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Criticality and LCA – Building comparison values to show the impact of criticality on LCA

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Abstract

Including criticality into Life Cycle Assessment (LCA) has always been challenging to achieve but desirable to accomplish. In this article, we present a new approach for the evaluation of resource consumption of products by building comparison values based on Life Cycle Impact Assessment (LCIA) combined with weighted criticality values to show the direct impacts of criticality on LCA results. For this purpose, we develop an impact indicator based on the Abiotic Depletion Potential (ADP) of natural resources and use the two main parameters defined by the EU to determine the criticality of a material - the economic importance and the supply risk – in our case studies to build the Criticality Weighted Abiotic Depletion Potentials (CWADPs), one for each parameter. These indicators allow identifying and measuring the impacts of criticality when comparing the results of resource depletion using the ADP methodology and the results that incorporate criticality. The comparison of the CWADPs to the corresponding EU criticality values and its thresholds ~~it~~ reflects the equivalent criticality of the assessed product. This information reflects the impacts of criticality on LCA and assesses the total resource consumption of critical materials in a system.

Keywords: Life Cycle Assessment, criticality, resources, materials, sustainability indicator

1. Introduction

With the rising urgency of sustainable actions needed to be taken, critical resources have been increasingly put into the spotlight within the last decades. Especially since the launch of the Sustainable Development Goals (SDGs) in 2016, raw materials and their related mining effort have gained more interest (United Nations General Assembly, 2015). The impact of resource use, mining, and recycling are mainly allocated to SDG 12: Responsible Consumption and Production. With this new attention, many new criticality methodologies and indicators have been released but most of them focus on the economic pillar of sustainability only. Solely focusing on the economic aspects does not meet all challenges – in particular challenges related to sustainability. Integrating the non-economic aspects into an economic framework for comparison on an economic basis will lead to severe ethical problems, especially, when it comes to charging economic values against ecological and social values. Conflict minerals are a good example for the ethical dilemmas that arise when you try to give their non-economic sustainability aspects an economic value. Conflict Minerals receive a benefit on the market (economy) but are made available through very low social standards as children work and are financing wars in their country of origin. But even putting values of different criticality indicators into an economic relation will always be a questionable matter and there is actually no proper indicator available that covers this issue ideally. Life Cycle Assessment (LCA) is a suitable

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and at this moment standard method to assess sustainable life cycles and there are many studies available (Cimprich et al., 2017; Nguyen, Fishman, Zhao, Imholte, & Graedel, 2018; Pell, Wall, Yan, & Bailey, 2019; Sonnemann, Gemechu, Adibi, Bruille, & Bulle, 2015) . It is a common technique used to determine the potential environmental impacts of a product or process over its entire life cycle and has become a major sustainability assessment tool not only for the industrial sector.

Nevertheless, an indicator reflecting the impact of criticality - regardless of its underlying criteria used - on LCA is urgently needed. One of the main environmental impact categories used in LCA is Abiotic Depletion. The Abiotic Depletion Potential (ADP) was initially developed by Guinée (1995) and was later modified and discussed by van Oers, Koning, Guinée, and Huppes (2002). The European Commission (2011) recommended ADP and its approach based on the reserve base as the LCIA method to be used for midpoint assessment in their ILCD Handbook.

As mentioned above numbers and values that could be compared directly to economic values should be avoided and there is no uniform opinion about the "ideal" indicator assessing and reflecting the criticality of resources. Therefore, this indicator should reflect the impact as an additional factor to be added to an existing and generally recognized method used in LCA.

2. Background

This paper is addressing a missing link in Life Cycle Assessment (LCA) and the impact of resources with a focus on their criticality. As suitable indicator the Abiotic Depletion Potential (ADP) was selected since on the one hand, it is comparable with other EU studies, and on the other hand, it reaches a high degree of abstraction in terms of economic values as it is related to and normalized to kg of antimony equivalent.

In general, abiotic depletion refers to the depletion of non-living (abiotic) and non-renewable material resources such as fossil fuels, minerals, clay, and peat. It is generally seen as the decrease of the availability of the total reserve of functions of a resource and most, if not all, methods acknowledge the depletion of natural resources from the functional point of view while other values, like the intrinsic value, of minerals are usually neglected (van Oers et al., 2002). Integrating criticality as an additional value of a resource into LCA is about adding an extra emphasis and weight to the resources in the input flow according to a chosen criticality parameter, namely as Criticality Weighted Abiotic Depletion Potential (CWADP).

The fundamental approach underlying the idea of CWADP does not depend on a specific data base used to build a criticality parameter. In this paper we have chosen to use the "Criticality Assessments" reports published by the European Commission (2017) as the data base for the examples in this paper. Apart from the fact that the authors of this paper are living and working in Europe the transparent process of the determination of the criticality parameters is a great advantage when using these parameters to build a new criticality parameter upon. Furthermore, the fact that until today three criticality assessments reports have been published by the EU - and are still ongoing - opens up the possibility to investigate the impact of criticality on the CWADP over time. In addition, the comparison to other criticality studies in Europe is given and addresses an already existing scientific community.

3. Idea and implementation

The basic idea to find a way to include criticality into Life Cycle Assessment (LCA) was to combine the ADP of mineral resources with the two main criticality parameters used by the EU in their criticality assessments reports - the Economic Importance (EI) and the Supply Risk (SR) - and introduce two new impact indicators, the *Criticality Weighted Abiotic Depletion Potentials* (CWADPs), one for each parameter.

The abiotic depletion (AD) is a result of the sum of each resource‘s ADP multiplied by its mass:

$$abiotic\ depletion = \sum_i ADP_i * m_i$$

with:

$$ADP_i = \frac{\frac{DR_i}{R_i^2}}{\frac{DR_{ref}}{R_{ref}^2}}$$

where:

ADP_i abiotic depletion potential of resource i (kg antimony equivalents / kg of resource i);
m_i quantity of resource i extracted (kg);
R_i ultimate reserve of resource i (kg);
DR_i extraction rate of resource i (kg / year) (regeneration is assumed to be zero);
R_{ref} ultimate reserve of the reference resource antimony (kg);
DR_{ref} extraction rate of the reference resource R_{ref} (kg / year).

Moving from the abiotic depletion to the criticality weighted abiotic depletion is achieved by multiplying the ADP_i of a resource with the normalized criticality factor c_{ix} of a resource to build the $CWADP_{ix}$ of this resource:

$$CWADP_{ix} = c_{ix} * ADP_i$$

where:

$CWADP_{ix}$ criticality weighted abiotic depletion potential of resource i based on the criticality parameter x;
c_{ix} normalized criticality factor of resource i based on the criticality parameter x.

To exclude a decreasing impact of the criticality parameter on the criticality weighted abiotic depletion its value will have to be normalized to avoid values below 1.0. Therefore, both parameters - the EI and the SR - of a resource will be divided by the lowest respective value of all critical resources in the report:

$$c_{ix} = \frac{c_{x_i}}{c_{x_{min}}}$$

where:

c_{x_i} criticality parameter *x* of resource *i*;

$c_{x_{min}}$ lowest (minimal) value of criticality parameter *x* in the data base.

This way the normalized criticality parameter of the resource with the lowest value of this criticality parameter will be 1.0 and have no effect regarding the impact of criticality on the AD while the ratio of the criticality parameters between two resources defined in the report remains. For the same reason all normalized criticality parameters of resources not listed in the report will be set to 1.0.

Since the criticality values are being updated by the EC in perennial cycles these CWADPs will change with any new report released. So the CWADPs will need to be indexed - here with the index *x* - with the corresponding report and the chosen criticality parameter to guarantee a unique assignment, e.g. "$\text{CWADP}_{\text{EI-EC2017}}$" for the CWADP using the economic importance parameter (EI) based on the report by the European Commission (EC) published in 2017 (European Commission, 2017). This indexing method allows the unique designation and the use of any criticality parameter of any data base in general.

By including the normalized criticality parameter into the equation of the abiotic depletion above, we obtain the equation for the criticality weighted abiotic depletion introducing the CWADP_{ix}:

$$criticality\ weighted\ abiotic\ depletion_x = \sum_i \underbrace{c_{ix} * ADP_i}_{CWADP_{ix}} * m_i$$

where:

x criticality parameter *x* used.

Creating the quotient of the criticality weighted abiotic depletion and the abiotic depletion defines the criticality factor which shows the impact of a given criticality parameter *x* within the LCA:

$$criticality\ factor_x = \frac{criticality\ weighted\ abiotic\ depletion_x}{abiotic\ depletion_x}$$

where:

x criticality parameter *x* used.

4. Case studies

The proposed indicators are applied to several case studies, using openLCA 1.8 including the ecoinvent 3.4 database and using a database of products used in data centres products database currently developed within a project on the total energy management on professional data centres (Peñaherrera & Szczepaniak, 2019). Using this characterization factors, the results on the different impact categories are calculated using the openLCA 1.8 calculation engine. The process takes into consideration the gathered information on the composition of the different devices to construct product systems based on the inventory information. The reference unit for the calculations is the manufacturing of one (1) unit.

As a basis for the impact assessment, the CML 2001 Method provides impact factors for each of the impact categories (Tukker et al., 2002). A set of new impact categories are developed using the impact factors for Abiotic Resource Depletion and the corresponding factors for Supply Risk and Economic Importance (European Commission, 2017). Figure 1 shows the results on impact factors for different input flows of raw materials.

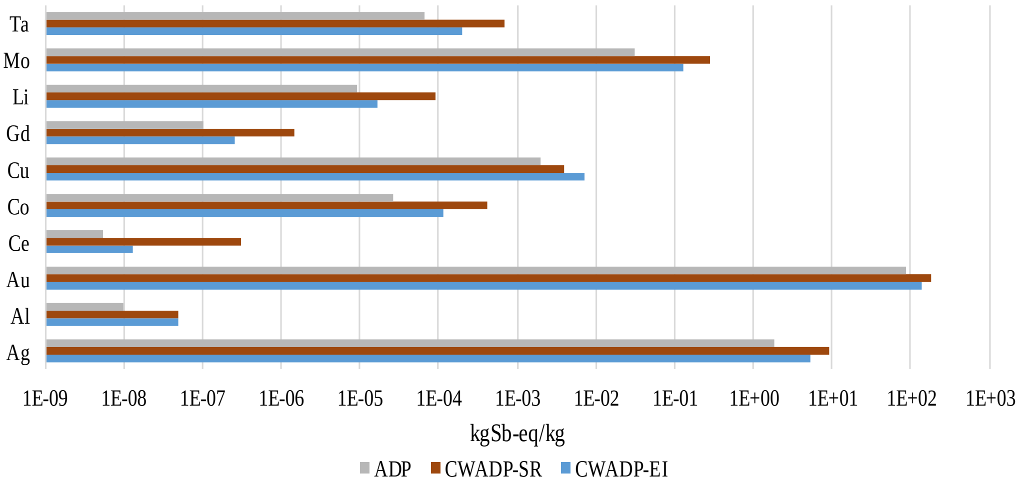

Figure 1. Impact Factors for the Impact Categories (log scale).

The product systems consist of several processes representing the input product flows required to produce the device. For each system, the impact contributions of the resource flows are calculated using the developed impact categories. Table 1 shows the results for a Power Distribution Unit. Figure 2 shows the fractional contributions of each flow of raw material to the total impact. From the results it can be seen that most of the mass is allocated to plastic components, that generally have lower impact on abiotic resources when compared to minerals due to less mining operation needed.

Table 1.Inventory results and impact contribution by material of a PDU.

Material	**Mass (kg)**	**ADP$_i$ (kg$_{Sb-eq}$)**	**CWADP$_{i\ (SR-EC2017)}$ (kg$_{Sb-eq}$)**	**CWADP$_{i\ (EI-EC2017)}$ (kg$_{Sb-eq}$)**
Ag	0.00019	0.00031	0.00157	0.00092
Au	0.18800	0.00024	0.00048	0.00037
Cd	0.00143	0.00047	0.00047	0.00047
Cr	0.29700	0.00025	0.00229	0.00133
Cu	0.92100	0.00174	0.00337	0.00635
Mo	0.01840	0.00048	0.00503	0.00211
Pb	0.03710	0.00050	0.00018	0.00143
Others	4.52000	0.00042	0.00151	0.00096
Total	5.98000	0.00442	0.01490	0.01390

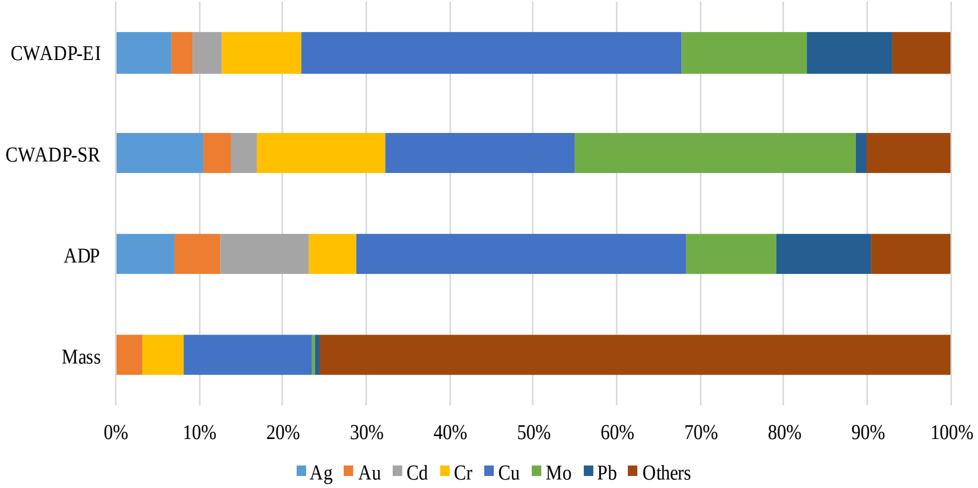

Figure 2. Contributions of each raw mineral to the total impact for a PDU.

Two product systems are compared to assess the differences in critical material content and the associated impacts. A Server Dell 1U (2008) and a Blade Server 1U (2011) are compared to calculate the influence of the critical material content in the impact contributions of resource depletion.

Table 2 shows the impact contributions of the different components for the ADP and for the proposed categories. The results are disaggregated into their components to point to the different configurations. Figure 3 and Figure 4 show the contribution of each of the components for the resource consumption impacts of manufacture.

Table 2. Impact contribution by component.

Component	**Server (1U)**			**Blade Server (1U)**		
	ADP$_i$ (kg$_{Sb\text{-}eq}$)	**CWADP$_i$ (SR-EC2017) (kg$_{Sb\text{-}eq}$)**	**CWADP$_i$ (EI-EC2017) (kg$_{Sb\text{-}eq}$)**	**ADP$_i$ (kg$_{Sb\text{-}eq}$)**	**CWADP$_i$ (SR-EC2017) (kg$_{Sb\text{-}eq}$)**	**CWADP$_i$ (EI-EC2017) (kg$_{Sb\text{-}eq}$)**
Integrated Circuit	0.33300	0.69000	0.52400	0.09000	0.18700	0.14200
Resistors	0.02060	0.05830	0.04370	0.00701	0.01560	0.01170
Capacitors	0.01300	0.04500	0.02940	0.00305	0.01060	0.00693
Copper Frame	0.00267	0.01040	0.00978	-	-	-
Iron Housing	0.00185	0.01120	0.00739	0.00023	0.00138	0.00091
Power Adapter	0.00102	0.00102	0.00321	0.00005	0.00018	0.00017
Fan	0.00101	0.00290	0.00204	1.2E-06	3.7E-06	3.3E-06
Cable Cat5	0.00014	0.00021	0.00028	-	-	-
Li-Ion Battery	0.00010	0.00029	0.00026	1.8E-06	5.2E-06	4.7E-06
Other	0.04090	0.10600	0.07450	0.00539	0.01590	0.01220

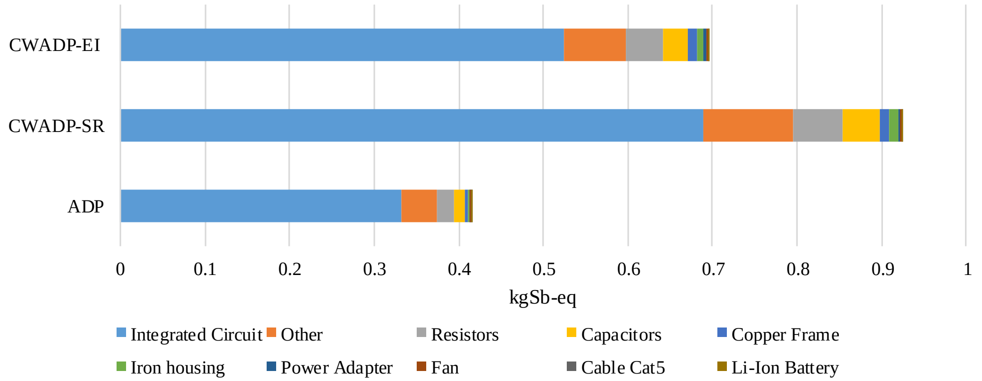

Figure 3. Resource consumption impact for the Server 1U (2008).

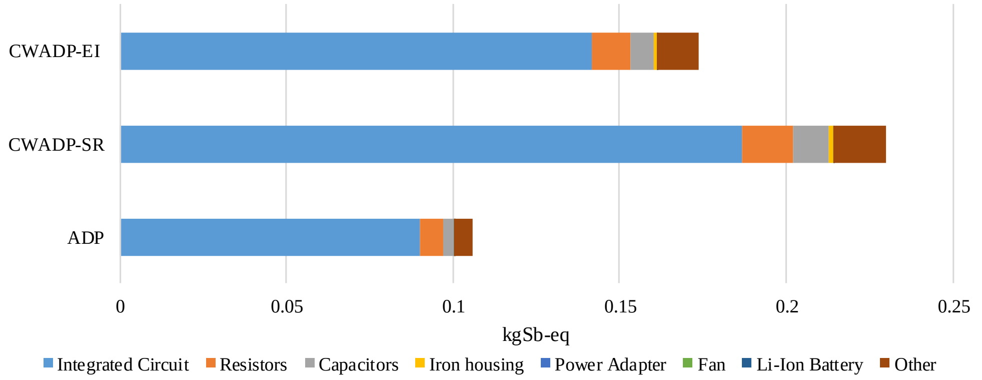

Figure 4. Resource consumption impact for the Blade Server 1U (2011).

When comparing products, the specific contribution indicates the concentration of valuable resources consumed during manufacturing. For both products, the normalized values are calculated. Figure 5 shows the specific values of resource consumption for the different indicators.

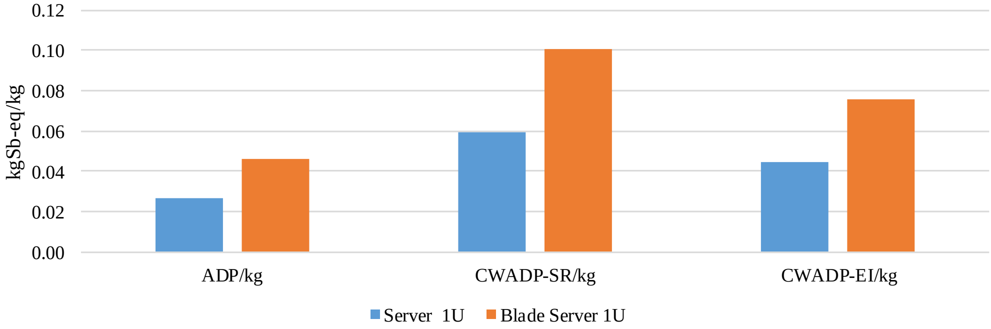

Figure 5. Specific resource consumption for the proposed indicators.

The results show a higher concentration of resources in the Blade Server, which is a more recent product, with a higher technical standard, and with a processing efficiency 4.4 times higher than the Server 1U (SPEC, 2019), even though the mass is lower.

To evaluate the equivalent criticality of the materials used, the CWADP indicators are divided by the ADP to calculate the criticality factors. The result in Figure 6 shows the mean value of criticality of the resources consumed for manufacturing the products. These values are de-normalized.

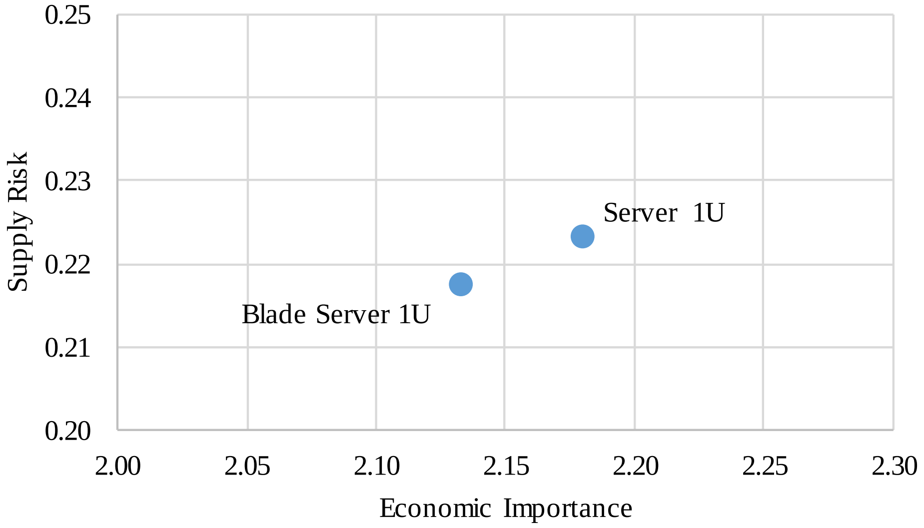

Figure 6. Equivalent values of criticality for the compared product systems.

These values show a slight reduction in the criticality of the average material, indicating to lower impacts of the consumed resources.

These results indicate the overall criticality of the materials of a product. When plotted together with the materials of the EU criticality list (European Commission, 2017), they indicate how the criticality of the material consumption to manufacture a product has an impact on the final result. From the product database of the data centre project (Peñaherrera & Szczepaniak, 2019), a selection of devices is plotted in Figure 7 to assess their criticality.

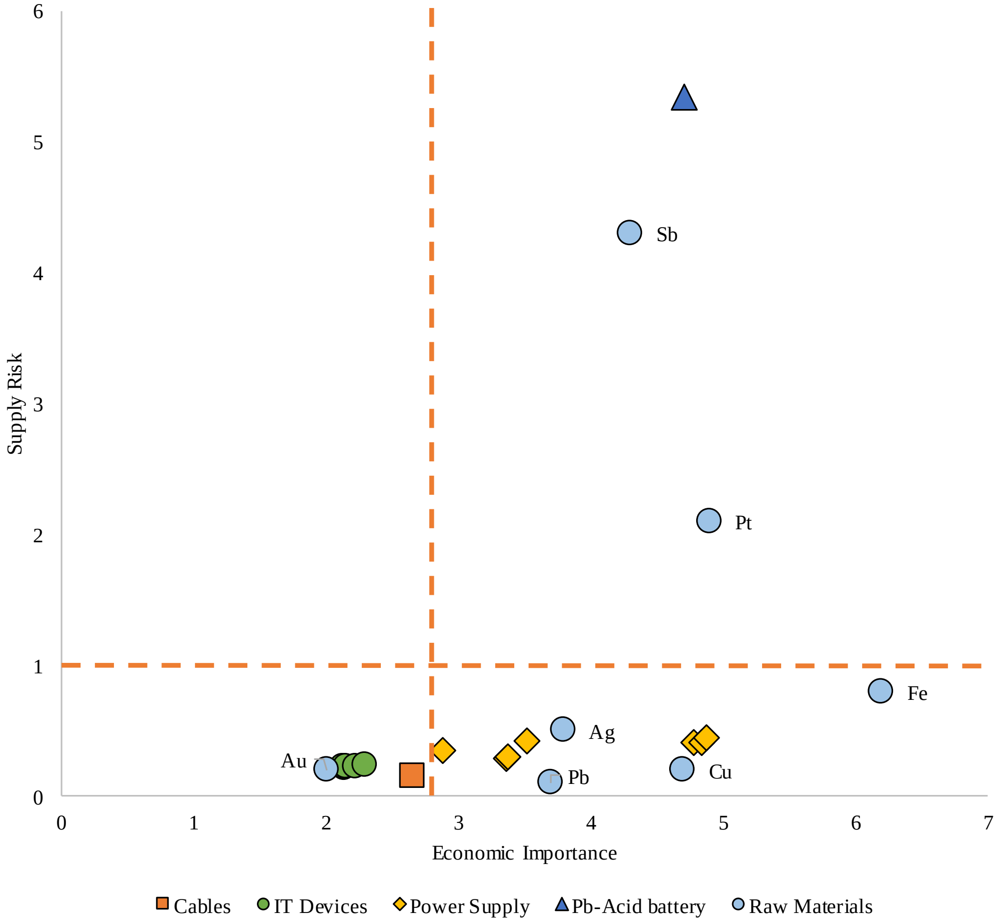

Figure 7. Resulting criticality for different sets of devices.

Figure 7 indicates the prevalence material in different categories of devices. IT Devices have mainly gold and precious metals as components. Power supply devices have high contents of Copper and Iron. Fuel cells have high economic importance due to the Pt content. In the case of the batteries, due to the use of Sb (Oliveira, 2012), they have high supply risk and economic importance.

5. Conclusion, Recommendations & Outlook

This paper shows the attempt to include the criticality weighted abiotic depletion potential (CWADP) as an extension of the well-known abiotic depletion potential (ADP). This could be a straightforward and universal method to include the impact of a criticality parameter into LCA and thus could be closer to the Sustainable Development Goals securing raw materials. Because of the normalization of the criticality parameter, its impact will result in a higher value of the criticality weighted abiotic depletion (CWAD) compared to the abiotic depletion (AD). The criticality factor resulting from the quotient of the CWAD and the AD of a product is a direct indicator for this impact and the underlying method is generally independent of the choice of the data base and the criticality parameter used.

The normalized criticality factor of a resource is the key factor in the interpretation of the results. This factor is depending on the data base for criticality parameters of a given report (European Commission, 2017). Depending on the data base and its underlying calculations used for the criticality parameter the normalized criticality factor might have non-linear amplitudes. Even effects of feedback due to correlations to the ADP are possible. An interpretation of the criticality factor should always be done based on the data base used. Due to the different determinations and calculations of these parameters, a comparison of results based on different data bases needs to be handled with care. Furthermore, the main purpose of normalization is to exclude negative impacts as decreasing values on the CWAD on the one hand, and to keep the relations between the parameter values on the other hand. Normalizing the criticality factor with these two propositions can only be done with a data base of positive values (greater than zero). Normalizing data bases of a criticality parameter with both positive and negative values will have to sacrifice the maintenance of relations in order to exclude the negative impacts mentioned above.

So far, the CWADP has only been examined on the data base given by the European Commission (2017) and its main criticality parameters Economical Importance and Supply Risk using selected products used in professional data centres, such as servers, hard disk drives (HDDs), power supply devices, and climatization devices. More case studies on other products and product groups as well as using different data bases will need to be done to collect more criticality factors.

As some data bases and their criticality parameters are being updated in perennial cycles a historical view on the impact of criticality on the CWADP of a product can be taken.

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References

Cimprich, A., Young, S. B., Helbig, C., Gemechu, E. D., Thorenz, A., Tuma, A., & Sonnemann, G. (2017). Extension of geopolitical supply risk methodology: Characterization model applied to conventional and electric vehicles. *Journal of Cleaner Production*, *162*, 754–763. https://doi.org/10.1016/j.jclepro.2017.06.063

European Commission. (2011). *International reference life cycle data system (ILCD) handbook: General guide for life cycle assessment: provisions and action steps* (First edition). *EUR, Scientific and technical research series: Vol. 24571*. Luxembourg: Publications Office.

European Commission. (2017). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the 2017 List of Critical Raw Materials for the EU: COM(2017) 490 final*. Brussels, Belgium. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52017DC0490&from=EN

Guinée, J. (1995). *Development of a Methodology for the Environmental Life-Cycle Assessment of Products: PhD dissertation*. Leiden, The Netherlands.

Nguyen, R. T., Fishman, T., Zhao, F., Imholte, D. D., & Graedel, T. E. (2018). Analyzing critical material demand: A revised approach. *The Science of the Total Environment*, *630*, 1143–1148. https://doi.org/10.1016/j.scitotenv.2018.02.283

Oliveira, F. (2012). *Life Cycle Assessment of a High-Density Datacenter Cooling System: TeliaSonera's 'Green Room' Concept: Master of Science Thesis*. Stockholm, Sweden.

Pell, R. S., Wall, F., Yan, X., & Bailey, G. (2019). Applying and advancing the economic resource scarcity potential (ESP) method for rare earth elements. *Resources Policy*, *62*, 472–481. https://doi.org/10.1016/j.resourpol.2018.10.003

Peñaherrera, F., & Szczepaniak, K. (2019). Development and Application of Metrics for Evaluation of Cumulative Energy Efficiency for IT Devices in Data Centers. In A. Pehlken, M. Kalverkamp, & R. Wittstock (Eds.), *Cascade Use in Technologies 2018: Internationale Konferenz zur Kaskadennutzung und Kreislaufwirtschaft - Oldenburg 2018* (pp. 142–153). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-57886-5_17

Sonnemann, G., Gemechu, E. D., Adibi, N., Bruille, V. de, & Bulle, C. (2015). From a critical review to a conceptual framework for integrating the criticality of resources into Life Cycle Sustainability Assessment. *Journal of Cleaner Production*, *94*, 20–34. https://doi.org/10.1016/j.jclepro.2015.01.082

SPEC. (2019). SPEC Power. Retrieved from https://www.spec.org/power_ssj2008/

Tukker, A., Bruijn, H. de, van Duin, R., Huijbregts, M. A. J., Guinée, J. B., Gorree, M., . . . Udo de Haes, H. A. (2002). *Handbook on Life Cycle Assessment* (Vol. 7). Dordrecht: Springer Netherlands. https://doi.org/10.1007/0-306-48055-7

United Nations General Assembly. (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development*. Retrieved from United Nations website: https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf

Van Oers, L., Koning, A. de, Guinée, J., & Huppes, G. (2002). *Abiotic Resource Depletion in LCA - Improving Characterization Factors for Abiotic Resource Depletion as Recommended in the New Dutch LCA Handbook*. Leiden, The Netherlands. Retrieved from https://www.leidenuniv.nl/cml/ssp/projects/lca2/report_abiotic_depletion_web.pdf