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

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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.

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

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(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).

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 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 con-