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Review

From a critical review to a conceptual framework for integrating the criticality of resources into Life Cycle Sustainability Assessment

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ABSTRACT

The importance of integrating resources criticality assessment into Life Cycle Assessment (LCA) under the Life Cycle Sustainability Assessment (LCSA) framework has been discussed for some time. However, the question how to proceed towards integration remain unclear. Only very few work is published on this issue and to our knowledge only Schneider et al. (2014) have developed one operational model. In this paper we review existing literature critically and explain why integration is important and how it could be done, using knowledge from outside the LCA field. The criticality assessment method proposed by Graedel et al. (2012) is identified as the best starting point. This paper shows based on a critical review why bridging towards such a method could help addressing criticality in LCSA, what are possible options and which research needs exists. It reveals that currently LCA does not adequately cover resource criticality and that methods like Graedel et al. (2012) are inspiring further development of LCA; both approaches have a complementary nature and hence could be developed towards integration within the LCSA framework. Currently resource indicators are not meaningful in LCA, wherefore there is no consensus in LCA community on what to recommend; hence the Area of Protection Natural Resources needs to be rethought. Broadening the scope of LCA towards LCSA provides a conceptual framework to keep LCA relevant for assessing sustainability challenges like access to resources.

1. Introduction

A strong interest has been raised recently about the integration of resource criticality assessment within life cycle assessment (LCA) context (Klinglmair et al., 2014; Mancini et al., 2013; Peña, 2013; Schneider et al., 2014; Sonnemann, 2013). However, why and how to proceed to such an integration remains unclear and to our knowledge no systematic review exists clarifying the current state of the art in LCA field in terms of resource criticality assessment. To the best of our knowledge, the recent work from Schneider et al. (2014) is the first attempt to introducing the concept of resource criticality under the Life Cycle Sustainability Assessment (LCSA) framework. It provides a new characterization factor for resource use impact assessment by introducing economic elements that could influence the supply of resources and their subsequent availability for human use. The proposed method is a complement to the already existing LCA methods, in which resource availability is being addressed by only modeling the geological availabilities. However, the work from Schneider et al. (2014) is focused on a model and not on a conceptual framework on how to bring the general idea of resource criticality into LCA context. Therefore, the purpose of the current paper is to identify clearly why there is a need in LCA to integrate resource criticality assessment and how it could be addressed according to the state of the art methodologies in this area. Furthermore the paper aims at understanding whether or not these methodologies answer the criticality challenges in an LCA compliant manner and what are the possible bridges and further research needs in order to enable an efficient integration of resource criticality assessment in LCA context.

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Meeting the energy, land, water and material supply needs of 9 billion people in 2050 while having less environmental impacts on climate change, biodiversity loss and health threats are one of the challenges our Planet Earth is facing today (UNEP, 2010a). This challenge can be basically met by altering the unsustainable consumption and production patterns through a transition toward a "green economy". The global extraction of natural resources has increased in the past and also expected to increase in the future. A study by SERI (2012) suggests that if the world economy continues to grow with a business-as-usual scenario, then the global extraction of resources would be 100 billion tons 2030, which is almost double the extraction in 2005. Specific to minerals, the high demand by the strong economic development of Brazil, China, India and other emerging countries and also the search for better product performance coupled with the technological advancement are among the main factors that foster the dynamics of their use both in terms of total quantity extracted and number of materials utilized for particular functionality (Duclos et al., 2010). From the early 1900s to 2005, the use of industrial minerals has increased by a factor of 27 (Krausmann et al., 2009) at the same time the number of metals utilized expanded from a few to almost the full range of the periodic table of elements. For example, the development of a computer chip in the last two decades has increased the spectrum of metal use from 12 to 70 (National Research Council, 2008). This remarkable increase of metal utilization coupled with potential supply restriction and the resulting price fluctuation have recently drawn the attention of researchers, governmental and individual decision-makers at different organizational levels and the general public to the issue of criticality assessment (Erdmann and Graedel, 2011).

Those concerns surrounding resources are among the major issues for different stakeholders all over the supply chain of industrial products (Seuring and Müller, 2008). Since the development of LCA in the early 1990s, the impacts from resource use (often referred as "Resource Depletion") have been an integral part of LCA (Jolliet et al., 2004). However, even if a variety of life cycle impact assessment (LCIA) methods already assess resources depletion as an impact category, impact assessment of resources in general and mineral metals use in particular is one of the most controversial issue in LCIA (Weidema et al., 2005). A lack of methodological consistency has hampered the development of widely acceptable indicators for resource use (Emanuelsson et al., 2013; Stewart and Weidema, 2005; Wäger and Classen, 2006; Yellishetty et al., 2009). This was also highlighted by the recent International Reference Life Cycle Data System (ILCD) handbook of the European Commission (EC) Joint Research Center (JRC) (European Commission, 2011a), which suggests the need for methodological improvements. This lack of consensus on how resource depletion should be handled urges – according to the EC – for the development of a harmonized LCIA method for resource use (Eldh and Johansson, 2006). The missing alignment among different LCIA methods for resource use impact comes not only from the differences in the nature of modeling, but also from the differences in definitions and understandings of what the resource depletion is, what limits the access to resources and why there is a need to consider resources as an Area of Protection (AoP) as such. There is a strong paradox as in theory all agree that what has to be protected is the access to a functional value of the resources. That means the services provided by the resources are what the society has to protect, not the resource for the sole value of its existence. However, in practice most LCIA methods are only based on the geological availability of resources without any consideration of their functionality or of the multiple barriers for their availability to human use (accessibility).

2. Resources as an Area of Protection in LCA

In LCA community a consensus exists in the definition of three Area of Protection (AoP), defining classes of endpoint category indicators Society wants to protect, namely: Human Health, Natural Environment and Natural Resources (Finnveden et al., 2009; Guinée et al., 2002; Udo de Haes et al., 1999; Udo de Haes and Lindeijer, 2002). They ensure a link between damages due to environmental interventions with societal values.

The way how direct impacts due to the use of function of natural resources are quantified and linked with societal values are controversial as the definition of natural resources as an AoP is not clear. The AoP Natural Resources contains those elements that are extracted physically for human use with implication for their present but also their future availability (Udo de Haes and Lindeijer, 2002). It includes abiotic resources, biotic resources, land and fresh water. In this definition of the AoP Natural Resources, the main focus is on quantifying the depletion due to their use to support production in the economy. It is based on the principle of future resource scarcity as a result of current consumption, therefore, it has an anthropocentric viewpoint. Since most abiotic natural resources such as minerals only have functional values to humans, but no intrinsic or existence value (a value that comes not from utility derived from its direct or indirect use, but from knowing its existence, e.g. unique natural environments like Grand Canyon), their societal values are limited to the possible functions they provide to the economic system to achieve other goals that have intrinsic value, for example human welfare or human health (Stewart and Weidema, 2005). The impacts from resource use in principle then have to be modeled as impact on human welfare due to reduced availability, increased competition, and limited accessibility due to social and geopolitical factors, in addition to the usual environmental impact assessment of their extraction (Finnveden, 2005). Currently direct impacts from the use of resources could be handled as socio-economic impacts or environmental impacts, however, there are not yet clear boundaries between the environment and socio-economic systems, and there is a need to clarify the boundaries between the ecosphere and the socio-economic systems. The current LCIA methods for impacts from resource use, hence, have several shortcomings in complying with the AoP Natural Resources. Therefore, a new perspective for LCIA is to address such issues through the introduction of the resource criticality concept under the LCSA framework, a framework of future LCA (Guinée et al., 2011). LCSA combines environmental LCA, social and socio-economic LCA and Life Cycle Costing (LCC) to evaluate all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products (Finkbeiner et al., 2010; Kloepffer, 2008; UNEP/SETAC, 2011; Valdivia et al., 2013).

An environmental LCA assesses the environmental performance of a product or process through accounting all the energy and material inputs and the associated emissions and waste outputs at each stage of its life cycle (ISO, 2006a, 2006b; Sonnemann et al., 2003). A social LCA addresses the social and the socio-economic implications of products throughout all the life cycle stages from extraction, raw material production, manufacturing, use, recycling and final disposal (O'Brien et al., 1996; UNEP/SETAC, 2009). Except for the focus on some aspects, it has almost a similar approach as the environmental LCA with regard to functional unit, system boundary, etc. According to UNEP's guidelines for social LCA (UNEP/SETAC, 2009) the social and socio-economic impacts associated with the product's life are captured in five suggested stakeholder categories: workers, local community, society, consumer and value chain actors. The social LCA can be used as a stand-alone assessment tool or as a complement to the environmental LCA. LCC

Table 1
Summary of criticality assessment studies.

	Scope	Time horizon	Objectives	Materials covered	Criticality concept	Indicators
AEA Technology (2010)	National (UK)	0–5 years for short-term 5–20 years for medium-term Greater than 20 for long-term	To review future resource risks faced by UK business	Ag, Al, Au, Co, Cu, In, Li, Mo, Ni, P, Pb, Pt, REE, Sb, Sn, Ta, Te, Ti and Zn	- Criticality matrix - Demand - Supply	- Combined availability to scarcity - Availability of alternatives - Supply distribution - Supply domination - Extent of geopolitical influences - Press coverage - Price fluctuation
DOE (2011)	Global	Present – 2015 for short-term 2015–2025 for medium-term	To analyze risk and opportunities, continue the public dialogue and identify programmatic directions through examining the role of REE and other key materials in the clean energy economy	Ce, Co, Dy, Eu, Ga, In, La, Li, Mn, Nd, Ni, Pr, Sm, Tb, Te and Y	- Criticality matrix	- Clean energy demand - Substitutability limitation - Basic availability - Competing technology demand - Political, regulatory and social factors - Co-dependence on other markets - Producer diversity

Erdmann et al. (2011)	National (Germany)	Up to 5 years short-term
		5–10 years medium-term
		10–20 long-term
		(2008 base year)
			To provide a complete picture of raw materials whose supply are proven to be critical to Germany in the medium to long term time horizon.	- Bentonite, Kaolin, Gypsum, Calcium carbonate
				- Diatomite, Mica, Talk, Vermiculite & Perlite
				- Bauxite, Magnesite, Ilmenite and rutile, Barite, Borate, Diamond, Fluorspar, Graphite, Phosphate, REE, Zircon
				- Al, Co, Cr, Cu, Fe, Mn, Mo, Nb, Ag, Ni, Pb, Sb, Sn, Sr, Ta, Ti, W, Zn
				- Be, Bi, Ga, Ge, Hf, In, Li, Mg, Pd, Pt, Re, Se, Si, Te, V
					- Criticality matrix
					  - Vulnerability
					  - Supply risk
						- Germany's share of world consumption
						- Change in share
						- Change in import in Ge
						- Sensitivity of the value chain in Germany
						- Global demand increase by future technologies
						- Substitutability
						- Country risk for Germany's import
						- Country risk for global production
						- Country concentration for global reserves
						- Corporate concentration of global production
						- Global reserves to global production ratio
						- Share of global primary and secondary production
						- Recyclability

BGS (2012)	Global	Specific year 2011	To supply a new supply risk index for chemical elements or element groups for UK's economy in 2011	Ag, Al, As, Au, Ba, Be, Bi, Diamond, Graphite, Cd, Co, Cr, Cu, F, Fe, Ga, Ge, Hg, In, Li, Mg, Mn, Mo, Nb, Ni, Pb, Platinum Group elements (Ru, Pd, Os, Ir and Pt), Re, REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu), Sb, Se, Sn, Sr, Ta, Th, Ti, U, V, W, Zn and Zr	- Supply risk	- Scarcity - Production concentration - Reserve distribution - Recycling rate - Substitutability - Governance (top producing nation) - Governance (top reserve-hosting nation)

Graedle et al. (2012), Nassar et al. (2012) and (Nuss et al., 2014)	Corporate (Solar Future, Inc.)
	National (US)
	Global
		0–5 years for Corporate
		5–10 years for National
		10–100 years for Global
			To propose a new methodological approach for metal criticality analysis (Graedel et al., 2012) and to apply it for geological copper family (Nassar et al., 2012)	Ag, As, Au, Cr, Cu, Fe, Mn, Nb, Se, Te and V	- Criticality space
					  - Supply risk
					  - Vulnerability to supply restriction
					  - Environmental implication (cradle-to-gate analysis)
						- Depletion time (reserves)
						- Companion metal fraction
						- Policy potential index
						- Human development index
						- Worldwide governance indicators (Political stability)
						- Global supply concentration
						- Percent of revenue impacted
						- Ability to pass-through cost increases
						- Importance to corporate strategy
						- Substitute performance
						- Substitute availability

						- Environmental impact ratio - Price ratio - Corporate innovation - National economic importance - Percentage of population utilizing - Net import reliance ratio - Net import reliance - Global innovation index - LCA cradle-to-gate: 'human health' & 'ecosystems'

Moss et al. (2013)	Continental (EU)	20 years 2010–2030	To identify critical metals that could become a bottleneck to supply-chain of different low-carbon energy technologies in EU	Ag, Au, Cd, Ce, Co, Cr, Cu, Dy, Eu, Ga, Gd, Ge, Graphite, Hf, La, Li, Ln, Mo, Nb, Nd–pr, Ni, Pb, Pt, Re, Se, Sm, Sn, Ta, Tb, Te, V, Y	- Supply chain bottleneck risk (Supply risk)	- Market factors
						  - Limitations to expanding supply capacity
						  - Likelihood of rapid global demand growth.
						- Geopolitical factors
						  - Cross-country concentration of supply
						  - Political risk related to major supplying countries

Goe and Gaustad (2014)	Country	Over a 20-year period	To quantify and compare criticality metrics for silicon-based and thin-film photovoltaic materials that focus on a more comprehensive systems approach	Al, As, Cd, Cu, Fe, Ga, Ge, Au, In, Mo, Pt, Se, Si, Ag, Te, Sn and Zn	- Criticality matrix
					  - Supply risk
					  - Economic risk
					  - Environmental risk
						- Net import reliance
						- Hirfindahl–Hirshmann index of primary material and ore producers
						- Recycling rate
						- Ratio of production to reserves
						- CERCLA points
						- Primary embodied energy
						- Energy savings
						- Primary material price
						- Domestic consumption
						- Economic value by sector

Roelich et al. (2014)	National (UK)	2012–2050	To develop a dynamic criticality assessment method that allows the identification of potential policy responses in transition towards a low-carbon infrastructure goal to reduce criticality	Nd	- Criticality matrix
					  - Supply disruption potential
					  - Exposure to disruption
						- Companion fraction
						- Access
						- Environmental constraints
						- Production requirements imbalance
						- Goal sensitivity
						- Price sensitivity

Zepf et al. (2014)	Global	Long-term	To identify materials that are constraints to the main energy pathway	Ag, Cd, Co, Cr, Cu, Ga, Ge, In, K, Li, Mo, Ni, Nb, P, Pd, Pt, Re, REE, Rh, Te, U, V and W	- Three scores for each indicators (High, Low and Medium)	- Reserves - Trade - Ecological impacts - Processing - Substitutability - Recyclability

assesses the cost implications of a product. It accounts all the relevant costs and benefits that are linked to the products life cycle (Swarr et al., 2011).

3. Review of resource criticality assessment methods

Resource criticality assessment is a systematic tool to determine the risk incorporated with the raw materials usage and their relative importance to an economy, be it at micro-, meso- or macro level. The criticality definition of resource is context dependent, (National Research Council, 2008) for example the National Research Council (NRC) considers mineral to be critical "… only if it performs an essential function for which few or no satisfactory substitutes exist…" and "…only if an assessment also indicates a high probability that its supply may become restricted, leading either to physical unavailability or to significantly higher prices for that mineral in key applications…" (National Research Council, 2008). According to the European Union's (EU) report on raw materials, resource critical is defined as "…those which display a particularly high risk of supply shortage in the next 10 years and which are particularly important for the value chain…" (European Commission, 2011b).

Recently the term "critical raw material" has come into prominence to refer to mineral resources, non-energy raw materials that combine a comparatively high economic importance with a comparatively high risk of supply disruptions (Buijs et al., 2012). Resource criticality is often assessed from an availability (supply risk) and importance in use (also known as vulnerability to supply restriction) points of view (European Commission, 2010a; National Research Council, 2008). On the one hand, the supply risk addresses issues such as the abundance of the resources in the Earth's crust as well as their economic, technological, geopolitical and social availability (Graedel et al., 2012). On the other hand, the dimension of vulnerability to supply restriction measures the degree of importance of a particular resource over the others through assessing how the supply restriction of a resource could potentially affect the functioning of its final use in the value chain (National Research Council, 2008). In this regard, the substitutability of a resource is among important indicators in determining vulnerability to supply disruption or importance in use. In many cases it is used as indicator to reflect the dependency of each end-user for specific resources as a consequence of any supply disruption (DOE, 2011; Erdmann et al., 2011; Graedel et al., 2012). On the other hand, it is also considered as an indicator in the supply risk dimension (European Commission, 2010a) based on the argument that substitution can be easily driven by market cost and can alter the demand on other resources to affect the overall supply risk. Evaluation substitutability, in general, is very difficult task as it comprises several sub-indicators and a number of steps to determine it (Graedel et al., 2012). In most cases measuring the substitution factors requires expert judgment, while in some cases mathematical algorithm is used to define it (European Commission, 2010a). Despite the fact that it is very challenging task to evaluate resource substitutability, it remains to be used as an important indicator in criticality assessment (Achzet and Helbig, 2013).

The qualitative analysis on criticality in determining the potential risk of supply disruption dates back to early 1970s (Buijs et al., 2012). In 1974 a study was conducted by the Ad Hoc Inter-Agency Group on Critical Imported Materials (US DoS, 1974) to assess the challenge of the US to providing its economy with imported critical materials at a reasonable cost. It also indicated important action the US needs to take in order to overcome this situation. In 1975 the Commission of the European Communities presented a criticality analysis on specific resources (minerals, vegetable, animal and protein products) (CEC, 1975). It acknowledged materials that give cause of concern to supply problems from different product categories. Since then the issue of resource criticality as a measure of potential risk of supply and the associated impacts have been addressed in different literature sources (AEA Technology, 2010; Bae, 2010; BGS, 2012; DOE, 2011; Erdmann and Graedel, 2011; European Commission, 2010a; Graedel et al., 2012; Knoeri et al., 2013; Mason et al., 2011; Morley and Eatherley, 2008; Moss et al., 2013; Nassar et al., 2012; Rosenau-Tornow et al., 2009; Schüler et al., 2011; Talens Peiró et al., 2012; UNEP, 2009; Zepf et al., 2014). A work from Erdmann and Graedel (2011) provides a detailed review on exiting methodologies up to the year of 2010. It aims at examining the rationale behind different methodological approaches for criticality assessment of non-fuel minerals and how the major choice of methodological frameworks and perspectives affects the final outcome of the studies. Therefore, basing us on the work done by Erdmann and Graedel (2011), who already reviewed criticality assessments, in this review, we focus on literature sources on criticality assessment published from 2010 up to date. A systematic literature review approach was used to identify the main studies that are dealing with resource criticality assessment. We looked for peer-reviewed literature as our principal source of information. The literature search for the peer-reviewed journal articles were conducted using bibliographic databases such as Scopus, ScienceDirect and Web of Knowledge. However, since lot of existing criticality assessment studies are not peer-reviewed, additional research was conducted using different websites and general Google enquires by introducing important key words, company or organization names, specific locations and so on. With regard to the language of the literature, mainly documents written in English that discuss resource criticality assessment methods were included, except for Erdmann et al. (2011), which is in German. Table 1 summarizes the most recent methodological development and application of criticality analysis from 2010 onwards (AEA Technology, 2010; BGS, 2012; DOE, 2011; Erdmann et al., 2011; Goe and Gaustad, 2014; Graedel et al., 2012; Moss et al., 2013; Nassar et al., 2012; Nuss et al., 2014; Roelich et al., 2014; Zepf et al., 2014). All listed criticality assessment methods are based on a common ground, comparing different raw materials using a number of measurable indicators considered to be relevant to the definition of criticality. However, a set of varying indicators were implemented in each case to assess the potential risk of supply and its consequence. There are some indicators that are common to all methods such as geological availability, substitutability and market concentration. Environment is included as an indicator in the work done by Zepf et al. (2014), Graedel et al. (2012) and Goe and Gaustad (2014). While most of the considered studies focused on continental or global perspective, the method proposed by Graedel et al. (2012) explicitly differentiates resource criticality between corporate, national and global context. One of the main challenges of the listed criticality assessment is their limitation to address the dynamic nature of most of the indicators that are thought to contributing to the determination of criticality. A static critical assessment only provide a snapshot at one point in time without taking into consideration the possible evolution of the indicators over time (Buijs et al., 2012). More recently, different methodologies and case studies have been proposed in order to overcome this limitation (Goe and Gaustad, 2014; Knoeri et al., 2013).

Having looked at these various resource criticality assessment methods, we have identified the three-dimensional criticality method of Graedel et al. (2012) to present relatively the most matured and robust methodology of those approaches (Lloyd et al., 2012). It is quite exhaustive in terms of relevant indicators and hence it is considered as being the current state of the art for criticality assessment. For this reason, this approach is used as a basis to evaluate the potential of LCA for criticality assessment and to come up with possible bridges and gaps to be filled in order to consider criticality within LCA within a new conceptual framework. The approach of Graedel et al. (2012) extends criticality matrix into space through the introduction of an environmental element in addition to the supply risk and vulnerability to supply restriction dimensions. Each dimension of Graedel et al.'s (2012) criticality space is composed of several elements in which they are equally weighted to finally give a single score in defining criticality. The supply risk side, for example, in a medium-term perspective has three major components: (1) geological, technological and economic, (2) social and regulatory and (3) geopolitical. Each component has a number of indicators and the final supply risk score will be derived by equally weighting the indicators. Likewise the vulnerability to supply restriction dimension has three components: importance, substitutability, and ability to innovate, and each major component has indicators. The environmental dimension has high relevance as environmental damage from extraction and metal production is considerable due to the energy intensiveness of these processes (Althaus and Classen, 2005; Classen et al., 2007). Here it is important to mention that Graedel et al. (2012) method is basically designed for metals, but it can also be adapted to be used for other abiotic resources. The main components and relevant indictors of Graedel et al.'s (2012) criticality assessment method are summarized in Table 2.

4. Reviewing the potential LCA to be integrated with criticality assessment under LCSA framework

LCA currently fails to consider criticality. However, integrating criticality considerations with LCA under LCSA framework would probably allow a more meaningful assessment of the impacts on the AoP Natural Resources. LCA could then potentially benefit from existing criticality assessment approaches such as Graedel et al.'s (2012) approach described above and be used to address the challenges of criticality in an LCSA context.

If Graedel et al.'s (2012) approach is promising as it exhaustively covers all the relevant indicators to be considered to assess criticality, it suffers from some drawbacks that make it unusable as such in LCA context (and the same drawbacks apply to all the other criticality assessment methods). The weighing procedure implemented in the criticality assessment is subjective and simplified. One can give more value to one component than the other depending on the priority of weighting. The relative importance of one component or indicator over the other is particular to users, location and time, hence it is very challenging and may not be possible to have a totally objective and universally acceptable weighting method. In LCIA, weighting has always been a controversial and debatable issue. The limitation mainly arises due to a non-scientific base of its procedure, which usually is based on value-choices, and due to the need for the incorporation of social, ethical and political values (Eldh and Johansson, 2006; Finnveden, 1997). It is among one of the optional elements according to the ISO framework for LCA (ISO, 2006a, 2006b) that should only be applied when it is no longer possible to model the environmental mechanisms on physico-chemical or biological bases and it can be included in the assessment depending on the goal and scope of LCA study. Despite it is optional and the most controversial issue, it has also been widely used in several LCA case studies. The main advantage of weighting is the ability to obtain an overall indicator that makes results communication easier and allows to see, based on those value choices, the trade-off between different indicators or components.

However, when it comes to criticality assessment, each dimension is derived from a number of rolling up of several sub-indicators and additional aggregating over the three major indictors (supply risk, vulnerability to supply restriction and environmental implication) would thus result in a high number of arbitrary choices. This could possibility be treated similarly as the LCIA scoring systems which aggregates across environmental impact categories following environmental mechanisms at the end-point level, but also allows to keep the environmental impacts disaggregated at the midpoint level for increased transparency. Therefore, in line with the human health and ecosystem quality impacts, in which they are expressed by a number of mid-point indicators, resource criticality could also be represented by different indicators such as the ones proposed by Graedel et al. (2012) before aggregation. However this is still a challenge as Graedel et al.'s (2012) components in each criticality axis are not additively affecting the same AoP as do all the human-health or ecosystem quality related mid-point indicators. The impacts of toxicity and global warming on human health can be compared together at the end-point level by comparing their contribution to human health burden, this is not the case when talking about the Graedel et al.'s (2012) geological and geopolitical indicators, which are not additively affecting the AoP Natural Resources. The framework may be more complex with a strong interaction between the different indicators. However, such interactions between different mid-point impact categories may also exist in other impact pathways but are not currently integrated in LCA framework. For example the increased vulnerability of ecosystems to toxic chemicals due to climate change is not considered and climate change impacts on ecosystems are considered additive with ecotoxicologic impacts. The additivity of the Graedel et al.'s (2012) indicators between each other as affecting independently the AoP Natural Resources is not an evidence as some of those indicators may be strongly intercorrelated. For example, if a resource is geologically abundant but in a critical region of the globe, the combination of those two indicators make the resource critical, but this would not be well represented by simply adding a geological availability indicator and a geopolitical accessibility indicator. Additional research efforts are therefore needed to find a way to consistently integrate those indicators in a LCSA framework, going beyond a focus on environmental aspect above LCA.

The following sections different indicators proposed by Graedel et al. (2012) are analyzed in detail to see to what extent they are already covered or not by the current LCA framework, to identify the overlap, the gaps and the possibilities of integration of criticality assessment into LCA context. The conceptual links between Graedel et al.'s (2012) indicators and LCA are represented in Fig. 1 and also summarized in the Table 3. The life cycle inventory from unit process modeling that are linked with damage to human health and ecosystem quality are addressed by using a well-established method such as ReCiPe (Goedkoop et al., 2013) while the impacts from the direct use of resources can be captured in the socio-economic dimension as resource scarcity. They will be explored more in depth in the next sections.

There are several issues that need to be addressed in attempts to bring the concept of criticality into the LCSA framework. These are, for example, how to develop a characterization factor to quantify resource criticality, whether to have a relative ranking or absolute values to provide a meaningful results and easy interpretation. LCA normally evaluates the environmental performance of a product or a service through linking energy and material requirements and the associated emissions to a number of midpoint impact indicators and finally to endpoint damages in absolute value per functional unit. Whereas, existing criticality assessments usually tempt to assess multiple resources at a time and compare the relative criticalness among resources. In a sense that a resource is regarded as “critical” when it poses a relatively higher supply risk, economic importance and environmental impacts compared with most of

Table 2
Summary of components and respective indicators of Graedel et al. (2012) approach.

Criticality axis	Components	Indicators
Supply risk – medium-term	- Geological, Technological and Economic	- Depletion time (Reserves) - Companion metal fraction
	- Social and Regulatory	- Policy potential index - Human development index
	- Geopolitical	- Worldwide governance indicators: political stability - Global supply concentration
Supply risk – long-term	- Geological, Technological and Economic	- Depletion time (Reserve base) - Companion Metal Fraction
Vulnerability to supply restriction – corporate	- Importance	- Percent of revenue impacted - Ability to pass-through cost increases - Importance to corporate strategy
	- Substitutability	- Substitute performance - Substitute availability - Environmental impact ratio - Price ratio
	- Ability to Innovate	- Corporate innovation
Vulnerability to supply restriction – national	- Importance	- National economic importance - Percentage of population utilizing
	- Substitutability	- Substitute performance - Substitute availability - Environmental impact ratio - Net import reliance ratio
	- Susceptibility	- Net import reliance - Global innovation index
Vulnerability to supply restriction – global	- Importance - Substitutability	- Percentage of population utilizing - Substitute performance - Substitute availability - Environmental impact ratio

other resources under assessment. Integration of criticality concept into LCA under the LCSA framework then needs a common understanding of the natural resource AoP and the significant of social and economic dimensions in additional to the environmental aspects. Unlike environmental LCA based models, indicators used in existing criticality studies have ordinal scale and they are not easily used as a base to develop characterization factors through establishing a cause and effect chain (Emanuelsson et al., 2013). But they can be used as social component that reflect the possible disruption of resources due to short-term supply constraints. There are some attempts made to address these issue. For example, Schneider et al. (2014) suggests the consideration of economic and social aspects to compliment exiting resource impact assessment LCA models so as to move towards a more comprehensive resource availability assessment within the context of LCSA.

4.1. Supply risk perspective

How the direct impacts from the use of mineral resources and water have traditionally been addressed in LCA is widely debatable and to our understanding do not allow to meaningfully address the AoP Natural Resources (Emanuelsson et al., 2013; Stewart and Weidema, 2005; Wäger and Classen, 2006; Yellishetty et al., 2009). This section aims at exploring the main shortcomings of already exiting methods for resource impact assessment and also aims at suggesting a new perspective and direction on how to integrate criticality in LCA under the LCSA framework to better define different issues surrounding resources.

The environmental impacts associated with the use of resources such as mineral and metals have been addressed by using three main approaches – as categorized initially by Stewart and Weidema (2005) and further refined by Finnveden et al. (2009): i) methods based on and an inherent property of the material such as exergy consumption or entropy production, (Bösch et al., 2007; Dewulf et al., 2007) ii) methods addressing the scarcity of the resource by basing the assessment on the ratio between what is currently extracted related to some measure of available resources or reserves (e.g.: EDIP and CML) (Guinée and Heijungs, 1995; Hauschild and Wenzel, 1998; Van Oers et al., 2002) and iii) methods based on environmental impacts from future extractions that results in the need for additional efforts which can be translated into higher energy or costs, and thus lead to an increased impact on the environment and economy (e.g.: EcoIndicator 99 and ReCiPe) (Müller-Wenk, 1998-1; Steen, 2006). None of these methods are judged sufficiently mature for recommendation by the EC (European Commission, 2010b). Their scope is so diverse that choosing one over the other might lead to different results and conclusions. At the same time, the LCA resource indicators cover a very limited types and number of elements (Klinglmair et al., 2014), resulting in misunderstanding and false conclusions. Moreover, LCA practitioners and decisions makers are often not aware of what exactly these indicators represent and what their underlying assumptions and limitations are. Finally, category iii) impact assessment methods based on environmental impacts from future extractions might rather be included in the inventory analysis (Finnveden, 2005; Weidema et al., 2005).

Furthermore, none of those methods adequately addresses social, nor regulatory nor geopolitical aspects of supply risk. However, the category ii) methods address at least partly the geological aspects of supply risk: the depletion of resources is based on the extraction-to-availability ratio and has been recommended by EC (ILCD) to be used as midpoint impact category in LCA. The CML method is currently only operational for abiotic resources, i.e. metals, minerals and fossil fuels. CML covers 48 minerals, 4 fossil fuels and nuclear fuel and none of biotic resources are covered with CML method (Klinglmair et al., 2014). These geological aspects will be further discussed in the following sub-section.

Resource issue for materials such as mineral metals should not stick to depletion, rather it has to address the issue of scarcity which should reflect not only the geological aspects, but also socio-economic, regulatory and geopolitical aspects that affects accessibility as proposed in the Graedel et al. (2012) approach. One of the

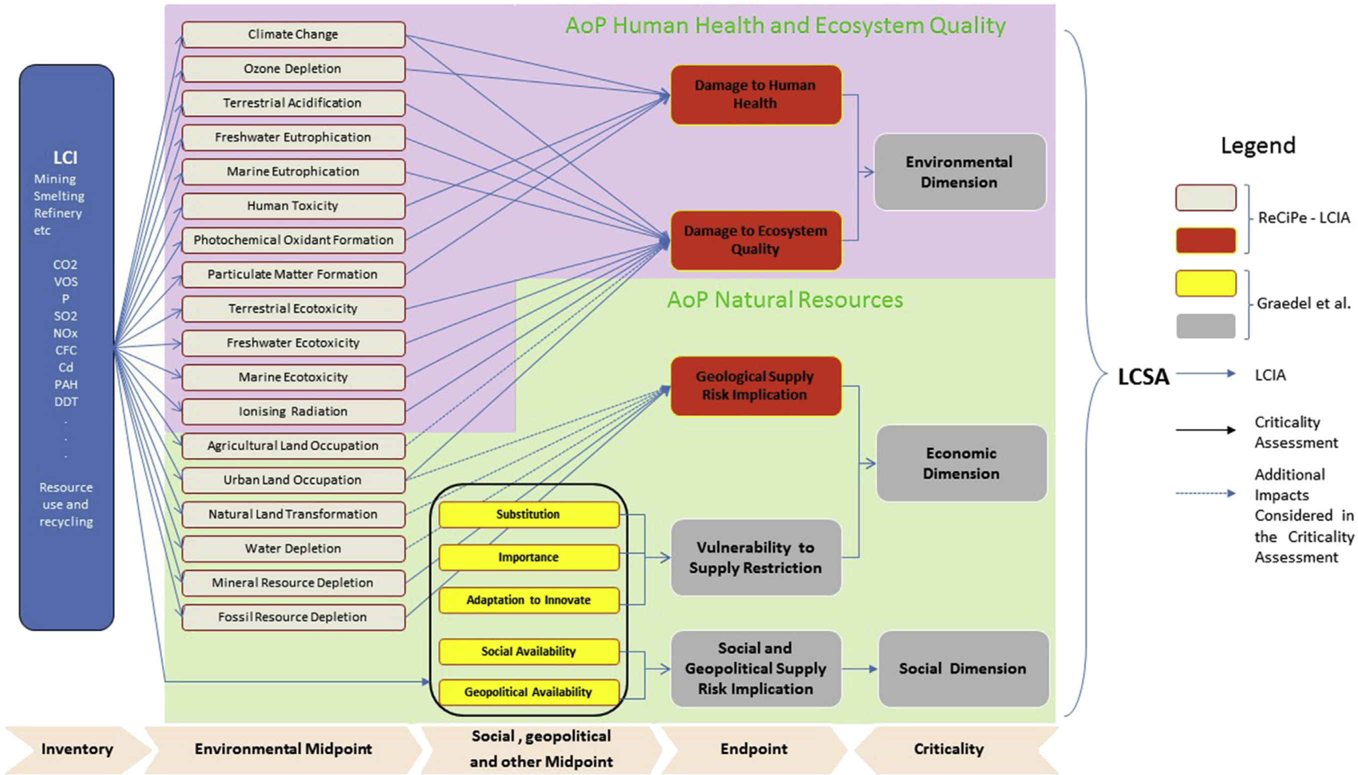

Fig. 1. Schematic representation of integration of Graedel et al. (2012) criticality assessment into LCA context under LCSA framework.

conclusions from the stakeholder consultation, a process organized by the European Commission to clarify Natural Resource AoP, was that resource impact assessment indicators for short-term time perspective should include political factors (Vieira et al., 2011). Hence, the shortcomings of the resource depletion issue urge the need for a new perspective in LCIA that would rather give emphasis to a broader dimension of availability (Goedkoop and Dubreuil, 2005) which can be referred to as supply risk. The introduction of such important indicators would allow LCA to evolve from a simple environmental performance evaluation tool to a more comprehensive LCSA method providing also information with regard to a resource criticality assessment.

4.1.1. *Geological aspects of supply risk*

The geological, economic and technological element in Graedel et al.'s (2012) approach is addressed through using two equally weighted indicators that are depletion time and companion metal fraction. The depletion time is the time required for a geological reserve of given resource to completely exhausted. The definition of resource depletion time is based on historical and estimated future demand statistics of the resource, end-of-life recycling rates and losses to tailings and slag and from other processes. The companion metal fraction estimates the percentage of a metal that is mined as daughter metal. The majority of metals are not extracted by themselves, rather they are naturally occurred in metal ores with similar physical and chemical properties and later recovered as by-products. Therefore, the availability of companion metals then depends both on the technological availability to extract them from the host metals and also the economic feasibility of their recovery (Graedel et al., 2011b).

Typically, mineral resource impacts are quantified in category ii) methods through assessing geological depletion, which focus on the future supply and demand of specific resources in long-term time horizon. In CML for example – the recommended category ii) LCIA approach by European Commission (2011a) – the characterization factors (CFs) are determined by dividing the average annual production by the square of the ultimate reserves, a geological reserve which is estimated by multiplying the average concentrations of chemical elements in the earth's crust by the mass of the crust (the result is then normalized to antimony as a reference substance) (Guinée et al., 2002; Guinée and Heijungs, 1995). But whether, the sources of minerals will become exhausted has been an issue of strong debates (Knoeri et al., 2013) as estimation the exact stock size of mineral deposits is very complex and highly uncertain. It was highlighted on the one hand by Graedel et al. (2011b) approach that it is impossible to quantify the extractable global resource (EGR) for any metal – the EGR referring to the amount of a given metal in ore that is judged to be extractable over the long term. Data on EGR have been compiled by different geological surveys (USGS, 2013). However, they can only provide a lower limit on geological availability of resources. CML considers on the other hand, the ultimate reserves, which are determined by multiplying the average concentration of the resource of interest in Earth's crust by the total mass of the crust. Nevertheless, it is understood that all the resources in the crust are not technically feasible to be extracted. Some of them are found in seabed or other areas where they cannot be easily accessed. Results based on ultimate reserves can be considered as hypothetical upper limits. Therefore, assessments based on both EGR and ultimate reserves do not provide information on the future availability as they may be far from the reality.

In addition to uncertainties associated with geological availability resources in use tock and landfill are drawing attention. Recent studies suggest that as a result of continuous increase of metal use over the 20th century, there is a considerable shift of metal stock from the lithosphere to the anthroposphere (Chen and

Table 3
Links between the Graedel et al. (2012) approach and the current practice in LCA and research need summary.

Graedel et al. (2012) criticality matrix components and indicators	Current integration in LCA	Research need identified
Supply risk – medium- term - -Geological, technological and economical - Social and regulatory - Geopolitical Supply risk – long- term - Geological, technological and economical	Most existing LCIA indicators are assessing the supply risk at long term based only on geological availability, without accounting for social, regulatory or geopolitical aspects. Social LCA allows accounting for some social impacts but not for the supply risk related to those social or other environmental impacts.	Need to integrate social, regulatory and geopolitical aspects of supply risk in LCIA resource use models and/or to consider a matrix of midpoint indicators allowing to better consider supply risk in the resources area of protection.
Vulnerability to supply restriction – corporate - Importance - Substitutability - Ability to innovate Vulnerability to supply restriction – national - Importance - Substitutability - Susceptibility Vulnerability to supply restriction – global - Importance - Substitutability	Some current methodological development in LCA tend to include the vulnerability to supply restriction accounting for the importance of the resource, the substitutability between resources and the ability to innovate and adapt through a functional approach.	Need to integrate the current knowledge already cumulated in the field of criticality assessment approaches in the LCIA models in development to consider importance, substitutability and ability to innovate and adapt using state of the art approaches
Environmental implications (cradle-to-gate analysis) - Damage to human health - Damage to ecosystem	Environmental impacts on human health and ecosystem quality of resources extraction is already included in a classical LCA in which all the emissions related to extraction processes are inventoried and their impacts characterized. However, LCA is inappropriate for some very site specific considerations in terms of impact (biodiversity hotspots) or in term of inventory of emissions (radioactivity of some rare earths ores), and some impacts considered in the Graedel approach are not included in the conventional LCIA framework (accident risk in mining).	Clarify which impacts considered in the Graedel approach are already considered in LCIA, which may be better characterized through social LCA. Identify the remaining uncharacterized impacts and determine if they are relevant for integration in an LCA context as impact categories. Clarify the link between environmental impacts and social acceptability of mining projects to be able to establish a cause effect chain between environmental impacts of ores extraction and resource criticality.

Graedel, 2012; Gerst and Graedel, 2008; Hatayama et al., 2010; Reck et al., 2008; UNEP, 2010b). For example, the average per capita anthropogenic stocks of copper and aluminum in industrialized countries are estimated to be 230 and 340 kg, respectively (UNEP, 2010b). This significant amount of anthropogenic stock could be available in the future with high potential of recycling and reuse to reduce the entire dependence on the primary resources, provided that recycling challenges are addressed in the future (Graedel et al., 2011a; Kapur and Graedel, 2006; Reck and Graedel, 2012). The use of anthropogenic stock can alter to a great extent the perception of resource availability (Frischknecht and Jungbluth, 2007). A recent study by Schneider et al. (2011) reveals that the consideration of anthropogenic stock to assess resource depletion influence significantly the characterization factors. Therefore, anthropogenic stocks need to be considered while assessing mineral resource depletion. However, so far, none of the existing operational LCIA methods in LCA software takes into account the anthropogenic stock so far.

Generally, and based on available data, LCIA category ii) methods can therefore be considered as appropriate approaches to model geological aspects of supply risk. However, these geological aspects alone are not really meaningful to represent the impacts on AoP Natural Resources and the “real” impact pathways through which the society is affected when a resource is dissipated, in line with the findings of Graedel et al. (2012) Therefore, additional indicators are proposed by Graedel et al. (2012) regarding social and geopolitical aspects. The following sections are focusing on those aspects and the possibilities to account for them in an LCA context.

4.1.2. Social aspects of supply risk

The social and regulatory elements in Graedel et al.'s (2012) approach of criticality assessment are intended to reflect the potential influence of a jurisdiction and the society's attitude towards any mining and related activities. This is addressed through introducing the Policy Potential Index (PPI) and the Human Development Index (HDI) as regulatory and social indicators in the supply risk dimension. The PPI evaluates the potential effect of public policy in encouraging or discouraging mining exploration investments. The index covers a wide range of indicators that can reflect the attractiveness of a given country's policy from mining exploration point of view. These are “uncertainty concerning the administration, interpretation, and enforcement of existing regulations; environmental regulations; regulatory duplication and inconsistencies; taxation; uncertainty concerning native land claims and protected areas; infrastructure; socioeconomic agreements; political stability; labor issues; geological data base; and security” (McMahon and Cervantes, 2011). The results are then averaged and normalized to a single score for each jurisdiction. PPI score ranges from a maximum of 100 (a jurisdiction that obtains the highest value in all measured policy issues) to a minimum of 0 (a jurisdiction that receives the lowest score).

The HDI is an informative indicator that measures the performance of a country to improve the well-being of a society through considering the three basic aspects of human development: a long and healthy life, access to knowledge and a decent standard of living (United Nations Development Programme, 2011). Societies with high HDI are considered to have strong awareness about the environmental and socioeconomic consequences of mining developments and vice versa. The HDI value of each country is a value between 0 and 100% (the higher, the more well-being there is in the country). Then the final social indicator for each metal is derived by multiplying the transformed HDI with the weighted-average mining, smelting, or refining production quantity of metals of interest in each country (Graedel et al., 2012). This model considers a linear correlation between HDI and social supply risk and assuming that there is high social supply risk for the countries with relatively high HDI scores.

This may be debatable and the correlation with the environmental and socioeconomic indicators is not straightforward: if in a more developed country there is a higher risk for a mining project with environmental or social impacts to be rejected, there is also a higher potential of adaptation to resource deprivation and there is a potential access to cleaner technologies, both lower the supply risk.

As an example, similar socio-economic indicators to HDI have been used in LCIA for water use impact assessment. A consensual framework was developed within the UNEP/SETAC Life Cycle Initiative (Bayart et al., 2010). In this framework water consumption leads first of all to a modification of the resource availability. The subsequent increased competition is captured by a competition index correlated with water scarcity (consumption to availability ratio) which may be considered similar to what is proposed in category ii) methodologies for mineral resources use. Three sets of impact pathways are then identified, each of them leading to impacts on a specific AoP: Human Health, Ecosystem Quality and Resources. First, a reduction in water availability to human users can potentially affect human health if water was fulfilling human essential needs (domestic use, agriculture or aquaculture). Direct impacts on human health related to water deprivation have already been addressed (Boulay et al., 2011; Motoshita et al., 2011; Pfister et al., 2009) and been compared qualitatively (Kounina et al., 2013) and quantitatively (Boulay et al., 2014, 2013) in order to try to reach a consensus within the UNEP/SETAC life cycle initiative. However, if sufficient financial resources are available (situation equivalent to a high HDI), which is currently considered using the Gross national income per capita, it is unlikely that humans will suffer direct consequences of water shortage. Users will be able to adapt by using a functionally equivalent alternative (for example desalinating water or importing food) that may, in turn, shift the environmental burdens to other life cycle stages and impact categories (indirect impacts) and to additional adaptation costs that may be considered as resource use impacts on human welfare (AoP Natural Resources). Adaptation of competing users is currently considered only in Boulay et al. (2011) approach, however, the indirect impacts and cost due to adaptation (e.g. the impacts related to water desalination) still need to be assessed. But this is a first attempt to integrate not only physico-chemical and biological environmental mechanisms, while modeling a cause effect chain in LCIA, but also some socio-economic mechanisms. In parallel to that, more conventional cause effect chains including only physic-chemical and biological mechanisms have been followed recently in order to model the impacts of water use on AoP Ecosystem Quality area of protection (Hanafiah et al., 2011; Maendly and Humbert, 2011; Pfister et al., 2009; Verones et al., 2012, 2010; Zelm et al., 2010).

Broader than the impact of the social development in different countries on the supply risk of resources extracted in those countries proposed by Graedel et al. (2012), the social LCA aims at quantifying the social impacts looking at the complete life cycle of the products (O'Brien et al., 1996; UNEP/SETAC, 2009). Models used in social LCA to assess the social impacts on the local community stakeholder category may bring interesting data and information to better assess the social aspects of supply risk. Moreover, one of its subcategories is defined as access to material resources, which could be considered as social resource indicator in modeling the social component of the supply risk. However, attention should be paid to avoid double counting between such a social LCA indicator and an environmental LCIA indicator assessing the impact of resource dissipation on competing users' access to the resource: here some overlaps may exist.

The social LCA is specific approach in a sense that the impacts are assessed by taking into account all the detailed social aspects particular to specific region. However, the social LCA is still in its infancy despite the fact that its concept has been introduced a while ago (Andrews et al., 2009; O'Brien et al., 1996). There is an increasing interest on its methodological development and application recently (Andrews et al., 2009; Dreyer et al., 2006; Ekener-Petersen and Finnveden, 2012; Feschet et al., 2012; Jørgensen et al., 2012, 2009; Mancini et al., 2013; UNEP/SETAC, 2009), therefore, the concept of social LCA in case it gains more maturity could be used as a starting point to complement the HDI to measure the potential human responses to mining related activities.

4.1.3. *Geopolitical aspects of supply risk*

The geopolitical element of Graedel et al.'s (2012) supply risk dimension measures the potential effects of geopolitical factors on the availability of resources. It comprises two indicators, worldwide governance indicators (WGI) and global supply concentration (GSC). The WGI is a measure of the risk imposed by political instability and policy actions to the extraction and supply of resources. Resources from politically unstable countries could pose higher supply risk than those from countries with a relatively stable political situation.

The political instability is of high relevance to supply disruption of resources when they are geographically concentrated in a global market. The Herfindahl–Hirschman Index (HHI) is utilized to measure the market concentration. It is calculated by summing the squares of the market share of a resource in the market supply. A higher value of HHI shows a more concentrated market.

LCA in its current state doesn't address the short-term impact on resources. This impact is better addressed by considering the potential effects of political and economic factors. The depletion of the physical availability of minerals is a long-term issue and according to Graedel et al. (2012) it is difficult to estimate most important factor that could lead to scarcity. Therefore, for some resources, political and economic factors are what really matters and this is of particular importance when a short-term perspective is considered. Some resource may be abundantly available in the Earth's crust, but only political factors can alter their accessibility as they make them hard to be extracted. For example, possessing only 36% of global reserve for rare earths (REs), China is been the most dominant producer and supplier, since it monopolizes more than 85% of world REs supply (USGS, 2013). In response to an increasing domestic demand on REs, China tightened its export quota. This lead to rapid price increase due to a misbalance in global supply and demand (Deboer and Lammertsma, 2013). This situation may induce a serious problem for a wide application of low-carbon technologies such as hybrid cars and wind mills, where REs are used (UNEP, 2009). Such a limit on the accessibility of resources due to geopolitical concerns has resulted in the reopening of mines outside China, relocating of global firms to China and also enhance the recyclability of REs (Deboer and Lammertsma, 2013). Recycling of REs from electronic wastes is also seen as an option that can contribute to overcome this problem. The US, the EU, Japan and emerging economies such as India and Brazil are among the most affected by Chinese's export restriction and its dominant control over rare-earths. Due to its importance for the introduction of sustainable technologies worldwide, the AoP Natural Resources should incorporate political and economic factors so that the short-term consequence of any supply disruption could be easily addressed in any LCA study.

When it comes to LCA, geopolitical elements have been overlooked in all previous studies, although they are of high significance especially for companies in order to properly understand the future constraints of their supply chain in short- and mid-term time horizon and to help them in their related decision making strategy. However, nowadays, there is an increased use of geographic information in LCA that allows also to map the supply chain of companies for their products and hence to identify potential future supply constraints (Seuring and Müller, 2008). This information in particular used to address the future availability of water due to risks related to changing weather patterns (UNEP, 2011) and the access to minerals due to the risk of conflicts (OECD, 2013; Young and Dias, 2011, 2012). In this context LCA could play a particular role to integrate geopolitical aspects in the life cycle of a product. In addition to providing information on the environmental impacts on ecosystems and human health, advanced LCA methods like the one for assessing the water footprint developed by Boulay et al. (2011) or Pfister et al. (2009) could provide also relevant information for decision makers on the scarcity of a resource which could result from sudden changes in supply mix from a particular area of the world. As stated before, only recently discussion has started within LCA community for the use of the raw materials criticality concept in LCA framework. The experts workshop on security of supply and scarcity of raw materials organized by the Joint European Centre – Institute for Environment and Sustainability (JEC–IES) (Mancini et al., 2013), the discussion by Sonnemann (2013) in the Society of Environmental Toxicology and Chemistry (SETAC) Europe meeting and by Peña (2013) in Life Cycle Management (LCM) conference can be seen as a starting point. The first reference made to the introduction of a geopolitical element under LCA context is proposed by LC-Impact (Emanuelsson et al., 2013), which is based on the EC report on defining critical raw materials for EU (European Commission, 2010a). The most recent work is from Schneider et al. (2014) who include HHI and Worldwide Governance indictors in a first attempts to develop an economic resource scarcity potential model to evaluate resource use within the LCSA framework.

The way forward in the possible integration of the geopolitical related supply risk into the LCSA can be explained as follow. In conventional LCA, for example in ReCiPe method, the direct impact from the use of mineral resource at midpoint level is defined as a marginal ore grade reduction as a result of marginal yield increase. This is then finally linked to damage oriented endpoint impact as an additional costs society has to pay by developing a cause and effect chain. In the same way, for the geopolitical aspect, the sustainable supply of a resource in a product life cycle is affected, on one hand when it is supplied from the concentrated market in which the global production is monopolized by few countries and on the other hand if the sourcing countries have high political instabilities. The combined effect of these two elements determine the supply risk associated with the consumption of that specific resource. This could be considered as a social midpoint impact (geopolitical related supply risk). The endpoint impact could be the cost increase associated with the possible supply disruption. It is obvious that any supply restriction induces price increase. When it is applied, for example, to an electric vehicle case study in which the material flow comprises large amount of industrial metals such as steel, iron, aluminum, copper but also small amounts of critical resources for special functions like magnesium, platinum group metals and rare earth elements. We can assume, while the resource depletion impact indicator tends to show high impact for copper, steel or aluminum due to their substantial use in the vehicle life cycle, the geopolitical impact would rather highlight those resources mentioned above that are important elements present in small quantities in the electric vehicle that however are evaluated as critical in the LCSA. In this way, the geopolitical supply risk indicator can provide a complimentary sustainable dimension which can be compared to the environmental LCA indicators under the LCSA framework.

4.2. Vulnerability to supply restriction perspective

As stated before, the over simplified assumption of resource depletion is one of the reasons for the shortfalls of the current resource impact assessment methods in LCA. In most category ii) methods (Guinée et al., 2002; Guinée and Heijungs, 1995; Hauschild and Wenzel, 1998), depletion indicators correspond more or less to the number of years remaining for the resource to be totally exhausted. Adding impact scores for different resources corresponds to making the underlying assumption that all the resources are substitutable between each other and that what has to be protected is an overall availability of “the” resource as if all resources could be used for any functionality.

The direct impact of resource use from the mid-term perspective is measured in category iii) by accounting the future consequence of present resource extraction through the approximation of surplus energy (Goedkoop and Spriensma, 1999; Jolliet et al., 2003) or marginal cost increase (Goedkoop et al., 2013). Both the ‘surplus energy’ and ‘marginal cost increase’ clearly link the mid-term geologically increased scarcity of resources to damage to natural resource area of protection. However, yet there is no consensus on which method is the best and no recommendation has been made by the EC as they are all considered immature (European Commission, 2011a). Among the methods, ReCiPe is suggested to be used as an interim solution by ILCD handbook, because it is considered to be scientifically the most robust endpoint method due to its scientifically justified links between radiative forcing, temperature and ecosystem impacts (European Commission, 2011a). Although ReCiPe represent well the cause and effect chain of resources, the method is far from being representative as it covers only 19 abiotic minerals, 4 fossil fuels and nuclear fuel. The complexity of the method makes it difficult to provide more characterization factors covering wide range of resources (Klinglmair et al., 2014). Resource have been treated in LCA for their natural existence, which is debatable as authors suggest that resources only have a value when they are usable due to their functions by humans (Boulay et al., 2011; European Commission, 2010b; Goedkoop et al., 2013; Stewart and Weidema, 2005; Van Oers et al., 2002; Wehmeier et al., 2005). In addition, resource depletion has been assessed by resource extraction, while resource extraction is only a form of movement of the resource's stock. Depletion only happens when a resource is made unusable as such for future users, i.e. dissipated. Following the approach developed recently by De Bruille et al. (2014) the dissipation of a resource implies an increase in the competition amongst the future users as they need to adapt to decreasing resource availability (Neumayer, 2000; Sonnemann, 2013). Adaptation to availability decrease depends on the functionality the resource has to different competing users. In the approach of De Bruille et al. (2014) resource depletion is looked at by taking into account the functionality and no longer by looking at the resource nature. As a single resource can have multiple functionalities, each functionality is being considered separately in the approach in order to determine a competition index (the Material Competition Scarcity Index – MACSI) which can be interpreted as the remaining unadapted fraction of the users when the resource will be fully depleted, accounting for resources substitutability for all the functions it fulfills. This novel approach comes to fill a gap in resource use impact consideration, including but not limited to life-cycle impact assessment that accompanies the idea of a resource having a value only when it is functional to humans. Although multiple authors have discussed the added value of looking at a resource from a functional point of view, De Bruille et al. (2014) are the first to implement a life-cycle impact assessment method with a functional approach to consider impacts from mineral and metallic resource use. As substitution is different for each end-use of the resource, it is not a material attribute, but a mitigation strategy for end-users of a given function of the resource. Substitution allows users to adjust the functionality they are fulfilling to other resources, reducing ultimate demand and reducing supply risk.

Substitution is a dimension that has not been taken into account in previous approaches while assessing resource depletion in LCA, but which is essential to include as a function provided by a given resource might be provided by another resource, given economical and technological feasibility. For those metals that are depleted, substitution could also be an alternative provided that there are minerals or organic materials (fossil or bio-based) with similar physical and chemical properties to offer the same functionality. Substitution possibilities have been documented in the literature: either for specific resources (Brooman, 1993, 2001; Cairns, 1985; Cairns, 1986; Gaydos, 2008; Graedel et al., 2013; Mohammadpour et al., 2012; Nassar et al., 2012), or by a general methodological approach adapted to a majority of resources (AEA Technology, 2010; DOE, 2011; European Commission, 2010a; Graedel et al., 2012; USGS, 2013; Zepf et al., 2014). Introducing functionality, recycling, resource substitution and user adaptation to depletion is done through an introduction of a competition factor, as proposed by Boulay et al. (2011) for water use impacts, De Bruille et al. (2014) for mineral and metal use impact and Fatemi Emamgheis (2013) for fossil resources use impact. Such approaches are a step forward in assessing resources criticality as they allow integrating the vulnerability of the Graedel et al. (2012) approach to a certain degree in a consistent indicator. However, here the challenge is how such integration could be possible, as the criticality assessment studies including Graedel et al. (2012) are not matured enough to be used at a product level. Further research is need to feel this gap.

4.3. Environmental implications perspective

The environmental implications as considered in the Graedel matrix are the environmental impacts related to the mineral extraction and commodity production activities, which includes impacts on the AoP Ecosystem Quality and Human Health. These are well covered by LCA, using straight forward calculations based on LCA inventory databases such as ecoinvent (Frischknecht and Jungbluth, 2007) and GaBi (PE International, 2013) and existing LCIA methodologies such as IMPACT 2002+ (Jolliet et al., 2003), ReCiPe (Goedkoop et al., 2013) or the ELCD (ELCD, 2012) impact assessment method. However these approaches still have some limitations in the sense that LCA remains a generic approach, which may not be adequate to focus on some site specific environmental issues around different mining sites which may lead to an increased criticality. The challenge is how to differentiate the environmental impacts of specific processes related to the extraction in different regions. Criticality issues are often related with radioactivity for rare earths, accident risk in mining, etc, which are specific to the geographical context. Some of those impacts such as radiation can be adequately characterized using current LCA tools but require very detailed and regionalized inventory data and the ability to characterize the environmental impact by accounting for regional specificities. A step forward has recently been done in this direction with the development of the IMPACT World+ (Bulle et al., 2014) LCIA methodology which offers regionalized characterization factors for regional or local impact categories. Other issues such as accident risk in mining are not considered in environmental LCA but may be considered using some social LCA indexes. When regarding the criticality challenges, the information on environmental impacts may be combined with additional socio-economic information such as HDI in order to assess to what extent an environmental impact leads to a criticality issue.

5. Discussion

From this critical review of the literature, it can be said that on the one hand there is evidence that LCA currently does not cover adequately resource criticality assessment although the related challenges are important for sustainability, and on the other hand the Graedel et al. (2012) approach that we have identified as the most mature approach to assess the criticality of resources is not LCA compliant as such. However, we could identify potential complementarities between both approaches and demonstrate that a discussion and actual work has been initiated in the LCA community to address more and more aspects of the Graedel et al. (2012) approach under the LCSA framework.

In particular, Schneider et al. (2014) have started to put the complementary elements into an economic resource scarcity potential for evaluating resource use based on LCA. Moreover, the UNEP/SETAC guidelines for social LCA (UNEP/SETAC, 2009) of products and recent innovative work by Boulay et al. (2011) for water use impacts, De Bruille et al. (2014) for mineral and metal use impact and Fatemi Emamgheis (2013) for fossil resources provide a foundation for LCIA approaches based on socio-economic criteria and resource functionality. Such approaches can combine in a consistent manner several Graedel et al.'s (2012) indices such as environmental impacts together with supply risk issues related to geological and socio-economic aspects as well as vulnerability in a set of scores compliant with the LCA framework, i.e. expressed in term of impacts on the three Areas of Protection Human Health, Ecosystem Quality and Natural Resources.

With regard to resource functionality, a competition factor is required to assess resource depletion by including resource recycling and resource substitutability as well as user adaptation to depletion. This competition factor should account for each functionality of a resource in order to show the adaptation capacity of different competing users dependently on the function that the resource carries out for them.

Further work is also needed in order to develop the geopolitical and supply distribution dimension of resources criticality within the LCSA framework and to integrate the various dimensions, using the strong knowledge developed outside LCA field by industrial ecology experts such as Graedel et al. (2012) in order to refine the LCIA resource impact assessment models to adequately reflect the importance of the AoP Natural Resources for sustainability. This could be possible if there is a shift in focus from only depletion in environmental LCA to a consideration of socio-economic, geopolitical and supply distribution risk aspects in a LCSA framework.

6. Conclusion

Environmental impacts are just one of three pillars in the matrix developed by Graedel et al. (2012) or are even not really taken into account by the European Commission (2010a) and other critical materials assessments. However, there are ongoing discussions within the LCA community on the importance of integrating criticality assessment into LCA under the LCSA framework in order to properly address the AoP Natural Resources. The information gathered in LCA databases, methods and studies allows to contribute to the criticality assessment of resources, not only materials but also water and land. Currently resource indicators are not meaningful, wherefore there is no consensus on what to recommend, and hence the AoP concept for resources needs to be rethought towards ecosystem/resource services and criticality.

Criticality assessment stems from the same family of system-analytical assessment tools as LCA, including in particular Material Flow Accounting and Environmentally Extended Input-Output Analysis. Hence, elements of the Graedel et al. (2012) approach being anchored in Material Flow Accounting, can be integrated into LCA, if socio-economic and geopolitical aspects are also considered. For this, the focus on the environmental LCA has to be broadened to cover the opportunities provided by LCSA framework. Broadening the scope of LCA in such a way and defining the goals of the study properly are ways forward for adequately addressing criticality challenges in a new conceptual framework. That means we see a complementary nature of LCA and criticality.

It is also worth mentioning that criticality should not be linked only with minerals but also with other resources such as water and land use. Evidently, there are difficulties in order to operationalize the integration of criticality assessment methods with LCA under LCSA framework. However, LCA can drive criticality assessment in an efficient way once integrated. Key challenges on how to operationalize the integration include data issues, in particular on site specific data and for those impacts usually not taken into account in an environmental LCA, and questions related to weighting to have or not have criticality be reported as a single score as it is done by Graedel et al. (2012). In this context, the model and characterization factors prepared by Schneider et al. (2014) show the direction of what can be in LCSA for integrating criticality.

Overall, the way impacts are currently defined in the AoP Natural Resources is not meaningful. A new perspective on criticality has to be developed for the AoP Natural Resources in the LCSA framework because the focus on environment alone is not enough to address this AoP in an adequate manner. The socio-economic and geopolitical issues related to natural resources are relevant for sustainability and hence need to be an integral part of LCSA if we want to keep the overall LCA methodology appropriate for current and future sustainability challenges.

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