baseline	S1	T1+T3+T6+T7	67.1	10	4.3	0
±10%	baseline	S2	T1+T3+T6+T8+T9	60.7	12	5.0	0
±10%	baseline	S3	T1+T3+T6+T7+T9	33.1	15	5.0	0
±10%	relaxed	S1	T1+T3+T6+T7	66.2	12	4.3	0
±10%	relaxed	S2	T1+T3+T6+T8+T9	60.7	13	5.0	0
±10%	relaxed	S3	T1+T3+T6+T7+T9	33.0	18	5.0	0
±10%	strengthened	S1	T1+T3+T6+T7	67.3	7	4.3	0
±10%	strengthened	S2	T1+T3+T6+T8+T9	60.7	10	5.0	0
±10%	strengthened	S3	T1+T3+T6+T7+T9	33.1	12	5.0	0
±20%	baseline	S1	T1+T3+T6+T7	32.6	41	4.4	0
±20%	baseline	S2	T1+T3+T6+T8+T9	35.4	47	4.7	0
±20%	baseline	S3	T1+T3+T6+T7+T9	16.8	61	4.8	0
±20%	relaxed	S1	T1+T3+T6+T7	30.0	65	4.3	0
±20%	relaxed	S2	T1+T3+T6+T8+T9	35.3	67	4.7	0
±20%	relaxed	S3	T1+T3+T6+T7+T9	16.0	85	4.8	0
±20%	strengthened	S1	T1+T3+T6+T7	34.5	33	4.4	0
±20%	strengthened	S2	T1+T3+T6+T8+T9	35.4	38	4.7	0
±20%	strengthened	S3	T1+T3+T6+T7+T9	17.3	48	4.8	0

Supplementary Table 11. Complete Pareto frontier in the carbon–lean objective space, obtained by exhaustive enumeration. Supported portfolios lie on the convex hull of the frontier; unsupported portfolios cannot be obtained by any positive weighted-sum scalarization of portfolio carbon and lean value.

#	Efficient portfolio	Carbon (CFU)	Lean value	Type	Goal-programming solution
1	(empty)	0	0	supported	
2	T9	36	54	unsupported	
3	T8	42	58	unsupported	
4	T1	45	68	supported	
5	T4	75	70	unsupported	
6	T8+T9	78	112	unsupported	
7	T1+T9	81	122	unsupported	
8	T1+T8	87	126	unsupported	
9	T1+T3	93	140	unsupported	
10	T1+T7	105	142	unsupported	
11	T1+T6	107	150	unsupported	
12	T1+T8+T9	123	180	unsupported	
13	T1+T3+T9	129	194	supported	
14	T1+T3+T8	135	198	unsupported	
15	T1+T6+T9	143	204	unsupported	
16	T1+T6+T8	149	208	unsupported	
17	T1+T3+T7	153	214	unsupported	
18	T1+T3+T6	155	222	unsupported	
19	T1+T6+T7	167	224	unsupported	
20	T1+T3+T8+T9	171	252	supported	
21	T1+T7+T8+T9	183	254	unsupported	
22	T1+T6+T8+T9	185	262	unsupported	
23	T1+T3+T7+T9	189	268	unsupported	
24	T1+T3+T6+T9	191	276	unsupported	
25	T1+T3+T6+T8	197	280	unsupported	
26	T1+T6+T7+T8	209	282	unsupported	
27	T1+T3+T6+T7	215	296	unsupported	S1
28	T1+T3+T7+T8+T9	231	326	unsupported	
29	T1+T3+T6+T8+T9	233	334	supported	S2
30	T1+T6+T7+T8+T9	245	336	unsupported	
31	T1+T3+T6+T7+T9	251	350	supported	S3