Appendix

Towards circular economy implementation in manufacturing systems using a multi-method simulation approach to link design and business strategy

Michael Lieder[1], Farazee M.A. Asif[1], Amir Rashid[1], Aleš Mihelič[2], Simon Kotnik[3]

Michael Lieder
ORCID: 0000-0002-5826-8670
e-mail: lieder@kth.se

Farazee M.A. Asif
ORCID: 0000-0002-6590-7514
e-mail: aasi@kth.se

Corresponding author:
Amir Rashid
ORCID: 0000-0002-5960-2159
e-mail: amirr@kth.se
phone: +46 8 790 63 73

Aleš Mihelič
e-mail: ales.mihelic@gorenje.com

Simon Kotnik
e-mail: simon.kotnik@gorenje.com

[1]Department of Production Engineering, KTH Royal Institute of Technology, Brinellvägen 68, SE-100 44 Stockholm, Sweden
[2]R&D Competence Centre Laundry Care, Gorenje d.d., Partizanska 12, SI- 3320 Velenje, Slovenia
[3]Joint R&D Centre, Gorenje d.d., Partizanska 12, SI- 3320 Velenje, Slovenia

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A1 End-of-life strategies on component level for design options 1 through 3

Component number	Material name	Component mass (kg)	Design option 1	Design option 2	Design option 3
1	Material A	0,92	Reuse	Recycle	Recycle
2	Material B	0,11	Reuse	Recycle	Reman
3	Material C	0,20	Reuse	Reman	Recycle
4	Material D	0,30	Reuse	Reman	Reman
5	Material D	1,00	Reuse	Reuse	Reman
6	Material B	0,10	Reuse	Reuse	Reuse
7	Material C	2,00	Reuse	Reuse	Reuse
8	Material E	5,39	Reuse	Reuse	Reman
9	Material F	5,00	Reuse	Reuse	Reman
10	Material B	0,05	Reuse	Reuse	Reman
11	Material B	0,02	Reuse	Reuse	Reman
12	Material B	0,58	Reuse	Reuse	Reman
13	Material G	0,40	Reman	Reman	Recycle
14	Material B	0,10	Recycle	Recycle	Recycle
15	Material G	0,09	Reman	Reman	Recycle
16	Material B	0,44	Reuse	Reuse	Reuse
17	Material A	0,50	Recycle	Recycle	Recycle
18	Material H	0,24	Reman	Reman	Reman
19	Material I	1,28	Reman	Reman	Reman
20	Material J	3,80	Reman	Reman	Reman
21	Material J	4,00	Reuse	Reman	Reman
22	Material J	2,56	Reuse	Reman	Reman
23	Material A	1,51	Reuse	Reman	Reman
24	Material A	0,80	Reuse	Reuse	Reuse
25	Material A	0,40	Reuse	Reuse	Reuse
26	Material A	1,10	Reuse	Reuse	Reuse
27	Material A	0,50	Reuse	Reuse	Reuse
28	Material K	0,30	Reuse	Reuse	Reuse
29	Material L	0,05	Reuse	Reuse	Reman
30	Material M	0,50	Reuse	Reuse	Reman
31	Material M	6,40	Reman	Reman	Reman
32	Material H	3,00	Reman	Reman	Reman
33	Material M	6,00	Reman	Reman	Reman

A2 Cost input data on component level (euro) for the linear scenario (baseline)

Component number	Material name	Component mass (kg)	Manufacturing	Reuse	Remanufacturing	Recycling	Assembly	Forward transport	Reverse transport	Disassembly	Internal logistics
1	Material A	0,92	10,50	2,7800	3,7067	6,4867	0,3707	0,0463	0,0927	0,9267	0,0232
2	Material B	0,11	1,26	0,3324	0,4432	0,7756	0,0443	0,0055	0,0111	0,1108	0,0028
3	Material C	0,20	2,28	0,6044	0,8058	1,4102	0,0806	0,0101	0,0201	0,2015	0,0050
4	Material D	0,30	3,42	0,9065	1,2087	2,1152	0,1209	0,0151	0,0302	0,3022	0,0076
5	Material D	1,00	11,41	3,0218	4,0290	7,0508	0,4029	0,0504	0,1007	1,0073	0,0252
6	Material B	0,10	1,14	0,3022	0,4029	0,7051	0,0403	0,0050	0,0101	0,1007	0,0025
7	Material C	2,00	22,82	6,0435	8,0580	14,1015	0,8058	0,1007	0,2015	2,0145	0,0504
8	Material E	5,39	61,50	16,2873	21,7164	38,0036	2,1716	0,2715	0,5429	5,4291	0,1357
9	Material F	5,00	57,05	15,1088	20,1450	35,2538	2,0145	0,2518	0,5036	5,0363	0,1259
10	Material B	0,05	0,57	0,1511	0,2015	0,3525	0,0201	0,0025	0,0050	0,0504	0,0013
11	Material B	0,02	0,23	0,0604	0,0806	0,1410	0,0081	0,0010	0,0020	0,0201	0,0005
12	Material B	0,58	6,62	1,7526	2,3368	4,0894	0,2337	0,0292	0,0584	0,5842	0,0146
13	Material G	0,40	4,56	1,2087	1,6116	2,8203	0,1612	0,0201	0,0403	0,4029	0,0101
14	Material B	0,10	1,14	0,3022	0,4029	0,7051	0,0403	0,0050	0,0101	0,1007	0,0025
15	Material G	0,09	1,03	0,2720	0,3626	0,6346	0,0363	0,0045	0,0091	0,0907	0,0023
16	Material B	0,44	5,02	1,3296	1,7728	3,1023	0,1773	0,0222	0,0443	0,4432	0,0111
17	Material A	0,50	5,70	1,5109	2,0145	3,5254	0,2015	0,0252	0,0504	0,5036	0,0126
18	Material H	0,24	2,74	0,7252	0,9670	1,6922	0,0967	0,0121	0,0242	0,2417	0,0060
19	Material I	1,28	14,60	3,8678	5,1571	9,0250	0,5157	0,0645	0,1289	1,2893	0,0322
20	Material J	3,80	43,36	11,4827	15,3102	26,7929	1,5310	0,1914	0,3828	3,8276	0,0957
21	Material J	4,00	45,64	12,0870	16,1160	28,2031	1,6116	0,2015	0,4029	4,0290	0,1007
22	Material J	2,56	29,21	7,7357	10,3143	18,0500	1,0314	0,1289	0,2579	2,5786	0,0645
23	Material A	1,51	17,23	4,5629	6,0838	10,6467	0,6084	0,0760	0,1521	1,5210	0,0380
24	Material A	0,80	9,13	2,4174	3,2232	5,6406	0,3223	0,0403	0,0806	0,8058	0,0201
25	Material A	0,40	4,56	1,2087	1,6116	2,8203	0,1612	0,0201	0,0403	0,4029	0,0101
26	Material A	1,10	12,55	3,3239	4,4319	7,7558	0,4432	0,0554	0,1108	1,1080	0,0277
27	Material A	0,50	5,70	1,5109	2,0145	3,5254	0,2015	0,0252	0,0504	0,5036	0,0126
28	Material K	0,30	3,42	0,9065	1,2087	2,1152	0,1209	0,0151	0,0302	0,3022	0,0076
29	Material L	0,05	0,57	0,1511	0,2015	0,3525	0,0201	0,0025	0,0050	0,0504	0,0013
30	Material M	0,50	5,70	1,5109	2,0145	3,5254	0,2015	0,0252	0,0504	0,5036	0,0126
31	Material M	6,40	73,02	19,3392	25,7857	45,1249	2,5786	0,3223	0,6446	6,4464	0,1612
32	Material H	3,00	34,23	9,0653	12,0870	21,1523	1,2087	0,1511	0,3022	3,0218	0,0755
33	Material M	6,00	68,46	18,1305	24,1741	42,3046	2,4174	0,3022	0,6044	6,0435	0,1511
Total	**---**	**49,64**	**566,38**	**150,00**	**200,0000**	**350,0000**	**20,0000**	**2,5000**	**5,0000**	**50,0000**	**1,2500**

A3 CO_2 input data on component level (CO_2 kg) for the linear scenario (baseline)

Component number	Material name	Component mass (kg)	Manufacturing	Reuse	Remanufacturing	Recycling	Assembly	Forward transport	Reverse transport	Disassembly	Internal logistics
1	Material A	0,92	98,23	20,9984	25,9468	96,6519	0,5931	0,0043	0,0085	3,7067	0,0019
2	Material B	0,11	11,74	2,5107	3,1023	11,5562	0,0709	0,0005	0,0010	0,4432	0,0002
3	Material C	0,20	21,35	4,5649	5,6406	21,0113	0,1289	0,0009	0,0019	0,8058	0,0004
4	Material D	0,30	32,03	6,8473	8,4609	31,5169	0,1934	0,0014	0,0028	1,2087	0,0006
5	Material D	1,00	106,77	22,8243	28,2031	105,0564	0,6446	0,0046	0,0093	4,0290	0,0020
6	Material B	0,10	10,68	2,2824	2,8203	10,5056	0,0645	0,0005	0,0009	0,4029	0,0002
7	Material C	2,00	213,54	45,6487	56,4061	210,1128	1,2893	0,0093	0,0185	8,0580	0,0040
8	Material E	5,39	575,48	123,0232	152,0145	566,2540	3,4746	0,0250	0,0499	21,7164	0,0109
9	Material F	5,00	533,84	114,1217	141,0153	525,2820	3,2232	0,0232	0,0463	20,1450	0,0101
10	Material B	0,05	5,34	1,1412	1,4102	5,2528	0,0322	0,0002	0,0005	0,2015	0,0001
11	Material B	0,02	2,14	0,4565	0,5641	2,1011	0,0129	0,0001	0,0002	0,0806	0,0000
12	Material B	0,58	61,93	13,2381	16,3578	60,9327	0,3739	0,0027	0,0054	2,3368	0,0012
13	Material G	0,40	42,71	9,1297	11,2812	42,0226	0,2579	0,0019	0,0037	1,6116	0,0008
14	Material B	0,10	10,68	2,2824	2,8203	10,5056	0,0645	0,0005	0,0009	0,4029	0,0002
15	Material G	0,09	9,61	2,0542	2,5383	9,4551	0,0580	0,0004	0,0008	0,3626	0,0002
16	Material B	0,44	46,98	10,0427	12,4093	46,2248	0,2836	0,0020	0,0041	1,7728	0,0009
17	Material A	0,50	53,38	11,4122	14,1015	52,5282	0,3223	0,0023	0,0046	2,0145	0,0010
18	Material H	0,24	25,62	5,4778	6,7687	25,2135	0,1547	0,0011	0,0022	0,9670	0,0005
19	Material I	1,28	136,66	29,2151	36,0999	134,4722	0,8251	0,0059	0,0119	5,1571	0,0026
20	Material J	3,80	405,72	86,7325	107,1716	399,2143	2,4496	0,0176	0,0352	15,3102	0,0077
21	Material J	4,00	427,07	91,2973	112,8122	420,2256	2,5786	0,0185	0,0371	16,1160	0,0081
22	Material J	2,56	273,33	58,4303	72,1998	268,9444	1,6503	0,0119	0,0237	10,3143	0,0052
23	Material A	1,51	161,22	34,4647	42,5866	158,6352	0,9734	0,0070	0,0140	6,0838	0,0030
24	Material A	0,80	85,41	18,2595	22,5624	84,0451	0,5157	0,0037	0,0074	3,2232	0,0016
25	Material A	0,40	42,71	9,1297	11,2812	42,0226	0,2579	0,0019	0,0037	1,6116	0,0008
26	Material A	1,10	117,45	25,1068	31,0234	115,5620	0,7091	0,0051	0,0102	4,4319	0,0022
27	Material A	0,50	53,38	11,4122	14,1015	52,5282	0,3223	0,0023	0,0046	2,0145	0,0010
28	Material K	0,30	32,03	6,8473	8,4609	31,5169	0,1934	0,0014	0,0028	1,2087	0,0006
29	Material L	0,05	5,34	1,1412	1,4102	5,2528	0,0322	0,0002	0,0005	0,2015	0,0001
30	Material M	0,50	53,38	11,4122	14,1015	52,5282	0,3223	0,0023	0,0046	2,0145	0,0010
31	Material M	6,40	683,32	146,0757	180,4996	672,3610	4,1257	0,0297	0,0593	25,7857	0,0129
32	Material H	3,00	320,31	68,4730	84,6092	315,1692	1,9339	0,0139	0,0278	12,0870	0,0060
33	Material M	6,00	640,61	136,9460	169,2184	630,3384	3,8678	0,0278	0,0556	24,1741	0,0121
Total	**---**	**49,64**	**5300,00**	**1133,0000**	**1400,0000**	**5215,0000**	**32,0000**	**0,2300**	**0,4600**	**200,0000**	**0,1000**

A4 Optimization run

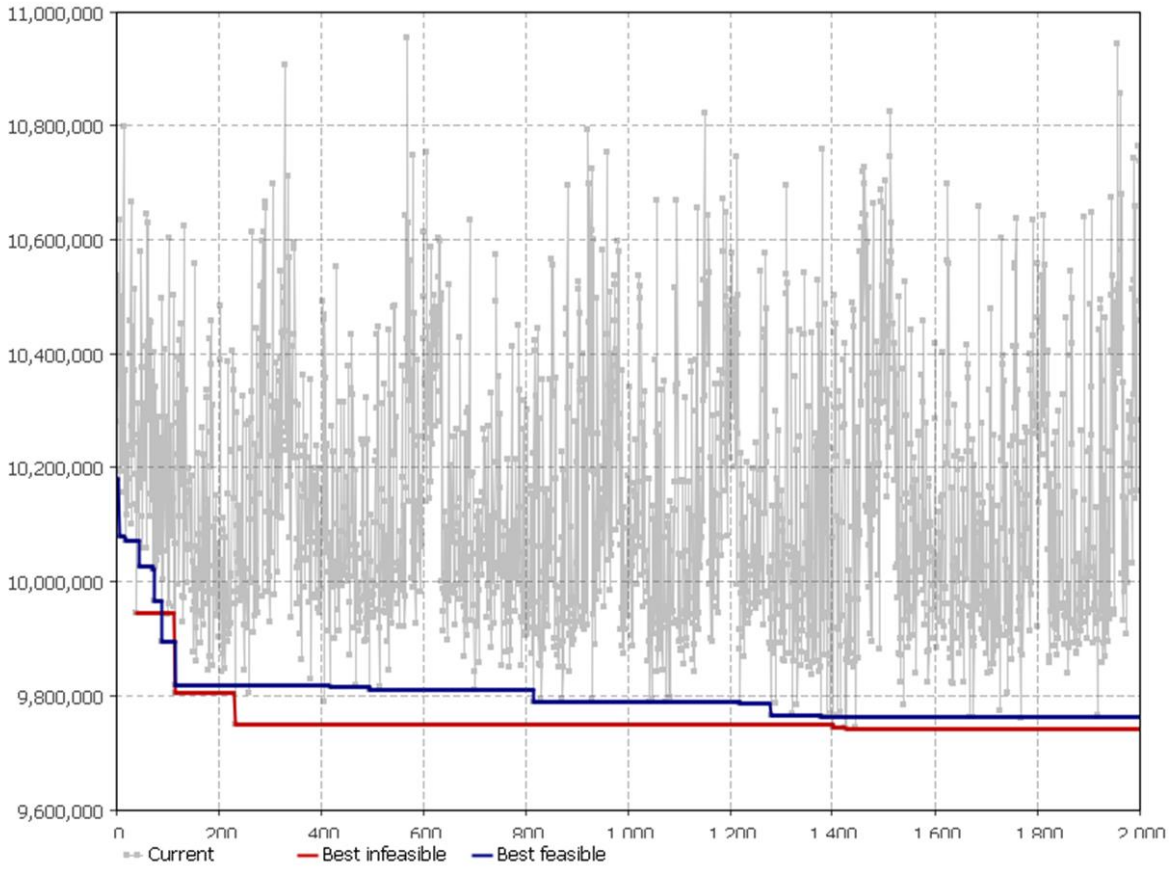

Fig 1 Screenshot of optimization result (2000 runs, 15 year scenario per run)

y-axis: Objective value to be minimized (aggregated lifecycle cost after 15 years, in euro)

x-axis: Number of simualtion run

Grey dots: Each grey dot represents one completed simulation run with the final result

Constraint (checked *before* start of each simulation run):
Each component has one end-of-life strategy, i.e. either reuse, remanufacturing or recycling.

Requirement (checked *after* start of each simulation run):
The overall design effort ΔD for the entire product may not exceed 0,249 , i.e. not more than 24,9% of the current design effort.

Blue line: All feasible solutions where $\Delta D \leq 0{,}249$

Red line: All infeasible solutions where $\Delta D > 0{,}249$

Best feasible solution has been provided by run number 1918 with total cost of 9.762.846,38 euro