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The Proposal of an Environmental Break-Even Point as Assessment Method of Product-Service Systems for Circular Economy

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Abstract

In this paper we propose a method to assess technology-based product-service systems and help manufacturing companies in decision making with a new indicator: the environmental break-even point (e-BEP), equivalent to the economic indicator applied to environmental performance. A case study is presented to provide a concrete application of the indicator: when designing an optical sorter for electronic waste, the e-BEP revealed how many mobile phones must be either repurposed or recycled for the sorter to offset the system's environmental impact. The e-BEP shows potential to make CEOs and production managers adopt a product life-cycle thinking in their technology investments.

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Keywords: Break-even point; sustainability assessment; technology assessment; circular economy; environmental performance; WEEE; sorting; mobile phones.

1. Introduction

1.1. Background and purpose of the study

This research work aims to support the reduction of the environmental impact related to production and end-of-life processes in the manufacturing industry. It intends to do so by displaying specific information that facilitates decision making taking place in technology assessments by production managers and CEOs of manufacturing companies. This research work aims therefore to support a more sustainable manufacturing industry from a decision-making standpoint.

Sustainable manufacturing is defined by [1] as a set of "processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers and are economically sound". As argued by [2, 3], sustainable manufacturing not only targets production processes occurring in manufacturing facilities, but also resource extraction and emissions throughout the whole product life cycle. Such a concept of sustainable manufacturing inherently brings a life-cycle thinking view to an industry which has historically been dominated by linear material flows, "from cradle to grave".

Circular economy (CE) brings life-cycle thinking to the forefront of supply-chain business models. CE has been defined by [4] as "an economy that provides multiple value-creation mechanisms which are decoupled from the consumption of finite resources". It follows that the adoption of CE causes new, "circular" material flows and information flows in manufacturing supply chains, which call for technologies that either cause or govern such flows. To demonstrate, novel technologies such as robots for the disassembly of mobile phones and machine-to-machine communication are two current examples that enable CE and even have the potential to disrupt entire industries [5].

Furthermore, part of these technologies falls into the realm of a product-service system (PSS) for production environments specifically (e.g., manufacturing, remanufacturing and recycling facilities). A PSS has been defined from different perspectives: business, entrepreneurial, industrial, among others. The first formal definition of a PSS defines it as "marketable set of products and services jointly fulfilling user's needs" [6]. According to Tukker et al. [7] "many see PSSs as

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an excellent vehicle to enhance competitiveness and to foster sustainability simultaneously".

An interesting question to be answered then is whether technology-oriented PSS purposely designed for CE can effectively increase environmental sustainability performance from a product-life cycle perspective. Answering this question implicitly demands cost-benefit analyses, which in turn have to be set with specific assumptions, system boundaries and meaningful outcome information. The motivation that justifies such a question and the purpose of this research work is that environmental cost-benefit analyses are not normally part of the core skills of CEOs and production managers, and yet these actors often make long-lasting decisions that dramatically affect the environmental performances of the product that their companies produce.

As a result, this work aims to provide a simple, graphic-based decision-making tool for CEOs and production managers whom evaluate the adoption of PSS for CE from an environmental perspective.

The scope of the PSS being considered is narrowed to technology-oriented PSS designed for production environments in the manufacturing and remanufacturing industry. Digital technologies that contribute to the realization of PSS for CE in production are, for instance, Radio Frequency Identification (RFID), and sensors and actuators that realize the Internet of Thing's architecture. They allow the tracking of material flows, enable value recovery and connect stakeholders across the value chain [8]. As a result, this study is of an interest for researchers in the field crossing technology assessment, sustainability assessment (SA) and CE.

The rest of this section reports the literature review on methods for SA of PSS. Section 2 illustrates the proposed method for environmental assessment of PSS for CE, named environmental break-even point (e-BEP) indicator.

Section 3 shows how the e-BEP has been applied to a case study of an optical automatic sorter of Waste Electrical Electronic Equipment (WEEE), providing decision support for product end-of-life strategies. Section 4 discusses the results and Section 5 concludes the paper and points to needs for future research.

1.2. Literature review

A categorization of the different SA tools applied in the manufacturing industry has been done by [9-11]. Some SA tools, like methods for calculating carbon footprint and life cycle sustainability assessment, are well applicable to the evaluation of PSS for CE specifically. However, some integrated SA tools suffer the same shortcomings of holistic and interdisciplinary approaches, such as a non-clear integration of methods and models, "especially regarding the paradox of seeking replicability and comparability while dealing with extreme complexity and non-linearities", as argued by [11].

Stand-alone indicators and indexes would of course not be considered as part of a holistic evaluation approach on their own, yet would "speak the language" of CEOs and production managers and provide information on environmental costs and benefits of potential to-be adopted technologies and business models. In fact, several scholars have suggested the application of indexes such as the green development index, resource productivity index [12] and an emergy indicators system [13] when assessing CE strategies on a national level [13, 14] and within industrial symbioses [12].

These recommendations corroborate the assumption underneath this study: namely that CEOs of manufacturing companies would likely be more inclined to receive information coming from indicators, rather than integrated tools for technology assessments and SA when evaluating the adoption of a PSS.

In this case, these indicators would be within the realm of managerial economics, including: total cost of ownership [15], net present value [16], break-even point (BEP) [17], return of investment [18] and payback period [19], sometimes called payback time (PBT).

The value of the information provided by these indicators is in giving a quick, intuitive figure on the expected future monetary value of the investment in a particular scenario.

Interestingly, the literature contains only a few instances of similar indicators representing environmental rather than economic return in the case of technologies for production environments.

To evaluate different car replacement schemes, Messagie et al. [20] devised an environmental breakeven point to represent "how long it takes until a newly produced car has an environmental return on investment. This period is called the environmental breakeven point" [20]. We argue that a measurement with such an intent would better be defined as payback time rather than a breakeven point, as the latter suggests a production amount and not a time. With respect to payback time, the energy payback time indicator has been used by [21] to examine the environmental performance of five photovoltaic-based electricity generation systems. Similarly, the energy payback time has been later used by [22] for the case of evaluating different photovoltaic rooftop designs.

However, these indicators have thus far been applied only on a specific product (e.g., cars, photovoltaic panels), and most importantly, the methodology underpinning them has not been articulated in a way that lends itself to use for PSS. We argue that indicators of this kind facilitate the fulfillment of the purpose of this study, provided that a methodology for calculating and using them is explicated.

2. Environmental Break-Even Point (e-BEP)

In this study, we propose the structure, the requirements and the modality needed in the use of an indicator named Environmental Break-Even Point (e-BEP). Within this context, we define the e-BEP as applicable for the evaluation of a PSS as *the amount of products being processed by a product-service system in order for it to offset its environmental costs with environmental benefits gained within the whole product life cycle thanks to the very use of the product-service system.* The e-BEP has been designed to support CEOs and production managers of manufacturing companies in SA of PSS dedicated to CE. It does so from an environmental standpoint only, by analyzing the impact of the PSS through a pre-decided environmental indicator, whether it be global warming potential (GWP), land use or aquatic toxicity.

2.1. Formulation of the e-BEP

The structure of the e-BEP stems from that of the well-established economic BEP indicator [17], but instead of considering monetary revenues and costs, it counts the environmental benefits and costs that would be brought by the adoption of a new PSS, and plots them in a 2-D graph.

When displaying the example of a PSS for CE, a type of environmental cost might be the environmental burden from building the components of a new piece of equipment, such as the amount of abiotic resources being depleted. Examples of abiotic resources are fossils fuels, metals and minerals [23]. An example of environmental benefit is the increased energy efficiency rate that the piece of equipment would guarantee, if compared to the efficiency rate currently achieved in a factory.

Given the aforementioned background, the intended purpose of the e-BEP, and the mathematical formulation of the economic BEP [17], the e-BEP for a PSS has been formulated as:

$$eBEP = \frac{FEC}{VEB - VEC} \tag{1}$$

Given that:

$$FEC = Fixed\ Environental\ Cost \tag{2}$$
$$VEB = Variable\ Environental\ Benefit \tag{3}$$
$$VEC = Variable\ Environental\ Cost \tag{4}$$

Equations 2, 3 and 4 refer to a given PSS that processes products, parts or transactions. In particular, equation 2 is the value of a selected indicator that measures the environmental cost of building the PSS in its components or infrastructure.

Equations 3 and 4 are relative measurements of benefits and costs, that is, measurements taken per unit of product/part/transaction being processed. Moreover, only “avoidable” costs and benefits must be calculated in equation 3 and 4, meaning that, they must result from the very use of PSS, and not be obtainable otherwise. Fig. 1 displays how the e-BEP is determined from a graphical standpoint.

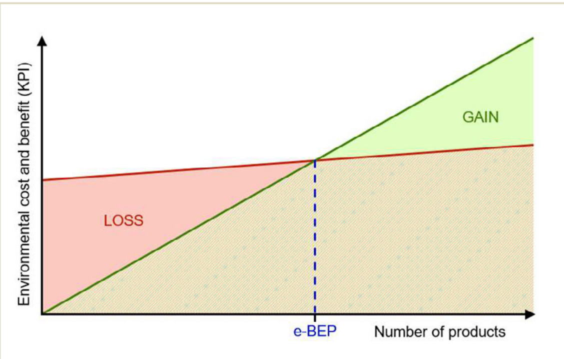

Fig. 1. Graphical formulation of the e-BEP.

The X-axis exhibits the amount of products/parts/transaction processed by the PSS, starting from when the PSS has been launched. The Y-axes displays the environmental key performance indicator (KPI) chosen by the decision makers.

Two curves must be plotted for this. The first one, displayed in red in Fig.1, describes the growth of environmental costs as more products/parts/transactions are processed. This curve, at x=0 is equal to the value of FEC in the Y-axis. The second curve, displayed in green in Fig.1, describes the growth of environmental gains as more products/parts/transactions are processed, if compared to the as-is situation. Fig. 1 shows that the e-BEP is the point in the X-axis where the cost curve crosses the benefits curve.

2.2. Use of the e-BEP

The following list contains requirements for the use of e-BEP in decision-making processes that evaluate the adoption of PSS for CE.

- The organization which aims to use the e-BEP must already have an inventory of data for the life cycle assessment as data input for the calculation of the e-BEP.
- For the sake of conformity and transparency of the methodology used for SA, the environmental analyses must be done in accordance with the Life Cycle Assessment framework [24, 25]. In fact, a “side” objective of the e-BEP is indeed to track results from the LCA methodology so that they are easily interpreted by decision makers not accustomed to environmental analyses. This means that the organization that evaluates a new PSS must either have employees whom are LCA practitioners or must outsource these skills.
- The results from the LCA analysis need to be summarized by one or more KPIs. Each of these KPIs constitute the dimension of the Y-axis of the graph showed in Fig. 1. As a result, the decision makers evaluate a potential adoption of a PSS by means of as many e-BEP indicators as the number of KPIs that will be selected. These KPIs can either be middle-point indicators, like global warming potential, or end-point indicators, like ReCiPe [26]. The latter averages a set of mid-point indicators according to certain damage categories. Naturally, the KPIs have to be selected for the relevance they play within the natural and technical ecosystem where the manufacturing or remanufacturing facility operates. In this regard, the knowledge of the environmental managers within the manufacturing company must come into play, in order that they can advise on the selection of the right KPIs.
- Following the very definition of the e-BEP, it is understood even prior to the analyses that the PSS has the potential to bring about environmental benefits from a product-life cycle standpoint, ideally from “cradle to cradle”. As for Fig. 1, this requirement makes equation 3 possible to exist.

The following list contains indications for the use of e-BEP. These indications are such that do not constitute requirements, but instead allow the recipients of the e-BEP to maximize its value in a decision-making setting.

- The e-BEP serves not only the case of a potential to-be PSS versus the as-is one. It can also be used when assessing a set of alternatives of PSS. In this case, the e-BEP can be calculated considering the marginal environmental costs and benefits among the two most promising PSS.
- In some circumstances, knowing the amount of products that allows the PSS to offset environmental costs and benefits is not as meaningful to CEOs and production managers as knowing when such an offset takes place. Starting from the e-BEP, it is possible to give time-based information, rather than quantity-based information, by means of the formulation in equation 5.

$$ePBT = eBEP \times CT \qquad (5)$$

Where:
$ePBT = Environmental\ PayBack\ Time$
$CT = Average\ Cycle\ Time$

Equation 5 explains how to calculate the environmental payback time (e-PBT) of a PSS by knowing the e-BEP of a PSS (from equation 1) and the cycle time with which products/parts/transactions are being processed by the PSS.

3. Application of the e-BEP

3.1. Case study background

The e-BEP has been tested on an automatic optical sorter of WEEE. The demonstrator of the optical sorter, called *e-grader*, has been developed by the company ReFind within the Swedish research project WEEE ID (Waste Electrical Electronic Equipment Identification) [27]. This new sorter constitutes the PSS of WEEE management, as presented by Taghavi et al. [28]. The main service being provided is statistics of e-waste streams which are detailed and automatically generated, and which enable new models for financing extended producer responsibility and improved quality of recovered material and recycling efficiency. The SA of the e-grader has been published in [29], where the economic, environmental and social performances of the e-grader were compared with the ones from an as-is manual WEEE sorting line. As explained in [29], "the demonstrator uses sensors and intelligent data processing to detect in real time whether used mobile phones are good for reuse, refurbishment or recycling, and sorts them accordingly.".

In this case study, we tested how the e-BEP would theoretically contribute to the SA of the e-grader. First, the requirements illustrated in section 2.2 appeared to be fulfilled.

It is important to remark that in many of the manual sorting lines of WEEE, recycling targets are the ones being considered rather than reuse targets. For this reason, the e-grader could offer additional environmental gains by allowing a fraction of mobile phones being sorted for reuse or repurposing, rather than recycling the raw materials within them.

As a result, the e-BEP for the case of the WEEE ID project shows at which production level the negative environmental impact brought by the construction and use of the e-grader in a sorting facility is offset by the positive environmental impacts brought by alternative product end-of-life treatments to recycling.

3.2. Calculation of the e-BEP

First, a Life Cycle Assessment (LCA) analysis has been performed in order to know the environmental impact from the building of the e-grader. The bill of material of the e-grader has been provided by ReFind and can be found in the Appendix A.

This data was entered into the OpenLCA software (version 1.4.1), which used LCI data from the EcoInvent database (version 3). The impact assessment method selected was the ReCiPe Midpoint (H), whereas the energy demand was calculated by the cumulative energy demand's impact assessment method, discussed in [30].

The environmental impact selected as Y-axis of the e-BEP graph was global warming potential, calculated in kilograms of CO_2 equivalents (kg CO_2 eq.). The LCA analysis, done in OpenLCA with respect to the several components of the e-grader (Appendix A), resulted in a fixed environmental cost of the e-grader $FEC = 9039{,}502\ kg\ CO2_2\ eq$. This is the amount of kg CO_2 eq. emitted to build all the main e-grader's components.

The representative WEEE item in the X-axis was chosen to be the smartphone, as analyzed by [31]. A simplified scenario of mobile phone reuse/repurposing would give, according to [31], a variable environmental benefit $VEB = 35{,}4\ kg\ CO2_2\ eq$ per unit of mobile phone being sorted for reuse. This amount considers savings of kg CO_2 eq. occurring in the mining stage and component manufacturing stage. With the hypothesis of 83% of utilization of the e-grader, calculated via discrete event simulation in [29] and validated by the WEEE ID project members, the variable environmental cost of the e-grader turned out to be $VEC = 0{,}009\ kg\ CO2_2\ eq$ per unit of mobile phone being sorted. The amount of CO_2 eq. occurring in the use phase of the e-grader stems from the electricity consumption in the pilot facility of the study and its sorting rate. The calculation procedure has been thoroughly reported in [29]. Following equation 1, the e-BEP for the e-grader is then $eBEP = 255$ sorted mobile phones. This means that the environmental burden of the sorting unit in terms of kg of CO_2 eq. emitted is paid off after 255 smartphones have been sorted, but only if they are suitable for reuse purposes. The graphical representation of this calculation is depicted in Fig. 2 (X-axis is not in scale with the Y-axis to ease the readability of the graph). If the mobile phones are suitable for recycling purposes instead (similarly to the as-is case of the manual sorting line), the e-BEP becomes higher than 255, worth $eBEP = 1848$ mobile phones precisely (following equation 1). The reason for a higher value of the e-BEP in the recycling scenario is that in this case only emissions from raw material extraction, and not for components manufacturing, are saved.

It is important to highlight that if the sorting accuracy and the sorting rate of the automatic sorting are the same as the manual sorting, then the environmental saving from recycling raw materials of mobile phones still remains the same among the as-is sorting line and the to-be sorting line upgraded through the e-grader.

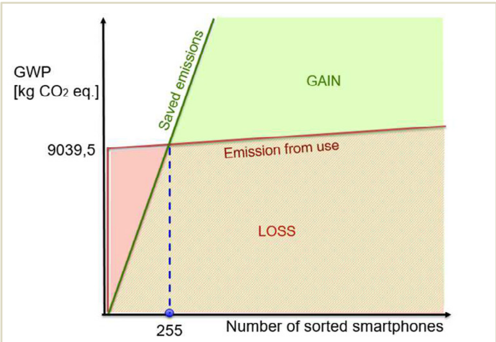

Fig. 2. Application of the e-BEP for the evaluation of the e-grader, an optical sorter of WEEE. Example for the case of smartphone sorting.

It follows then that the value of the VEB would be equal to 0. Therefore, the e-BEP of 1828 mobile phones is a meaningful indicator only when assessing the offset of the e-grader *per se*, against a scenario of “no-phone sorting” and not in comparison with an as-is manual sorting line with a similar sorting rate. In future applications it is possible to calculate the e-BEP by choosing an “average smartphone” representative of the mix being sorted (for instance 70% recyclable and 30% reusable devices). The “average smartphone” has not been considered for this theoretical case study, because of data unavailability concerning the phones mix (amount of repurposed phones and recycled phones).

4. Discussion

The e-BEP calculates and visualizes the link between environmental performance and production rates. As a result, the main argument for advocating the use of the e-BEP by CEOs and production managers is that in most cases these two actors are not knowledgeable in environmental sciences, but still make decisions that affect the environment when evaluating purchases or the adoption of new technology-oriented PSS.

For these reasons, the visualization of the e-BEP gained positive feedback from the project partners of WEEE ID.

Although this does not certify the validity of e-BEP as an assessment method, it can be stated that the e-BEP is well-suited to the assessment of technologies in product end-of-life that promise to reduce products’ ecological footprint by better, smarter selection of the proper end-of-life treatments (which is one of the concerns of CE models). It remains to be tested whether using the e-BEP indicator for other types of PSS (outside the scope of this study) is a preferable option in comparison to other kinds of environmental assessment methods and SA tools that have been reviewed in this paper.

For the e-BEP to provide good-quality decision support, it is pivotal that different scenarios are considered: an average, most-likely scenario, a best-case scenario and a worst-case one.

Each of these scenarios differs from each other in terms of key parameters, like future customer trends, availability of critical materials, and product mix. This scenario design would generate three different e-BEP indicators, which might be plotted in the same graph.

In regard to SA applied in the manufacturing industry, Moldavska and Welo argued in [32] that “although previous research has recognized the potential of systems thinking applied to sustainability assessment, few practical examples have been demonstrated”.

Even though the use of a single indicator might be regarded as a return to a reductionist approach, at odds with the advocacy of a system-thinking approach, we argue that an indicator like e-BEP has the potential to connect different aspects of a complex evaluation problem. The most salient aspects are: the environmental performance of the PSS, the characteristics of the facility in which it has to work, and product environmental impacts in its different life cycle stages. Furthermore, we see no obstacles in embedding the e-BEP in established frameworks and methods for environmental assessments.

5. Conclusion

In this paper the formulation and modality of utilizing the e-BEP indicator have been presented. The e-BEP allows CEOs, and production managers (e.g., plant managers and operations managers) to use a single, intuitive and easy-to-read piece of information that facilitates the assessment of new PSS for CE.

These types of decisions are likely to be more and more recurrent following the implementation of Industry 4.0 in the manufacturing sector and the need for decoupling natural resource use from economic growth. Based on the experience being recounted in this paper, it has been concluded that the e-BEP has potential in fulfilling the objective of this study.

Further case studies need to take place in order to:

- demonstrate the validity of the e-BEP in different production and remanufacturing environments
- collect feedback from the intended recipients of the indicator on the informative value brought by the e-BEP.

In case the e-BEP will prove to serve its purpose, we see the use of the e-BEP in conjunction to established frameworks and methods of environmental SA targeting PSS for CE.

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Appendix A.

Table 1: Bill of material of the e-grader. Data from kind concession of ReFind.

Equipment Components – data from ReFind	Number of components per equipment	Material per components	Material contents %	Material weight per equipment [kg]
Conveyor belt	1	PP	15%	18
		Aluminum	30%	36
		Steel	55%	66
Total			100%	120
RGBD camera and illumination	1	Fiber glass	10%	4
		Electronics	5%(*)	2
		LED	5%(*)	2

Equipment Components – data from ReFind	**Number of components per equipment**	**Material per components**	**Material contents %**	**Material weight per equipment [kg]**
		Aluminum	80%	32
Total			100%	40
Stands and settings	1	Steel	25%(*)	12,5
		Paint	5%(*)	2,5
		plastics door handles and hinges	70%(*)	35
Total			100%	50
Actuator	2	Steel	85%	204
		Stainless steel	5%	12
		Aluminum	10%	24
Total	2		100%	240
Electrical cabinet (including PLC, IPC)	2	Electronic components machinery[1]	100%	20
Auxiliary Equipment Components – data from EcoInvent	**# of components per equipment**	**Name in EcoInvent database**		
Keyboard	1	Keyboard - GLO		
Computer desktop, without screen	1	Computer desktop, without screen - GLO		
Liquid crystal display	1	liquid crystal display, minor components, auxiliaries and assembly effort - GLO		
Backlight	1	backlight, for liquid crystal display – GLO		
Pointing device	1	pointing device, optical mouse, with cable - GLO		

(*) Assumption of components' material contents from EcoInvent.

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