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A framework for evaluating the accessibility of raw materials from end-of-life products and the Earth's crust

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ABSTRACT

An increasing number of geochemically scarce metallic raw materials are entering into our lives via new technologies. A reversal of this trend is not foreseeable, leading to concerns regarding the security of their supply. However, the evaluation of raw material supply is currently hampered by inconsistent use of fundamental terminologies and incomplete assessment criteria. In this paper, we aim to establish a consistent framework for evaluating raw material supply from both anthropogenic and geological sources. A method for concept extraction was applied to evaluate systematically the use of fundamental terms in the evaluation of raw material supply. The results have shown that 'availability' is commonly used in raw material supply evaluations, whilst other researchers suggest that raw material supply should be evaluated based on 'accessibility'. It was revealed that 'accessibility' actually comprises two aspects: 'availability' and 'approachability'. Raw material 'approachability' has not previously been explicitly addressed at a system level. A novel, consistent framework for evaluating raw material supply was therefore developed. To demonstrate the application of the established framework, we evaluated the raw material supply of four rare earth element case studies. Three case studies are End-of-Life products (the anthroposphere) from Switzerland: (i) phosphors in fluorescent lamps, (i) permanent magnets in the drive motors of electric cars and (iii) fibre optic cable. The fourth case study source is the Earth's crust (the geosphere): Mount Weld deposit in Australia. The framework comprises a comprehensive evaluation of six components relating to raw material mining and processing: their geological knowledge, eligibility, technology, economic, societal and environmental impacts. Our results show that metals are not considered to be fully accessible in any of the case studies due to a lack of necessary technologies and potential societal and environmental impacts. The framework presented here can serve as a starting point for the development of an evaluation framework for raw material accessibility at an early project development stage.

1. Introduction

Due to continuing technological advancement, an increasing number of geochemically scarce metallic raw materials[1] are entering into our daily lives. With a reversal of this trend not foreseeable (Zepf et al., 2014), there are growing concerns for the security of raw material

Abbreviations: Ap., approachability; Av., availability; CO_2 eq., carbon dioxide equivalent; EC, existing conceptualisations; EoL, end-of-life; Er, erbium; Eu, europium; Eu_2O_3, europium oxide; EUR, Euro; HHI, Herfindahl-Hirschman Index; MA, mining the anthroposphere; MG, mining the geosphere; Nd, neodymium; $Nd_2Fe_{14}B$, neodymium–iron–boron; ORDEE, ordinance for the return, take-back, and disposal of electrical and electronic equipment; PPI, Policy Potential Index; ReCiPe, RIVM and Radboud University, CML, and PRé Consultants; REE, rare earth elements; REO, rare earth oxide; REO, rare earth oxides; UBP, environmental impact points; UNEP, United Nations Environment Programme; UNFC, United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources; USD, United States Dollar; USDOE, U.S. Department of Energy; EEE, electrical and electronic equipment; WEEE, waste electrical and electronic equipment; WGI, world governance indicator.

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[1] Geochemically scarce metallic raw materials' are those metals whose crustal abundance is <0.01 wt.% (Wäger et al., 2012).

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supply. For many raw materials, the supply situation is considered critical due to: (i) their production being concentrated in a few countries (Simoni et al., 2015), (ii) limited options for appropriate substitutes (Graedel et al., 2013), and (iii) very low recycling rates for these materials (UNEP, 2012). To improve the long-term sustainability[2] of critical material supply (Giurco et al., 2014), there is a view that raw material management needs to be rethought (Ongondo et al., 2015). Specifically, raw material management needs to consider the mining of materials from both the geosphere and the anthroposphere. To ensure comparability and consistency, both mining management approaches should be developed and evaluated in parallel. In the cycle of a material, a parallel development and evaluation requires the establishment of linkages between mining the geosphere, anthroposphere and the subsequent processing. In this sense, for both the mining of geosphere and anthroposphere, knowledge of the material (e.g. physical and chemical properties, element concentration, and abundance) and knowledge about potential economic viability is required (Brunner, 2008).

Raw material supply has previously been evaluated based on the 'availability' of materials (UNEP, 2013b; USDOE, 1996). Evaluation of material availability can be based, for example, on the geological knowledge (UNFC, 2010). Availability can also be evaluated through material criticality assessment, which assesses raw material supply based on two functions: their 'availability' and 'importance of uses' (Graedel et al., 2012). Studies of material availability show a large degree of variability in how availability is defined.

It has been suggested that material availability evaluation is too narrow in its scope and that evaluation of raw material supply should be expanded to consider the 'accessibility' of materials (USDOE, 1996). Cook and Harris (1998), for example, recommend that such an evaluation should consider environmental, legal, social, and political aspects in addition to an evaluation of project feasibility. This would be particularly important for materials that are currently unavailable but approachable. Materials in this category include for instance the large amounts of illegally-exported raw materials from End-of-Life (EoL) products, such as obsolete Waste Electrical and Electronic Equipment (WEEE) from the European Union (Huisman et al., 2015). Rankin (2011) adds that it is important to understand, how access to raw materials will change in the long term. Gruber et al. (2010) considered raw material 'accessibility' in relation to policies about raw materials at the European level and they concluded that indicators and specific targets for raw material conservation remained absent. Accessibility has further been applied to evaluate product recycling, specifically in identifying the relevant product parts for dismantling (Hagelüken, 2014) and in geological mining, where 'accessibility' has been used to describe the physical path to a deposit (Weber, 2015). At a systems level, individual aspects of evaluating raw material accessibility have been implicitly included in the fields of economic geology. For instance, accessibility has been integrated in resource classification frameworks (Cook and Harris, 1998) and ecological and social sustainability studies (MacDonald, 2015).

There is need to advance the management of raw materials at different levels. Firstly, there is a lack of consistency in how the terms 'availability' and 'accessibility' are used in studies of raw material supply and what these terms actually mean. Clarification of fundamental terms used in the evaluation of raw material supply is required before a commonly agreed, rational raw material mining strategy can be developed (Cossu and Williams, 2015; Winterstetter et al., 2015). Secondly, although different efforts have been undertaken to link quantitative evaluation methods across different disciplines, there is a lack of a broadly applicable assessment method for a potential supply of sustainable raw materials (Haines et al., 2014). Thirdly, there is a deficiency in a strategy that evaluates the different operational steps along the collection/mining, processing for continual sourcing of raw material (Roelich et al., 2014). Fourthly, there is need for consistent quantitative evaluations for elements with few available data such as rare earths (Gleich et al., 2013; Weber, 2013). This is particularly important for implementing new waste management regulations, such as the currently revised Swiss 'ordinance for the return, take-back, and disposal of electrical and electronic equipment' (ORDEE). The future ORDEE will require for the first time the recovery of scarce metallic elements from technological equipment wherever possible (FOEN, Federal Office for the Environment Switzerland, 2013).

In this paper we aim to establish a consistent framework for evaluating raw material supply from both anthropogenic and geological sources at an early project development stage. The objectives were to:

(i) systematically investigate the use of fundamental terms in the evaluation of raw material supply;
(ii) develop a novel, consistent framework for evaluating the supply of raw materials; and
(iii) demonstrate the utility of the developed framework by evaluating the raw material supply in four rare earth element (REE) case studies.

2. Method

2.1. Extraction of conceptual framework

Concept extraction was used to elucidate the meaning and use of accessibility and related terms. This process comprised four main stages: pre-processing, text analysis, establishment, and concept extraction (Fig. 1), based on the work of Weinhofer (2010).

2.1.1. Pre-processing

The scope of this research was determined and the opportunistic corpora[3] were established (Fig. 1). For the former, a standard definition of 'accessibility' was created by critically reflecting the definitions and synsets from the Cambridge (Cambridge Dictionaries Online, 2014), Oxford (Oxford Dictionary, 2014), WordNet[4] (WordNet, 2014), and Britannica (Britannica Academic Dictionary, 2014) Dictionaries. Three opportunistic corpora were developed: 'existing conceptualisations' (EC), 'mining the anthroposphere' (MA), and 'mining the geosphere' (MG). The EC corpus was created for the purpose of analysing the use of 'accessibility' and its conceptualisation. For this, relevant literature sources were identified through a key word search for 'concept of accessibility' and 'concept of availability' in *Google Scholar*, *Scopus*, and *Google*. Thereafter, the MA and MG were built with the aim of investigating the use of 'accessibility' and its related terms. Both these corpora were developed based on the bibliography of Simoni (2012) as suggested by Cronin et al. (2008). This literature selection was expanded with a

[2] 'Sustainability' means in this study "certainly a sustainable society would use non-renewable gifts from the Earth's crust more thoughtfully and efficiently than the present world does. It would price them properly, thereby keeping more of them [accessible to] future generations. But there is no reason not to use them, so long as their use meets the criteria of sustainability already defined, namely that they do not overwhelm a natural sink and that renewable substitutes are developed." (Meadows et al., 2004).

[3] 'Opportunistic corpus' is a selection of texts that are needed for the present purpose (Hausser, 2014). They often represents an incomplete collection of electronic texts (Sekhar, 2008).

[4] 'WordNet' is a large lexical database of English that covers a wide range of words, establishes cross linkages between them and is widely applied in linguistics. Nouns, verbs, adjectives and adverbs are grouped into sets of cognitive synonyms (synsets), each expressing a distinct concept (WordNet, 2014).

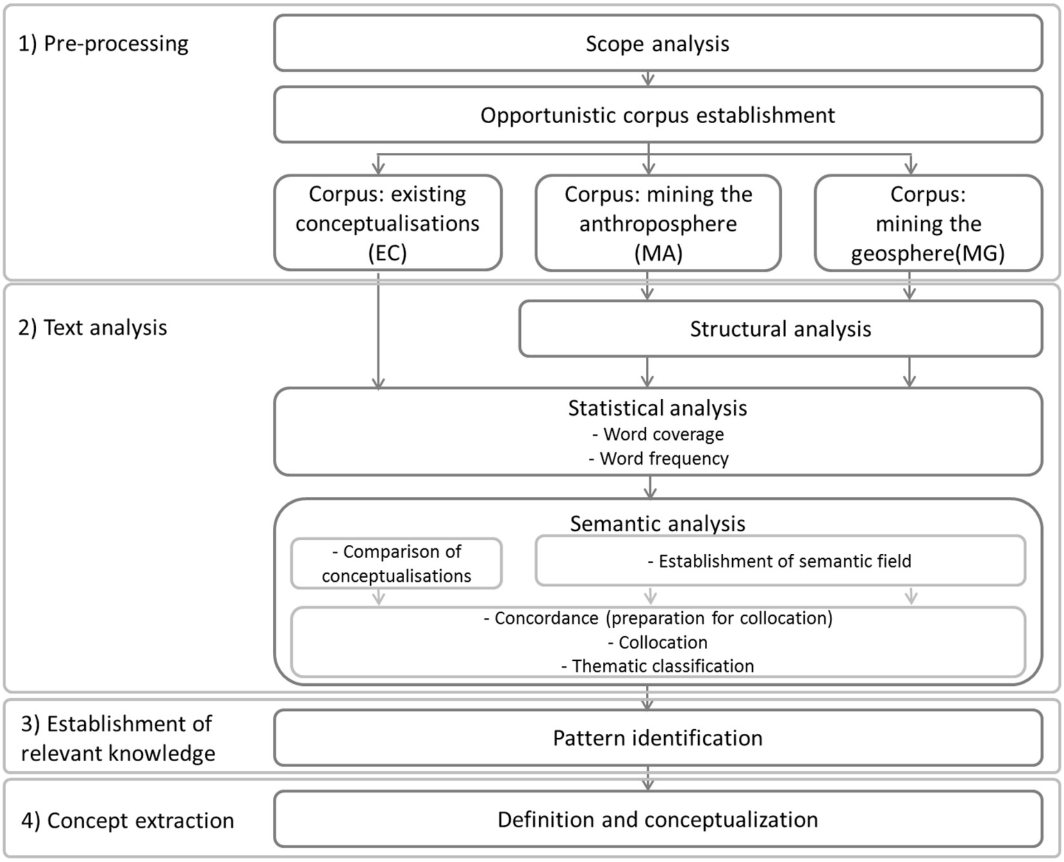

Fig. 1. Sequential methodological approach: concept extraction for developing the conceptual framework for evaluating accessibility. Adapted from Weinhofer (2010).

scholarly article search in *Scopus* using different combinations of the keywords 'accessibility', 'integrated assessment', 'mineral resources', 'mineral resources', 'quantitative assessment', and 'environment'. The 275 documents consulted are shown in the Supporting information.

2.1.2. Text analysis

Stepwise analysis of the literature in the MA and MG corpora focused on three aspects: (1) a structural; (2) a statistical, and (3) a semantic[5] analysis (Fig. 1).

For the structural analysis, we analysed the content of the text headings in the literature. This step thereby obtained a general understanding of the relative usage of the term 'accessibility' and related terms in the two mining corpora (MA and MG). Text headings were analysed as they give a direct indication of the content of the main text body (Weinhofer, 2010).

For the statistical analysis, the coverage and distribution of the use of the words 'accessibility' and other related keywords were analysed. Word coverage identifies how often a term occurs and whether it is used in many different documents, whilst implying importance in meaning for a document. The word coverage is analysed following Zipf's law (Li, 1992), which can be used to identify the phenomena whereby a few words occur often and the majority of words occur sparingly. For instance, the most frequent 150 words usually account for around half the words of a corpus (Powers, 1998). The distribution analysis quantifies terminological variance in sections of text and identifies the relative frequency of the most used terms (see Supporting information for details).

[5] Analysis of the meaning of a word (Weinhofer, 2010).

For the semantic analysis, we analysed (1) the meaning of conceptualisations, (2) semantic field creation, (3) collocation and (4) thematic classification. To identify a viable concept at the system level in the EC corpus literature, definitions of the word 'accessibility' were compared and contrasted. In parallel, a semantic field around 'accessibility' was established, which provided the basis for connecting our conceptualisation of accessibility with the EoL products. A collocation analysis was then carried out on each of the three corpora. Collocation analysis is the most important and widely used investigation in corpus linguistics (Rychlý, 2008) and identifies statistically the proximity of semantically similar terms.

$$logDice = 14 + log_2 \frac{2fxy}{fx + fy} \tag{1}$$

Where fx is the number of occurrences of word x, fy is the number of occurrences of word y and fxy is the number of co-occurrences of words x and y in the range of ±10 words.

Subsequently, semantic trends were identified by thematically classifying the collocation candidates with components from an established sustainable mining perspective. The five domain framework was selected (Cooper and Giurco, 2011; DFID, 1999), since it includes key areas of concern 'technology', 'economy', 'society' and 'environment' (Dewulf et al., 2015); and is based on the widely established five capital model (Corder et al., 2010), which includes the components: technology, society, environment, economy and eligibility (Table 1). The term 'eligibility' is used instead of governance, since only with a well-defined ownership can a process take place. The five domain framework was expanded to include the 'geological knowledge' of raw materials; for any processing purposes the type, quantity and grade of materials are fundamental considerations (Arndt and Ganino, 2012; Mueller et al.,

Table 1
Description of the thematic classifications, respectively components, quantitative and qualitative indicators.

Thematic class/component	Definition	Scope	Indicator (quantitative and qualitative)	Unit
Geological knowledge	The understanding of the context of the intended material deposit	Type, quantity, grade, and mine life at a specific point or extent in space (Mueller et al., 2015)	Quantitative: mass and mass fraction; Qualitative: description about the level of confidence in the geological knowledge, (i.e. high, medium, low) (UNFC, 2010)	[t], [t/t]
Eligibility: Including legislation and policy	The system or form by which a community, company or other political unit is eligible to govern raw materials (adapted from Giurco and Cooper, 2012)	Ownership and regulatory requirements	Quantitative: World governance indicators (WGI), rule of law (RL), which quantifies the ability of a country to abide the quality of contract enforcement, property rights, and the courts (Kaufmann et al., 2010); Qualitative: ownership description along collection/mining and processing	[%]
Technology	The application of the knowledge, usage of tools (such as machines or utensils), and techniques to control one's environment	Collection/mining, and processing of EoL and the Earth's crust (Giurco and Cooper, 2012) with their existing infrastructure	Quantitative: mining or processing yield; or collection and recycling rate; Qualitative: situation description if no mining, processing or recycling currently exist	[%]
Economy: Including marketing of mining companies	The system of production and distribution and consumption of minerals (Giurco and Cooper, 2012)	Costs, prices of obtaining the material of interest and information on the market stability, i.e. sensitivity or volatility and investments	Quantitative: processing costs if available, or else raw material price if processing takes place; Qualitative: economic situation description if no mining, processing or recycling exist	[USD per kg]
Society	Social networks with shared norms, values, and understandings that facilitates co-operation within or among groups (UNU, 2012)	Societal stability, human rights conditions, and working condition	Quantitative: World governance indicators (WGI), political stability and absence of violence (PV), which quantifies the perceptions of the likelihood of political instability and/or politically-motivated violence, including terrorism (Kaufmann et al., 2010); Qualitative: description of local social impact monitoring and prevention measures	[%]
Environment	The natural and resource condition of the nature and ecosystem processes (Giurco and Cooper, 2012)	Climate change, ecosystems, human health and resource depletion	Quantitative: global warming potential or if data available: life cycle impacts by means of e.g. ReCiPe, ecological scarcity method with environmental impact points (UBP); Qualitative: description of hazardous or radioactive substances and if present, a description on their impact monitoring and prevention measures	[CO_2eq./kg metal-oxide], [UBP/kg metal-oxide]

2015). We selected 'geological knowledge' as a framework component rather than 'physical and chemical properties' (which geological knowledge depends on), since it reflects a geologist's application of these properties in practice.

2.1.3. Establishment of relevant knowledge

The results of the text analysis were employed to generate the conceptual framework (Fig. 1). Firstly, the most relevant conceptualisation was based on the highest collocation and the semantically most relevant description. Secondly, the established semantic field was used to identify parallels and establish linkages between mining the anthroposphere and geosphere. The thematic classes were then assigned to 'accessibility' and its related terms based on the established threshold of 9.00 (see Supporting information for details). These classes subsequently provide the fundamental structure of the conceptual framework.

2.1.4. Concept extraction

The definition of, and a conceptual framework for, raw material 'accessibility' was extracted (Fig. 1). This conceptualisation was obtained through the most relevant conceptualisation and thematic classes, which were integrated at the established linkages between mining the anthroposphere and geosphere.

2.2. Evaluation of raw material accessibility

To demonstrate the utility of our framework, we performed an initial evaluation of raw material accessibility using four REE case studies. These case studies were selected, because REE are widely used in modern technologies and are considered critical for their continual smooth supply (Moss et al., 2013). The EoL product case studies from 'deposit' Switzerland encompass: (i) fluorescent lamps containing Europium (Eu); (ii) a drive motor in an electric car containing Neodymium (Nd); and (iii) fibre optic cable containing Erbium (Er). The Earth's crust case study includes fourth the REE deposit, Mount Weld Australia, containing the same three elements. These case studies are described and, quantified (within the limits of available data) regarding their geological knowledge, eligibility, technology, economy, society, and environment. The system is described with components, for which each component is underpinned by one quantitative and one qualitative indicator (Table 1). Collectively these indicators provide an overview of the current situation in terms of raw material supply and are selected on the basis of existing indicators, which were applied in 12 studies that consider material availability (BGS, 2015; Dewulf et al., 2015; EC, 2014; Graedel et al., 2012; Long et al., 1998; Moss et al., 2013; Neugebauer, 2013; NRC, 2008; Oakdene Hollins, 2008; Sprecher et al., 2015; Tuma et al., 2014; UNFC, 2010).

3. Results

3.1. Extraction of conceptual framework

3.1.1. Pre-processing

Based on the reflected definitions from the Britannica Academic Dictionary (2014), Cambridge Dictionaries Online (2014), Oxford Dictionary (2014), the definition proffered by WordNet (2014) was found to cover succinctly the key facets of each of the above definitions. 'Accessibility' can semantically be considered to

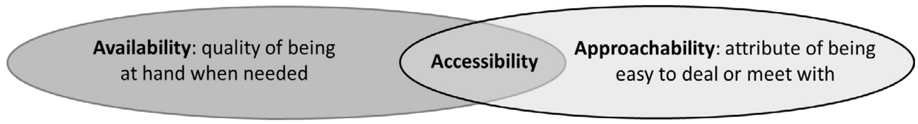

Fig. 2. 'Accessibility' is defined by comprising both synonyms 'availability' and 'approachability'; 'accessibility' is located at the intersection.

Table 2
Definition of accessibility for raw material supply.

Accessibility	Raw materials are accessible if there are no 'significant' constraints (e.g. ownership, protected areas, environmental restrictions) to 'get to' the material of interest in order for potential treatment or production

occupy the intersection between 'availability' and 'approachability' (Fig. 2, see Supporting information for details).

The pre-processing stage revealed that, whilst 'availability' is commonly referred to in discourse, reference to 'approachability' is rare. Our definition of 'accessibility' for raw material supply is shown in Section 3.1.4 (Table 2).

The three resulting corpora encompassed: (i) EC 18 documents; (ii) MA 141 documents; and (iii) MG 116 documents.

3.1.2. Text analysis

3.1.2.1. Structural analysis. Both raw material 'accessibility' and 'availability' were found to be rarely used other than in the one example of mineral policy research Tiess (2011), in which raw material 'accessibility' describes policy situations: "Geological availability does not necessarily mean access to raw materials for the mining companies" (Tiess, 2011).

3.1.2.2. Statistical analysis. For the EC corpus, 'accessibility' was found to be used extensively in urban planning and economic geography. The distribution analysis shows the higher relative word frequency was 1.0% to 3.2%. This included the terms: information, accessibility, access, assurance, data, and planning (Fig. 3a). For the MA corpus, the word coverage of <0.40% showed a low relative word frequency, which was confirmed by showing no 'accessibility' related term in the tag cloud (Fig. 3b). For the MG corpus, the word 'accessibility' showed a low relative word frequency of fewer than <0.10% in most documents. No 'accessibility' related term was among them (Fig. 3c).

The statistical word coverage investigation of availability showed that, in most documents, 'availability' was found with a coverage of <0.1%.

3.1.2.3. Semantic analysis. The semantic comparison of accessibility in the EC corpus showed that accessibility originates from a number of subject areas, including urban planning, economic geography, and information sciences. At a system level, geology comprises raw material availability only. The resulting semantic field demonstrated the root term 'ability' was able to be linked to the cycle of a material.

In the semantic collocation analysis of accessibility, for the corpus EC a logDice value of >10 resulted. The terms with the highest collocated values to 'accessibility' were 'measure' and 'indicator'. However, a lower collocation results from the corpus MA with a logDice value of 7.76. Here the closest collocations to 'accessibility' were 'availability' and 'metallurgical'. In the MG corpus, use of the word 'accessibility' occurs only twice and consequently no logDice value could be established. The adapted collocation analysis shows this term occurs 8 times. The resulting high collocation was in 'infrastructure' (logDice score = 11.63). The collocation analysis of availability is shown in the Supporting information.

3.1.3. Establishment of relevant knowledge

For developing our framework, the conceptualisation in urban planning was considered implementable. Comparable operational steps between mining the anthroposphere and geosphere were established as: 'collection of EoL products' to 'mining the Earth's crust', followed by 'processing of components' to 'processing of crude ore', and the joint operational step 'manufacturing of metal'. From the semantic analysis, the relevant thematic classes to availability were identified as 'geological knowledge' and 'eligibility'. We referred to the standard definition of 'accessibility' for allocating the other relevant thematic classes. The most relevant classes were found to be 'technology', 'economy', 'society', and 'environment'. These thematic classifications will henceforth be referred to as 'components'.

3.1.4. Concept extraction

Our accessibility and sustainability definitions for raw material supply are shown in Table 2. To quantify raw material accessibility at each process step, both 'availability' and 'approachability' need to be determined during the operational steps: EoL product at recycler, crude ore at mining company and processability (Fig. 4). Processability is the first common process for both mining the anthroposphere and the geosphere. The next destination could be either 'metal at processor' or extended to 'component at manufacturer'; 'manufacturability at manufacturer' could thus be included in 'approachability'. 'Reusability', 'remanufacturability', and 'designability' are deemed out-of-scope, since access to the raw material applies to the end states 'metal' or 'component'. Consequently, the processes 'usability', 'extendibility' and 'maintainability' were also excluded, since a product can only be mined after it reaches its end-of-life.

3.1.4.1. Conceptual framework. 'Accessibility' was divided into 'availability' and 'approachability', which were respectively classified as 'low', 'moderate', or 'high' (Fig. 5; Table 3). 'Availability' is based on 'geological knowledge' and 'eligibility' whilst 'approachability' is built on 'technology', 'economy', 'environment' and 'society'. At this point in time, it is assumed that the components are equally weighted; we will test this assumption during our future research activities. Note that the uncertainty of the component evaluation is described as a precursor to a detailed future assessment.

3.2. Evaluation of raw material accessibility

The results of the evaluation of raw material accessibility are shown in Fig. 6 in the form of an aggregated evaluation grid. This grid shows that the Mt. Weld deposit results in moderate to high accessibility, due to high availability and moderate to high approachability. The EoL phosphor of fluorescent lamps with Eu in Switzerland shows moderate accessibility, i.e. high availability but moderate approachability. The other two case studies, EoL drive motor of electric car with Nd in Switzerland and EoL fibre optic cable with Er in Switzerland, were found to have low accessibility.

The results of evaluating the application of the framework are presented in Table 4. All deposits considered in this instance resulted in quantifiable geological knowledge. The deposits fluo-

Fig. 3. Relative distribution of the word frequency. The more frequently a term is used, the bigger the term becomes in relation to the other terms. (a) Corpus: existing conceptualisations (EC); (b) corpus: mining the anthroposphere (MA); (c) corpus: mining the geosphere (MG).

rescent lamps with Eu, Switzerland and REE deposit, Mt. Weld, Australia contain hazardous and radioactive substances. All deposits showed clear eligibility apart from deposit fibre optic cable, which resulted with several potential ownerships. Hence, this deposit was classified as low availability. The approachability evaluation demonstrated various approachability levels. The REE deposit, Mt. Weld, Australia showed moderate to high approachability, because of its associated and potentially high impacts on society and environment. The deposit fluorescent lamps with Eu, Switzerland showed moderate availability, due to technology and society. The deposit drive motor in an electric car with Nd, and fibre optic cable with Er, Switzerland showed low availability, because of both barriers in technology and economy.

Fig. 7 provides an overview of 'accessibility' along the operational steps: collection/mining and processing. In particular, it illustrates, whether the operational steps are established, in upscale development and market launching phase, under basic development, or not developed.

4. Discussion

4.1. Extraction of conceptual framework

Raw material 'approachability' has not previously been explicitly addressed at a system level. The text analysis suggests that 'accessibility' and 'availability' are not yet established terms in the literature. Only Tiess (2011) was found to distinguish clearly between accessibility to, and availability of, minerals in the context of exploration and policy development. The statistical analysis shows that for the EC corpus, the conceptualisation in urban planning has a high occurrence of the word accessibility, whereas in the MA and MG, accessibility occurs less frequently. This clearly indicates the words were distributed as Zipf's law predicted (Li, 1992). The semantic analysis of the EC corpus revealed that accessibility was strongly collocated to 'measure' and 'indicator', which indicates that an evaluation should include indicators and be measureable.

The conceptualisation of accessibility played a major role in urban planning research (Klaesson et al., 2015). This urban planning conceptualisation dates back to work undertaken by Hansen (1959) (Karlsson and Gråsjö, 2013), are widely applied, and is based on the physical law of gravitation (Klaesson et al., 2015). However, the integration of different interdependencies for 'availability' and 'approachability' may lead to ambiguity in the definition and quantification of 'accessibility' (Janelle and Hodge, 2013), especially since they have been described as an unclear notion with numerous definitions and conceptualisations (Curl et al., 2011; Karlsson and Gråsjö, 2013). To overcome this problem, our conceptualisation was developed following evaluations in urban planning, the UNFC-2009 classification framework, and material criticality assessments (EC, 2014; Graedel et al., 2012; Tuma et al., 2014).

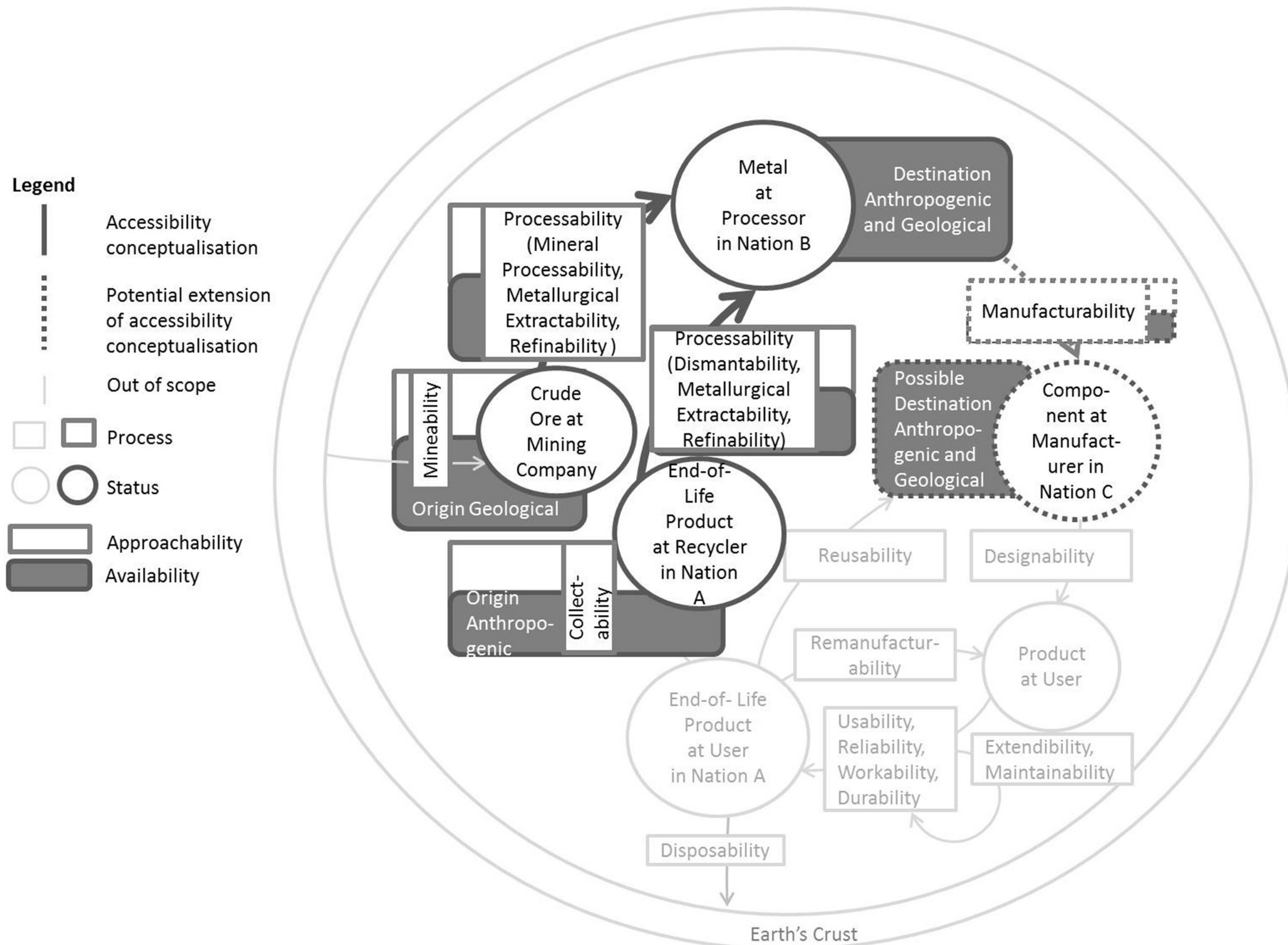

Fig. 4. Positioning our conceptualisation of raw material 'accessibility' in the cycle of a material. This includes both mining anthropogenic and geological deposits.

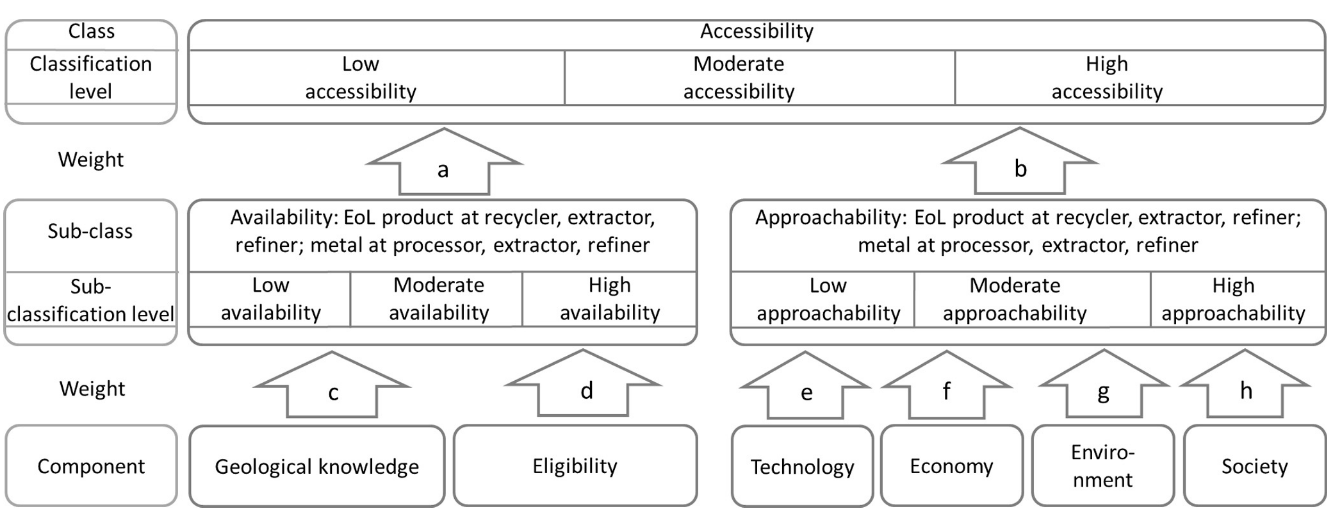

Fig. 5. Evaluation framework for raw material accessibility with its sub-classes, and its constituent components, developed for an early project evaluation of a national or corporate level but also the common evaluation between mining the anthroposphere and geosphere as well as processing, where a-h are to be verified.

The evaluation framework proposed in this study (Fig. 5) contributes to other raw material classifications, such as UNFC-2009 (UNFC, 2010) or CRIRSCO (CRIRSCO, 2013), in that it addresses raw material approachability at a system level. Furthermore, our framework considers the eligibility of raw materials for extraction, a component not explicitly included in other raw material classifications. Considering eligibility, this is essential for raw material assessments, as without clear eligibility (inter alia legal permission to mine/processing), raw materials cannot be accessed. Our approach explicitly evaluates the influence of technology, which is reportedly the most important consideration for effective recycling (Hagelüken, 2014) and mining (Tilton, 2002). To ensure

Table 3
Criteria and description of the evaluation of raw material accessibility.

	Criteria	Description		
Class	**Accessibility**	'Getting to' the material of interest for potential treatment or production by means of fully meeting the components for availability: geological knowledge and eligibility; as well approachability: technology, economy and social and environmental impacts		
	Classification level	**High accessibility** No 'significant' restrictions to 'accessibility'	**Moderate accessibility** Moderate restrictions to 'accessibility'	**Low accessibility** 'Significant' restrictions to 'accessibility'
Sub-class	**Availability: EoL product at recycler/crude ore at mining company and metal at processor**	'Original location and existing destination with opportunities' in the geosphere and/or anthroposphere at 'relevant' condition by means of processable amount with associated location that can be estimated with a high level of confidence (UNFC, 2010) and transparent ownership and policy enforcement		
Component	**(i) Geological knowledge**	Average processable amount at original location to be produced per year today and in foreseeable future and level of confidence (UNFC, 2010)		
	(ii) Eligibility	Description of the ownership and determination of enforcement of policies and regulatory requirements		
	Sub-classification level availability	**High availability** No 'significant' restrictions to 'availability'	**Moderate availability** Moderate restrictions to 'availability', which are processable amounts of EoL products or the Earth's crust at associated location that can be estimated with moderate level of confidence; and raw material stream does not yet flow. Transparent ownership and policy enforcement	**Low availability** 'Significant' restrictions to 'availability' with sufficient quantity to be processed of EoL products or the Earth's crust at associated locations that can be estimated with low level of confidence and estimated quantity of potential deposits based mainly on indirect evidence; and no transparent ownership and policy enforcement
Sub-class	**Approachability: Collection/mining and processing**	'Getting' to the material of interest with ease by means of fully operating technology. This includes collection/mining and processing "has been confirmed to be economically viable" (UNFC, 2010); no adverse impacts on society and environment		
Component	**(i) Technology**	The status of infrastructural and technological application during collection/mining and processing		
	(ii) Economy	The economic viability determination during collection/mining and processing (UNFC, 2010) today and in the foreseeable future		
	(iii) Society	The social impact monitoring and prevention description and determination of selected indicators during collection/mining and processing		
	(iv) Environment	The ecological impact monitoring and prevention and determination of selected indicators during collection/mining and processing		
	Sub-classification level approachability	**High approachability** No 'significant' restrictions to 'approachability'	**Moderate approachability** Moderate restrictions to 'approachability', in which infrastructure/technology is in the testing and scale-up phase in order to obtain the material of interest, which "is expected to become economically viable in the foreseeable future." (UNFC, 2010). No adverse impacts on society and environment	**Low approachability** 'significant' restrictions to 'approachability', in which infrastructure/technology is not developed yet and the material of interest "is not expected to become economically viable in the foreseeable future." (UNFC, 2010), adverse impacts on society and environment

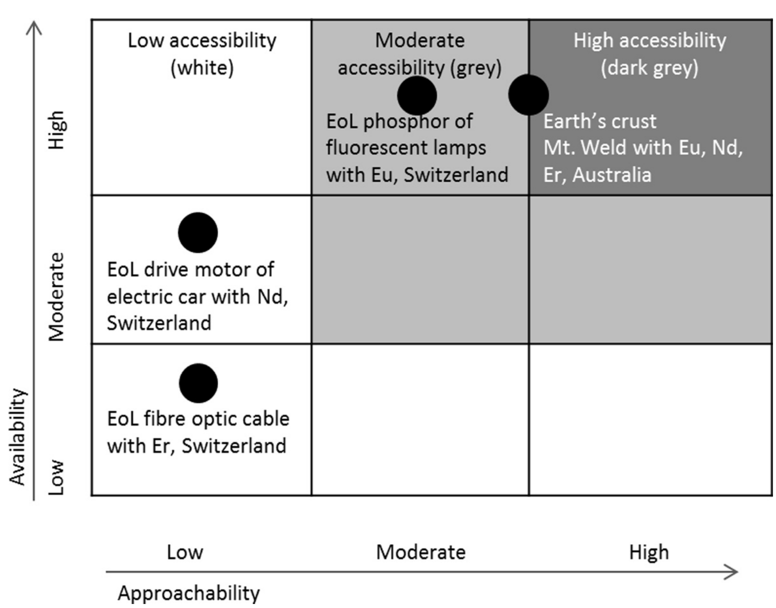

Fig. 6. Proposed raw material accessibility evaluation grid of current and future 'accessibility' with selected EoL products and the Earth's crust. The black dots show the position of each deposit considered. The aggregation of 'high accessibility' is denoted in dark grey, 'moderate accessibility' in grey and 'low accessibility' in white.

Table 4
Investigation of the current raw material accessibility status of anthropogenic and geological deposits.

EoL phosphors in fluorescent lamps with Europium (Eu) in deposit 'Switzerland'	
Availability	• **Geological knowledge**: Available quantity of almost 1,169 t lamps in 2014 (Huber and Schaller, 2015) with a mass fraction of up to 0.012 wt.% Eu per lamp (Schüler et al., 2011). The quantities are systematically and longitudinally monitored by a foundation for light recycling Switzerland (Huber and Schaller, 2015). This leads to high level of confidence (Mueller et al., 2015) • **Eligibility**: The WGI, RL is 98%, which means abiding by the quality of contract enforcement, property rights, and the courts (World Bank, 2016). During collection the owner is either the producer or the responsible organisation. In the subsequent processing, the treatment operator becomes the owner of the materials (FOEN, 2005) • **Sub-classification level**: high availability
Approachability	• **Technology**: With current technologies the collection rate of fluorescent lamps was 83% in 2014 (BAFU, 2015; 2012; Huber and Schaller, 2015). Similarly, a yield of 80% is estimated by means of solvent extraction, with development potential for demonstrating a recovery yield of 98–99% (Machacek et al., 2015). The recycling implementation of phosphors remains uncommon (Turner et al., 2015); the lamp powder is disposed underground with option for retrieval (Huber and Schaller, 2013). In 2014 a test batch was sent to Solvay for assessment (SWICO/SENS/SLRS, 2015) • **Economy**: The costs for collection and recycling account for 0.15–2 Euro (EUR) per kg for up to 80% REE recovery rate; and USD 6 per kg for extraction from mercury phosphor dust (Machacek et al., 2015). Low profitability of a processing plant lead to their closure at by the end of 2016 (Guenard, 2016) • **Society**: Processing was possible (December 2016) in France (Guenard, 2016), consequently, these parameters are used for our evaluation. There is moderate to little impact on society from processability. This can be exemplified by the WGI, PV 57% which means moderately politically stable and absence of violence/terrorism (World Bank, 2016) and the implementation of stringent monitoring system and safety standards (Ali, 2014) • **Environment**: (Simoni et al., 2015) reported that the greenhouse gas emissions for recycling any fluorescent lamps were about 23.5 kg CO_2eq./kg for rare earth oxides (REO) and the life cycle impacts were about 32,576 UBP/kg REO. The lamp powder contains mercury (Richter and Koppejan, 2015). The implementation of stringent safety standards ensure, there will be little human health impacts (Ali, 2014) • **Sub-classification level**: Moderate approachability (due to technology and society)
EoL permanent magnets in drive motor of electric car with Neodymium-Iron-Boron ($Nd_2Fe_{14}B$) in deposit 'Switzerland'	
Availability	• **Geological knowledge**: The average available weight is estimated 1.6 t in 1 million electric cars in 2017 in Switzerland with a share of 2 wt.% Nd. The available weight is estimated, which leads to low level of confidence (Mueller et al., 2015) • **Eligibility**: The WGI, RL is 98%, which means abiding by the quality of contract enforcement, property rights, and the courts (World Bank, 2016). The ownership is transparent, namely the recycler and metal processors • **Sub-classification level**: Moderate availability (due to the current barrier in geological knowledge)
Approachability	• **Technology**: The collection system for vehicles is well established in Switzerland (Widmer et al., 2015). Consequently, the annual average collection is 100%. Note, that the 100% excludes export to developing countries, whereby the material is used again (Althaus and Gauch, 2010). Recycling techniques are currently under investigation (Elwert et al., 2015) • **Economy**: Dismantling and processing is expected to become economically feasible in the medium or long term future (Elwert et al., 2015) • **Society**: Apart from shredding of vehicles in Switzerland, the processing is currently carried out. There is little impact on society from processability in Switzerland. This can be exemplified by the WGI, PV of 95%, highly politically stable and absence of violence/terrorism (World Bank, 2016) and the implementation of stringent monitoring system and safety standards (SWICO/SENS/SLRS, 2015) • **Environment:** (Elwert et al., 2015) reported that there was little impact on the environment with global warming potential from recycling: about 14 kg CO_2eq./Nd-oxide based on mass allocation. There are no hazardous and radioactive substances related to the permanent magnets in drive motors (Haan et al., 2013) • **Sub-classification level**: Low approachability (due to the current barriers in technology and economy)
EoL fibre optic cable with Erbium (Er) in deposit 'Switzerland'	
Availability	• **Geological knowledge**: Available quantities with a total of 15,551 t (Müller et al., 2013) with 0.01 wt.% Er (Hering, 2006). The available weight is estimated with little information on the precise location. This bases mainly on indirect evidence (Mueller et al., 2015) • **Eligibility**: The WGI, RL is 98%, which means abiding by the quality of contract enforcement, property rights, and the courts (World Bank, 2016). The ownership of construction and maintenance are both nationally licenced private telecom companies and municipalities (BAKOM, 2015a, 2015b), which is not transparent. At present, it seems no efforts are undertaken to change this • **Sub-classification level**: Low availability (due to current barriers in geological knowledge and eligibility)
Approachability	• **Technology:** No recycling infrastructure exists or is in planning. Consequently, the recycling technologies are also not under development (Angerer, 2009) • **Economy:** Collection, dismantling and processing is not expected to become economically viable in the foreseeable future (Angerer, 2009) • **Society**: Collection and processing are currently not carried out but the material is hosted in Switzerland. At present there is little impact on society in Switzerland. This can be exemplified by the corruption perception index of 95%, meaning highly politically stable and absence of violence/terrorism (World Bank, 2016) and the implementation of stringent monitoring system and safety standards (SWICO/SENS/SLRS, 2015) • **Environment:** Stocker (2014) reported that the global warming potential was about 0.2 kg CO_2eq./m cable. There are no hazardous and radioactive substances related to the fibre optic cable • **Sub-classification level**: Low approachability (due to the current barriers in technology and economy)
Earth's crust deposit at Mt Weld with Nd/Eu/Er in 'Australia'	
Availability	• **Geological knowledge**: Available quantity of 3,133 t REO in 2015 (Lynas, 2015) and total estimated deposit mass in the central lanthanide of 9.88 Mt with a mass fraction of 10.7 wt.% REO, 0.85 wt.% Nd, 0.02 wt.% Eu, 0.001 wt.% Er (Hoatson et al., 2011). Mining commenced in 2011, which means there is high level of confidence (Mueller et al., 2015) • **Eligibility:** Mining is carried out in Australia and processing in Malaysia; consequently, both countries parameters' are used for our evaluation. The WGI, RL is, 94% for Australia and 71% for Malaysia. This shows the quality of contract enforcement, property rights, and the courts are abided (World Bank, 2016). The ownership is transparent at Lynas Corporation Limited (Machacek and Fold, 2014) • **Sub-classification level**: High availability
Approachability	• **Technology**: Infrastructure, mining and processing technology has commenced operating in 2012 (Machacek and Fold, 2014; Schmidt, 2013). With the current technologies a yield of 90–95% is achieved by means of solvent extraction (Peiró and Méndez, 2013) • **Economy**: The value of concentrate is about United States Dollar (USD) 28 per kg (Machacek et al., 2015) • **Society**: There is moderate impact on society from processability. This can be exemplified by the WGI, PV 77% for Australia, which means highly politically stable and absence of violence/terrorism; and 55% for Malaysia, which means moderately politically stable and absence of violence/terrorism (World Bank, 2016) and the implementation of stringent monitoring system and safety standards during operation (Schmidt, 2013). Consequently, there is moderate impact on society

- **Environment**: (Simoni et al., 2015) reported that the combined global warming potential of general mining and processing activities were about 55.7 kg CO_2eq./kg REO and the life cycle impacts were recycling about 59,142 UBP/kg. This deposit is associated with radioactive thorium and uranium (Hoatson et al., 2011). Regarding impact prevention, the potential emissions to water and air are carefully monitored during processing, which concentrates radioactive uranium and thorium. However, a site for long-term storage has still to be established (Schmidt, 2013)
- **Sub-classification level**: Moderate to high approachability (moderate approachability in environment and society)

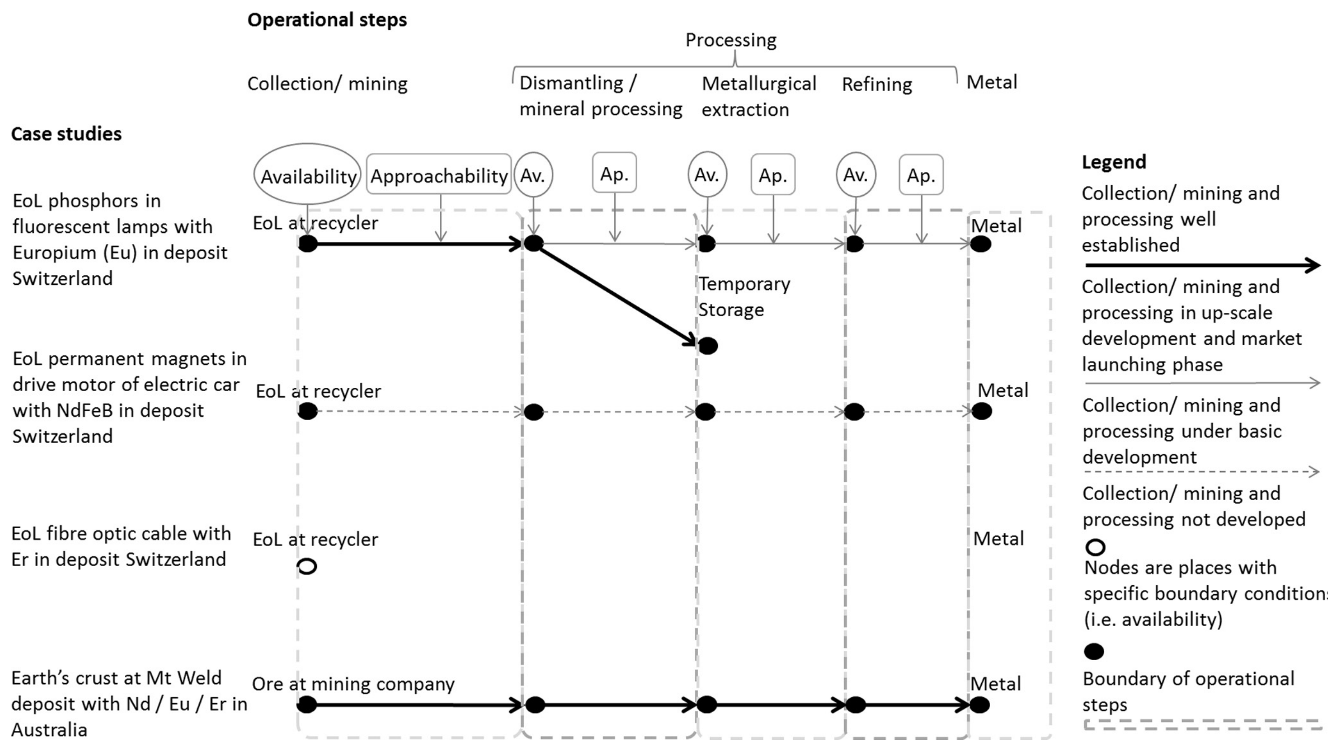

Fig. 7. Visualisation of the raw material 'accessibility' investigations of the collection/mining and processing and the four deposit case studies. Accessibility is considered at each operational step and provides an overview of whether the accessibility to a raw material from collection or mining is well established, in up-scale development, under basic development or not yet considered. 'Av.' indicates availability; 'Ap.' indicates approachability.

long-term raw material accessibility, it is also essential to consider the sustainability aspects: society, environment, and economy (Corder et al., 2010). For our framework, the different components and their indicators are currently being verified by means of expert's survey with a Delphi study. The framework further differs from alterative evaluations as it aims to facilitate early project stage evaluation with limited availability of robust data (Roelich et al., 2014) and which often involves high uncertainty (Weber, 2013). Our use of three categories ('low', 'medium', 'high') does reflect the lack of data (Table 3). Similarly to our framework, the UNFC-2009 comprises three to four categories. However, in contrast, our framework comprises one main category ('accessibility'), two sub-classes ('availability' and 'approachability'), and six components (namely 'geological knowledge', 'eligibility', 'technology', 'economy', 'society' and 'environment'). Additionally, our framework provides an indication about the current supply situation rather than a detailed assessment. This indication could particularly support the prospection phase, which aims to develop knowledge on type, location, volume, legislation, technology and costs (Winterstetter et al., 2016a). The insights gained from the application of our framework could provide valuable information to support a UNFC-2009 classification. Hence, the availability component 'geological knowledge' could provide basic knowledge for the UNFC category G (also known as geological knowledge). The approachability component 'technology' could provide basic knowledge on the existing technology and infrastructure, which are needed in the category F (field project status and feasibility). The availability component 'eligibility' and the approachability components 'economy', 'society' and 'environment' could deliver fundamental information, as this is required in the category E (economic and social viability).

4.2. Evaluation of raw material accessibility

The application of our developed evaluative framework to the case studies has shown that it is possible to describe and quantify the components of 'accessibility': 'availability', and 'approachability' of different anthropogenic and geological raw material deposits (Fig. 6). Perhaps unexpectedly, the currently mined Mt. Weld deposit generates an 'approachability' outcome of medium to high, because the quantified societal and environmental impacts associated with processing in Malaysia require the same level as European standards. The evaluations show that it is possible to compare the mining of deposits from EoL products with mining the Earth's crust. This could potentially be applied to any EoL products and mine from the Earth's crust. Our evaluation could be extended to cover multiple metals per product or deposit. The former, multiple metals per products were evaluated by means of obsolete personal computers and Neodymium Iron Boron permanent magnets (Winterstetter et al., 2016b). The former, multiple metals per deposit were evaluated by a landfill (Winterstetter et al., 2016b) and Vienna's subway network (Lederer et al., 2016). There are two constraints on our aggregated evaluation, namely that the different components are not apparent and that the current evaluation is static.

The investigation of the accessibility components demonstrates that it is possible to underpin this evaluation with numerical statements (Table 4). Nevertheless, the selection of each indicator requires expert justification (Tuma et al., 2014). Our quantification of the operational steps: collection/mining and processing could be expanded with a more detailed investigation of each step.

Quantitative evaluation of the availability component 'geological knowledge' demonstrated that the mass fractions of raw material in anthropogenic deposits are higher than those of the geological deposits (Table 4). However, its quantification is influenced by the limited availability of relevant data and assessment of associated uncertainty, particularly with respect to the very low concentration of REEs (Simoni et al., 2015). This quantification could be expanded with a calculation on the energy use as implemented by Peiró and Méndez (2013).

The evaluation of the availability component 'eligibility' revealed that with unclear and restricted ownership (such as was the case for fibre optical cable), accessibility to raw materials becomes difficult (Table 4). This can be exemplified by China's ownership of 63% of the world market for REE and their intentions to buy REE mines in Australia and Greenland (Sprecher et al., 2015). However, quantification of material eligibility proved demanding, with most existing data being descriptive rather than quantitative. Consequently, here 'eligibility' was quantified with the rule of law indicator from the WGI project (World Bank, 2016) and then described. For future research, alternative approaches should also be considered, which may include the Policy Potential Index (PPI) or, the Herfindahl-Hirschman Index (HHI). The PPI is used to provide governments with a report card on how attractive their policies are from an exploration manager's point of view (Graedel et al., 2012) and includes issues concerning mining permissions. The PPI provides information on the mining at system level but does not explicitly account for the influence of ownership of mining companies to the government or society. However, to understand the worldwide restrictions better, the HHI provides information on the concentration ratio of metal producing companies or countries in a bigger geographical area, i.e. country or world (Gleich et al., 2013), yet lacks on information about a single company. Given that ownership was identified as a central criterion for 'eligibility' in this study (Table 4), it is important that an appropriate method is determined to quantify this facet.

Following the quantification of the component 'technology', we found that only limited information is available to quantify the recovery rate for the different processes with a high degree of certainty (Table 4). An alternative approach may be the technology readiness assessment (Winterstetter et al., 2015), which is commonly applied in the oil and gas industry to rank the establishment of a technology on a scale of 1 (low) to 9 (high) (Strutt et al., 2009). However, no efforts have been undertaken to implement this in the non-energy extractive industry.

The results for the 'economy' component evaluation revealed that there is a dearth of information concerning the costs of mining either the anthroposphere or the geosphere (Table 4). For instance, the recovery of EoL permanent magnets from drive motors is in its infancy; consequently, no price could be established. Nevertheless, a prediction of economic viability was possible. For deposits in the Earth's crust, price data with the lowest uncertainty were available from the metal trading price index. The quantitative evaluative approach of this component requires further investigation.

The impacts on society were worse in the case of mining the geosphere than the anthroposphere (Table 4). Impact quantification was based on a single indicator, the politically stability and absence of violence/terrorism from the WGI project (World Bank, 2016). This approach potentially limits the overall statement of the impacts on the society. However, there are only a few other indicators at system level that may be applied, namely control of corruption, risk of child labour and freedom of speech (Tuma et al., 2014). It is being verified to expand this system level statement with indicators, such as hours of work or occupational injuries (Dewulf et al., 2015) to provide a more comprehensive statement on social impacts. In contrast to Graedel et al. (2012), the use of the human development index was rejected in the present study, as we concluded that quantification of health, education and income of a country is not sufficiently specific for an industry processing in a country.

Our results show that, in the cases examined, the negative impacts on the environment from geological mining (based on global warming potential only) are considerably higher than those for anthropogenic mining (Table 4). Environmental impact was assessed in the present study based solely on potential global warming impacts. This approach represents a limitation of our method as such a singular focus does not address the wide range of potential environmental impacts that may be caused by raw materials mining and production activities (e.g. freshwater acidification, ecotoxicity, etc.). However, such an approach is considered justified and appropriate for an early project stage evaluation. Further, since there is limited data availability for many metals, with more data available on global warming potential, this becomes an important environmental impact category (Nuss and Eckelman, 2014). For the quantification of this important impact category, a clear choice of system boundary, location and energy mix are central, as these can make a significant difference on the final result (Laner et al., 2016). Additionally, as a complementation, measures for impact monitoring prevention were described (Table 4).

Finally, our use of a one-directional graph at different operational steps (Fig. 7) enables easy comparison of the availability and approachability of raw material in EoL products or the Earth's crust along operational steps and provides a simple representation of reality. This approach in turn elucidates potential collection/mining and processing disruption, which is currently lacking (Roelich et al., 2014). This graphical interpretation could be further developed with the bipartite graph from e.g. Pauliuk et al.'s (2015) accounting framework to model the socio-economic situation in detail.

5. Conclusion and outlook

Availability is commonly used in raw material supply evaluations, whilst other researchers suggest that raw material supply should be evaluated based on accessibility. This difference has led to semantic confusion within the field of raw material supply. Based on the quantitative linguistic approach, we conclude that raw material supply evaluation can be evaluated based on the accessibility of materials, 'accessibility' comprising: availability and approachability. However, whilst raw material availability is commonly addressed in previous studies, raw material 'approachability' has not yet been explicitly evaluated at a system level. Consideration of this aspect is essential to gain a thorough understanding of the accessibility of raw materials. To address this, the urban planning framework was the basis for our conceptual framework for raw material 'accessibility' evaluation. Our proposed framework comprises an assessment of raw material 'availability', for which the components 'geological knowledge' and 'eligibility' are considered; and 'approachability', for which the components 'technology', 'economy', 'society', and 'environment' are considered. The framework was applied to evaluate the raw material accessibility of four different REE deposits. The results demonstrate the potential of our framework tool as an early stage assessment for projects mining the anthroposphere and geosphere. Possible next steps include further differentiation and quantification of the criteria and querying with a large number of experts.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.wasman.2017.05.043.

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