SCANDERE - WP3 Deliverable 3.1

Introduction

In the Scandere project, front runners in European industry and academia join forces to tackle the challenges on efficiency and security of critical raw materials (CRMs) for Europe with PaaS (product-as-a-service) business models, taking consumer electrical and electronic equipment as an example. This document is the deliverable 3.1 Results from LCC of a CRM efficient PaaS case (for conference presentation).

Method and material used

The method used for the economic is Life Cycle Costing (Hoogmartens et al., 2024). The PaaS offering assessed here is electrical and electronic equipment (EEE) provided by an industrial partner of the Scandere project. The materials for the assessment for the economic aspect was provided by the industrial partner.

Results and analysis of the economic aspect

In the development of LCC, one fundamental aspect is to adapt the inputs and outputs according to the expectations of the receiver of the information. In this case, it is BSH's expectations of the value its new business model can provide. These expectations correspond to the incentives for companies to gain interest in a change, thus leading to a transformation of reaching higher levels of circular flows, better handling of CRM, and improved sustainability performance. This area was investigated in a paper accepted for publication in Procedia CIRP, see Vogt Duberg et al. (2024), involving BSH among seven other companies in similar situations. The results identified five types of incentives: (1) business model, (2) access to cores, (3) environmental reasoning, (4) future regulations, and (5) technological development. Each of these sets the perspective and direction of the LCC. For example, the incentive for *future regulations* is characterised by modelling the LCC to support companies in meeting the requirements for future regulations, while the *business model* incentive supports business model innovation and identifying the measures needed to reach the best possible state. For BSH's case, it was the latter incentive that guided the development of the LCC as it was incentivised by better CRM and sustainability performance by introducing a PaaS business model.

The next step of the development was to determine the specific inputs and outputs. Here, Figure 1 is used to illustrate how different inputs could build the understanding of certain aspects, e.g., remanufacturing process costs, and how these aspects could be derived from multiple inputs. As such, in an LCC model, costs for, e.g., transports, could either be based on predetermined inputs stating the cost for a product, or the costs could be calculated based on distance, weight, physical dimensions, and time. This is analogous for all parameters and significantly influences how an LCC model is developed and how it supports a company. These results are acknowledged in Vogt Duberg and Sakao (2024), together with an approach for estimating the cost of value-retention processes and providing clear LCC results. Moreover, the theoretical interlinkages between LCC, PaaS and CRM, have been reviewed and presented in a joint conference paper with the other WPs; see Sakao et al. (2023). This created a solid theoretical foundation for the LCC model and ensured that the results could contribute to creating efficient PaaS business models with considerations of CRM in its further development.

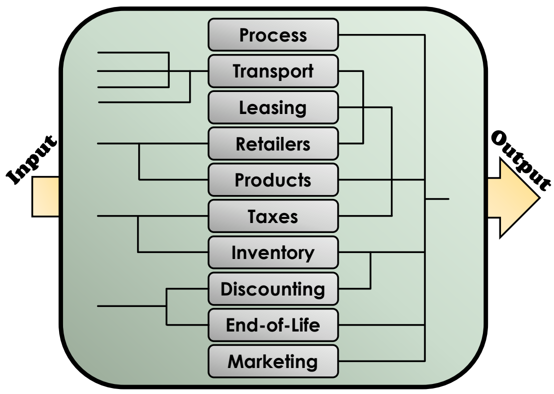

Figure 1. The interconnection of life cycle costing parameters from inputs to outputs (Vogt Duberg and Sakao, 2024).

A set of data has been received from BSH to be integrated into the LCC model and an initial LCC model based on net present value (NPV), total cost of ownership (TCO), and equivalent annual annuity (EAA) has been developed by WP3. Using these discounting methods, the PaaS offerings can be compared with the current linear business models of BSH as well as relate the lucrativeness of PaaS for the provider (BSH) and the user, respectively. The initial LCC model has been discussed together with BSH and the rest of the project team to refine what data could be used within the project and which additions are needed to develop the final LCC model. WP3 contributed to the PaaS business model development led by WP4. In this development, WP3 primarily provided inputs from a cost perspective, that is, how different business models influence the cash flows when transitioning from a one-off sales business model towards PaaS. For this, a rough version of a LCC model was developed to compare different PaaS setups and provide decision support. The model is based on discounting and a bottom-up approach; see Appendix A for the technical specifications. In Figure 2, three approaches for setting the PaaS subscription fee in relation to the PaaS contract length are illustrated. As such, scenarios can be created which provide benefits to loyal customers (see PaaS Long-term loyal) while still providing the same total profitability as other business models where there are constant PaaS subscription fees throughout the contract (see, e.g., PaaS long-term). These considerations contribute to understanding the impact, value, and trade-off of the proposed business models, and support their development.

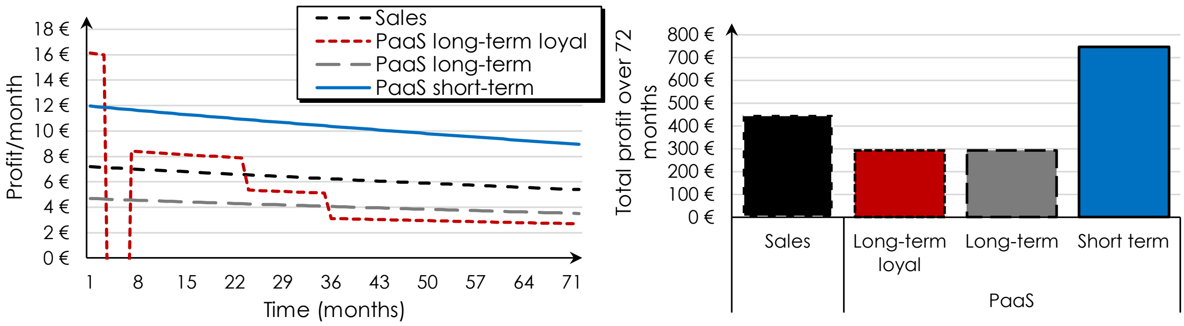

Figure 2. Overview of the rough life cycle costing outputs for four different business models where the PaaS subscription fee is altered depending on scenarios. The profit of the sales business models is distributed equally over the time period (Hidalgo-Crespo et al., 2024).

The results of the rough LCC were incorporated in a joint conference paper for LCE2024 between WP3 and the other WPs; see (Hidalgo-Crespo et al., 2024). Since that contribution, the final business model for BSH has been decided, and WP3 is working on the LCC that provides insights on how the business model can be modified to perform better than the original business model in terms of CRM efficiency and financial performance. In Figure 3 and Figure 4, the LCC modelling logic of the business model is illustrated. The PaaS business model consists of two parts: *short* and *long* contract length. The modelling logic acts as the basis for the LCC, and it is the size and frequency of these flows that are modified in the scenario-based analysis of the LCC to derive insights for the business model development.

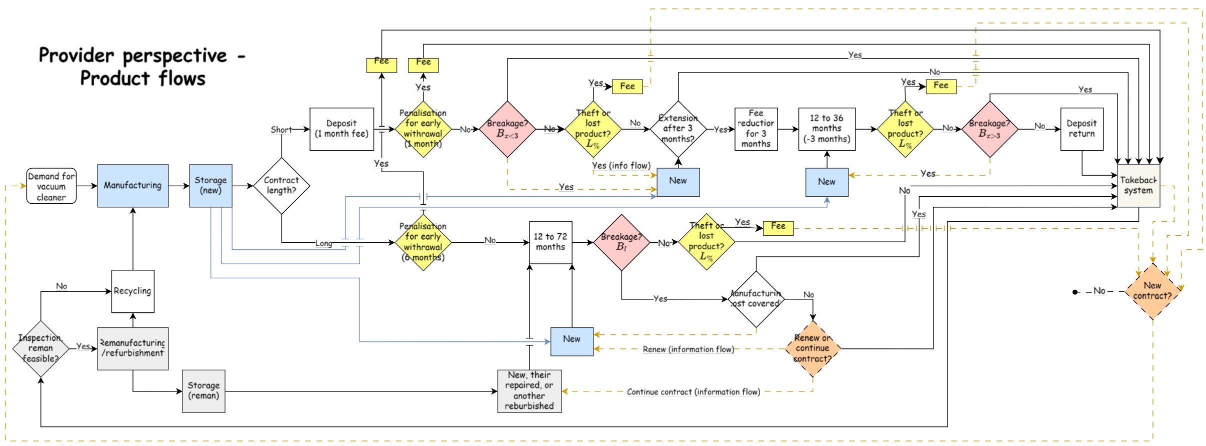

Figure 3 Flow chart of the product stages of the proposed business model from the provider perspective.

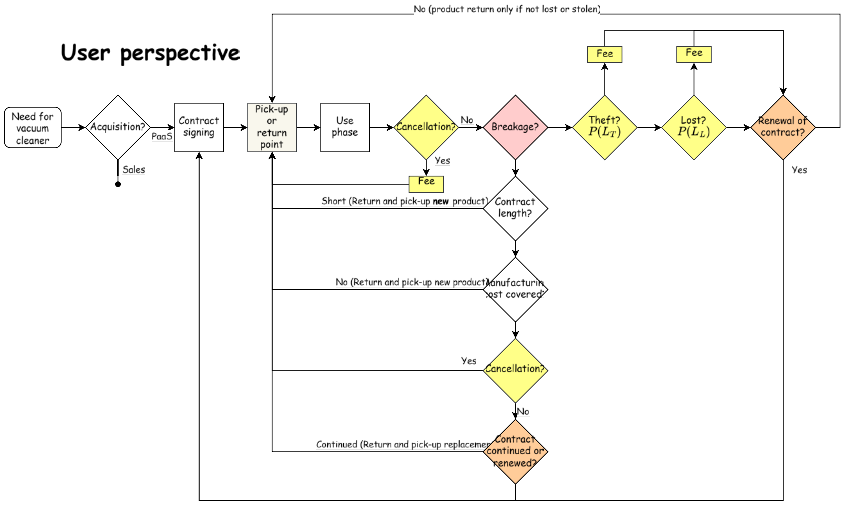

Figure 4 Flow chart of the product stages of the proposed business model from the user perspective.

So far, WP3, within the LCC scope, has contributed to four conference papers (Hidalgo-Crespo et al., 2024; Sakao et al., 2023; Vogt Duberg et al., 2024; Vogt Duberg and Sakao, 2024), that provide an understanding of the preparatory work of LCC development, its limits and possibilities. Moreover, the LCC model used for BSH is currently under review for the International Journal of Production Research entitled *Unveiling the financial viability of transformation from product sales to product-as-a-service*. This paper developed a systematic assessment approach consisting of three steps: (1) provide a cost overview for each business model, (2) create scenarios by modifying the cost drivers, and (3) combine scenarios to reach synergetic effects. It also described the modelling logic of the LCC. A condensed version of the modelling logic is provided in Appendix A. The final results of the LCC related to BSH is planned to be published in another journal paper.

SCANDERE - WP3 Deliverable 3.2

Introduction

This document is the deliverable 3.2 Report on an analysis of the sustainability assessment of one case (for journal paper) from WP3 of the Scandere project, i.e., Assessing the sustainability of PaaS offerings. The economic aspect was delivered as D3.1.

Methods and materials used

The methods used for the environmental and social assessment are Material Flow Analysis (Brunner and Rechberger, 2004) and the social LCA (UNEP, 2020 and UNEP, 2021), respectively, focusing on the CRM efficiency. The PaaS offering assessed here is electrical and electronic equipment (EEE) provided by an industrial partner of the Scandere project. The materials for the assessment for the environmental aspect were provided by the industrial partner; for the social assessment, they were collected from commercial websites and scientific literature on PaaS.

Results and analysis of the environmental aspect

Method in details

For the environmental aspect, a material flow analysis is performed using four 3 scenarios of a portable vacuum cleaner powered by a battery. The focus is on critical raw material (CRM) as defined by the European Commission (Grohol and Veeh, 2023). MFA is an analytical method to quantify flows and stocks of materials and or substances in a defined system. The following diagram in Figure 5 shows the studied system and the included material flows.

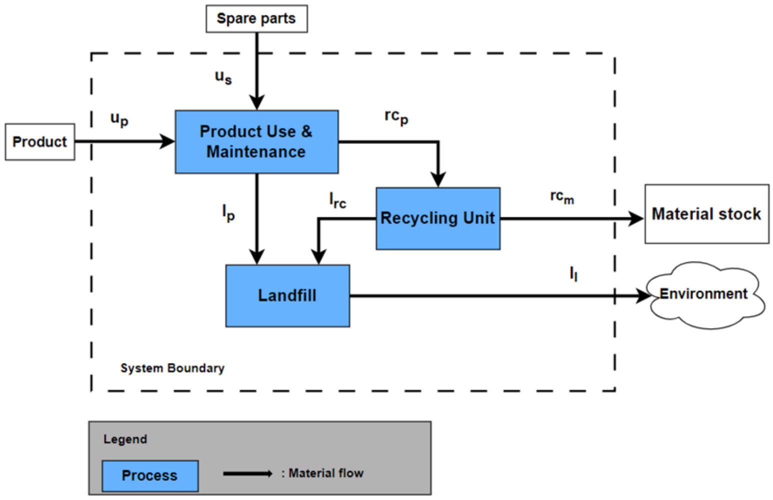

Figure 5 Processes and material flows that are covered in the MFA.

Formulae are developed to build the MFA model and to understand the material flows through the system, see Appendix B for the factors and formulae according to the mass balance for the static model as shown in Figure 5. In the Appendix B the assumptions regarding recycling yield.

In the material flow analysis, the use phase and end-of-life phases are considered, the product is sold and used in the EU region and its service life is considered to be 8 years (Gallego-Schmid et al., 2016), and the battery has an expected life length of 5 years. Three scenarios are investigated, see Table 1, and the functional unit is defined as **using a vacuum cleaner for one year**. The impact assessment method ReCiPe (H) Midpoint (Huijbregts et al., 2017) is used to investigate the environmental effect on mineral resource scarcity based on the estimated material flows.

Table 1 Scenarios in the MFA

Scenario	Description
1	A traditional product sales model, where the product is purchased by the end user. The collection rate at EoL is assumed to be 33%.
2	A PaaS model. The product ownership lies with the provider. The product is offered as a short-term contract of 3 years. After the end of the contract period, the battery is replaced, the vacuum cleaner is used for 5 more years. The collection rate at EoL is assumed to be 100%.
3	A PaaS model. The product ownership lies with the provider. The product is offered as a lease for a long-term contract of 6 years. During the lease, the batty is replaced one time. After the end of the contract period, the vacuum cleaner is used for 4 more years. The collection rate at EoL is assumed to be 100%.

Data collection and assumptions

BSH has provided the data, i.e. bill of material (BoM) for the vacuum cleaner and based on the BoM and the list of CRMs, an analysis is conducted to identify the CRMs present in the product. In the case of the vacuum cleaner, these specific components are printed circuit boards (PCBs), permanent magnets, and battery packs. The identified components containing CRMs is presented in Table 2.

Table 2 CRM content in the studied vacuum cleaner (Heimes et al. 2023, Kara et al. 2010)

Components	CRM
Li-ion battery	Lithium (Li) Cobalt (Co) Nickel (Ni) Manganese (Mn)
PWB	Aluminium (Al) Beryllium (Be) Bismuth (Bi) Cobalt (Co) Copper (Cu) Magnesium (Mg) Manganese (Mn) Antimony (Sb) Strontium (Sr) Titanium (Ti)
Permanent magnet	Neodymium (Nd) Dysprosium (Dy)
Other components	Aluminium (Al) Copper (Cu)

Material flow

The resulting material flows in the different scenarios are illustrated in Figure 6 to Figure 9. As expected, The Product sales have the highest material flow of the CRM found in the PWB and in the permanent magnets, and also of the aluminium and copper. The use of these two materials is relatively high which is also expected since they are commonly used in several components of the product. Notably, the two PaaS scenarios stand out with regard to the CRM in the batteries. The total outflow, including both recycling and landfill, is dependent upon the input material. In Product sales, repair activities are absent, and no components are replaced. This also leads to a shorter use period of the vacuum cleaner compared to the PaaS. In the PaaS alternatives, spare parts are added to the system, thereby increasing the in- and outflow of the studied system. This is due to the need to replace the batteries after 5 years when its state of health (SOH) has reached a threshold where the capacity is too low. Even though more material is needed with repairs, with the PaaS the amount that can be recircled back into the economy is higher compared to Product sales due to the higher collection rate. This also is the case with the other CRMs included in the study.

Li in the battery and several of the CRMs in the PWB and permanent magnets are not recycled today, even if it is technically possible. Consequently, it becomes evident that there is a pressing need to enhance collection and recycling processes, for lithium and rare earth metals. To some extent, this depends on the relatively low cost of the raw material leading to the recycling is not cost-effective. However, the demand for CRM is increasing, hence the price of the raw material will likely rise, and there will also be a larger stock of material that can be recycled. Therefore, it is likely that recycling will become more cost-efficient in the future. The capacity to recycle Li is increasing in Europe where several larger facilities are being built. The development of methods to recycle CRMs used in permanent magnets is also promising.

The outflow of materials is closely tied to the **service lifetime** of the scenario at hand. The longer a product or a component can stay in use the better it is. The PaaS business model, where the provider takes back the product after use, has the potential of remanufacturing or refurbishing crucial components that can be used again. Hence, further prolonging the use of resources. This may primarily concern the battery and the electric motors. This possibility is though not investigated in the scenarios presented.

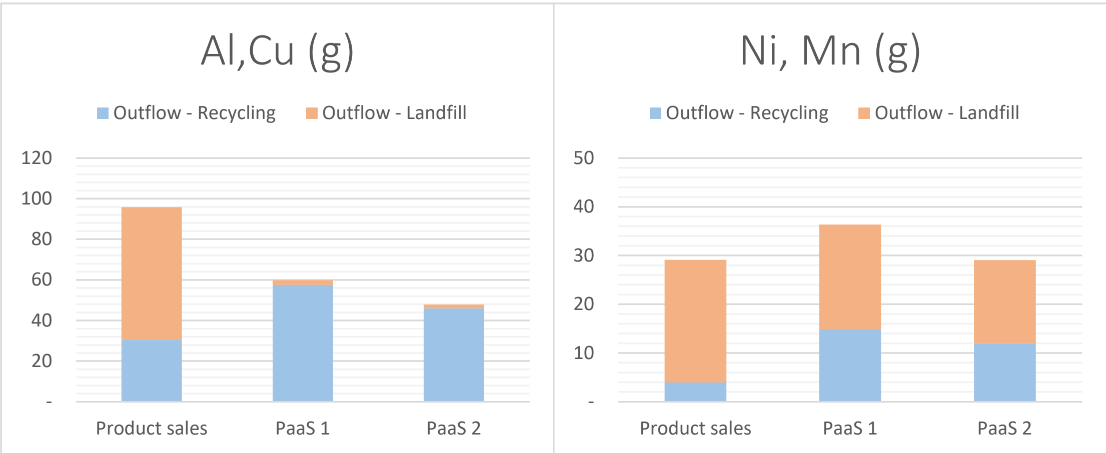

Figure 6 Outflow of Al, Cu, Ni and Mn to landfill and from recycling to market in the studied scenarios.

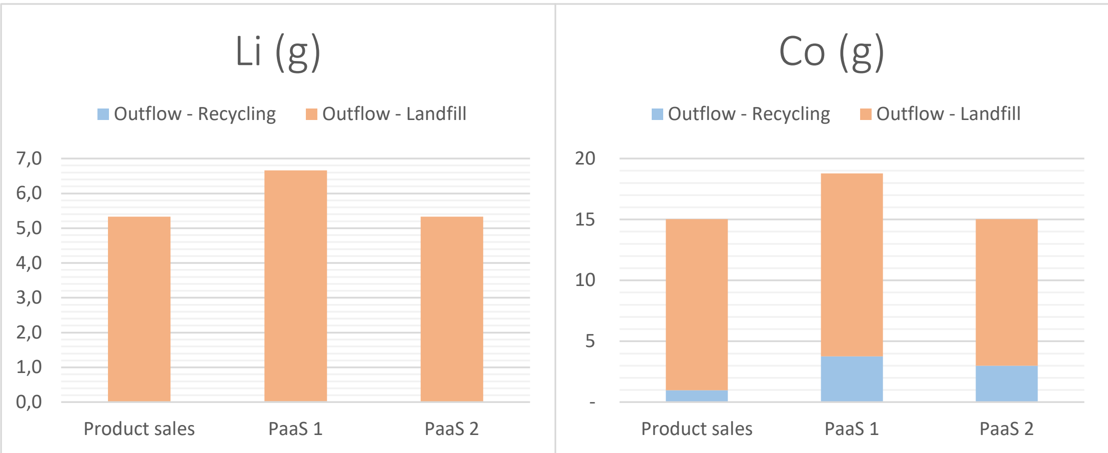

Figure 7 Outflow of Li and Co to landfill and from recycling to market in the studied scenarios.

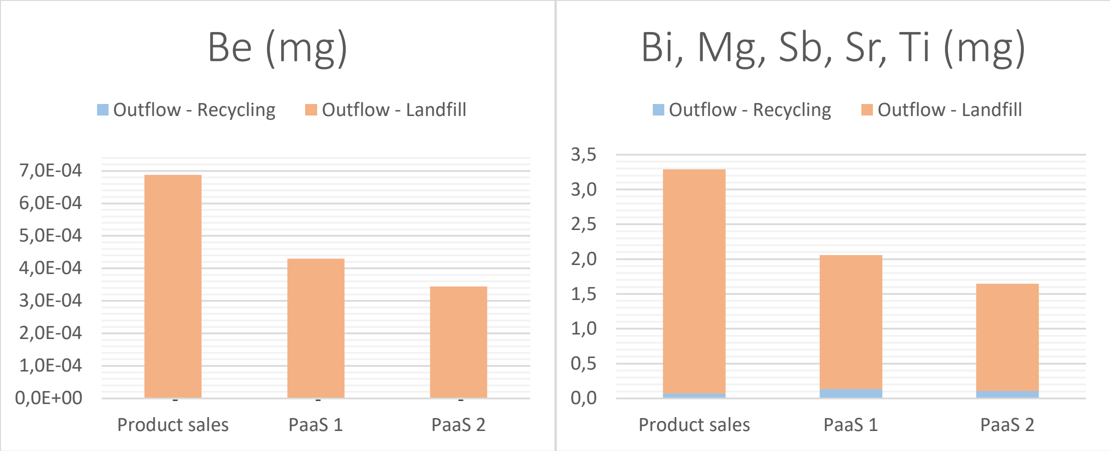

Figure 8 Outflow of Be, Bi, Mg, Sb, Sr and Ti to landfill and from recycling to market in the studied scenarios.

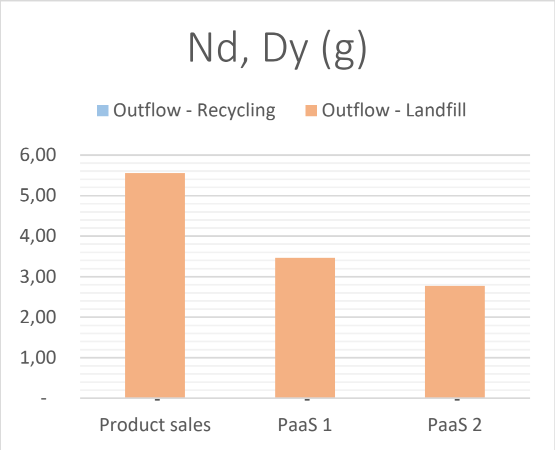

Figure 9 Outflow of Nd and Dy, to landfill and from recycling to market in the studied scenarios.

Mineral resource scarcity

Using the impact factors regarding mineral resource scarcity as defined by ReCiPe (H) Midpoint and measured in Cu-equivalent, it is possible to show the relative importance of the various CRMs in the system and to compare them. The estimated impact in the scenarios is illustrated in Figure 10. Nd and Dy are not included in the figure due to a lack of data regarding environmental impact factors. As illustrated, Co and Ni are the CRMs with the highest relative importance in the system in all three scenarios. This is primarily due to the absolute amount. In addition, Co and Ni also have a high impact factor in this environmental impact category, as does Li. However, the amount of Li used in the scenarios is lower than Co and Ni, hence the relative importance of Li is lower which is shown in Figure 11. Furthermore, Cu is relatively important in the case of Product sales, which is due to the low collection rate. A conclusion is that components where these materials are present, i.e. mainly the batteries, should be in focus when prioritising remanufacturing, refurbishing or recycling.

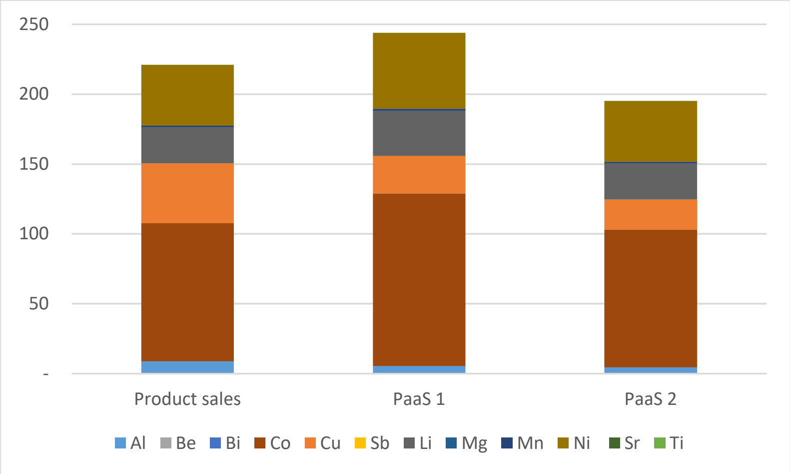

Figure 10. The environmental effect of mineral resource scarcity of the investigated scenarios in Cu-eq.

Results and analysis of the social aspect

The assessment results are shown in Appendix C. The local community in this case is on a municipality level, while the society is considered at the national level. The value chain includes manufacturers, service providers, and logistic partners, who play key roles in producing, offering services, and distributing goods. Consumers represent the end users of these products and services.

Under the PaaS offering, in the workers category, positive impacts are observed in terms of occupational safety for workers (W2). Reduced manufacturing and thereby limited exposure to production machinery contribute to a potentially lower rate of workplace accidents. However, the need for continuous service provision in the PaaS offering may result in increased working hours (W5) for employees to support 24/7 operations, related to work-life balance for workers.

Local communities are also expected to experience changes under the PaaS offering. There is a potential increase in local employment (L1) opportunities as the PaaS offering has a potential to foster local supply networks and increase the percentage of hiring local people. Moreover, improved living conditions (L7) might be observed due to reduced exposure to hazardous materials, contributing to overall community well-being. Access to intangible resources (L4) within communities could also see positive impacts under the PaaS offering.

In terms of value chain actors, the PaaS offering encourages stronger supplier relationships and collaboration (V3) to improve the supply chain. However, challenges arise in terms of intellectual property rights (V4), as some actors may need or want to share data with Original Equipment Manufacturers (OEMs) to monitor and improve services, impacting proprietary information and control over intellectual property.

Consumers benefit from improved product performance and safety standards (C1) under the PaaS offering. However, possible concerns exist regarding consumer privacy (C3), with potential data sharing between service organizations impacting consumer integrity. On a positive note, the PaaS offering promotes responsible end-of-life practices (C5), with products being returned for recycling, contributing to sustainable disposal practices.

From a societal perspective, the PaaS offering has a potential for economic development (S2) through technological advancements (S4), skills enhancement, and job creation.

Acknowledgement

The SCANDERE (Scaling up a circular economy business model by new design, leaner remanufacturing, and automated material recycling technologies) project has been granted from the ERA-MIN3 program under the grant number 101003575.

ERA-MIN 3

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References

Brunner, P.H., Rechberger, H. 2004. Practical Handbook of Material Flow Analysis. Lewis Publishers, New York. ISBN 978-1-56670-604-9.

Gallego-Schmid, A., F. Mendoza, J. M., Jeswani, H. K., Azapagic, A. 2016. Life cycle environmental impacts of vacuum cleaners and the effects of European regulation. Science of the Total Environment, 558, 192–203. http://dx.doi.org/10.1016/j.scitotenv.2016.03.149

Grohol, M., Veeh, C. 2023. European Commission, Study on the Critical Raw Materials for the EU 2023 – Final report.

Hidalgo-Crespo, J., Riel, A., Vogt Duberg, J., Bunodiere, A., Golinska-Dawson, P., 2024. An exploratory study for product-as-a-service (PaaS) offers development for electrical and electronic equipment, in: Procedia CIRP 31st CIRP Conference on Life Cycle Engineering.

Hoogmartens, R., Van Passel, S., Van Acker, K., Dubois, M., 2024. Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. Environ. Impact Assess. Rev. 48, 27–33. https://doi.org/10.1016/j.eiar.2014.05.001

Hujibregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R. 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The International Journal of Life Cycle Assessment, 22, 138-147.

Sakao, T., Golinska-Dawson, P., Vogt Duberg, J., Sundin, E., Hidalgo Crespo, J., Riel, A., Peeters, J., Green, A., Mathieux, F., 2023. Product-as-a-service for critical raw materials: challenges, enablers, and needed research, in: Proceedings of Going Green: CARE INNOVATION. Vienna, Austria, May 9-11.

UNEP (United Nations Environment Programme) (2020). Guidelines for Social Life Cycle Assessment of Products and Organisations 2020. https://wedocs.unep.org/20.500.11822/34554

UNEP (United Nations Environment Programme) (2021). Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA).

Vogt Duberg, J., Sakao, T., 2024. Supporting the Transformation to Access-Based Business Models in a Circular Economy with a Practical Model for Calculating the Costs of the Provider, in: Advances in Transdisciplinary Engineering. Volume 52: Sustainable Production through Advanced Manufacturing, Intelligent Automation and Work Integrated Learning, Advances in Transdisciplinary Engineering. IOS Press, Trollhättan, Sweden, pp. 532–542. https://doi.org/10.3233/ATDE240195

Vogt Duberg, J., Sundin, E., Kurilova-Palisaitiene, J., 2024. Exploring the incentives for initiating remanufacturing: experiences from eight European original equipment manufacturer, in: Procedia CIRP 31st CIRP Conference on Life Cycle Engineering.

Appendix A – Equations for the financial assessment

Table 3. Nomenclature.

EAC	Equivalent annual cost
T	Time span
TBM	Time between maintenances
L	Cycle length
l	Downtime between cycles, e.g., remanufacturing lead time
L_{pre}	Cumulative length of all previous cycles and downtimes between cycles
$L_{\%}$	Point of time in cycle length product needs repair. $L_{\%} \in \{0, \dots, 1\}$
n	Number of maintenances per cycle
α	Discount factor
τ	Discount rate
f	Remanufacturing fail rate. $f \in \{0, \dots, 1\}$
c_r	Core collection rate. $c_r \in \{0, \dots, 1\}$
c_{rc}	Collection rate for recycling. $c_{rc} \in \{0, \dots, 1\}$
b	Discounted at start of cycle ($b = 0$), or at end of cycle ($b = 1$)
W	Warranty length in cycle. $W \in \{0, \dots, L\}$
W_q	Warranty active ($W_q = 1$) or inactive ($W_q = 0$). $W_q \in \{0,1\}$
d	Value depreciation rate over time. $d \in \{0, \dots, 1\}$
$P_M\%$	Maintenance cost mark-up for provider. $P_{M\%} \in \{0, \dots, 1\}$
$P_F\%$	PaaS fee mark-up. $P_{F\%} \in \{0, \dots, 1\}$
COSTS	
C_{bb}	Acquisition cost (buy-back) or revenue (sell-back)
C_{cl}	Commission cost (PaaS)
C_{cs}	Commission cost (Sales)
C_d	Disposal cost
C_M	Maintenance cost
C_{Mf}	Manufacturing cost
C_a	PaaS management cost
C_{rc}	Recycling cost
C_{Rf}	Remanufacturing cost
C_{rl}	Repair cost (PaaS)
C_{rs}	Repair cost (Sales)
U_{rs}	Repair cost (Sales, user)
C_{tot}	Total cost
T_p	Transport cost provider
T_{ux}	Transport cost user, $x = f$ and $x = r$ indicate forward and reverse, respectively
F	PaaS fee (Same as revenue)
REVENUES	
F	PaaS revenue (Same as cost)
R_{rs}	Repair revenue (Sales)
S_N	Sales price of a new product
S_R	Sales price of remanufactured product

Equivalent annual annuity (EEA) is used in the financial assessment as in Eq. (1) given that $\tau \neq 1$ and $T \neq 1$.

$$EAA = NPV\left(\sum_{t=1}^{T} \tau^t\right)^{-1} = NPV\frac{\tau - 1}{(\tau^{T+1} - \tau)} \tag{1}$$

The NPV for the *provider* is based on retracting discounted costs from revenues to derive the NPV value, see Eq. (1) and (2), while for the *user*, it is primarily based on costs; Eq. (3) and (4). The NPV in Eq. (1) corresponds to $NPV_{Sales}, NPV_{PaaS}, TCO_{Sales}$, and TCO_{PaaS} below.

$$NPV_{Sales} = S_N + S_R - C_{bb} - C_{cs} - C_{cl} \pm (1 - P_{M\%})C_M - C_{Mf} - C_{rc} - C_{Rf} - C_{rs} \pm R_{rs} \tag{2}$$

$$NPV_{PaaS} = F - C_a - C_{cl} - C_M - C_{Mf} - C_{rc} - C_{Rf} - C_{rl} \tag{3}$$

$$TCO_{Sales} = C_d + (1 - P_{M\%})C_M + U_{rs} + S_N + S_R - C_{bb} \tag{4}$$

$$TCO_{PaaS} = F + (1 - P_{M\%})C_M + U_{rs} + S_N + S_R \tag{5}$$

Each parameter has a corresponding discount and scaling factor according to Table 2.

Table 4. The parameters used in the financial assessment model and their corresponding discount and scaling factor to discount the values over time. Four scenarios are indicated by the signs ■, □, •, and ○ as defined at the bottom.

Type	Parameter	Discount and scaling factors
Acquisition	■C_{bb} □C_{bb}	$(1-c)\tau^{L_{pre}+bL}$
PaaS management	•C_a	$\tau^{L_{pre}}[single]$ OR $\frac{\tau^{L_{pre}+L+1} - \tau^{L_{pre}+1}}{\tau - 1}$ $[recurring]$
Commission	■C_{cs} •C_{cl}	$\tau^{L_{pre}}$
Disposal	□C_d	$c\beta^{L_{pre}+L}$
PaaS fee	•○F	$\frac{\tau^{L_{pre}+L+b} - \tau^{L_{pre}+b}}{\tau - 1}$
Maintenance	•C_M ■$(1-P_{M\%})C_M$ □$(1-P_{M\%})C_M$	$\frac{\tau^{\frac{L}{n+1}+L_{pre}}\left(\tau^{\frac{L}{n+1}n} - 1\right)}{\tau^{\frac{L}{n+1}} - 1}$
Manufacturing	•■C_{Mf}	$\left(1-(1-f)(1-c_r)\right)\tau^{L_{pre}}$
Recycling	•■C_{rc}	$(f + c_{rc})\tau^{L_{pre}+L}$ OR $\tau^{L_{pre}+L}\frac{\tau - 1}{\tau(\tau^{L_{pre+L}} - 1)}$
Remanufacturing	•■C_{Rf}	$(1-f)(1-c_r)\tau^{L_{pre}+bL}$
Repair	•C_{rl} ■C_{rs}	$\tau^{L_{pre}+L\cdot L_{\%}}$ $[single]$ OR $\frac{\tau^{L_{pre}+L+1} - \tau^{L_{pre}+1}}{\tau - 1}$ $[recurring]$
	■R_{rs} □U_{rs}	$W \geq L \cdot L_{\%}$ $then$ $W_q = 1, else$ $W_q = 0$ $W_q\tau^{L_{pre}+L\cdot L_{\%}}$ OR $\frac{\tau^{L_{pre}+L+1} - \tau^{L_{pre}+W+1}}{\tau - 1}$
Sales	■$S_N + S_R$ □$S_N + S_R$	$\tau^{L_{pre}+bL}$

■ Sales model (provider): τ = α • PaaS model (provider): τ = α
□ Sales model (user): τ = β ○ PaaS model (user): τ = β

Repair transaction

The discounted repair transaction is described by Eq. (6) where if $W \geq L \cdot L_{\%}$ then $W_q = 1$, otherwise $W_q = 0$

$$Repair = W_q R_{rs} \alpha^{L_{pre}+L\cdot L_{\%}} \tag{6}$$

Maintenance transaction

The discounted maintenance is described by Eq. (7).

$$Maintenance = (1 - P_{M\%})C_M \frac{\tau^{\frac{L}{n+1}+L_{pre}}\left(\tau^{\frac{L}{n+1}n} - 1\right)}{\tau^{\frac{L}{n+1}} - 1} \tag{7}$$

Remanufacturing transaction

Depending on the scenario, the remanufacturing acquisition and process are either at the start of a cycle or at the end, depending on whether a manufacturing activity is present, as in Eq. (8) and Eq. (9), respectively, by adapting the Boolean parameter b.

$$C_{bb} = (1 - c_r)\tau^{L_{pre}+bL} \quad (8)$$

$$C_{Rf} = (1 - f)(1 - c_r)\tau^{L_{pre}+bL} \quad (9)$$

End-of-life transitions

The collection rate c_{rc} handles disposal instances where the core disappears, while Eq. (10) and Eq. (11) describe the discounting and scaling of these transactions.

$$Disposal = C_d c \beta^{L_{pre}+L} \quad (10)$$

$$Recycling = (f + c_{rc}) C_{rc} \alpha^{L_{pre}+L} \quad (11)$$

Other transactions

PaaS fee is calculated based on the total cost with a mark-up value up to an upper limit; see Eq. (13).

$$F = \max\left\{\frac{C_{tot}(1 - P_{F\%})}{L_{pre}}; F_{max}\right\} \quad (13)$$

In cases where the collection rate and remanufacturing yield induce non-binary values, the model provides an average scenario, as shown in Eq. (14)

$$Sales\ price = (1 - f)(1 - c_R)S_R + \big(1 - (1 - f)(1 - c_R)\big)S_N \quad (14)$$

Transport transactions

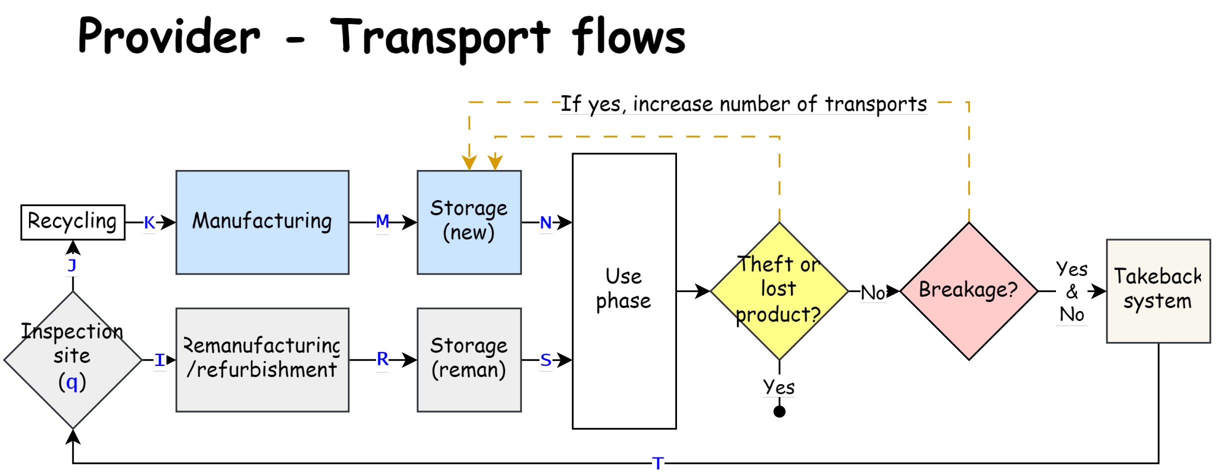

Figure 11. Flow chart of the transport flows of the proposed business model.

The equations and nomenclature below correspond to the transports flows of Figure 9.

$$\text{Avg. No. of transports per PaaS contract} = q\big((M + N)(1 + L_{\%} + B_{\%}) + T(1 + B_{\%}) + (J + K)(1 + B\%)\big) + (1 - q)\big((R + S + I)(1 + L_{\%} + B_{\%}) + T(1 + B_{\%})\big)$$

$$where\ \ q = (1 - Y_r)F_{lc}$$

q : Share of total PaaS fleet that are new products

$B_{\%}$: $Probability\ of\ failures\ in\ PaaS\ (long\ or\ short\ contract)$

Y_r : $Remanufacturing\ yield\ rate$

F_{lc} : $Probability\ of\ failure\ in\ long - term\ contract, = 1\ if\ short$

$B_{\%} = b * \text{Short contract} + (1 - b) * \text{Long contract} = b(B_{x<3} + B_{x>3}) + (1 - b), B_l$ where b is a binary parameter for short or long contract

$B_{x<3}, B_{x>3}$: $Probability\ of\ failure\ in\ short\ contract\ before\ or\ after\ 3\ months$

$L_{\%} = L_{Theft} + L_{Lost}$: $Probability\ of\ theft\ or\ lost\ product$

$L_{\%} = P(L_{Theft}) + P(L_{Lost}) = P(L_T) + P(L_L)$

Appendix B – Equations and assumption for the environmental assessment

The flows in Figure 5 are defined as:

u_p= Mass of material entering the product in use phase per unit of time (g)

u_s= Mass of material entering the use phase for spare parts used per unit of time (g)

rc_p= Mass of material entering the recycling unit within the used products or spare parts per unit of time (g)

rc_m= Mass of material entering into material stock from the recycling unit per unit of time (g)

rc_y= Recycling yield of recycling unit (%)

l_p= Mass of material entering the landfill from within the used products per unit of time (g)

l_{rc}= Mass of material entering the landfill from the recycling unit per unit of time (g)

l_l= Mass of material leaking to the environment per unit of time (g)

L_p= Length for use in product sales case (years)

CR_p= Collection rate in product sales case (%)

I = total material input into the system

Formulae are developed to build the MFA model and to understand the material flows through the system. In this analysis, the use phase and end-of-life phase are considered. According to the mass balance for this static model shown in Figure 5, the following formulae are used.

$$u_p + u_s = rc_p + l_p \quad (1)$$

$$rc_p = rc_m + l_l \quad (2)$$

$$l_p + l_{rc} = l_l \quad (3)$$

$$l = u_p + u_s \quad (4)$$

The following formulae are used in estimating the values for the above model.

$$rc_y = rc_m / rc_p \quad (5)$$

$$CR_p = rc_p / (u_p + u_s) \quad (6)$$

The following formulae are valid for the balancing of the total system, i.e. total mass entering the system per unit of time equals total mass entering stock per unit of time plus total mass leak into the environment per unit of time.

$$l = rc_m + l_l \quad (7)$$

The recycling unit yield (rc_y) is defined as the ratio of recycled materials processed (rc_m) to materials collected for recycling (rc_p). rc_y is determined by the statistics of recycling yield in Europe. Table B-1 lists the recycling yield for the identified materials in the product.

Table B-1 Recycling unit yield for the included metals and minerals.

Material	Recycling unit yield, rc_y
Al, Cu	96%
Sb, Bi	23%
Co	32%
Li	0.4%
Mn	40%
Ni	42%
Be, Nd, Dy, Mg	0%

Source: Chancerel et al. 2016, Torres De Matos et al. 2020, van Nielen et al. 2023

Collection rate (CR_p) is the materials removed from the product during refurbishment/repair that goes to recycling. When the provider is responsible for EoL, all the materials go to recycling. When an end user is responsible for EoL, the share that is recycled is based on the statistics of WEEE in Europe.

The repair parts ratio (RR) is determined by the average repair activity in Europe and the BOM. As per previous studies, (Sakao et al., 2019) PCBs are mostly replaced during repair/refurbishing. In addition to that, it is assumed that batteries are replaced in repair/refurbishing. As per BOM provided by the case company PCB has a mass of 0.349 g (7% of the product weight) and the battery pack has a mass of 0.668 g (14% of the product weight). No parts containing Al and Cu nor permanent magnets are replaced in all scenarios.

Appendix C – Result of social assessment of a PaaS offering

ID	Stakeholder category[1]	Subcategories[1]	Inventory Indicators[2]	PaaS offering
W1	Workers	Freedom of association and collective bargaining	Employment is not conditioned by any restrictions on the right to collective bargaining	No influence
W2	Workers	Health and Safety	Occupational accident rate	Positive – reduction in product Manufacturing and exposure to the production machines might reduce workplace accidents
W3	Workers	Forced labor	Percentage (estimate) of forced labor	No influence
W4	Workers	Child labor	Working children younger than 15 and under the local compulsory age are attending school	No influence
W5	Workers	Working hours	Number of hours effectively worked by employees	Negative – to provide continuous service 24*7 to the user, working hours might increase
W6	Workers	Fair Salary	Lowest-paid worker, compared to the minimum wage	Unknown
W7	Workers	Equal opportunities / discrimination	Women in the Labor force participation rate by country	No influence

[1] Guidelines for SOCIAL LIFE CYCLE ASSESSMENT OF PRODUCTS AND ORGANIZATIONS 2020,UNEP(2020)
[2] The Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA), UNEP & SETAC (2013)

W8	Workers	Social benefits / social security	List and provide a short description of social benefits provided to the workers (eg. Health insurance, pension fund, child care, education, accommodation etc.)	Unknown
W9	Workers	Employment relationship		Unknown
W10	Workers	Sexual harassment		No influence
W11	Workers	Smallholders including farmers		Possibly Positive – provides opportunities for smallholders to provide service tools, delivering the product.
L1	Local Community	Local Employment	Presence of Local Supply Networks, Percentage of workforce hired locally, Percentage of spending on locally based suppliers	Possibly Positive – open new market opportunities for local entrepreneurs Improve the local skills and competencies
L2	Local Community	Access to drinking water		Unknown
L3	Local Community	Access to material resources	Extraction of Material Resources, Levels of Industrial Water Use	No influence
L4	Local Community	Access to immaterial resources	Presence/strength of community education initiatives	Possibly positive (on repair resource)
L5	Local Community	Delocalization and migration	Strength of organizational policies related to resettlement	Unknown
L6	Local Community	Cultural heritage	Strength of Policies in Place to Protect Cultural Heritage	No influence
L7	Local Community	Safe and healthy living conditions	Management effort to minimize use of hazardous substances	Possibly positive – less exposure to hazardous materials
L8	Local Community	Respect of Indigenous rights	Indigenous Land Rights Conflicts/Land Claims	Unknown
L9	Local Community	Community engagement	Diversity of community stakeholder groups that engage with the organization	Unknown
L10	Local Community	Secure living conditions		Unknown
V1	Value chain actors	Fair competition		Unknown
V2	Value chain actors	Promoting social responsibility	Support to suppliers in terms of consciousness-raising and counseling concerning the social responsibility issues	Possibly Positive – influence the supply chain to promote social responsibility -logistic partners
V3	Value chain actors	Supplier relationships	Reasonable volume fluctuations	Positive-provide opportunities to improve the supply chain and their relationships – collaboration is key
V4	Value chain actors	Respect of intellectual property rights	Organization's policy and practice, Use of local intellectual property	Negative – supply chains have to share their data with OEM to monitor the services for improvement Positive- OEM gets more information
V5	Value chain actors	Wealth distribution		Unknown
C1	Consumers	Health and Safety	Presence of management measures to assess consumer health and safety	Positive- manufacturers takes care about product performance
C2	Consumers	Feedback mechanism	Presence of a mechanism for	Positive – improved feedback

			customers to provide feedback	mechanism through customer support system
C3	Consumers	Consumer privacy	strength of internal management system to protect consumer privacy, in general	Possibly Negative- user data is shared with service org for monitoring and control of services
C4	Consumers	Transparency		Positive – it is improved transparency by sharing business operation details
C5	Consumers	End-of-life responsibility	Strength of national legislation covering product disposal and recycling, Do internal management systems ensure that clear information is provided to consumers on end-of-life options (if applicable)?	Positive -products are returned after every use
S1	Society	Public commitments to sustainability issues		Positive- it improved public commitment by using the products whenever needed
S2	Society	Contribution to economic development	Contribution of the product/service/organization to economic progress (revenue, gain, paid wages, R&D costs in relation to revenue, etc.)	Positive- it is influenced by new technology developments, skills enhancements, and job creation
S3	Society	Prevention and mitigation of conflicts	Disputed products	Unknown
S4	Society	Technology development	Involvement in technology transfer program or projects	Positive- technologies are developed to increase the product's lifetime
S5	Society	Corruption		No influence
S6	Society	Ethical treatment of animals		No influence
S7	Society	Poverty alleviation		No influence
H1	Children	Education provided in the local community		No influence
H2	Children	Health issues for children as consumers		No influence
H3	Children	Children concerns regarding marketing practices		No influence