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Extension of geopolitical supply risk methodology: Characterization model applied to conventional and electric vehicles

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Highlights

- This article proposes a characterization model for Geopolitical Supply Risk.
- The characterization model is based on a socio-economic cause-effect mechanism.
- Supply risk is the multiple of probability and vulnerability.
- Two embodiments of the characterization model are presented.
- The methods are applied to conventional and electric vehicles.

Abstract

The diversity of materials employed in modern products and the complexity of globalized supply chains raise the importance of assessing supply risk of commodity inputs to product systems. Therefore, this article extends the Geopolitical Supply Risk methodology by proposing a characterization model to quantify product supply risk in relation to a functional unit under the Life Cycle Sustainability Assessment framework. The characterization model is based on a socio-economic cause-effect mechanism drawing upon supply chain resilience concepts. Supply risk – or “criticality” – of a given “intermediate product” is defined as the multiple of probability of supply disruption and vulnerability to supply disruption. Two embodiments of the characterization model are proposed, each supplementing the previously developed probability indicators with different indicators for vulnerability. They are demonstrated with a comparative case study of an electric vehicle and internal combustion engine vehicle. The results are highly sensitive to how vulnerability is measured, and a number of methodological complications arise. The most promising embodiment of the characterization model “cancels out” the amounts of commodity inputs, as it can be strongly argued that every input to the product system is equally important for product performance as expressed by the functional unit. Thus, the Geopolitical Supply Risk characterization model shows the importance of integrating raw material criticality considerations into Life Cycle Sustainability Assessment to better inform management decisions at a product level.

Keywords

Product supply risk

Life cycle assessment

Life cycle sustainability assessment

Criticality assessment

Vulnerability

Electric vehicle

Extension of geopolitical supply risk methodology: Characterization model applied to conventional and electric vehicles**1. Introduction**

The last decades have been a period of tremendous economic growth and technological innovation. Consumption of industrial minerals is 27 times greater than in the early 1900s (Krausmann et al., 2009), while the variety of metals employed in modern products has expanded from just a handful in the early 20th century to nearly the entire periodic table at present (Greenfield and Graedel, 2013; National Research Council, 2008). By some estimates, global extraction of resources by 2030 could be double the level from 2005 (Sustainable Europe Research Institute, 2012). Consequently, resource-related issues, such as geological scarcity, technological constraints, armed conflicts and geopolitical related supply risks, to name a few, are particularly important for sustainable development.

According to Porter and Kramer (2006), the inter-relations between sustainable development and business activities can be examined in two ways. The “outside-in” relation describes how firms are impacted by external environmental and socio-economic conditions (Porter and Kramer, 2006). For example, business risks and opportunities are affected by consumer preferences, policy and regulatory regimes, supply constraints, and environmental phenomena such as droughts and other extreme weather events. On the other hand, the “inside-out” relation describes the impacts of internal business operations on society and the environment (Porter and Kramer, 2006).

With regard to the “inside-out” relation, Life Cycle Assessment (LCA) is a tool for measuring potential environmental impacts of a product system from the “cradle” where resources are extracted to the “grave” where the product arrives at the end of its useful life. Though not explicitly required by the international LCA standards (ISO, 2006a), there is strong consensus in the LCA community that “environmental” impact categories should cover three areas of protection (AoPs): human health, ecosystem quality, and natural resources. As Dewulf et al. (2015) point out, these AoPs extend beyond the environmental dimension of sustainable development. Human health is not an “environmental” issue per se, and arguably issues pertaining to resources are largely socio-economic in nature. Therefore, the term Life Cycle Sustainability Assessment (LCSA) has emerged to incorporate the economic and social dimensions in addition to the environmental dimension (Heijungs et al., 2010; Traverso et al., 2012; Valdivia et al., 2013; Zamagni et al., 2013). Indeed, according to ISO 14040, “LCA typically does not address the economic or social aspects of a product, but the *life cycle approach* [...] can be applied to these other aspects” [emphasis added] (ISO, 2006b, p. vi). LCSA therefore embodies the “triple bottom line” concept of sustainable development (Elkington, 1997) by combining environmental LCA, social LCA, and (often economic) life cycle costing (LCC) (Kloepffer, 2008; Parent et al., 2013; Sala et al., 2013; Traverso et al., 2012; Valdivia et al., 2013).

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While Life Cycle Impact Assessment (LCIA) methodology for environmental impact categories linked to the AoPs human health and ecosystem quality is relatively well developed, the “natural resources” AoP has long been controversial (Dewulf et al., 2015; Drielsma et al., 2016; Finnveden, 2005; Finnveden et al., 2009; Schneider et al., 2015, 2014, 2011). It is not even clear what it means to have “natural resources” as an AoP (Dewulf et al., 2015; Drielsma et al., 2016; Sonnemann et al., 2015). There are a variety of LCIA methods that address the “natural resources” AoP, making it difficult for the LCA practitioner to choose an appropriate method. However, there is actually quite a strong consensus regarding the *anthropocentric view* – that what is to be protected is the functional value of resources for humans (Dewulf et al., 2015; Finnveden, 2005; Sonnemann et al., 2015; Stewart and Weidema, 2005). To define the “natural resources” AoP more precisely, Dewulf et al. (2015) proposed five perspectives within the anthropocentric view: the “asset” of resources, their provisioning capacity, their global functions, the supply chain of goods and services, and ultimately human welfare. It may be problematic, however, that the “global functions” perspective includes the functional importance of resources for ecosystem services (which contribute indirectly to human welfare). This could lead to “double counting” with the AoP “ecosystem quality.”

Newer approaches for assessing “criticality” of resources and commodities have emerged outside the LCA community. Criticality is typically defined in terms of “risk” of supply disruption (or “supply risk”) and vulnerability to supply disruption (Achzet and Helbig, 2013; Erdmann and Graedel, 2011; Helbig et al., 2016b; Mancini et al., 2016; Sonnemann et al., 2015). However, as Glöser et al. (2015) point out, what is referred to as “risk” in this context arguably represents the *probability* of supply disruption. Therefore, this paper uses the term “supply risk” to refer to the multiple of probability *and* vulnerability. Examples of criticality assessment methods include those developed by Graedel et al. (2012) and Oakdene Hollins (2013), along with the Mining Risk Footprint (MRF) by Nansai et al. (2015). The methodology of Oakdene Hollins (2013) underpins the critical raw material (CRM) report of the European Commission (EC, 2014). Mancini et al. (2016) explored the potential for integrating criticality indicators into LCSA, testing 6 different methods on Life Cycle Inventory (LCI) data (from Ecoinvent version 2) for a laptop computer – with greatly diverging results.

Sonnemann et al. (2015) reviewed existing criticality assessment methods and proposed a conceptual framework for integrating criticality aspects into LCSA. Towards that end, their Geopolitical Supply Risk (GPSR) methodology as proposed by Gemechu et al. (2015a) aims to quantify the risk of short run supply disruptions due to geopolitical factors. The approach has been applied to an LCSA case study of a European manufactured electric vehicle (EV) based on a widely cited study and LCI data from Hawkins et al. (2012). As noted in the case study (Gemechu et al., 2015b), two of the primary limitations of the approach have been (1) the simplified representation of supply chains (the methodology implicitly assumes a single-stage supply chain, which is unrealistic for complex products) and (2) the lack of an LCIA *characterization model* to relate supply risk to a functional unit. Helbig et al. (2016a) addressed

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limitation (1) by extending the methodology for multi-stage global supply chains and demonstrating the extension with a case study of polyacrylonitrile-based carbon fibers. However, limitation (2) remains.

A connection to a functional unit is essential for integrating criticality considerations into LCSA – a framework that can be useful for assessing supply risk in addition to environmental implications. By expressing potential environmental and socio-economic impacts of material flows in common units of measure, the LCSA framework puts these “loadings” into an additive form. This allows the *total* load (i.e., category indicator) to be quantified in relation to the *functional unit* of a given product system. The functional unit provides the basis for product-level assessment, which is significant because decisions made at this level (such as product design and material selection) play an important role in supply chain risk management. Moreover, the notion of a functional unit is consistent with the anthropocentric view of the “natural resources” AoP. The “life cycle” approach also facilitates identification of “hotspots” in the product system, whether these are major contributors to environmental loads or “critical” input commodities in terms of supply risk. Finally, the LCI phase identifies the types and amounts of input commodities needed to make the product. Therefore, as Mancini et al. (2016) suggest, product supply risk – which is arguably a socio-economic issue – can be linked to physical processes captured under environmental LCA.

This article, therefore, aims at addressing one of the main limitations of previous attempts of integrating criticality into LCSA. It extends the GPSR methodology as proposed by Gemechu et al. (2015a) and Helbig et al. (2016a) from a relative assessment of raw material criticality to an LCIA characterization model for assessing product supply risk in relation to a *functional unit* under the LCSA framework. In its previously published forms, however, the GPSR methodology arguably measures *probability* of supply disruption. Therefore, it is referred to in this paper as the *GeoPol indicator*. The proposed GPSR characterization model is demonstrated with a comparative case study of an EV and internal combustion engine vehicle (ICEV) using the same LCI data – from Hawkins et al. (2012) – and thus building upon the earlier study by Gemechu et al. (2015b) and providing tangible products for discussion.

The next section of this paper explains the theoretical and methodological basis of the GPSR characterization model. The third section applies two embodiments of the characterization model to the comparative case study. The fourth section discusses the contributions of this paper and implications for LCSA research and practice. The paper ends with some concluding remarks.

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This paper adopts the “supply chain” perspective proposed by Dewulf et al. (2015), in which the “natural resources” AoP is defined as the *contribution* to human welfare (that is, the functional value) provided by products (including goods and services) for which resources are employed. Further, a *characterization model*, which is based on an underlying cause-effect mechanism, is proposed to aggregate relevant elementary flows from the LCI and assess potential impacts on the “natural resources” AoP in relation to the functional unit. In conventional (environmental) LCA, the elementary flows are physical inputs and outputs that cross the boundary between the product system (or “technosphere”) and the environment (or “ecosphere”). In contrast, assessment of product supply risk cannot be done solely on the basis of conventional elementary flows (i.e., raw inputs of unprocessed resources). Rather, the total supply risk associated with a product system depends on *all* upstream stages of the supply chain. Thus, a reasonable approach would be to assign a supply risk CF to each unit process. As suggested by Mancini et al. (2016), the physical amount of the “intermediate product” (ISO, 2006a) input to each process could serve as the elementary flow for which supply risk is measured.

2.1. Cause-effect mechanism

Whereas conventional LCIA impact categories like climate change and acidification have *environmental* cause-effect mechanisms, product supply risk has a *socio-economic* mechanism. As illustrated in Figure 1, the total supply risk for a product system depends on the probability of supply disruption and vulnerability to supply disruption across all unit processes. Supply disruption (due to geopolitical factors, for example) could negatively impact the performance of the product (i.e., the ability to actually provide the functional unit) and/or increase the cost of producing the product. This is the “outside-in” impact pathway. Impaired product function and/or cost increases could negatively impact human welfare through the “inside-out” pathway. Impacts on human welfare are at the “endpoint” level, whereas product supply risk is at the “midpoint” level (representing *potential* impacts).

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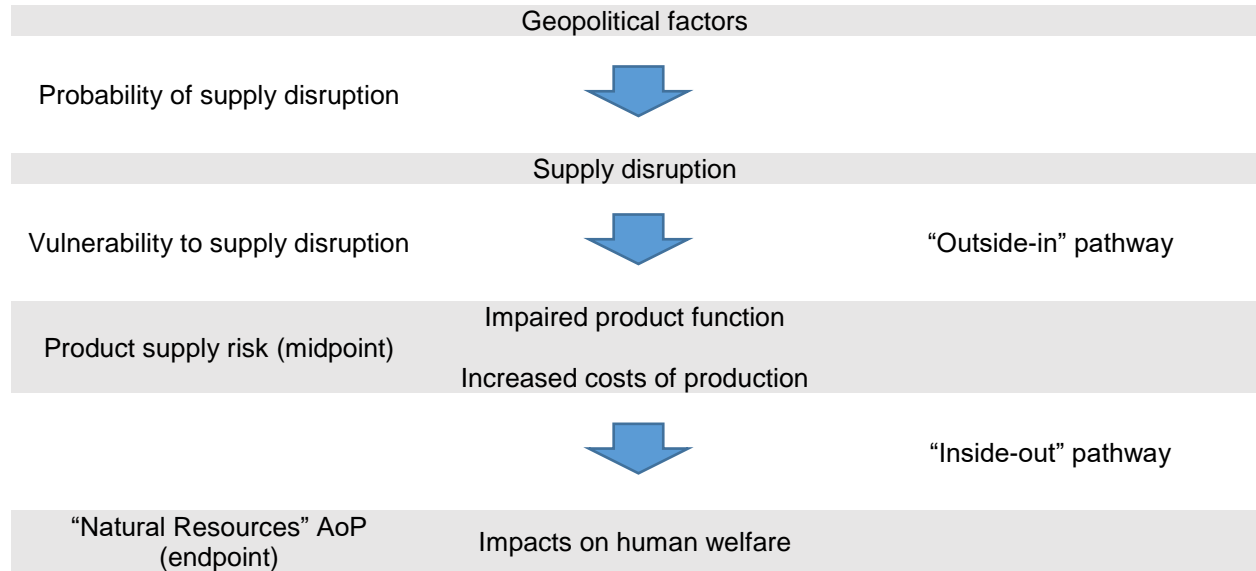


Figure 1: Theoretical cause-effect mechanism for product supply risk.

Product supply risk depends on the *resilience* of the supply chain. According to Sprecher et al. (2015), a resilient supply chain is resistant to supply disruption, able to recover rapidly from disruption, and flexible enough to adopt alternative supply strategies or find substitutes as necessary. These characteristics reduce the probability and vulnerability factors of supply risk. Sprecher et al. (2015) suggest several factors that determine the resilience of a supply chain, including the diversity of supply, substitution potential, improvement of material properties, and stockpiling. These factors serve to mitigate supply risk. The question is how to measure these theoretical constructs and relate them to a functional unit under the LCSA framework. Section 4 of this paper will revisit these ideas with respect to the proposed GPSR characterization model.

2.2. Characterization model

The GeoPol indicator according to the methodology proposed by Gemechu et al. (2015a) and Helbig et al. (2016a) represents *probability* of supply disruption due to geopolitical factors, but to assess supply *risk*, a vulnerability indicator is also needed. As illustrated in Figure 2, Geopolitical Supply Risk for a given unit process ($GPSR_{APc}$) depends on the probability of supply disruption of the input commodity ($GeoPol_{Ac}$) – which serves as an “intermediate product” (ISO, 2006a) – as well as the vulnerability to supply disruption ($Vuln_{APc}$). The elementary flow for a given unit process is defined as the physical amount of the input commodity (or intermediate product) needed to make the end product (Equation 1).

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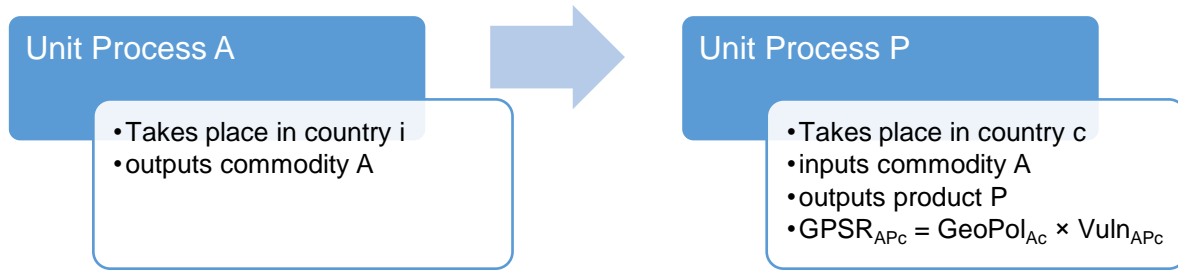


Figure 2: Connection between unit processes and supply risk.

$$GPSR_{APc} = m_{APc} \times CF_{APc}$$

$$CF_{APc} = GeoPol_{Ac} \times Vuln_{APc}$$

where

- $GPSR_{APc}$ = Geopolitical Supply Risk for commodity A needed to produce product P in country c
- m_{APc} = amount of commodity A needed to produce product P in country c (from LCI)
- $Vuln_{APc}$ = vulnerability indicator for commodity A needed to produce product P in country c
- $GeoPol_{Ac}$ = GeoPol indicator for commodity A imported to country c. According to Helbig et al. (2016a), it is defined as $GeoPol_{Ac} = HHI_A \sum_i g_i \frac{f_{Aic}}{p_{Ac} + F_{Ac}}$, where HHI_A = Herfindahl-Hirschman Index for commodity A, g_i = political (in)stability of (producing) country i, assessed using the Worldwide Governance Indicator (WGI) – Political Stability and Absence of Violence/Terrorism, f_{Aic} = import tonnage of commodity A from country i to country c, F_{Ac} = total import tonnage of commodity A to country c, p_{Ac} = domestic production of commodity A in country c

Equation 1

While probability of supply disruption is measured using the GeoPol indicator (Gemechu et al., 2015a; Helbig et al., 2016a), vulnerability is another construct that needs to be operationalized. Conceptually, the vulnerability of a product system to supply disruption of a commodity depends on the importance of the commodity input to product performance (i.e., the functional unit) and the potential for substitution. “Substitutability” is the most frequently used indicator for vulnerability in criticality assessments, followed by several “importance” calculations like value of products, value of materials, or strategic importance (Helbig et al., 2016b). Vulnerability is positively related to importance and negatively related to substitution potential (the latter being a risk mitigation factor). *From an economy-wide perspective*, the “economic importance” (EI) of a commodity can be calculated according to the methodology by Oakdene Hollins (2013) as

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applied in the CRM report of the EC (2014). This calculation defines EI as the weighted sum of the gross value added (GVA) of each end use “megasector” (s) in which the commodity is employed. The demand shares of the megasectors (D_{As}) are used as the weights (Equation 2).

$$EI_{Ac} = \sum_s (GVA_s \times D_{As})$$

Equation 2 (Oakdene Hollins, 2013)

The EI indicator can be used to measure vulnerability for calculation of supply risk CFs by normalizing the EI of each commodity to a reference commodity. We use tungsten (elemental symbol W) as a reference – as it is a particularly critical commodity – though the choice of reference commodity is ultimately arbitrary. When normalizing the EI indicators, it is important to account for the apparent consumption of the commodity to derive a mass-based “equivalency” ratio (Equation 3).

$$EI_{A/Wc} = \frac{EI_{Ac}}{M_{Ac}} \times \frac{M_{Wc}}{EI_{Wc}}$$

where

- $EI_{A/Wc}$ = economic importance of commodity A to country c, normalized to tungsten (W)
- EI_{Ac} = economic importance of commodity A to country c (per Equation 2)
- EI_{Wc} = economic importance of tungsten (W) to country c (per Equation 2)
- M_{Ac} = apparent consumption of commodity A in country c
- M_{Wc} = apparent consumption of tungsten (W) in country c

Equation 3

Apparent consumption is defined as the sum of total imports and domestic production minus total exports. As a simplification for the purpose of this paper, domestic production and total exports for the European Union (EU-27) are assumed to be zero, so the total imports are used as a first approximation (see supplementary material). While this is a limitation, it is overcome by further methodological developments presented in the remainder of this paper. The rationale for dividing EI by apparent consumption is discussed in section 4.

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Whereas the methodology by Oakdene Hollins (2013) measures “importance” at an *economy-wide* level, LCA (or LCSA) is a *product-level* assessment tool. On a product-level resolution, the resulting vulnerability factor is the ratio of the amount of the reference commodity to the amount of a given commodity (per functional unit), as seen in Equation 4.

$$EI_{APc} = \frac{GVA_{Pc}}{M_{Ac} \left(\frac{m_{APc}}{M_{Ac}} \right)} = \frac{GVA_{Pc}}{m_{APc}}$$

$$EI_{A/RPc} = \left(\frac{GVA_{Pc}}{m_{APc}} \right) \left(\frac{m_{RPc}}{GVA_{Pc}} \right) = \frac{m_{RPc}}{m_{APc}}$$

where

- EI_{APc} = economic importance of commodity A for product P produced in country c
- GVA_{Pc} = gross value added by product P in country c
- M_{Ac} = apparent consumption of commodity A in country c
- m_{APc} = amount of commodity A needed to produce product P in country c (from LCI)
- $EI_{A/RPc}$ = economic importance of commodity A for product P produced in country c, normalized to a reference commodity (R)
- m_{RPc} = amount of the reference commodity (R) needed to produce product P in country c (from LCI)

Equation 4

It follows that the category indicator result is the multiple of the GeoPol indicator and the amount of the reference commodity (which is effectively a constant). This further implies that the *total* category indicator for the product is effectively the sum of the GeoPol values of all materials in the product, multiplied by a constant. Therefore, replacing m_{RPc} with a constant of 1 would not change the effect of “cancelling out” the elementary flows, and it is justified to use $1/m_{APc}$ in place of $EI_{A/RPc}$ when calculating the supply risk CF.

By supplementing the GeoPol indicator – which serves as a proxy for probability of supply disruption – with the aforementioned vulnerability indicators, two embodiments of the GPSR characterization model (as defined in Equation 1) are constructed. The first applies the *economy-wide* EI methodology according to Oakdene Hollins (2013), normalized to tungsten as a reference commodity (Equation 5).

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$$CF_{APC} = GeoPol_{Ac} \times EI_{A/Wc}$$

Equation 5

As seen in Equation 6, the second embodiment applies the *product-level* importance factor ($1/m_{APc}$).

$$CF_{APC} = GeoPol_{Ac} \times \frac{1}{m_{APc}}$$

Equation 6

The results of each embodiment are presented in the next section, followed by further discussion in section 4. Note that Hawkins et al. (2012) already conducted a comparative environmental LCA of the EV and ICEV, and their environmental LCIA results are not duplicated here.

3. Results

This section presents the results of the two embodiments of the GPSR characterization model defined in Equations 5 and 6. Table 1 presents CFs for 14 commodities included in the LCI for the EV and ICEV, assuming the vehicles are produced in the EU-27. Values of the GeoPol indicator used to calculate the CFs are provided in the supplementary material. For comparison, Abiotic Depletion Potentials (ADPs), as are commonly used in LCA (Guinée and Heijungs, 1995; van Oers et al., 2002; van Oers and Guinée, 2016) are also presented. The ADPs presented in Table 1 were calculated by Mancini et al. (2016) using estimates of the reserve base and ultimate reserves (also known as “crustal content”). Note that for the ADP and Equation 5, the CFs are identical for the EV and ICEV, whereas for Equation 6, the CFs differ between the two vehicle types. The rationale for applying different CFs to different products is explained in section 4.

Table 1: Characterization factors for EV and ICEV (EU-27).

	CF Equation 5 (kg W eq / kg A)	CF Equation 6 (kg ⁻¹ A)		ADP Crustal content (kg Sb eq / kg A) according to Mancini et al. (2016)	ADP Reserve base (kg Sb eq / kg A) according to Mancini et al. (2016)
Commodity (A)	EV and ICEV	EV	ICEV	EV and ICEV	EV and ICEV
Al	1.57E-05	3.97E-04	1.15E-03	1.09E-09	2.53E-05
Fe + Steel	6.80E-06	1.13E-04	9.50E-05	5.24E-08	1.66E-06

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	CF Equation 5 (kg W eq / kg A)	CF Equation 6 (kg⁻¹ A)		ADP Crustal content (kg Sb eq / kg A) according to Mancini et al. (2016)	ADP Reserve base (kg Sb eq / kg A) according to Mancini et al. (2016)
Cu	1.37E-05	5.67E-04	3.20E-03	1.37E-03	2.50E-03
Pb	No data available	3.66E-01	3.78E-01	No data available	No data available
Mg	2.31E-03	2.22E+00	2.22E+00	2.02E-09	2.48E-06
Ni	4.03E-05	4.20E+01	0.00E+00	6.53E-05	4.18E-03
Sn	6.93E-04	1.28E+01	0.00E+00	1.62E-02	1.15E-01
Nd	5.95E-02	3.05E-01	0.00E+00	No data available	No data available
Brass^a	4.76E-03	4.16E-01	0.00E+00	1.37E-03	2.50E-03
Au	6.00E-07	1.64E+02	0.00E+00	5.20E+01	3.60E+01
B	No data available	3.71E+00	0.00E+00	4.27E-03	4.27E-03
PGMs	1.48E-04	0.00E+00	1.78E+01	2.22E+00	2.22E+00
Ag	2.87E-05	3.34E+02	0.00E+00	1.18E+00	8.42E+00
Zn	1.73E-04	7.07E-01	7.07E-01	5.38E-04	3.65E-03

^aCopper used as proxy for ADP.

When applying Equation 5, the only substantial “hotspot” from a supply risk perspective is neodymium in the EV (Figure 3A). This curious finding is a result of methodological aspects of Equation 5, as discussed in section 4. It should also be noted that Oakdene Hollins (2013) do not report EI values for lead and boron. Therefore, the supply risk associated with these commodities is not accounted for. Another gap is that, according to the LCI data from Hawkins et al. (2012), neodymium is not present in the ICEV (see supplementary material). Consequently, the supply risk for the ICEV is likely underestimated.

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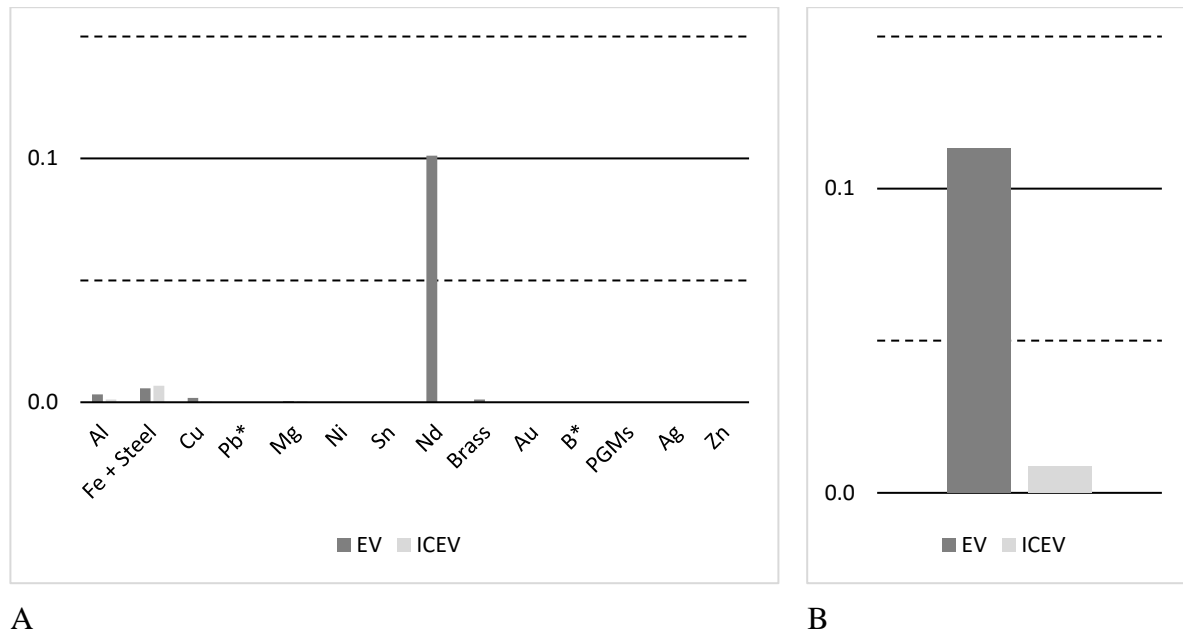


Figure 3: A. GPSR, economic importance, contribution analysis (kg W eq.). B. GPSR, economic importance, total per functional unit (kg W eq.).

*Data missing for economic importance.

As can be seen in Figure 4A, the biggest hotspots when applying Equation 6 are neodymium, magnesium, boron, tin, and platinum group metals (PGMs). As Equation 6 “cancels out” the elementary flow and replaces it with the GeoPol indicator, the proportional contribution of each commodity to the total supply risk associated with the EV is *identical* to that in the earlier publication by Gemechu et al. (2015b). That publication, however, did not compare the supply risk of the EV and ICEV, as seen in Figure 4A and B. As the category indicator results per Equation 6 are determined solely by the GeoPol indicator – which is independent of the product(s) under consideration – the supply risk contribution of a given material is identical provided said material is present in the LCI for each product. For example, aluminum, steel, copper, lead, magnesium, and zinc are present in both the EV and ICEV, so the GPSR results for these materials are the same for both vehicles (Figure 4A). It does not matter *how much* of a material is needed to produce the product, as long as the amount is greater than zero. However, if the same material is sourced from different suppliers, the GeoPol indicator will reflect the relative riskiness of those suppliers. According to the LCI data from Hawkins et al. (2012), nickel, tin, neodymium, brass, gold, boron, and silver are present in the EV, but not in the ICEV (see supplementary material). Therefore, these materials contribute only to the supply risk of the EV (Figure 4A). On the other hand, PGMs are present only in the ICEV exhaust system, and thus contribute only to the supply risk of the ICEV (Figure 4A).

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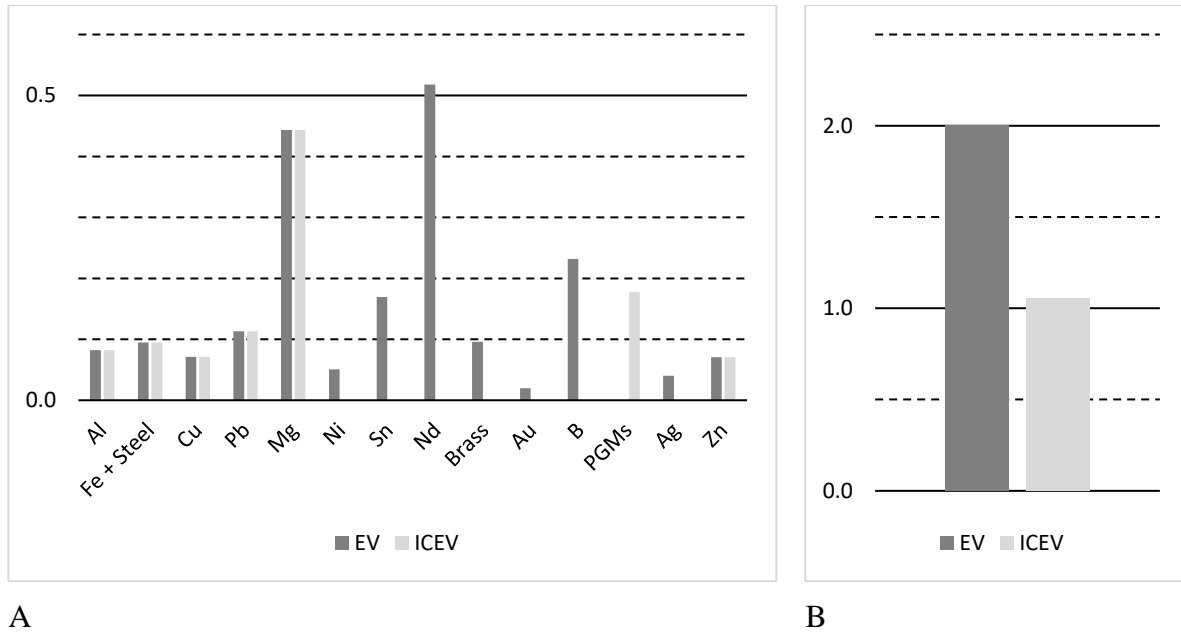


Figure 4: A. GPSR, product-level importance, contribution analysis (dimensionless). B. GPSR, product-level importance, total per functional unit (dimensionless).

Using estimates of crustal content – as recommended by Drielsma et al. (2016) and van Oers and Guinée (2016) – the ADP method flags copper (especially in the EV) and PGMs in the ICEV as the most critical commodity inputs (Figure 5A). Similar results are obtained using estimates of the reserve base for the ADP calculation.

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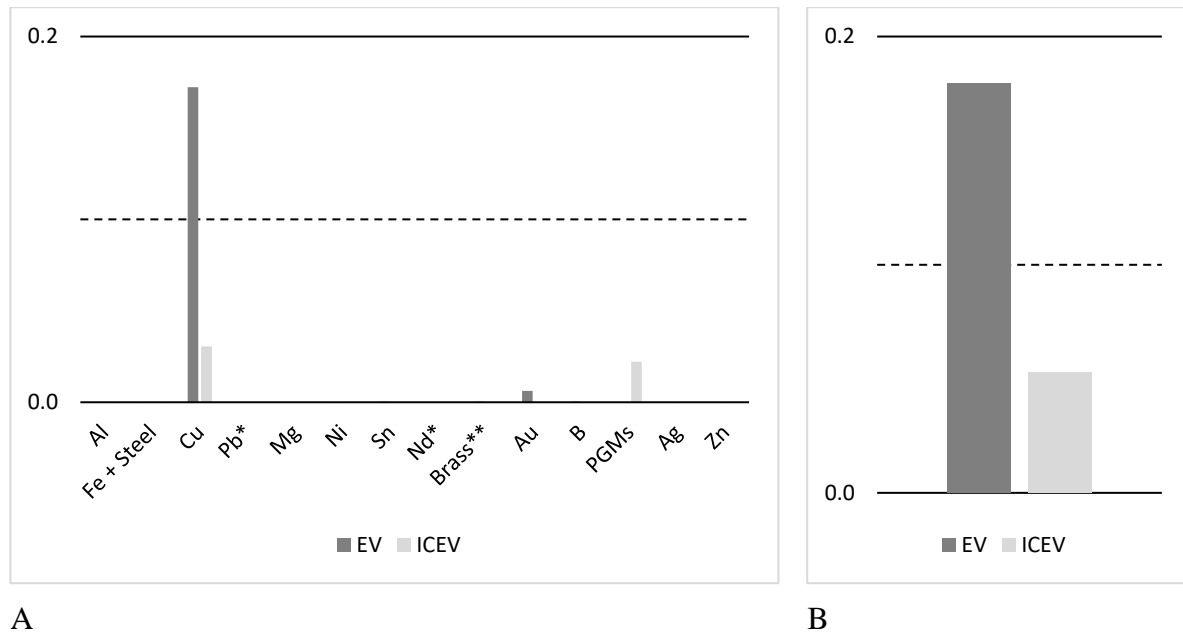


Figure 5: A. Abiotic Depletion Potential (crustal content), contribution analysis (kg Sb eq.). B. Abiotic Depletion Potential (crustal content), total per functional unit (kg Sb eq.).

*No data available.

**Copper used as proxy for brass.

While the *relative contributions* of the 14 materials to the category indicator results vary widely depending on the method, the *total* category indicator results are remarkably consistent; the EV is found to have significantly higher supply risk and resource depletion potential. However, as discussed in the next section, the difference may be overestimated due to data limitations. Nonetheless, the facility for making such comparisons is a strength of the GPSR characterization model.

4. Discussion

The GPSR characterization model presented in this paper significantly advances the integration of criticality assessment into LCSA and provides a new approach towards the “natural resources” AoP. In that regard, it is important to distinguish between a characterization *factor* and a characterization *model*. Whereas previous attempts at integrating criticality into LCSA (Gemechu et al., 2015a; Mancini et al., 2016; Schneider, 2014; Schneider et al., 2014) have proposed characterization *factors*, a valid characterization *model* is not only a set of operational CFs, but is grounded in a theoretical cause-effect mechanism (ISO, 2006a). In particular, the Economic Scarcity Potential (ESP) method proposed by Schneider et al. (2014), which is further accompanied by the Environmental Scarcity Potential (EnSP) and Social Scarcity Potential

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(SSP) (Schneider, 2014), aggregates a number of indicators to derive *characterization factors* (CFs) for economic, environmental, and social aspects of criticality. Though it is a step forward, this approach has important drawbacks from an LCA perspective. First, the definition of the relevant AoP is not clear, though Drielsma et al. (2016) argue the implicit safeguard subject is *the product itself* – corresponding to the “outside-in” relation as defined by Porter and Kramer (2006). Second, there is no clear cause-effect mechanism; rather the CF is a constructed index. Aggregation of indicators also implies *weighting* choices – which are very controversial in the LCA community. Finally, the use of global average values for the indicators masks important regional variations and therefore limits utility for decision-making.

Therefore, this article takes a step forward by proposing a cause-effect mechanism – albeit of socio-economic rather than environmental basis – for the GPSR characterization model. A novel feature of the cause-effect mechanism is that it includes both “outside-in” and “inside-out” impact pathways as defined by Porter and Kramer (2006). While conventional LCA is concerned with “inside-out” pathways (i.e., the potential environmental impacts of a product system), resource criticality assessments have been more concerned with “outside-in” pathways (i.e., the potential impacts of supply disruptions on provision of goods and services).

The “outside-in” impact pathway has important implications for the GPSR characterization model. In conventional LCA, the CFs are independent of the studied product system. For example, the global warming potential (GWP) of methane is the same for an EV and ICEV. Of course, the category indicator could differ, but only because of differences in the LCI. Even where environmental impacts exhibit spatial variability (for example, localized emissions), the CF may vary by the location of an emission but not by the product system responsible for the emission. Conventional approaches towards the “natural resources” AoP, which do not address “outside-in” mechanisms, also apply CFs that are independent of the product system. For example, the ADP of copper is the same regardless of whether the product is an automobile or a dishwasher. Similarly, Equation 5 applies the same CFs to the EV and ICEV. Neither the GeoPol indicator nor the “tungsten equivalent” EI differs between the two vehicle types. In contrast, the *product-level* importance factor included in Equation 6 is defined by product-specific elementary flows (i.e., the amounts of the various input commodities needed to make the product).

Equations 5 and 6 define two embodiments of the GPSR characterization model, so it is important to consider the strengths and limitations of each. For starters, Equation 5 applies the EI methodology by Oakdene Hollins (2013) – which, though a valuable contribution, introduces several problems. First, as can be seen in Equation 2, the EI indicator for a given commodity is determined solely by the distribution of the commodity across the economy (i.e., demand shares of end use “megasectors”) and the GVA of each “megasector.” This further implies that the *relative* EI of commodities can change merely due to changes in definitions of the megasectors

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(i.e., how commodities are assigned to various end uses). This property of the calculation is a major weakness with respect to the validity and reliability of the methodology.

Another potential problem is that the EI values of commodities according to Oakdene Hollins (2013) are relatively close together, and when normalized to the commodity with the highest EI, range from 0 to 1. The elementary flows, however, theoretically take on values from 0 to infinity. For example, according to LCI data from Hawkins et al. (2012), the mass of gold in the EV is less than 1 g, whereas the mass of iron and steel is over 800 kg. Consequently, the mass contribution could become the dominant factor in the supply risk calculation – as observed by Mancini et al. (2016). This means that materials used in small amounts, regardless of their supply risk, are unlikely to be assessed as “critical.” Therefore, some suggestions have been to apply crude mathematical transformations, such as exponential magnifications, to give more weight to criticality indicators (Mancini et al., 2016). Instead, Equation 5 addresses this problem by dividing the EI values from Oakdene Hollins (2013) by apparent consumption (approximated by total imports) to derive an EI indicator in monetary units per mass of a given commodity. This calculation dramatically increases the spread of the EI factors so that the mass contribution is not the dominant factor in the characterization results. Moreover, in contrast to the approach of Mancini et al. (2016), Equation 5 is based on an underlying cause-effect mechanism and conceptual definition of supply risk – the multiple of a probability indicator and a vulnerability indicator. By calculating EI per unit of mass of each commodity, it is possible to express the “equivalency” of commodities – in terms of vulnerability – on a mass basis.

But perhaps the biggest gap when applying the EI methodology by Oakdene Hollins (2013) is that the *level of analysis* is incongruent with the LCA (or LCSA) framework. Whereas the methodology by Oakdene Hollins (2013) measures EI of commodities at an *economy-wide* level, LCSA is a *product-level* assessment. This discrepancy is problematic because a given commodity may not be very “important” in terms of GVA to the economy as a whole, but could be critical to the functionality of particular products. For example, gold scores relatively low in terms of EI (see supplementary material), but has unique and desirable properties in products such as electronics and jewelry. Rare earth elements (REEs) and lithium do not have very high EI either, yet these commodities are particularly critical for emerging “clean” energy technologies such as EVs and wind turbines. Emerging technologies by definition do not yet have a high value added for the whole economy, but are of strategic importance. Moreover, as can be seen in Figure 3A, neodymium in the EV appears to be the only critical input commodity according to Equation 5. This curious finding is a result of the fact that the apparent consumption of neodymium is up to 3 orders of magnitude smaller than that of the other commodities (see supplementary material). As Equation 5 divides the EI according to Oakdene Hollins (2013) by apparent consumption, the resulting ratio is higher for commodities with lower apparent consumption. This implies that the CF for a given commodity input to a product system *increases* as economy-wide apparent consumption of the commodity *decreases*. Thus, applying

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an economy-wide measure of EI to a product-level assessment yields misleading results from an LCSA perspective.

In contrast, Equation 6 measures “importance” in relation to product performance (i.e., the *functional unit*). In that regard, it does not matter whether a tonne or a gram of material is needed to produce the product; every input to the product system is, by definition, equally necessary to produce the end product that provides the functional unit. If supply of any number of inputs becomes disrupted – regardless of the *amounts* of the inputs required – a completed product cannot be produced. Therefore, it is justified that Equation 6 “cancels out” the elementary flows and *eliminates* the mass dominance problem observed by Mancini et al. (2016). It follows that the relative contribution of each input commodity to the total supply risk is determined solely by the GeoPol indicator – which represents the *probability* of supply disruption.

With regard to the supply chain resilience factors defined by Sprecher et al. (2015), the GPSR characterization model accounts for the diversity of supply (based on the HHI and import shares), as well as the political stability of suppliers (based on the WGI). The latter aspect does not seem to be captured in the resilience framework of Sprecher et al. (2015), but is relevant to supply risk assessment. Notably, however, the GPSR characterization model does not presently account for the risk mitigating effects of material “substitutability” and stockpiles (or “safety stocks”). This paper considers the situation in the EU-27, so it is assumed that there are no safety stocks in this case. It would be useful to measure the risk mitigating effect of safety stocks, but this raises a number of methodological complications that are worthy of further study. Future work will also aim to incorporate “substitutability” indicators – for example, using concepts from material sciences and economics.

It is tempting to compare the GPSR characterization model with the ADP method commonly used in conventional LCA. While this temptation is understandable, the two approaches are not really comparable, as they measure different things. The objective of the ADP is to measure physical depletion of resource availability *in the long run*. It should also be noted that the Anthropogenic Stock Extended Abiotic Depletion Potential (AADP) method proposed by Schneider et al. (2015, 2011) extends the ADP by accounting for resources that remain (potentially) available in the anthroposphere. However, this paper presents the ADP merely for the sake of illustration; the topic of interest is the risk of geopolitically induced supply disruptions *in the short run* (for example, over a 2- to 3-year timeframe).

In that regard, the GPSR characterization model is useful to LCSA practitioners in a number of ways. First, the model expresses supply risks of different input commodities in common units of measure, thus enabling summation of risks per functional unit. This facilitates comparisons of supply risk for alternative product designs, as demonstrated by comparing the EV and ICEV.

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Moreover, the summation of risks implies that the *total* risk will inevitably be higher for more complex products (i.e., those having a greater variety of materials employed). The more complex the product, the higher the probability that supply of *at least* one material or component will be disrupted. For example, a passenger vehicle consists of numerous assemblies and subassemblies – and supply disruption of any one component could halt vehicle production. Finally, the methodology facilitates identification of supply risk “hotspots” and highlights opportunities to mitigate risk (for example, by increasing diversity of supply and/or sourcing from more reliable suppliers).

However, the GPSR characterization model as defined in Equation 6 ignores the *amounts* of commodity inputs to the product, and thus provides no incentive for using less material – despite “resource efficiency” being part of the EU Raw Material Initiative (RMI). This raises the question of how resource efficiency relates to resource “criticality.” There is a tension between promoting resource efficiency, on the one hand, and avoiding the mass dominance problem observed by Mancini et al. (2016), on the other hand. The former would require placing emphasis on the amounts of commodity inputs to a product system, whereas the latter would require de-emphasizing or even ignoring them. As resource extraction has environmental impacts (as assessed in conventional LCA), resource efficiency is of environmental relevance. Resource extraction also has potential to lead to *physical* depletion of geological resource availability (as is the underlying rationale for the ADP method). Notably, the contribution of brass to the total ADP of the EV and ICEV is negligible compared to that of copper (Figure 5A), even though the same CF is applied to both materials. The difference can only be explained by the mass contribution of the materials. Therefore, we argue resource efficiency is relevant to the environmental and geological aspects of criticality, but not to the geopolitical and socio-economic factors presently covered by the GPSR characterization model. One way of accounting for resource efficiency in product supply risk assessment could be to incorporate the risk mitigating effect of “safety stocks,” as a product that requires a larger amount of material may require a larger safety stock. However, the issue of safety stocks needs further work and is not captured in the GPSR characterization model at this time.

LCSA practitioners need to be mindful of a number of methodological complications associated with the GPSR characterization model. First, there is an important conceptual difference in the definition of the “elementary flow.” Applying the conventional LCA approach according to the ISO standards would define input elementary flows as raw concentrations of resources (i.e., ores) extracted from the environment. However, the total supply risk associated with a product system depends not only on resource extractions, but on *all* upstream stages of the supply chain. Therefore, we argue that the “elementary flow” from a supply risk perspective should be defined as the amount of “intermediate product” (ISO, 2006a) input to each unit process.

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Second, application of the GPSR characterization model imposes data and data quality requirements that in some ways exceed those of conventional (environmental) LCA. For example, the LCI data from Hawkins et al. (2012) do not identify any neodymium or other REEs present in the ICEV; the data suggest that neodymium is only present in the EV powertrain. This is questionable for modern automobiles that contain many electric motors (and therefore magnets) for numerous functional aspects of the vehicle (for example, power seat and door/window controls and windshield wiper motors). We do not mean to fault the work of Hawkins et al. (2012), which we believe provides a commendable balance between transparency and data quality. The objective of Hawkins et al. (2012) was to assess *environmental* implications of EVs in comparison to ICEVs; whereas the main interest in this paper is supply risk assessment. In that regard, LCSA practitioners need to take extra care when applying “cut-offs” or threshold values – particularly in the LCI phase. Materials present in small amounts may be negligible from an environmental perspective, but *not* from a supply risk perspective. In fact, Equation 6 implies that the amount is irrelevant as long as it is greater than zero. On the one hand, this implies extreme sensitivity to LCI data. On the other hand, the data can be of *lower* quality than for environmental LCA, as the *actual* amounts of elementary flows need not be known. Processes that have been found to contribute little to environmental loadings (for example, assembly and transportation processes) may contribute significantly to the total supply risk of a product system (for example, if assembly takes place in a small number of unstable countries). Moreover, as the probability of supply disruption depends on the suppliers from which commodities are sourced, LCI data need to be spatially explicit – identifying locations where unit processes take place. The importance of geographical information has already been highlighted with respect to assessment of water use in LCA (Bayart et al., 2010; ISO, 2014).

While we believe the GPSR characterization model presented in this paper advances the state of product supply risk assessment in LCSA, a number of important limitations remain. First, despite the work of Helbig et al. (2016a) towards modelling multi-stage supply chains, the GPSR characterization model presented in this paper still does not assess supply risks over an entire supply chain. Doing so would require further methodological development (for example, to measure “vulnerability” with respect to fabrication and assembly processes). It should be noted that the methodology by Helbig et al. (2016a) adopts a supply chain management perspective and is not a “life cycle” approach in its previously published form. Second, there are a number of challenges pertaining to availability and quality of data, to which the GPSR characterization model is extremely sensitive. Finally, the GPSR characterization model in its present form assesses supply risk at a country level, whereas supply chains actually consist of sourcing relationships between firms. However, the methodology could be adapted to a firm-level resolution.

Extension of geopolitical supply risk methodology: Characterization model applied to conventional and electric vehicles**5. Conclusion**

This article extends the Geopolitical Supply Risk (GPSR) methodology from a relative assessment of raw material “criticality” to a Life Cycle Impact Assessment (LCIA) characterization model under the Life Cycle Sustainability Assessment (LCSA) framework. The GPSR characterization model is based on a socio-economic cause-effect mechanism drawing upon supply chain resilience concepts. The cause-effect mechanism consists of an “outside-in” pathway (i.e., the potential impact of supply disruption on the product system) and an “inside-out” pathway (i.e., the impact of impaired product performance and/or cost increases on human welfare). The outside-in pathway is represented by a “midpoint” indicator – *product supply risk* – defined as the multiple of *probability* of supply disruption and *vulnerability* to supply disruption. The elementary flow is defined as the physical amount of the “intermediate product” input to a given unit process. The supply risk associated with the intermediate product serves as the characterization factor (CF).

Two embodiments of the characterization model are presented, each supplementing the previously proposed probability indicators with different indicators for vulnerability. The first applies the methodology by Oakdene Hollins (2013) to derive an “economic importance” (EI) indicator for each intermediate product. However, as this methodology measures EI at an *economy-wide* level, it is not suitable for LCSA. Therefore, the second approach adapts the EI concept to a *product-level* resolution, with the implication that every input to the product system is equally important. The two methods are demonstrated with a comparative case study of an electric vehicle (EV) and internal combustion engine vehicle (ICEV).

The second method is evidently the more reasonable embodiment of the GPSR characterization model. However, it introduces a number of methodological complications and is highly sensitive to data availability and quality. Nonetheless, this article sheds new light on the integration of criticality assessment into LCSA and illustrates how environmental LCA methodology can be adapted to cover socio-economic issues like product supply risk.

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Supplementary data

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Supplementary Material

Table S1: Bill of Materials for EV and ICEV based on Hawkins et al. (2012)

Commodity	Mass in EV (kg)	Mass in ICEV (kg)	GeoPol EU-27 (dimensionless) according to Gemechu et al. (2015) and Helbig et al. (2016)
Aluminum	2.06E+02	7.13E+01	0.0820
Iron + Steel	8.35E+02	9.97E+02	0.0947
Copper	1.26E+02	2.23E+01	0.0713
Lead	3.10E-01	3.00E-01	0.1134
Magnesium	2.00E-01	2.00E-01	0.4435
Nickel	1.20E-03	0.00E+00	0.0505
Tin	1.32E-02	0.00E+00	0.1691
Neodymium	1.70E+00	0.00E+00	0.5181
Brass	2.31E-01	0.00E+00	0.0961
Gold	1.20E-04	0.00E+00	0.0198
Boron	6.25E-02	0.00E+00	0.2318
PGMs	0.00E+00	1.00E-02	0.1777
Silver	1.20E-04	0.00E+00	0.0401
Zinc	1.00E-01	1.00E-01	0.0707

EV = electric vehicle

ICEV = internal combustion engine vehicle

Table S2: Economic importance of commodities for EU-27

Commodity	Economic Importance (€B) as calculated by Oakdene Hollins and Fraunhofer ISI (2013)	Total Imports (kg) according to UN Comtrade (for 2012)	Economic Importance (€ / kg)	Economic Importance (kg W eq. / kg)
Tungsten	165	4.52E+06	36,477	1.00E+00
REEs (light)*	95	2.27E+07	4,189	1.15E-01
Magnesium	100	5.26E+08	190.0	5.21E-03
Tin	123	8.23E+08	149.4	4.10E-03
Zinc	158	1.77E+09	89.4	2.45E-03
PGMs	120	3.95E+09	30.4	8.34E-04
Nickel	161	5.54E+09	29.1	7.97E-04
Silver	87	3.33E+09	26.1	7.16E-04
Copper	105	1.50E+10	7.01	1.92E-04
Aluminum	138	1.98E+10	6.96	1.91E-04
Iron	135	5.15E+10	2.62	7.18E-05
Gold	69	6.23E+10	1.11	3.04E-05
Lead	No data available	N/A	N/A	N/A
Brass**	105	5.82E+07	1,805	4.95E-02
Boron	No data available	N/A	N/A	N/A

*Economic importance (€B) is for all "light" REEs (including neodymium) as defined by Oakdene Hollins and Fraunhofer ISI (2013). However, the total imports in this table only include neodymium.

**Copper used as proxy

N/A = not applicable

Extension of geopolitical supply risk methodology: Characterization model applied to conventional and electric vehicles

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Supplementary Material

One way of deriving a *product-level* vulnerability indicator is to calculate the “product consumption” in relation to a reference commodity (Equation S1).

Equation S1

$$Product\ Consumption_{APC} = \left(\frac{1}{M_{Ac}}\right) \left(\frac{M_{RC}}{m_{RPC}}\right)$$

Where

- M_{Ac} = apparent consumption of commodity A in country c
- M_{RC} = apparent consumption of reference commodity (R) in country c
- m_{RPC} = amount of reference commodity (R) needed to produce product P in country c (from LCI)

Importantly, the reference commodity must be present in the LCI of the studied product system. Note that when product consumption is multiplied by the elementary flow (m_{APc}), the result is the ratio of the commodity input to the product (per functional unit) to (economy-wide) apparent consumption of the commodity, normalized to the reference commodity. This approach is not employed in any proposed embodiment of the GPSR characterization model, as testing revealed it produces very similar results compared to using the economy-wide economic importance indicator.

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