Supplementary Information for

Accounting for imperfect displacement in life cycle assessment for refurbishing and remanufacturing operations

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Appendix A – Economic Model Details

A.1 Derivation of Demand Functions

Based on the customer behavior model described in Section 2.2 of the manuscript – refer to Table 1 for the model notation – and illustrated in Figure 2, we can define two critical willingness-to-pay (WTP) levels, denoted by θ_1 and θ_2 respectively, such that:

1. Customers with WTP $\theta > \theta_1$ buy the new product;
2. Customers with WTP $\theta_2 < \theta < \theta_1$ buy the remanufactured product;
3. Customers with WTP $0 < \theta < \theta_2$ remain inactive.

As illustrated in the upper panel of Figure 2, θ_1 and θ_2 can be characterized as follows:

- $\theta_1 = \theta \mid U_n(\theta) = U_r(\theta)$
- $\theta_2 = \theta \mid U_r(\theta) = 0$

Using the utility functions specified in equations (3) in the manuscript, we derive:

- $\theta_1 = \theta \mid \theta - p_n = \delta \cdot \theta - p_r \;\rightarrow\; \theta_1 = \frac{p_n - p_r}{1-\delta}$
- $\theta_2 = \theta \mid \delta \cdot \theta - p_r = 0 \;\rightarrow\; \theta_2 = \frac{p_r}{\delta}$

As illustrated in the lower panel of Figure 2, we can finally derive the demand functions as follows:

$$q_n^R(p_n, p_r) = \frac{B - \theta_1}{B}\;; \qquad q_r^R(p_n, p_r) = \frac{\theta_1 - \theta_2}{B} \tag{A1}$$

These lead, with some simple manipulation, to the equations (4) in the manuscript.

A.2 Solution to the Profit Maximization Problem – Karush-Kuhn-Tucker Analysis

Given the optimization problem presented in the manuscript – see expressions (5) – the single inequality constraint on the supply of remanufactured products activates the Karush-Kuhn-Tucker (KKT) analysis.

Introducing a multiplier $\lambda \geq 0$ for the supply constraint, the *Lagrangian* is:

$$\mathcal{L}(p_n, p_r, \lambda) = q_n(p_n - c_n) + q_r(p_r - c_r) - \lambda(q_r - \alpha q_n) \tag{A2}$$

The multiplier λ has the economic interpretation of the shadow value of an additional unit of remanufacturing capacity: it equals the marginal profit gain from relaxing the supply constraint.

KKT Conditions

The KKT first-order necessary conditions for optimality are:

- *Stationarity with respect to p_n*

$$\frac{\partial \mathcal{L}}{\partial \mathrm{p_n}} = 0 \ \rightarrow c_n - c_r + B(1-\delta) - \lambda(1+\alpha) - 2p_n + 2p_r = 0 \tag{A3}$$

- *Stationarity with respect to p_r*

$$\frac{\partial \mathcal{L}}{\partial \mathrm{p_r}} = 0 \ \rightarrow c_r - c_n\delta + \lambda(1+\alpha\delta) + 2\delta p_n - 2p_r = 0 \tag{A4}$$

- *Complementary slackness*

$$\lambda(\alpha q_n - q_r) = 0, \qquad \lambda \geq 0, \qquad \alpha q_n - q_r \geq 0 \tag{A5}$$

Condition (A5) forces one of two cases:

i. $\lambda>0$ (*constrained regime*): the supply constraint binds, i.e., $q_r=\alpha\, q_n$; an additional first-order condition must be satisfied.

ii. $\lambda=0$ (*unconstrained regime*): the supply constraint is slack; prices are set independently.

We report below the solution in each regime.

Constrained Regime ($\lambda > 0$, supply binds)

Here, the system (A3)-(A4), together with $q_r=\alpha\, q_n$, yields the constrained optimum presented in expressions (6) in the manuscript, with:

$$\lambda^* = \frac{c_n(1+\alpha)\delta - B\alpha(1-\delta)\delta - c_r(1+\alpha\delta)}{1+\alpha(2+\alpha)\delta} \tag{A6}$$

where $\lambda^* > 0$ holds if and only if:

$$B < \frac{2c_n\delta - c_r(1+\delta)}{\delta\,(1-\delta)};\ \text{or if}\ \ B > \frac{2c_n\delta - c_r(1+\delta)}{\delta\,(1-\delta)}\ \text{and}\ \alpha < \frac{c_r - c_n\delta}{(c_n - c_r - B(1-\delta))\delta} \tag{A7}$$

The constrained profit is:

$$\Pi^*_{con} = \frac{(B - c_n - \alpha c_r + \alpha B\delta)^2}{4(B + \alpha(2+\alpha)B\delta)} \tag{A8}$$

Unconstrained Regime (λ=0)

Setting λ=0 in (A3)-(A4) and solving jointly leads to the optimal prices and corresponding optimal quantities presented in expressions (7) in the manuscript.

This case occurs if and only if $0<q_r<\alpha\, q_n$, i.e.:

$$\frac{\delta c_n - c_r}{2B\delta(1-\delta)} < \alpha < \frac{B - c_n + c_r - B\delta}{2B(1-\delta)} \tag{A9}$$

which simplifies to:

$$B > \frac{2c_n\delta - c_r(1+\delta)}{\delta\,(1-\delta)} \text{ and } \alpha > \frac{c_r - c_n\delta}{\left(c_n - c_r - B(1-\delta)\right)\delta} \tag{A10}$$

The unconstrained profit is:

$$\Pi^*_{uncon} = \frac{(B-c_n)^2\delta + (c_r - B\delta)(c_r + (B-2c_n)\delta)}{4B(1-\delta)\delta} \tag{A11}$$

<u>*Regime Thresholds*</u>

The relationship between the maximum WTP for the new product *B* or the recovery rate *α* and the other model parameters determines which regime applies (see expressions A7 and A10). The *constrained regime* is binding if either of the following conditions holds:

- *Scenario A: Low-WTP* → *B* is below the critical threshold:

$$B \le \frac{2c_n\delta - c_r(1+\delta)}{\delta\,(1-\delta)}$$

OR

- *Scenario B: High-WTP* → *B* exceeds the threshold, requiring a strictly bound *α*:

$$B > \frac{2c_n\delta - c_r(1+\delta)}{\delta\,(1-\delta)} \quad and \quad \alpha \le \frac{c_r - c_n\delta}{\left(c_n - c_r - B(1-\delta)\right)\delta}$$

If both *B* and *α* exceed the indicated critical thresholds, the *unconstrained regime* applies.

Appendix B – Life Cycle Assessment Details for the Case Study

B.1 Life Cycle Inventory Process

To calculate the inventory of the *Production* phase for the new product, we exploded the bill of materials (BoM; including packaging) provided by the company and linked each low-level code/item (purchased component, sub-component, or raw material) to a relevant *ecoinvent* dataset or group of datasets representing its upstream production. Following the Environmental Product Declaration (EPD) study carried out by the company (Schneider Electric, n.d.), we increased the mass of low-level items by a specific factor to account for losses in the assembly process, especially for items made of plastics, metals, and paper/cardboard. This loss factor is computed and regularly updated by the company using average facility-level data. The end-of-life treatment of assembly residues is included in the *Production* phase and modeled following the approach described below for the *Disposal* phase. The transportation of all items from upstream suppliers to the assembly site – located in China – was modeled assuming transport by articulated lorry over 3,500 km, as recommended by the relevant Product Category Rules (PCR) for intracontinental transport (P.E.P. Association, 2015). Like the EPD study, we neglected electricity consumption for the assembly process due to the lack of reliable data and its expected negligible contribution to the overall results. Table A1 provides the aggregate list of *ecoinvent* datasets used and associated

total values (*Production or Recovery* section, *New Product* column). For confidentiality reasons, we cannot disaggregate this further into the specific reference flows for all materials/components. To calculate the inventory of the *Recovery* phase for the remanufactured product, we modeled the following processes: the reverse logistics to take the product back and the upstream production of spare parts needed for remanufacturing. We instead excluded the electricity consumption of the remanufacturing process itself (for inspections, dismantling, re-assembly, and testing activities). Interviews with company personnel revealed that this was negligible. For the reverse logistics, we assumed transportation by lorry over 600 km, an average value indicated by the company to capture the distance between a generic European customer and the repair center – located in France. To obtain the *tkm* value, we estimated the net product weight by subtracting the packaging weight from the new product weight. Regarding the spare parts, they can vary based on the conditions of the collected product, which are inspected upon its arrival at the repair center. The repair center has kept track of the specific spare parts that have been replaced in all taken-back products since the inception of the refurbishing program. We used this data to identify all potential spare parts and derive their average replacement frequencies for the product studied. Hence, we carved out a subset of the BoM containing only the spare parts needed for remanufacturing and corrected their reference flows based on their replacement frequencies. For example, if a given component was replaced in only half of the remanufactured products, we discounted its quantity by 0.5[1]. The reduced BoM further included a whole new packaging set. We leveraged the same datasets and assumptions used for the new product to model the production and upstream transportation of raw materials/components making up the spare parts (including the generation and disposal of assembly residues). The list of linked *ecoinvent* datasets and associated total values is reported in Table A1 (*Production or Recovery* section, *Remanufactured Product* column).
To calculate the inventory of the *Distribution* phase, we modeled the following transportation processes: a) articulated lorry from the assembly site to the departure port in China – around 140 km; b) container ship from the departure port to the arrival port in France – around 19,110 km; c) articulated lorry from the arrival port to the company distribution center (new product) or repair center (remanufactured product) in France – around 120 km; d) articulated lorry from the distribution/repair center to a generic distributor in Europe – 600 km; e) lorry from the distributor to a generic customer in Europe – 200 km. The PEP PCRs (2015) include processes a), b), c) in the *Production* phase (called *Manufacturing* therein), which is another reason for the deviation of our results from the EPD results (Schneider Electric, n.d.). Distances for the processes a), b), c) above represent true values, whereas distances for d) and e) represent average values, assumed based on the company's general logistic model in Europe. For the new product, all transportation processes concern the full product (including packaging), whose weight was multiplied by the relevant distances to obtain *tkm* values. For the remanufactured product, processes a), b), and c) concern only the spare parts (whose weight was discounted by their replacement frequencies as in the *Recovery* phase), whereas d) and e) concern the full product. Table A1 reports the list of linked *ecoinvent* datasets and associated values for both the new and remanufactured products (*Distribution* section).
To calculate the inventory of the *Use* phase, we estimated the electricity consumption of the variable speed drive by taking the same average power ratings and use scenario (namely, 80% of the time in active mode and 20% in standby mode, respectively) reported in the EPD (Schneider Electric, n.d.). Considering the 10-year lifetime specified by the functional unit, this yields a total

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[1] This approach grounded on primary data is more accurate than other approaches used for remanufacturing, like considering all potential spare parts to represent a sort of worst-case scenario (Ardente et al., 2018).

value of around 31,115 kWh. As indicated in the main text, this is the same for new and remanufactured products, as the same use span, conditions, and energy efficiency are assumed in the base case. Like the EPD study, we considered a generic European customer and modeled the supply of low voltage electricity from the grid using a relevant *ecoinvent* dataset – reported in Table A1 (*Use* section).

To calculate the inventory of the *Disposal* phase, we matched each low-level code in the BoM (including packaging materials) with a specific waste stream, which we then modeled using relevant *ecoinvent* datasets representing general treatment processes for that stream[2]. For the new product, this procedure refers to the full BoM, whereas for the remanufactured product, it refers to the reduced BoM containing only the spare parts. Regarding transportation processes involved in the end-of-life, we assumed transport by articulated lorry over the same distances used in the EPD study, partly based on values recommended by the relevant PCRs (P.E.P. Association, 2015). We followed the same approach for the disposal of assembly residues, which, however, is included in the *Production* phase. Table A1 provides the aggregate list of linked *ecoinvent* datasets and associated total values for both the new and remanufactured products (*Disposal* section). The processes/flows related to the product packaging are reported separately.

[2] We modeled electric and electronic waste with particular care, differentiating it into more specific sub-streams and using more granular datasets.

Activity	Ecoinvent Dataset [a]	Unit	New Product	Remanufactured Product
Production or Recovery				
Upstream transportation	Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6	kgkm	65906.264	13521.426
Reverse logistics	Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6	kgkm	0	8676
Chemical components/items	Barium oxide {GLO}| market for barium oxide	g	0.45480	0.00074
	Cobalt oxide {GLO}| market for cobalt oxide	g	1.364	0.00222
	Epoxy resin, liquid {RER}| epoxy resin production, liquid	g	1.084	0
	Manganese dioxide {GLO}| market for manganese dioxide	g	0.90960	0.00148
	Silica sand {DE}| silica sand production	g	89.270	87.520
	Silica sand {GLO}| market for silica sand	g	0.45480	0.00074
	Silicone product {RoW}| silicone product production	g	29.338	11.284
	Zinc oxide {GLO}| market for zinc oxide	g	42.296	0.06868
Electronic components/items	Battery, Li-ion, LiMn2O4, rechargeable, prismatic {GLO}| battery production, Li-ion, LiMn2O4, rechargeable, prismatic	g	2.900	0
	Cable, three-conductor cable {GLO}| cable production, three-conductor cable	m	25.443	1.415
	Cable, unspecified {GLO}| cable production, unspecified – **modified** [b]	g	566.247	
	Capacitor, electrolyte type, < 2cm height {GLO}| capacitor production, electrolyte type, < 2cm height	g	26.110	9.763
	Capacitor, electrolyte type, > 2cm height {GLO}| capacitor production, electrolyte type, > 2cm height	g	525	80.769
	Capacitor, film type, for through-hole mounting {GLO}| capacitor production, film type, for through-hole mounting	g	138.378	12.647
	Capacitor, for surface-mounting {GLO}| capacitor production, for surface-mounting	g	9.029	2.610
	Diode, glass-, for through-hole mounting {GLO}| diode production, glass-, for through-hole mounting	g	1.756	0.67538
	Electric connector, peripheral component interconnect buss {GLO}| electric connector production, peripheral component interconnect buss	g	43.510	5.661
	Electric connector, peripheral type buss {GLO}| electric connector production, peripheral type buss	g	226.935	56.244
	Electric connector, wire clamp {GLO}| electric connector production, wire clamp	g	0.37500	0.09615
	Electronic component, active, unspecified {GLO}| electronic component production, active, unspecified	g	8.459	2.228
	Inductor, low value multilayer chip {GLO}| inductor production, low value multilayer chip	g	6.157	0.845307692
	Integrated circuit, logic type {GLO}| integrated circuit production, logic type	g	4.468	0.62360
	Integrated circuit, memory type {GLO}| integrated circuit production, memory type	g	0.613	0.08560
	Light emitting diode {GLO}| light emitting diode production	g	5.280	2.024

	Liquid crystal display, unmounted, mobile device {GLO}| liquid crystal display production, unmounted, mobile device	g	25	0
	Mounting, surface mount technology, Pb-free solder {GLO}| mounting, surface mount technology, Pb-free solder	m2	0.26281	0.05320
	Mounting, through-hole technology, Pb-free solder {GLO}| mounting, through-hole technology, Pb-free solder	m2	0.20725	0.04021
	Plug, inlet and outlet, for computer cable {GLO}| plug production, inlet and outlet, for computer cable	p	0.00641	0.00164
	Plug, inlet and outlet, for network cable {GLO}| plug production, inlet and outlet, for network cable	p	1.264	0.16087
	Printed wiring board, for surface mounting, Pb free surface {GLO}| printed wiring board production, for surface mounting, Pb free surface	m2	0.11589	0.02287
	Printed wiring board, for through-hole mounting, Pb free surface {GLO}| printed wiring board production, for through-hole mounting, Pb free surface	m2	0.10531	0.01905
	Resistor, surface-mounted {GLO}| resistor production, surface-mounted	g	4.132	1.061
	Resistor, wirewound, through-hole mounting {GLO}| resistor production, wirewound, through-hole mounting	g	85.690	3.462
	Switch, toggle type {RoW}| switch production, toggle type	g	42.200	12.262
	Transformer, low voltage use {GLO}| transformer production, low voltage use	g	1.520	0.58462
	Transistor, surface-mounted {GLO}| transistor production, surface-mounted	g	8.518	2.758
	Transistor, wired, big size, through-hole mounting {GLO}| transistor production, wired, big size, through-hole mounting	g	4.430	1.704
	Transistor, wired, small size, through-hole mounting {GLO}| transistor production, wired, small size, through-hole mounting	g	7.500	2.885
Metal components/items	Aluminium scrap, new {RER}| treatment of aluminium scrap, new, at refiner	g	766.687	0.32614
	Aluminium scrap, new {RER}| treatment of aluminium scrap, new, at remelter	g	538.975	0.22927
	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| aluminium production, primary, ingot	g	1414.468	0.60170
	Brass {RoW}| brass production	g	164.384	9.048
	Brass removed by turning, average, conventional {RER}| brass turning, average, conventional	g	29.440	0
	Bronze {RoW}| bronze production	g	3.282	0
	Copper scrap, sorted, pressed {RER}| treatment of copper scrap by electrolytic refining	g	160.451	5.873
	Copper, cathode {GLO}| copper production, cathode, solvent extraction and electrowinning process	g	198.159	7.253
	Copper, cathode {GLO}| electrorefining of copper, anode	g	703.146	25.735
	Copper, cathode {SE}| gold mine operation and refining	g	7.917	0.28975
	Ferrite {GLO}| ferrite production	g	9.266	0
	Forging, steel {GLO}| market for forging, steel	g	1148.324	6.852
	Iron pellet {RoW}| iron pellet production	g	2168.386	0

	Metal working, average for steel product manufacturing {RER}| metal working, average for steel product manufacturing	g	1808.947	1.347
	Powder coat, steel {RER}| powder coating, steel	mm2	49127.900	0
	Reinforcing steel {Europe without Austria}| reinforcing steel production	g	90.896	3.497
	Section bar extrusion, aluminium {RER}| section bar extrusion, aluminium	g	2483.658	0
	Section bar rolling, steel {GLO}| market for section bar rolling, steel	g	10.940	3.366
	Sheet rolling, copper {RER}| sheet rolling, copper	g	29.754	1.258
	Sheet rolling, steel {GLO}| market for sheet rolling, steel	g	2344.307	1.474
	Sheet rolling, steel {RER}| sheet rolling, steel	g	193.659	35.575
	Steel removed by milling, average {RER}| steel milling, average	g	24.617	0.19462
	Steel removed by turning, average, conventional {RER}| steel turning, average, conventional	g	28.067	1.079
	Steel, chromium steel 18/8 {RER}| steel production, electric, chromium steel 18/8	g	4.595	0
	Steel, low-alloyed {GLO}| market for steel, low-alloyed	g	943.095	14.954
	Steel, unalloyed {GLO}| market for steel, unalloyed	g	1605.811	25.461
	Wire drawing, copper {RER}| wire drawing, copper	g	858.237	0
	Zinc {RoW}| primary zinc production from concentrate	g	89.839	0
	Zinc coat, coils {GLO}| market for zinc coat, coils	m2	0.10713	0.00007
	Zinc coat, coils {RER}| zinc coating, coils	m2	0.00885	0.00163
	Zinc coat, pieces {RER}| zinc coating, pieces	mm2	2292	48.923
Paper components/items	Acrylic varnish, with water, in 53% solution state {RER}| acrylic varnish production, with water, in 53% solution state	g	69.786	69.786
	Containerboard, linerboard {RER}| containerboard production, linerboard, kraftliner	g	34.974	34.974
	Containerboard, linerboard {RER}| containerboard production, linerboard, testliner	g	63.486	63.486
	Corrugated board box {RER}| corrugated board box production	g	2724	2724
	Paper, woodcontaining, lightweight coated {RER}| paper production, woodcontaining, lightweight coated	g	109.501	79.147
Plastic components/items	Acrylonitrile {RER}| acrylonitrile production, Sohio process	g	2.818	0
	Extrusion, plastic film {RER}| extrusion, plastic film	g	31.819	30.017
	Extrusion, plastic pipes {RER}| extrusion, plastic pipes	g	3.630	0
	Injection moulding {RER}| injection moulding	g	3467.754	38.858
	Nylon 6 {RER}| nylon 6 production	g	39.384	0
	Nylon 6-6 {RER}| market for nylon 6-6	g	27.105	0
	Nylon 6-6 {RER}| nylon 6-6 production	g	39.384	0

	Nylon 6-6, glass-filled {RER}| nylon 6-6 production, glass-filled	g	4.337	0
	Polybutadiene {RER}| polybutadiene production	g	6.574	0
	Polycarbonate {RER}| market for polycarbonate	g	0.21880	0.01683
	Polycarbonate {RER}| polycarbonate production	g	2725.448	31.483
	Polyethylene terephthalate, granulate, amorphous {RER}| polyethylene terephthalate production, granulate, amorphous	g	18.828	0
	Polyethylene terephthalate, granulate, amorphous {RER}| polyethylene terephthalate production, granulate, amorphous – **modified** [c]	g	66.871	0
	Polyethylene, high density, granulate {RER}| polyethylene production, high density, granulate	g	152.230	36.436
	Polyethylene, low density, granulate {RER}| polyethylene production, low density, granulate	g	32.820	32.820
	Polyphenylene sulfide {GLO}| polyphenylene sulfide production	g	38.257	14.714
	Polypropylene, granulate {GLO}| market for polypropylene, granulate	g	131.776	0
	Polyurethane, flexible foam {RER}| polyurethane production, flexible foam, TDI-based, low density	g	0.196920	0
	Synthetic rubber {RoW}| synthetic rubber production	g	32.147	0
	Triphenyl phosphate {GLO}| triphenyl phosphate production	g	880.373	10.200
Textile components/items	Fibre, polyester {RoW}| polyester fibre production, finished	g	0.10940	0
Processes losses disposal	Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6	kgkm	1582.036	106.193
	Waste electric and electronic equipment {GLO}| treatment of waste electric and electronic equipment, shredding	kg	0.05347	0.00927
	Used printed wiring boards {RoW}| treatment of scrap printed wiring boards, shredding and separation	kg	0.05347	0.00927
	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill	kg	0.04075	0.00008
	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, sanitary landfill	kg	0.02087	0.00094
	Waste glass {CH}| treatment of waste glass, inert material landfill	kg	0.00305	0.00001
	Waste graphical paper {CH}| treatment of waste graphical paper, sanitary landfill	kg	0.00150	0.00040
	Municipal solid waste {RoW}| treatment of municipal solid waste, sanitary landfill	kg	0.02617	0.00363
	Waste glass {CH}| treatment of waste glass, municipal incineration FAE	kg	1.028E-05	0
	Municipal solid waste {RoW}| treatment of municipal solid waste, municipal incineration	kg	1.486E-02	0.00396
Distribution				
Transportation from assembly site to distribution center	Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship	kgkm	333712.980	67538.925
	Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6	kgkm	4487.220	908.152
	Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6	kgkm	10476	10476

Transportation from distribution center to customer	Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6	kgkm	3492	3492
Use				
Average European user	Electricity, low voltage {Europe without Switzerland}| market group for electricity, low voltage	kWh	31115.520	31115.520
Disposal				
Product disposal	Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6	kgkm	16862.466	778.982
	Waste electric and electronic equipment {GLO}| treatment of waste electric and electronic equipment, shredding	kg	14.303	0.54141
	Used cable {GLO}| treatment of used cable	kg	0.54973	0.01668
	Used liquid crystal display {RoW}| treatment of used liquid crystal display, manual dismantling	kg	0.02500	0
	Used printed wiring boards {RoW}| treatment of scrap printed wiring boards, shredding and separation	kg	2.246	0.44190
	Used Ni-metal hydride battery {GLO}| treatment of used Ni-metal hydride battery, pyrometallurgical treatment	kg	0.00290	0
	Municipal solid waste {RoW}| treatment of municipal solid waste, municipal incineration	kg	0.78318	0.12993
	Municipal solid waste {RoW}| treatment of municipal solid waste, sanitary landfill	kg	2.497	0.27762
Packaging disposal	Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6	kgkm	2996.200	2996.200
	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, sanitary landfill	kg	0.02136	0.02136
	Waste glass {CH}| treatment of waste glass, inert material landfill	kg	0.02120	0.02120
	Waste graphical paper {CH}| treatment of waste graphical paper, sanitary landfill	kg	0.01443	0.01443

[a] *ecoinvent v3.10* was used as the source of background data for this study (Wernet et al., 2016)
[b] dataset modified to exclude copper-related inputs, as these had already been included/modeled with ad-hoc datasets
[c] dataset modified by changing the input monomer used (1,4-butanediol instead of ethylene glycol) to represent the production of polybutylene terephthalate (PBT). Assumption deemed reasonable since PET and PBT have a similar chemical composition and production process.

Table A1 Background datasets used for the LCI

B.2 Life Cycle Impact Assessment Results

Impact Category	**Unit**	**New Product**					**Remanufactured Product**					**$DR_{B.E.}$**
		Total	**Production**	**Distribution**	**Use**	**Disposal**	**Total**	**Recovery**	**Distribution**	**Use**	**Disposal**	
Acidification	mol $H+_{eq}$	6.95E+01 *7.27E+00*	13.63% *155.67%*	0.15% *1.44%*	86.20% *527.03%*	0.02% *-584.1%*	6.06E+01 *3.09E+01*	1.05% *2.73%*	0.04% *0.08%*	98.90% *124.10%*	0.00% *-26.91%*	87.16% *424.67%*
Climate change	kg CO_{2eq}	1.06E+04 *7.60E+03*	3.27% *5.54%*	0.05% *0.08%*	96.63% *93.75%*	0.05% *0.64%*	1.03E+04 *7.18E+03*	0.35% *0.51%*	0.02% *0.04%*	99.61% *99.31%*	0.01% *0.14%*	97.00% *94.39%*
Ecotoxicity, freshwater	CTUe	5.56E+04 *5.24E+04*	23.74% *18.19%*	0.03% *0.04%*	76.14% *80.22%*	0.09% *1.56%*	4.33E+04 *4.29E+04*	2.24% *1.63%*	0.02% *0.03%*	97.73% *97.93%*	0.01% *0.42%*	77.91% *81.92%*
Particulate matter	disease inc.	2.46E-04 *2.17E-04*	13.01% *15.61%*	0.12% *0.14%*	86.77% *95.17%*	0.10% *-10.91%*	2.17E-04 *2.05E-04*	1.27% *1.25%*	0.08% *0.09%*	98.63% *100.90%*	0.02% *-2.23%*	87.97% *94.32%*
Eutrophication, marine	kg N_{eq}	1.01E+01 *7.99E+00*	6.48% *11.13%*	0.26% *0.33%*	93.20% *84.62%*	0.06% *3.92%*	9.47E+00 *6.90E+00*	0.62% *0.91%*	0.06% *0.09%*	99.30% *98.07%*	0.01% *0.93%*	93.86% *86.29%*
Eutrophication, freshwater	kg P_{eq}	1.03E+01 *5.47E+00*	7.71% *8.37%*	0.00% *0.01%*	92.28% *90.18%*	0.01% *1.45%*	9.54E+00 *4.99E+00*	0.60% *0.74%*	0.00% *0.00%*	99.40% *98.92%*	0.00% *0.34%*	92.84% *91.16%*
Eutrophication, terrestrial	mol N_{eq}	9.29E+01 *8.75E+01*	9.00% *13.85%*	0.31% *0.33%*	90.66% *80.46%*	0.03% *5.35%*	8.50E+01 *7.23E+01*	0.81% *1.17%*	0.08% *0.09%*	99.11% *97.41%*	0.00% *1.33%*	91.47% *82.60%*
Human toxicity, cancer	CTUh	2.72E-05 *6.00E-05*	11.83% *10.56%*	0.11% *0.08%*	88.00% *88.04%*	0.06% *1.33%*	2.41E-05 *5.34E-05*	0.86% *0.73%*	0.06% *0.05%*	99.07% *98.91%*	0.01% *0.32%*	88.83% *89.01%*
Human toxicity, non-cancer	CTUh	2.55E-04 *2.93E-04*	35.08% *41.10%*	0.01% *0.01%*	64.88% *51.12%*	0.02% *7.77%*	1.71E-04 *1.62E-04*	3.16% *4.33%*	0.01% *0.01%*	96.82% *92.59%*	0.00% *3.07%*	67.01% *55.21%*
Ionising radiation	kBq $U\text{-}235_{eq}$	6.58E+03 *2.54E+03*	0.52% *0.79%*	0.00% *0.00%*	99.48% *99.30%*	0.00% *-0.09%*	6.55E+03 *2.53E+03*	0.05% *0.08%*	0.00% *0.00%*	99.95% *99.94%*	0.00% *-0.02%*	99.53% *99.36%*
Land use	Pt	5.65E+04 *1.76E+05*	6.58% *5.51%*	0.06% *0.02%*	93.30% *93.12%*	0.06% *1.35%*	5.32E+04 *1.65E+05*	0.76% *0.54%*	0.05% *0.02%*	99.18% *99.14%*	0.01% *0.30%*	94.07% *93.93%*
Ozone depletion	kg $CFC11_{eq}$	1.96E-04 *2.19E-04*	4.05% *5.45%*	0.05% *0.04%*	95.88% *94.51%*	0.03% *-0.01%*	1.89E-04 *2.08E-04*	0.44% *0.47%*	0.03% *0.02%*	99.53% *99.50%*	0.00% *0.00%*	96.33% *94.98%*
Photochemical ozone formation	kg $NMVOC_{eq}$	3.05E+01 *2.57E+01*	8.83% *13.71%*	0.27% *0.33%*	90.86% *92.21%*	0.04% *-6.24%*	2.80E+01 *2.37E+01*	0.84% *1.17%*	0.08% *0.09%*	99.07% *100.02%*	0.01% *-1.29%*	91.71% *92.19%*
Resource use, fossils	MJ	2.42E+05 *1.46E+05*	2.15% *4.16%*	0.03% *0.05%*	97.81% *95.51%*	0.02% *0.27%*	2.38E+05 *1.40E+05*	0.21% *0.37%*	0.01% *0.03%*	99.77% *99.54%*	0.00% *0.06%*	98.03% *95.95%*
Resource use, minerals and metals	kg Sb_{eq}	2.68E-01 *6.21E-01*	48.86% *54.81%*	0.00% *0.00%*	51.13% *42.72%*	0.00% *2.47%*	1.47E-01 *2.92E-01*	7.18% *7.80%*	0.00% *0.00%*	92.82% *90.72%*	0.00% *1.48%*	55.09% *47.09%*
Water use	m3 depriv.	3.13E+03 *2.19E+03*	6.09% *12.51%*	0.01% *0.01%*	93.90% *86.46%*	0.00% *1.02%*	2.96E+03 *1.92E+03*	0.54% *0.96%*	0.00% *0.01%*	99.45% *98.76%*	0.00% *0.27%*	94.41% *87.55%*

Table A2 Full LCIA results for new and remanufactured products and associated break-even DRs with an ALCA (regular text) or CLCA (italic text) background

Appendix C – Products with Production-dominated Environmental Profiles

This section applies the conceptual framework developed in the manuscript to a smartphone. Unlike the industrial electronic device examined in the manuscript, smartphones typically have use-dominated environmental profiles (Zink et al., 2014) and relatively low recovery and processing costs (Ovchinnikov et al., 2014). Specifically, the example focuses on a smartphone model renowned for its CE features, for which the producing company commissioned and published an LCA report[3], and shared relevant economic data with us regarding its refurbishing. In fact, the company's refurbishing program was launched with this specific model.

The LCA report specifies a carbon footprint of 39.5 kg CO_{2eq} for the new product, with the following breakdown: 81.5% from *Production*, 1.5% from *Distribution*. 21.3% from *Use*, and -4.2% from *Disposal*. Importantly, this LCA study employs different boundary definitions, modeling assumptions, and databases than our primary case study. Specifically, the results refer to an ALCA background only, though substitution is used for recycling, as evidenced by the negative *Disposal* contribution. We leveraged the report's data to estimate the carbon footprint of the refurbished version (12.3 kg CO_{2eq}), with a breakdown of: 31.8% from *Recovery*, 0.4% from *Distribution*, 68.3% from *Use*, and -0.5% from *Disposal*[4]. This implies a $DR_{B.E.}$ of 31.1%, demonstrating that products with production-dominated profiles are superior candidates for refurbishing/remanufacturing. Indeed, a significantly lower displacement is needed to achieve environmental savings.

Regarding the endogenous *DR*, we calibrated the economic model following the same procedure as in our primary case study. The parameter values differed significantly in this instance: the company was able to collect a relatively larger number of used products (α=9.5%) and the processing cost was substantially lower relative to the new production cost (c_r=19.4% c_n)[5]. This low-cost structure represents another key differentiating feature for this product. The calibrated model returned a value of 62.2% for DR^*, which is considerably lower than in the primary case, indicating a larger rebound effect. However, because the break-even value mentioned above is so low, the company remains safely above the threshold. Figure A1 replicates the analysis of Figure 4 in the manuscript for this product. As illustrated, the company always remains within the constrained regime in this case, primarily due to the low collection and processing costs. Indeed, the profit margin on the secondary product is sufficiently high that it is always profitable to recondition as many units as possible. These considerations point toward a win-win solution for this product type: expanding the refurbishing program is likely to both reduce corporate emissions and increase the firm's profit.

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[3] Details on the report are available from the authors upon request.

[4] Details on this estimation are available from the authors upon request. Notably, as in the primary case study, we assume that secondary products have the same use span and use profile as new products.

[5] As with the primary case, we cannot disclose the other parameter values due to confidentiality.

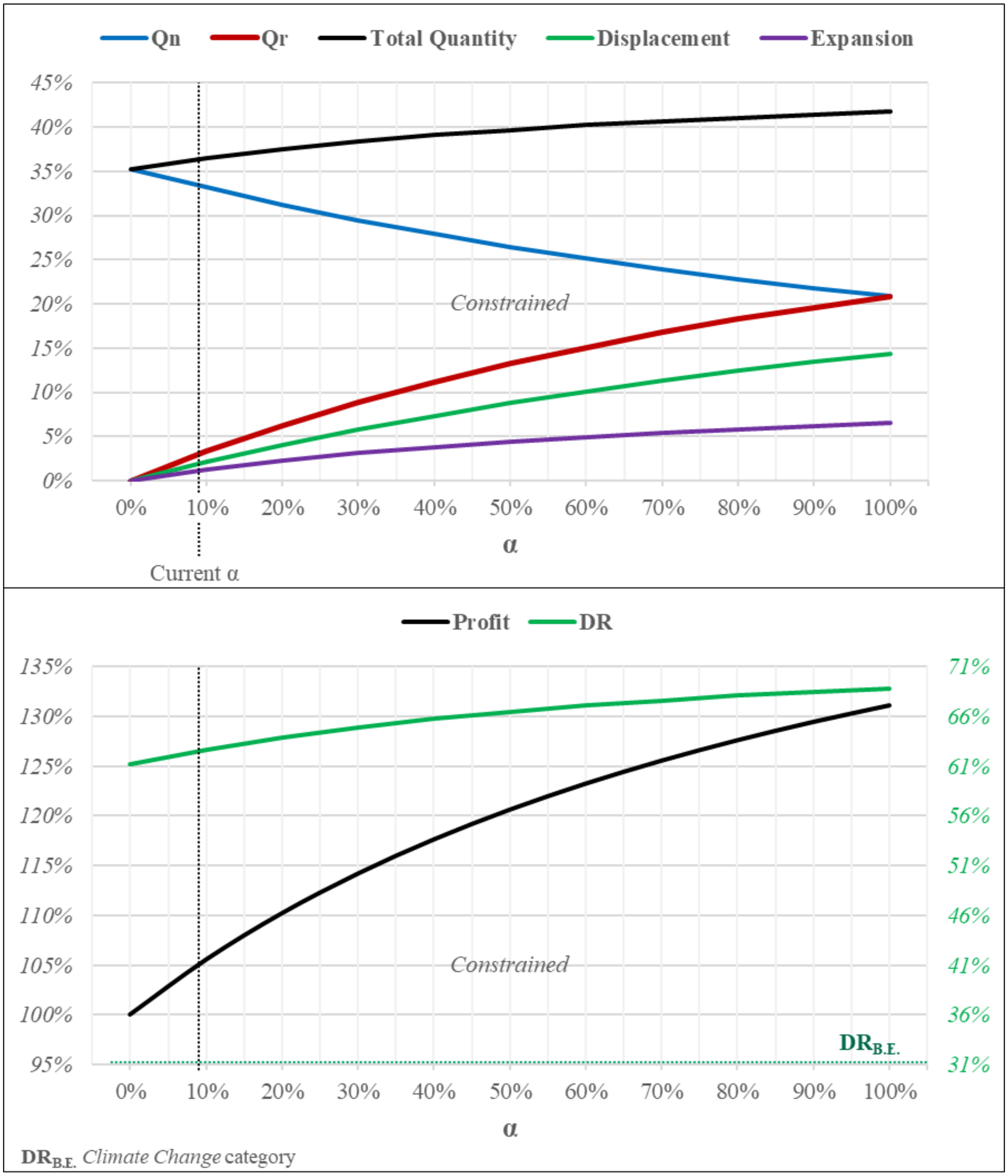

Fig. A1 Optimal quantities (upper panel), profit and DR (lower panel) for the smartphone example

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