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Towards sustainable resource management: identification and quantification of human actions that compromise the accessibility of metal resources

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ABSTRACT

Although metals and minerals represent a prominent asset for sustainable development, continuous population growth and the current accelerations in energy and mobility transitions are increasing concerns regarding their accessibility for current and future generations. As recent insights have identified access rather than depletion to be the dominant factor for resources, this paper elaborates on the (in)accessibility concept of such raw materials once they have entered the technosphere. It identifies six human actions that compromise accessibility: emitting, landfilling, tailing, downcycling, hoarding and abandoning. It analyses the degree of the generated inaccessibility and proposes estimated duration of inaccessibility as a proxy. It further explores how current sustainability management tools like material flow analysis and life cycle analysis could be further developed to address resource (in)accessibility. Finally, the paper presents a case study on cobalt in the EU, where five compromising actions make 70% of the extracted cobalt inaccessible due to tailings (21.3%), landfilling (31.2%), downcycling (11.6%), dissipation (1.4%) and hoarding (4.3%); only 30% is used to expand the functional stock.

1. Introduction

Natural resources, including minerals and metals, are key to satisfying mankind's needs now and in the future. Mancini et al. (2018) investigated the function of raw materials in meeting the UN's Sustainable Development Goals for 2030. Their supply chain contributes to several environmental impacts, including water pollution and climate change, but they are essential in final applications. In addition to long standing use in housing, transport and communication infrastructure, they become more and more key in energy supply and storage to address climate change. In comparison to fossil based energy generation, the application of neodymium, dysprosium and terbium into permanent magnets in wind mills results in 95 to 98% climate impact reduction of electricity use, despite the energy intensive supply chains (UNEP, 2013). Apart from sustainable energy sources like wind, solar or hydropower, the energy transition urges for an expansion of in-use-stock of raw materials for its infrastructure. Low-carbon mobility (electric and hybrid vehicles) is following a similar pattern, with exponentially growing in-use stocks of metals e.g. Rare Earth Elements (REEs) in electric engines and cobalt in traction batteries (EC, 2020a). The employment of metals in the coming years and decades will be tremendous in the energy and mobility value chains to face the climate challenge: the European Commission anticipates that for electric vehicle batteries and energy storage, the EU would need up to 18 times more lithium and 5 times more cobalt in 2030, and almost 60 times more lithium and 15 times more cobalt in 2050, compared to the current supply to the whole EU economy. Demand for rare earths used in permanent magnets, e.g. for electric vehicles, digital technologies or wind generators, could increase tenfold by 2050 (EC, 2020a; EC, 2020b). The above numbers, alone, illustrate that in no way are growing demand and growing stock compatible with circular economy policies (e.g. EC, 2015) based on enhanced qualitative recycling only. One should be aware that recycling does not always deliver the same quality of the resources as in the original product, as illustrated by the cascading concept discussed by

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Campbell-Johnston et al. (2020). An injection of metals from mining of primary resources will remain necessary to meet the growing demand and allow for the projected change. Hence, transfer of primary metals from the ecosphere to the technosphere will be essential to deliver the infrastructure through a Net Addition to the Functional Stock (NAFS). Indeed, it is vital to understand the key role of resources: they fulfill ultimately a function at the user by becoming part of the 'Functional Stock'. As we have a continuous renewal, change and growth of this 'Functional Stock' because of changing needs and technologies, we face a continuous need for a 'Net Addition to the Functional Stock'. We introduce this new term to highlight the functionality at the user; stocks at user or in-use stock might be ambiguous as a fraction might be not functional but hoarded and/or at end-of-life. We intend to address the mass flows and stocks that are related to the build-up of the functional stock, rather than the function and functionality of the functional stock itself.

It has to be examined to what extent the energy and mobility transitions shift the climate and energy challenge into a material challenge. One heavily debated material challenge, with metals in particular, is so-called resource depletion. In other words, will future generations have sufficient natural resources to meet the demand of metals? The Life Cycle Assessment community historically used methods like ADP (Abiotic Depletion Potential) that characterizes 'Abiotic Resource Depletion', based on quantification of use-to-natural stocks rates - in other words an application of the fixed-stock paradigm -, or as a function of additional energy use or costs due to decreasing ore grades or increasing efforts as with extraction of oils from oil sands (Sonderegger et al., 2017; Sonderegger et al., 2020; Berger et al., 2020). However, the underlying assumption has been heavily criticized as the natural stocks quantification is scientifically questionable in terms of the rationale behind. On top, it is very challenging methodologically and quantitatively speaking, especially given the economic context and the dynamics of exploration, see e.g. Drielsma et al. (2016). The mining sector equally argues that metals as such are not necessarily depleted or gone by transferring them to the technosphere as metals do not vanish. They argue that there is no justification to leave e.g. cobalt underground (to avoid depletion), if cobalt can remain in use within the technosphere for decades, thus delivering benefits to current and future generations. Interestingly, this idea has been coined in the LCA community by Frischknecht (2014) where he brought in terms like resource borrowing and post-consumer resource availability; but the latter concepts have not further been developed according to the knowledge of the authors.

In a recent European project, SUPRIM (Sustainable Management of Primary Raw Materials through a better approach in Life Cycle Sustainability Assessment), stakeholders from various backgrounds have been brought together to develop a better understanding of the resource problem (Schulze et al., 2020a, Schulze et al., 2020b). Rather than 'depletion', the project brought forward that the concern is continued access to resources by humans for use in the economy. Accessibility is defined as the ability to make use of a resource (Schulze et al., 2020a). This is in line with Berger et al. (2020), who define the safeguard subject for mineral resources as "[…] the potential to make use of the value that mineral resources can hold for humans in the technosphere". Hence, actions that compromise accessibility to resources should be framed and quantified, as well as counter-measures should be adopted in function of sustainable resource management. Kral et al. (2019) discussed recently that next to material cycles also so-called final sinks exist, both man-made and environmental media. Ciacci et al. (2015) mentioned the problem named 'lost by design', i.e. there are common uses of metals where losses are intended in the application, e.g. copper in brake pads. Recent work by Charpentier Poncelet et al. (2019) and Zampori and Sala (2017) pointed to dissipation as key to develop new life cycle impact assessment methods for resource use under the area of protection natural resources. Helbig et al. (2020) quantified dissipative losses of 18 metals. Van Oers et al. (2020) define several compromising actions like dissipation in the environment, hibernation in the technosphere and occupation in use. Dissipation in the environment has been taken further into a new life cycle impact assessment model (van Oers et al., 2020). All in all, current sustainability assessment tools like life cycle assessment (LCA) or material flow analysis (MFA) are not specifically designed to unravel the nature of compromising actions systematically.

The research work cited in the paragraph above points to the importance of actions in the technosphere, which can take place anywhere along the value chain, as key actions that compromise accessibility, rather than the ecosphere-technosphere transfer by mining. However, the sustainability impact of the primary production should not be forgotten and assessed with impacts on ecosystem quality and human health. Indeed, extraction processes contribute 50% to the global carbon emissions and even 80% to biodiversity losses (Oberle et al., 2019). Hence, the burdens associated with the primary supply of raw materials and metals should be minimized by cleaner technologies for both expanding and maintaining the functional stock. This means that, ideally, minerals and metals extracted by the primary production sector are fully transferred as a net addition to the functional stock (NAFS) and there is no need to compensate for resources already mined, but made inaccessible by the abovementioned compromising actions.

Whereas a lot of research has been dedicated to the quantification of what we keep in the loop by proposing so-called circular economy indicators (see e.g. Moraga et al., 2019), this paper envisages rather quantification of material losses than materials retention by elaborating the (in)accessibility concept. Looking at material losses can allow mapping where reduction of inaccessibility can be achieved. The focus is on metals, which have a stock and non-renewable character (Sonderegger et al., 2017). In principle, they cannot disappear at the element level and theoretically full continued access is possible in absence of compromising actions. The goal and the novelty of this paper are to bring forward, develop and support the concept of (in)accessibility in function of sustainable resource management and to contribute to rethinking sustainability assessment tools like MFA and LCA in function of better addressing resource (in)accessibility. In order to illustrate the obtained insights from the concept, an exploratory case study on cobalt within the EU has been elaborated. For sake of clarity, key terminology is explained in Appendix 1.

2. Development of the inaccessibility concept

2.1. Identification of nature of compromising actions and related actors

Van Oers et al. (2020) point to human actions that lead to a change in accessibility of resources, rather than to their depletion. Indeed, elements cannot be transformed as such and hence they cannot be depleted, unless they undergo nuclear fission or decay. Moreover, Van Oers et al. (2020) point out that exploration by the mining sector increases the stock of accessible resources, supporting the critique that reserves as a base for depletion methods is flawed and too narrow in scope. In terms of actions that decrease accessibility, they identify environmental dissipation, technosphere hibernation and occupation in use.

Environmental dissipation is rather obvious: emission leads to very low concentrations in environmental compartments; these diluted stocks become inaccessible for mankind with the current state of technology and economics. There is quite a common vision on this type of compromising action which can be called emissions into the environment, dissipative or dispersive flows into the environment, or disposal in atmosphere, hydrosphere and geosphere. They can be from both point and diffusive sources (Kral et al., 2019). Both terms dissipation and dispersion are used. Dissipation is a far broader term as it is related to the outcome of an irreversible process and can in principle relate to other physical issues than matter (e.g. energy), whereas dispersion clearly points to the spreading of mass in a larger volume (see Appendix 1).

The second type of human activity that leads to inaccessibility, hibernation in the technosphere, is less intuitive. Van Oers et al. (2020)

mention two terms: dissipation in the technosphere and hibernation. Van Oers et al. (2020) state that it is not always straightforward to distinguish between the two. Nevertheless, they identify three hibernating stocks: landfills, tailings and abandoned products.

Landfills and tailings are clearly confined stocks, i.e. intended to be kept in a closed place. Landfills originate from all kind of disposal activities from industrial or household end-of-life materials. Tailings stem from mining activities. Mining processes lead actually not only to tailings as hibernating stocks, but also to waste rock (overburden and interburden, or 'scalpings') (Shaw et al., 2013). Depending on the concentration of desired metals in the waste rock, waste rock might be labelled as a second hibernating stock from mining activities in addition to the tailings.

Abandoned products need a closer look. On one hand, there are clearly products at the user that are not in use anymore and are stored before disposal. This can be called hoarding. There are obvious examples of electronic equipment like mobile phones and laptops (Thiébaud et al., 2017a). However, there is also infrastructure that is abandoned. There are not only abandoned residential areas like abandoned villages (Jaszczak et al., 2018) but also abandoned industrial infrastructures, sometimes named brownfields, see e.g. De Sousa and Spiess (2018). Furthermore, there is a lot of formerly used infrastructure no longer utilized within active industrial and residential areas. In particular, abandoned metals-based infrastructure embedded in urban areas has to be mentioned. Swedish researchers investigated in detail copper stocks in local power grids, identifying that almost 20% of the copper in the grid is no longer in use in cities like Gothenburg (Krook et al., 2011). Next to power grids, old railways are known as abandoned infrastructure (Quattrone et al., 2018). A lot of abandoned infrastructure may be poorly documented. The European Commission estimated 4.1 million vehicles with 'unknown whereabouts' in the EU (EC, 2018), being vehicles that are deregistered but not destructed, potentially exported, hoarded or abandoned.

Whereas the inaccessibility of abandoned products hoarded by users is rather easily reversible, abandoned infrastructure may lead to a more severe and persistent inaccessibility. Hence, it is proposed to differentiate hoarding from abandoning infrastructure as human activities that lead to inaccessibility.

Further on, we may identify other inaccessible stocks of materials within the technosphere in addition to the aforementioned landfills, tailings, hoarded stocks and abandoned. Indeed, production and end-of-life processing lead to dispersion of metals in all kind of products withheld in the technosphere. The level of complexity of modern products makes it extremely challenging – if not impossible – to make all embedded resources fully accessible at the end of the product's service. It should be recognized that in many cases recycling keeps materials and metals in the loop in society but in other applications where the metals do not deliver the same functionality as in the first application. This downcycling leads to a dispersion of metals in metal alloys or in (road) infrastructure, making them inaccessible and preventing them to re-enter the initial functional stock. As an example, De Meester et al. (2019) analysed the recycling of waste electronic and electrical equipment in Belgium. Despite quite significant recycling rates of metals like aluminium and palladium of 81% and 60% respectively, only half and one third of these percentages add back to the stock with the same functionalities. The other half and two thirds flow into the dispersed stock within the technosphere. The complexity of products today challenges high quality recycling, see the example of smartphones where at least 70 of the 83 stable elements can be found (Rohrig, 2015).

Finally, there is also the stock in use or the functional stock ('occupation in use') that Van Oers et al. (2020) identified as inaccessible. Its inaccessibility may be questioned as it is indeed inaccessible for many humans but at the same time accessible for its users. This might raise questions about the distribution of accessibility, be it geographically, socially, economically or culturally, but these aspects are beyond the scope of this paper. At least, metals serve a purpose in providing services as part of the functional stock. In this sense it plays an essential role and is to be separated from the other inaccessible concentrated and dispersed stocks that do not deliver any service. However, the quantities that lead to service should be investigated to better understand the system. More resource efficient products with less materials leading to the same functionality, typically part of product service system (PSS) models, and which may be expressed by resource efficiency metrics, like Material Input Per unit of Service (MIPS), are important in sustainable resource management strategies (Wiesen and Wirges, 2017), in addition to addressing inaccessibilities. A typical example where more service can be provided with lower quantities of materials is sharing products, e.g. car sharing.

Table 1
Six inaccessible stocks with respective human compromising actions, their location, their status dispersed or confined with a typical example.

Stock	Compromising action	Location of stock	Dispersed or confined*	Example of compromising action
Dispersed stock in the environment	Emitting	Ecosphere	Dispersed	Emitting copper from brakes in cars
Landfills	Landfilling	Technosphere	Confined	Landfilling of household waste
Tailings**	No metal recovery because of techno-economics	Technosphere	Confined	Tailings at metal mining
Abandoned stock	Abandoning	Technosphere	Confined/ dispersed	Abandoning power grids
Hoarded stock	Hoarding	Technosphere	Confined	Storing mobile phone in the attic
Dispersed stock in the technosphere	Downcycling	Technosphere	Dispersed	Using metal containing ash in road infrastructure

* Dispersed: Spread into a relatively large area/volume; Confined: Present within a relatively low area/volume (See Appendix 1). ** Mining/metallurgical processing wastes may be added to the tailings if they contain substantial metal concentrations.

As a result, six inaccessible stocks are identified and are summarized in Table 1 with the associated human compromising action, their location, their status dispersed or confined, together with a typical example. It should be highlighted that the stocks identified are not only dispersed or dissipated stocks, the latter getting most of the attention in rethinking life cycle assessment impact methods (Zampori and Sala, 2017; Charpentier Poncelet et al., 2019; van Oers et al., 2020).

2.2. Bringing in the time dimension: duration of the inaccessibility

2.2.1. Factors affecting the duration of the inaccessibility

The human actions that compromise inaccessibility through transfer into six different stocks have to be differentiated in terms of its severeness or degree. The characteristics of the stocks, together with the socio-economic framework and technological development may determine when these stocks may become accessible again. The uncertainty about the duration of inaccessibility may be very different from one accessible stock to another.

In a broader context, inaccessibility may be limited by technological and societal factors. The latter do not only govern the in-use stocks but also to some extent the duration of inaccessible stocks because of ownership. In this section we focus on socio-economic and technological constraints in particular. The latter are fundamentally governed by thermodynamics (Castro et al., 2004; Castro et al., 2007; Reuter et al., 2006). When the thermodynamics are unfavorable, e.g. in case of huge dilutions or in case of extremely strong interactions in between metals like in alloys, technology becomes economically unfeasible to make metals accessible again.

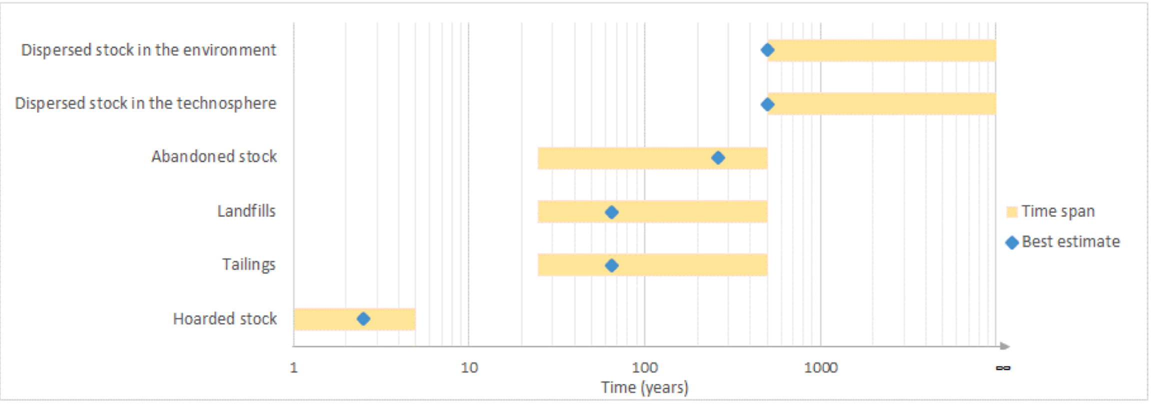

Fig. 1. Rough estimates of the duration of inaccessibility of raw materials in various stocks, positioned within time spans delineated between today (0 yrs), short term (5 yrs), medium term (25 yrs), long term (500 yrs) and infinite

The most reversible inaccessibility – at least from a technical point of view - is clearly related to the hoarded stock. Its location and confinement and the current state of the technology with proper take-back, pretreatment and recycling schemes in many countries demonstrate the feasibility of making it accessible, see e.g. metal recycling from waste electric and electronic equipment (see e.g. Thiébaud et al., 2017a; De Meester et al., 2019). Actually, the cause of the inaccessibility is the socio-economic context where there is insufficient (economic) incentive to avoid hoarding.

In line with these latter inaccessible stocks are abandoned stocks. The metal stocks therein are concentrated (present with a relatively high mass fraction in the infrastructure) and relatively confined (present in places with a volume, i.e. urban areas or brownfields, relatively low compared to environmental compartments or the technosphere as a whole), but at the same time relatively dispersed (spread over an area and volume relatively large). Equally, on the short to medium term, they are not expected to become accessible again, despite technology might be available either to (re)use or to recycle this stock. The continuation of the inaccessibility may stem predominantly from the socio-economic context. The economic feasibility is low, but an even more important obstacle may be the practical feasibility. Indeed, making these stocks accessible again requires knowledge about their exact location and composition. The historic build-up of these stocks is not properly documented. A second practical unfeasibility, for those stocks documented, lies in the physical technical hindrances. Selective removal of abandoned infrastructure amongst functional structures can lead to malfunctioning of the latter, or may even require full temporary removal of it, which may be socially inacceptable.

Finally, landfills and tailings may be the stocks with a degree of inaccessibility in between. They are usually well located and confined. They are a result of lack of proper technology to make use of the materials (e.g. too low concentrations) or lack of interest in particular raw materials (e.g. co-occurring metals) at the point of their generation. The exploitation of these stocks is currently a significant subject of study with prospective studies where sampling is key (see e.g. Blasenbauer et al. 2020), and even exploitations, as the socio-economic context changes over time. Equally, mining them as part of their environmental management can occur to mitigate environmental impacts and risks. Graedel et al. (2004) studied the importance of tailings for copper, where reworked tailings were estimated as 2% of the global copper inputs to production. It must be clear that the duration range of this type of inaccessible stocks might reveal the highest spread, given that they may be extremely variable in terms of particular raw materials embedded, concentrations and chemical structure.

In conclusion, differences in confinement, nature of confinement, technology development for the reversal of the inaccessibility of the respective stocks and the socio-economic context lead to a differentiation in terms of degree of inaccessibility amongst them. The size, the geographical location, the spatial distribution and the lack of mobility of the stocks may be key in the reversal. It is a challenge to bring forward (semi)quantitative measures to express the degree of irreversiblity.

2.2.2. *Duration as a measure to differentiate the degree of inaccessibility*

A possible way to qualify and quantify the difference in degree of inaccessibility may be its anticipated duration of inaccessibility. To put a number of years on this duration is extremely challenging as it is looking into the future. In this section, an effort is put forward, based on a literature study and interviews with specialists in various areas. The results are summarized in Fig. 1.

The effort has been done in two manners. First of all, a best estimate of the inaccessibility duration has been based on available information (cited further in this section), along with a quality assessment of the estimate. Secondly, as uncertainty is high, a range with minimum and maximum duration estimates has been put in function of three agreed time horizons as defined in the SUPRIM project. Degrees of inaccessibility have been classified in time spans in between today (0 years), short term (5 years), medium term (25 years), long term (500 years) and infinite. Results are summarized in Fig. 1.

The best estimates could be put forward for the hoarded stock. Indeed several surveys have been done on hoarding of materials at household levels for appliances that contain important raw materials (Thiébaud et al., 2017a; Wilson et al., 2017; Zhang et al., 2019; Glöser-Chahoud et al., 2019; Godoy León and Dewulf, 2020) but equally for industrial equipment (Godoy León and Dewulf, 2020). For voluminous devices such as flat panel displays, hoarding is less than one year, whereas for more tiny products it may rise up to 3-4 years. A best estimate with a rather high quality leads to a duration estimate of 2.5 years, clearly within the short term time window: 0-5 years. The quantities of these inaccessible stocks are anticipated to be rather limited. However, based on the service and hoarding times, the study of Thiébaud et al. (2017a) indicate their relative importance at a household level with 20-25% of the stock hoarded at households.

Based on the SUPRIM project where several experts have been consulted (see acknowledgement in Schulze et al., 2020a), and based on discussions with various other experts (see acknowledgement in this paper), it becomes clear that the dispersion in the environment leads to a long term inaccessibility, i.e. for multiple generations. There is clear consensus that it is long term, despite the number of years assigned might be subject of debate. Within the SUPRIM project, the minimum was set at 100 years with finally adoption of the value of 500 years, in line with other long term effects modeled in LCA, e.g. global warming potential of greenhouse gases at a 500 years span. It must be mentioned that other LCA practitioners set long term horizons in the 60 000 – 80

Table 2
Analysis of a few exploration and mining activities of tailings.

Type of metals	Mine	Country	Mining history			Tailings potential			Reference
			Start	End	Metals mined	Metals to be re-mined	Year of assessment	Status	
Precious metals	Hellyer	Australia	1989	?	Au, Ag	Au, Ag	2017	Resource	Campbell et al., 2015
	Hellyer	Australia	1989	?	Au, Ag	Au, Ag	2019	In operation	Medianet, 2018
	Various	South Africa	1886	?	Au	Au	1995	In operation	Laznicka, 2006
Other metals	Century	Australia	1999	2018	Zn	Zn	2017	Reserve	Attila Resources Limited 2017
	Kipushi	DRC	1925	1993	Cu, Pb, Zn	Cu, Zn, Co	2019	Resource	Cape Lambert, 2019
	Kamativi	Zimbabwe	1936	1994	Sn, Ta	Li	2018	Resource	Cronwright et al., 2018
	Kamativi	Zimbabwe	1936	1994	Sn, Ta	Li	2019	In operation	Schmidt, 2019
	Kolwezi	Congo	1952	?	Cu	Cu,Co	2003	Pilot	Pryor and Lunt, 2003
	Chvaletice	Czech Republic	1951	1975	Mn	Mn	2019	In operation	NS Energy, 2019

Footnote. For definitions of 'resources' and 'reserves', the reader is referred to Drielsma et al. (2016): (1) A (mineral) resource is a concentration or occurrence of solid material of economic interest in or on the Earth's crust in such form, grade or quality, and quantity that there are reasonable prospects for eventual economic extraction. The location, quantity, grade or quality, continuity, and other geological characteristics of a mineral resource are known, estimated, or interpreted from specific geological evidence and knowledge, including sampling. (2) A (mineral) reserve is the economically mineable part of a measured and/or indicated mineral resource. It includes diluting materials and allowances for losses, which may occur when the material is mined or extracted and is defined by studies at pre-feasibility or feasibility level as appropriate that include application of modifying factors. Such studies demonstrate that, at the time of reporting, extraction could reasonably be justified.

000 years range (Weidema et al., 2013). All in all, the time span can be set at minimally 500 years.

Tailings is another stock from which metals could be made available again (Lottermoser, 2011; Shaw et al., 2013). Ongoing developments point to a finite duration of the inaccessibility (decades), which is well illustrated by the recent report from the MINEA (Mining the European Anthroposphere) project (Blasenbauer et al., 2020). Information of their potential is not all in the public domain because of strategic reasons (Lottermoser and Suppes, 2019). Nevertheless, from various reports, an indication of ongoing and planned activities of mining of tailings could be made, exemplified in Table 2. Economics set the scene for making the tailing stocks accessible. Precious metals from tailings are made available sooner as it becomes techno-economically feasible. Based on the limited cases, it may be suggested that these re-mined tailings are in the order of 50 years old. For other metals, cases show economic viability of mining tailings with an age of about 80 years. If this retrospective analysis is used as a proxy to anticipate the duration of the tailings generated today, an average estimate of 65 years can be proposed, clearly in between the medium (25 years) and long term (500 years). It must be emphasized that the spread on the estimate of 65 years may be huge, as the embedded raw materials might have very different concentrations given that the currently targeted raw materials might be different from the originally targeted ones, that the chemical structure might be very different as a result of the original mining and processing technology, and that the environmental conditions may require environmental remediation that can include mining (Sözen et al., 2017). Additionally, the composition of tailings may also change over time due to weathering. Economic recovery may also be influenced by the spatial context and the presence of penalty elements.

In a similar way, there is growing activity and economic analysis to mine old landfills (Winterstetter et al., 2016; Laner et al., 2019). Winterstetter et al. (2016) analyzed this anthropogenic deposit following the UNF-2009 classification. Based on a negative net present value, they concluded that the landfill under study cannot be classified as reserve. Nevertheless, with potential future changes of a set of key modifying factors such as an assumption of doubling ferrous and non-ferrous prices within 20 years, more efficient energy technologies and avoided aftercare costs, they consider landfill mining as 'potentially commercial', categorizing it into the 'resource' category. Hence, the duration of the inaccessibility can be set at medium term, i.e. 25 years, in best case. However, the variability might be high as not all landfills might have the potential as the case in the study of Winterstetter et al. (2016). It can be anticipated that many other landfills are far less favorable to be mined (e.g. if mainly plastic waste is landfilled), setting the range from medium term (25 years) to long term (500 years). To make a best average estimate, we may rely on the estimates for tailings as a proxy, given the similar nature to some extent; both stocks are stocks that are well confined and geographically well identified. Obviously, in this way the estimate for landfills is of lower quality than for tailings.

Abandoned stocks have been studied by Swedish researchers (Krook et al., 2011; Krook et al., 2015; Wallsten et al., 2015), albeit mainly limited to copper cables in cities. They concluded that under current conditions mining urban infrastructure does not make economic sense. Apart from these interesting studies, to the best of our knowledge there is no other study available that gives any base to estimate the duration of the inaccessibility of abandoned stocks. In conclusion, the duration of inaccessibility is to be situated somewhere in the medium to long term range, this with a limited quality of the estimate. As best possible estimate, we suggest to set it at 262.5 years, i.e. at the middle of the 25–500 years time frames. Despite the high level of uncertainty, as an operational solution aimed at a transparent discussion and subsequent fine-tuning, we positioned the duration above the 65 years of landfills and tailings. At the same time - given the confined nature - we equally positioned it below the 500 years of stocks dissipated into the environment.

Finally, there is poor ground to make estimates on the duration of stocks dispersed into the technosphere. To the best of our knowledge, there is hardly information on developments on economically viable technologies that are capable to recover particular raw materials or metals out of plastics, paints, papers, glass, ceramics, complex alloys or road infrastructure, just to name a few anthropogenic stocks. Ciacci et al. (2015) simply labeled these stocks as 'lost by design'. Hence, based

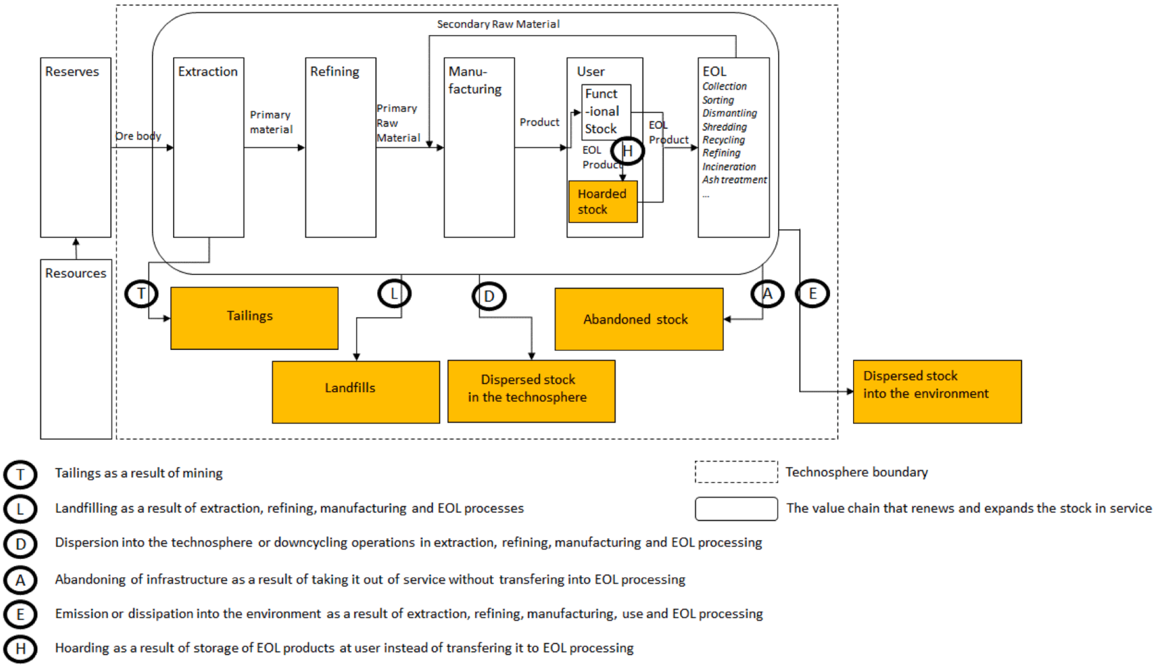

Fig. 2. Material Flow Analysis scheme visualizing six inaccessible stocks (in orange) and the six associated human induced flows towards these stocks. Note: Confined inaccessible stocks like tailings and landfills might also lead to emissions, hence transferring part of their stock into the dispersed stock in the environment, if they are not managed properly. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

on lack of indication of their recovery on the short to medium term, it may be suggested that their inaccessibility is at the long term, 500 years, in line with the stock dispersed into the environment counterpart, although with less clear indications and hence assigning a lower quality degree to the estimate.

Fig. 1 summarizes the minimum and maximum time horizons of the inaccessibility for the various stocks, along with the best estimate and the associated level of the quality of the estimate.

3. Steps towards further implementation of the inaccessibility concepts

In order to implement the inaccessibility concept in function of sustainable resource management, one may start from existing methods and data as a good starting point. In this section, we discuss material flow analysis and life cycle assessment as relevant methods, followed by a section that looks into available data.

3.1. Rethinking MFA schemes to bring human compromising actions forward

When looking into MFA practice today, there is good ground to embed flows into inaccessible stocks. Highlighting flows to inaccessible stocks in Sankey diagrams could take advantage of MFA's strong visualization capabilities and convey the inaccessibility issue to many stakeholders. It must be said that some MFA practices already partially embed inaccessible stocks. In their handbook of material flow analysis, Brunner and Rechberger (2016) demonstrate the common practice to include emissions into the environment (e.g. into the planetary boundary layer for atmospheric emissions) and landfilling, which is confirmed in a recent review by Graedel (2019), although landfilling is assigned as a flow to the environment in the latter document. In an MFA of aluminium, copper and iron for the EU, transfer to hibernating stocks in the technosphere covers both landfills and tailings (Passarini et al., 2018). Recently, Helbig et al. (2020) covered four inaccessible stocks: environmental dissipation, tailings, downcycling and landfilling. The authors put them under one single umbrella term, dissipation, whereby they considered tailings and landfilling as transfers to the environment. To the best of our knowledge, MFAs with a systematic visualization of flows towards the six inaccessible stocks have not been reported. One main reason is that the stock at the user is usually not differentiated in terms of stock-in-use versus stock-hoarded; the quantification of stock-hoarded is challenging and information is not widely available. Additionally, abandoning is not considered, most probably because of lack of quantitative information.

Fig. 2 shows human activities and related transfers to inaccessible stocks, situating five stocks within the technosphere and one in the environment. The Fig. is in principle at the global level as resources and their inaccessibility need a global perspective given their tradeability; however a similar scheme can be developed at regional or national level on the condition that trade is represented.

3.2. Rethinking cause-and-effect chains for the Area Of Protection Natural Resources in LCA

Natural resources are an Area Of Protection (AOP) in LCA where it has for a long time been questioned what exactly we aim to protect (Dewulf et al., 2015). Recently, the Life Cycle Initiative, hosted by the UN Environment, established an expert task force on "Mineral Resources" to review existing methods (Sonderegger et al., 2020). They classified existing life cycle impact assessment methods that deal with resources into four groups: depletion methods, future effort methods, supply risk methods and thermodynamic methods. Berger et al. (2020) mention that the ADP (abiotic depletion potential) model is valid and it has also been recommended by several initiatives. However, the authors acknowledge that the method does not distinguish between the part of the resource extraction that is occupied for current use (but can be available for other uses in the future) and the part that is "dissipated" into a technically and/or economically unrecoverable form. The discussion in the paper by Berger et al. (2020) states that mineral resources are not "lost" for human use when extracted from nature into the technosphere, as long as they can be reused, recycled, or recovered in some way. According to the authors, resources are only "lost" if converted to an "irrecoverable" state.

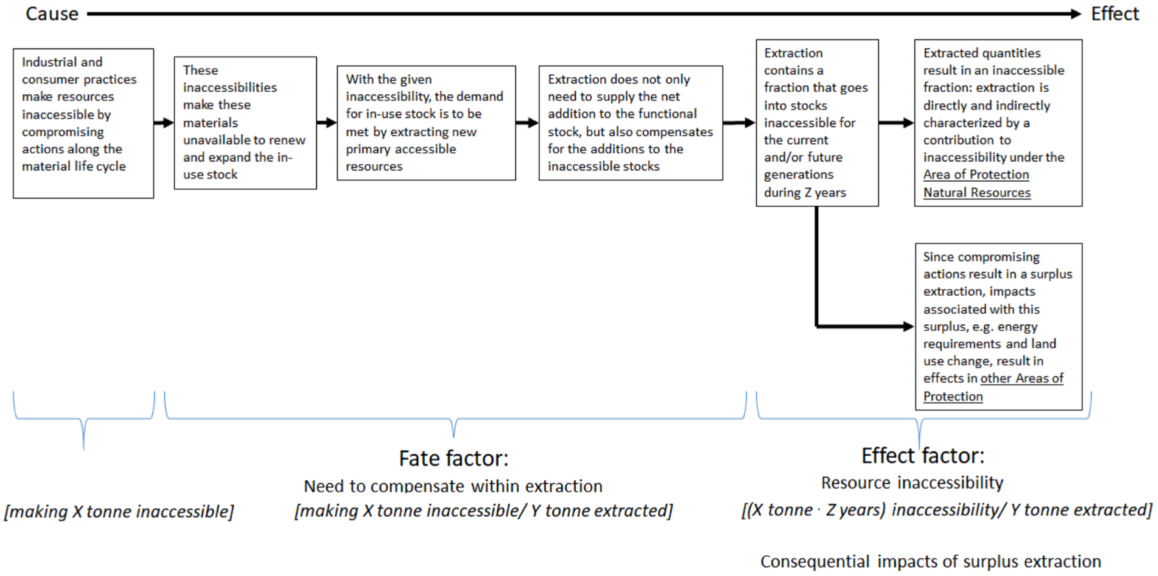

Fig. 3. Cause-and-effect chain analysis, starting with actions that compromise accessibility and ending with impacts on Areas of Protection in a life cycle analysis context

Hence, identification and quantification of "irrecoverable" states or actions that compromise the recoverability or accessibility are exactly the key subject in the current paper and could be an important step forward in improving LCIA methods for mineral resources. It must be clear that this is not straightforward as the compromising actions in Table 1 are flows within the technosphere, except emitting to the environment. Hence, only the quantification of the compromising action dissipation into the environment leads to an immediate potential to model and characterize inaccessibility associated with this elementary flow, i.e. a flow between technosphere and ecosphere. This has been elaborated by van Oers et al. (2020) with the Environmental Dissipation Potential (EDP) as characterisation factor for environmental dissipation of resources.

For the other five compromising actions that are associated with flows within the technosphere, classical LCIA modeling that typically starts from elementary flows is far more challenging. An exercise is presented in Fig. 3:

- The compromising actions affect elementary flows as in consequential life cycle thinking, since compromising actions make resources inaccessible for the demand to renew or expand the functional stock at the user;
- By consequence, the demand has to be met by virgin supply. That means that mining does have to deliver beyond the expansion of the in-use stock as it needs to fuel also the increase of the stocks hoarded, abandoned, landfilled, dissipated into the environment, dissipated into the technosphere, or put into mining wastes such as tailings.
- That means that an elementary flow of resource use, considered to start within the ecosystem where it is appropriated by humans and where it considered as fully accessible, is characterized by a fraction that leads to inaccessibility along its further life cycle. If hypothetically 50% of the mined metal A in the end is going to be deposited in inaccessible stocks along its further fate in the technosphere, which means that 0.50 tonne (X tonne) is made inaccessible per tonne extracted (Y tonne). If for a certain metal A the tonnages that go into inaccessible stocks along the value chain in the technosphere (e.g. 0.50 tonne inaccessible/tonne extracted) are the double compared to a metal B (0.25 tonne inaccessible/tonne extracted), that means that the elementary flow of A is associated with a higher contribution to inaccessibility than B. This higher contribution to inaccessibility for metal A is to be attributed not only because of the mining via tailings, but clearly also because of more compromising actions at the manufacturing, the use and the end-of-life processing due to emissions, landfilling, downcycling, hoarding and abandoning.
- A step further in developing characterization factors may lie in the differentiation of the compromising actions that can be different from one metal to another. Indeed, if the management within society for a metal C leads to the same tonnage made inaccessible as for metal A (both 0.50 tonne inaccessible/tonne extracted), metal C can be less contributing to resource inaccessibility if it has a higher share of hoarding and a lower share of dissipative flows compared to metal A. To aggregate the different degrees of inaccessibility, the estimated duration of inaccessibility (Z years) can be used as a starting point, cf. Fig. 1. If inaccessibility of A is fully due to dissipation into the environment with a duration of 500 years and the inaccessibility of C is fully due to hoarding with an estimated duration of inaccessibility of 2.5 years, that means that the inaccessibility of A is to be characterized as 200 times that of C, i.e. an inaccessibility of (0.50 kg tonne inaccessible x 500 years of inaccessibility)/tonne extracted = 250 tonne.years inaccessibility of metal per tonne extracted of A, versus an inaccessibility of (0.50 kg tonne inaccessible x 2.5 years of inaccessibility)/tonne extracted = 1.25 tonne.years inaccessibility per tonne extracted of metal C. The unit tonne.years represents a certain mass inaccessible (X tonne) for a certain time (Z years). It might not be a unit that is easily graspable intuitively; however it has some similarities with land use characterization in LCA. Therein, land use is typically expressed in terms of m^2.years, reflecting the occupation or accessibility for its owner or user and at the same time quantifying the lack of inaccessibility for other users. Both land occupation and mass occupation/inaccessibility have an interchangeability of time and what is occupied or made inaccessible: yrs and m^2, and yrs and kg, respectively. A time unit is also common for assessing impact on ecosystem services, such as for land use and toxicity, where impacts can be long-term (such as for persistent chemicals) or limited in time in case of short-lived compounds.

Clearly, the reasoning here sets some first proposals on how to characterize resource inaccessibility within an LCA context and its area of protection Natural Resources. Further on, inaccessibility does not only result in extra primary sourcing to be characterized under the area of protection Natural Resources: extra primary sourcing consequently leads also to other effects, e.g. energy needs that can contribute to global

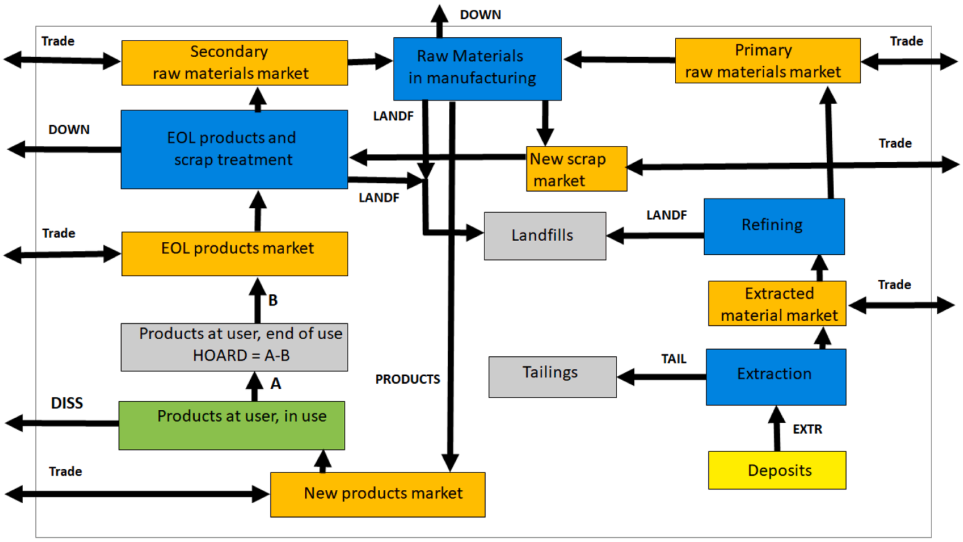

Fig. 4. Flows of cobalt associated with the renewal of and addition to the functional stock at the EU user (Products at user, in use). In order not to overload the Fig., only key flows are labeled: (1) flows that compromise accessibility; (2) the product flow; and (3) trade flows. Identified actions that lead to inaccessibility are environmental dissipation (DISS), hoarding (HOARD), landfilling (LANDF), tailings (TAIL) and dispersion into the technosphere by downcycling (DOWN). For sake of the simplicity of the Fig., the destination of the refinery wastes is landfilling, although in practice they may be stored differently. Similarly, extraction may lead to storage of waste being different from tailings. The system boundary contains the stocks and flows of cobalt within the EU, excluding those dispersed into the environment and the technosphere. Markets are colored in orange, industrial operations in blue, materials in use in green, inaccessible stocks in grey, and natural deposits in yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

warming or land use impacts that can lead to biodiversity impacts, hence impacting other areas of protection; see Fig. 3.

3.3. *The data requirements: what do we have so far?*

In order to understand the magnitude of actions that compromise accessibility, data on the flows of emitting, landfilling, tailing, downcycling, hoarding and abandoning should be available for various abiotic resources like metals. They should be available for the system under study, be it at macro-scale (globally, nationally), meso-scale (sector level) or micro-scale (specific production and consumption chains). To the best of our knowledge, there is no study published that comprises the quantification of the six compromising actions systematically for one system for one abiotic resource such as a specific metal.

However, typically information on tailings, landfilling and emissions is available in material flow analysis, see e.g. Graedel (2019) and Kral et al. (2019). These flows are indeed clearly flowing from one subsystem into another one in Sankey diagrams. Less obvious is downcycling as the ‘flow’ stays within the subsystem of stocks within the technosphere. It is not common practice in MFA to differentiate this dispersed state, as MFA typically targets quantification, usually without specification of concentration, chemical speciation, separability or recoverability that could assist in assessing (in)accessibility. The delineation amongst accessibility and inaccessibility depends on the design, where Ciacci et al. (2015) conceptually differentiates three fractions in products that are theoretically all potentially recyclable: a fraction that is functionally recycled (hence accessibility is continued) next to two fractions that are made inaccessible and hence lost by design: downcycled and currently not recyclable at all. Recently, Helbig et al. (2020) have brought forward dissipation into the technosphere by introducing a subsystem ‘Other Materials’ to point to losses to other materials, e.g. as contaminants in other material cycles. It allowed them to quantify four compromising actions for 18 metals, i.e. emissions, tailings, landfilling and dissipation into the technosphere. Equally challenging in MFAs is hoarding where materials are at the user and where MFA typically does not differentiate amongst in-use and hoarded, despite in-use and hoarded stocks may be in physically separated locations within households. Hoarding is rather studied as a subject on its own, see e.g. Thiébaud et al. (2017a); Thiébaud et al. (2017b); Golev et al. (2016); Polak and Drapalova (2012); Wilson et al. (2017); Zhang et al. (2019) and Glöser-Chaboud et al. (2019).

The quantification of abandoning and the historical build-up of abandoned stocks may be the most challenging. To the best of the knowledge of the authors, studies that systematically address abandoning in function of materials management and its contribution to inaccessibility have not been brought forward. The work of Swedish researchers on copper stocks in power grids in urban environments is a very rare exception (Krook et al., 2011; Krook et al., 2015; Wallsten et al., 2015).

When we look at what compromising actions are addressed by public bodies that deal with resource management, we observe that UNEP points to tailings and environmental dissipation at use in the visualization of metal cycles (UNEP, 2011). The latest UNEP Global Resources Outlook Report (Oberle et al., 2019) touches upon emissions, downcycling and landfilling because of several reasons, mainly from emission and toxicity point of view, not systematically from making or keeping resources accessible. The public body that studies compromising actions most systematically may be the European Commission in function of its Raw Materials Initiative. In this context, Raw Materials System Analysis (MSA) systematically studies flows into tailings and landfills within the EU for dozens of raw materials, see also in the next section.

Apart from MFAs, there is a lot of information at the micro-level in LCA work, in particular within life cycle inventories of thousands of products and processes, see e.g. databases owned by eco-invent (Switzerland) and Thinkstep (Germany). This vast bottom-up information offers quantification possibilities for dissipation into the environment. For the other compromising actions like landfilling and tailings, information is in principle embodied to quantify the flows. But also here, dissipation into the technosphere by downcycling, hoarding and abandoning is not covered.

In summary, there are no studies or databases that quantify the six compromising actions fully. However, there are various sources that cover compromising actions like tailings, landfilling and dissipation into the environment. Equally, information on hoarding is available despite it typically stands separately. Dispersion into the technosphere is less obvious and certainly abandoning is a challenge to quantify.

4. An exploratory case study: cobalt in the EU

In function of the calculation of the criticality of raw materials for the EU, the EC-JRC and Ghent University have made a raw material system analysis (MSA) for cobalt (Matos et al., 2020a). In essence, MSA studies

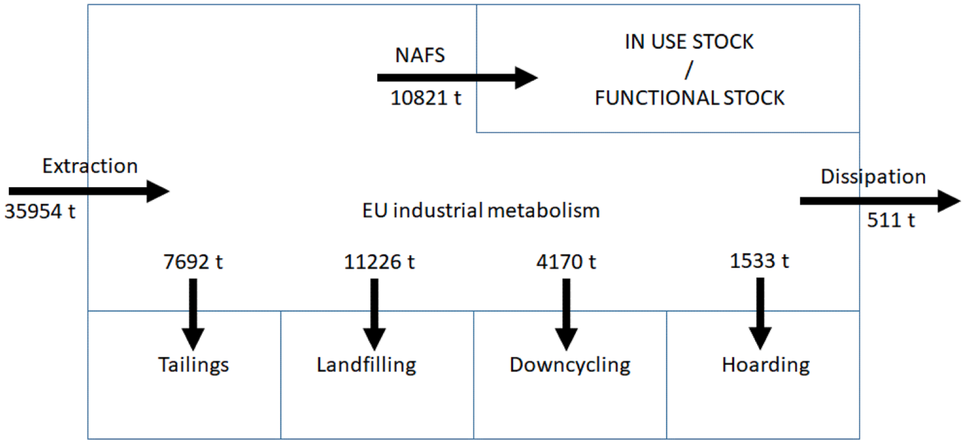

Fig. 5. Quantification of generated inaccessibilities by tailings, landfilling, downcycling, hoarding and dissipation into the environment, in order to renew and expand the functional stock of Cobalt in the EU (2016), and associated extraction quantity to compensate for these inaccessibilities and net addition to the functional stock (NAFS).

apply the basic principles MFA on material systems within the geographical scope of the European Union, or an EU member state. They provide a material flow of a particular raw material in the EU with life cycle stages like extraction, processing, manufacturing, use, collection and recycling; with stocks like tailings, landfills, in-use stocks, and import and export of raw materials, embedded in various commodities, e.g. primary raw materials, processed materials, products, and products at end-of-life. The methodology is generic and is explained by BIO by Deloitte (2015) and in a recent report (Matos et al., 2020b). The MSA methodology and the utilization of it for the case in this paper is further documented in Appendix 2.

For the exploratory case, the EU MSA cobalt study was used as starting point. Cobalt is an important metal in many applications, such as in hard metals, magnets and especially more and more in batteries (Godoy León and Dewulf, 2020). The goal was to quantify the human actions that lead to the generation of inaccessibility of cobalt along the value chain, associated with the renewal of the functional stock at the user in the EU and the net addition to it, for the year 2016. The MSA has been reworked in two stages. In a first stage, the MSA flow scheme has been reconFig.d. One first reconfiguration concerns the markets: the raw materials market has been split into a primary and a secondary raw materials market and the market in between manufacturing and use has been split into new products market and a new scrap (i.e. scrap from manufacturing) market, while the extracted materials market and end-of-life products market have been kept. Secondly, the stock at user has been split into a stock of products at user, in use, and a stock at user, end-of-use. Next, for the processes of the primary supply, extraction has been kept but the refining processes have been separated from operations that process end-of-life products and scrap. For the operations related to secondary materials, collection has been merged with recycling into end-of-life products and scrap treatment. This leads to the scheme represented in Fig. 4, which allows highlighting flows that lead to inaccessibility because of processes within the EU, with a clear separation of operations of the primary and secondary raw materials generation, next to the trade from and to the non-EU at the respective markets. By doing so, all compromising actions of Table 1 are captured, except abandoning; this latter one is presumed to be of minor importance in case of cobalt based on the understanding of its applications (Godoy León and Dewulf, 2020).

From the analysis and available data, the main activities that lead to inaccessibility have been identified and quantified (see Appendix 2). With respect to the dissipation into the environment (DISS), dissipation at the user is key, dissipation at the other stages is in comparison considered negligible. Known dissipation pathways at user are at industrial applications in catalysts and hard metals. Dispersion into the technosphere stems mainly from downcycling (DOWN), occurring at end-of-life treatment and at manufacturing. Equally, the cobalt MSA study allows an estimation of the hoarding (HOARD = A-B): the net increase of cobalt embedded in end-of-life products stored at the user. Further on, landfilling (LANDF) by end-of-life treatment, manufacturing and refining operations and the production of tailings (TAIL) by extraction operations can be assessed.

In a second stage, the compromising actions associated with the renewal of and net addition to the functional stock at the EU user, which take place outside the EU through net imports have to be factored in. This can be done by mirroring the processes within the EU. Indeed, in the end the renewal of and the addition to the functional stock within the EU relies on materials extracted within the EU and on imported extracted materials, both with their associated actions that lead to inaccessibility. In this way, inaccessibilities taking place within and outside the EU that are associated with the processing of the EU end-of-use stock have been calculated.

Overall, based on the law of conservation of mass, extraction (EXTR) provides the net addition to the functional stock (NAFS) and to inaccessible stocks (INACCESS), i.e. at tailings (TAIL), landfilling (LANDF), dissipated in the environment by emissions (DISS), dispersed in the technosphere by downcycling (DOWN), and hoarded by the user (HOARD):

$$\mathrm{EXTR} = \mathrm{INACCESS} + \mathrm{NAFSINACCESS} = \mathrm{TAIL} + \mathrm{LANDF} + \mathrm{DOWN} \\ + \mathrm{DISS} + \mathrm{HOARD}$$

The results of the calculations are presented in Fig. 5. The scheme indicates that 30% of the extracted materials are net-added to the functional stock, whereas 70% are compensating additions to inaccessible stocks due to tailings (21.3%), landfilling (31.2%), downcycling (11.6%), dissipation (1.4%) and hoarding (4.3%).

When the results are compared to the simplified Sankey diagram of the corresponding MSA study, first the reader should be aware that the system under study is different, in the sense that Fig. 5 represents all flows, within and outside the EU, that are associated with operations that lead to net addition of the in use stock within the EU. This is different from the MSA studies that look to the geographical entity where processes within the EU are studied, whether the final use is in the EU or abroad via trade. Fig. 5 highlights the limited fraction that is extracted worldwide and that goes into the EU in-use stock, as there are important associated additions to inaccessible stocks both within and outside the EU at landfills and tailings, downcycling and hoarding.

The results are remarkable in the sense that the society as a whole does not benefit from more than two thirds of the extracted cobalt due to actions that make it inaccessible. Hence, there seems to be huge

Table 3

Estimations of contributions to inaccessibilities to cobalt due to compromising actions associated with the renewal and extension of the functional stock in the EU in 2016, expressed in ktonne, ktonne.years (for minimum, best estimate and maximum according to Fig. 1) and % contribution to ktonne.years (for minimum and best estimate according to Fig. 1; at maximum it is undefined given the infinite ktonne.years for both dispersed stocks).

	ktonne	ktonne.years (min)	ktonne.years (best est.)	ktonne.years (max)	%contribution (min)	%contribution (best est.)
Hoarding	1.5	0	4	8	0	0
Tailings	7.7	192	500	3846	7	14
Landfills	11.2	281	730	5613	10	20
Dispersed stock in the technosphere	4.2	2085	2085	∞	74	58
Dispersed stock in the environment	0.5	256	253	∞	9	7
Total	25.1	2814	3574	11807	100	100

Table A2.1

List of material flows and stocks parameters related to the MSA.

Material Flow/Stock Parameter
A.1.1 Reserves in EU
A.1.2 Reserves in ROW
B.1.1 Production of primary material as main product in EU
B.1.2 Production of primary material as by product in EU
B.1.3 Exports from EU of primary material
B.1.4 Extraction waste disposed in situ/tailings in EU
B.1.5 Stock in tailings in EU
M.1.1 Material send to processing in the EU
M.1.2 Primary material send to manufacturing
C.1.1 Production of processed material in EU
C.1.2 Exports from EU of processed material
C.1.3 Imports to EU of primary material
C.1.4 Imports to EU of secondary material
C.1.5 Processing waste in EU sent for disposal in EU
C.1.6 Exports from EU of processing waste
C.1.7 Output from the value chain
C.1.8 Imports of semi-processed material send to processing in the EU
M.2.1 Processed material send to manufacturing
D.1.1 Production of manufactured products in EU
D.1.2 Exports from EU of manufactured products
D.1.3 Imports to EU of processed material send to manufacturing
D.1.4 Manufacture waste in EU sent for disposal in EU
D.1.5 Manufacture waste in EU sent for reprocessing in EU
D.1.6 Exports from EU of manufacture waste
D.1.7 Output from the value chain
D.1.8 Imports to EU of products requiring further manufacturing steps in the EU
D.1.9 Imports of secondary material send to manufacturing in the EU
M.3.1 Manufactured products send to use in the EU
E.1.1 Stock of manufactured products in use in EU
E.1.2 Stock of manufactured products at end-of-life that are kept by users in EU
E.1.3 Exports from EU of manufactured products for reuse
E.1.4 Imports to EU of manufactured products
E.1.5 In use dissipation in EU
E.1.6 Products at end-of-life collected for treatment in EU
E.1.7 Annual addition to in-use stock of manufactured products in EU
E.1.8 Annual addition to end-of-life stock of manufactured products at end-of-life that are kept by users in EU
M.4.1 Products at end-of-life in EU collected for treatment
F.1.1 Exports from EU of manufactured products at end of life
F.1.2 Imports to EU of manufactured products at end of life
F.1.3 Manufactured products at end-of-life in EU sent for disposal in EU
F.1.4 Manufactured products at end-of-life in EU sent for recycling in EU
F.1.5 Stock in landfill in EU
F.1.6 Annual addition to stock in landfill in EU
G.1.1 Production of secondary material from post-consumer functional recycling in EU sent to processing in EU
G.1.2 Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU
G.1.3 Exports from EU of secondary material from post-consumer recycling
G.1.4 Production of secondary material from post-consumer non-functional recycling
G.1.5 Recycling waste in EU sent for disposal in EU

potential for improvement through research and innovation, as well as through policy and legal instruments. For the EU for instance, reduction of inaccessibility due to landfilling, the biggest contribution with 44.7%, could take advantage of economic instruments to reduce landfilling, as for example proposed in Waste Framework Directive 2018/851 or by setting more ambitious collection targets of cobalt-rich equipment, for example in WEEE Directive 2012/19/EU. Apart from setting collection targets, behavorial change at the sorting by households and better pretreatment after collection could lead to improvements for WEEE with small items like cobalt-rich batteries (e.g. mobile phones, portable media player, etc.) (De Meester et al., 2019). Further on, policies that offer better techno-economic conditions that lead to higher extraction efficiencies and less tailings (30.6% contribution) could be put forward. More high-quality recycling instead of downcycling (16.6%) could be ensured by setting specific high quality recycling targets for certain raw materials contained in specific products; such targets are currently under discussion for the revision of various EU policies such as the Waste Battery Directive and the End-of-life vehicles Directive.

The energy and mobility transition could take advantage of the mitigation of raw materials inaccessibility with cobalt as a key example, enabling socio-economic benefits in line with the 2030 UN Sustainable Development Goals. Equally, if inaccessibilities could be reduced, mining would need only to deliver the net addition to the functional stock, which would mean a reduction of the activities and associated impacts by about a factor of three. As we learn from the Global Resources Report (Oberle et al., 2019) where extraction processes contribute 50% to the global carbon emissions and even 80% to biodiversity losses, reduction of human activities leading to inaccessibilities are a key but hidden mechanism to be tackled in function of sustainable development.

From the section above on estimating the duration, we may differentiate amongst the compromising actions because of their difference in degree of inaccessibility. Based on the minimum and maximum and best estimate of the duration of the different actions, we obtained the contribution of them in terms of tonne.years they make cobalt inaccessible. These numbers allows the calculation of the contributions of the compromising actions in percentages. The results are summarized in Table 3.

When estimated durations are taken at minimum and best estimate, the contribution of hoarding and emissions into the environment have a minor contribution, i.e. below 1 and 10% respectively. Far more contributing are tailings, landfills and dispersion into the technosphere by downcycling: they make up at least 90% of the generated inaccessibilities. Amongst these, downcycling is dominating based on the minimum and best estimate of the duration.

Analysing from an elementary flow point of view as in LCA, the results show that there is an elementary flow of 35.9 ktonne of cobalt associated with the renewal and extension of the in-use stock in the EU in 2016, i.e. 10.8 ktonne net-added to the functional stock but 25.1 ktonne flowing into inaccessible stocks. The compromising actions make that the technosphere as a whole generate an inaccessibility of 3754 ktonne.years, based on the best estimate. This means that about 100 tonne.years inaccessibility is generated per tonne cobalt extracted. This may be a base in LCA to characterize the inaccessibility generated within the technosphere in function of the quantities extracted from the environment. This can be used as an indicator for the AoP Protection of Natural Resources.

5. Conclusions

With respect to their sustainable management, the concepts of "running out" or "depleting" metals and minerals are not anymore so common and dogmatic as they used to be in the past: there is a growing understanding that they do not vanish by human activities. Rather, their accessibility and the continuation of their accessibility are emerging issues, especially with regards to the growing needs, including those for the energy and mobility transition. Recent work in this context mainly pointed to dissipation as important human phenomenon that compromises the accessibility. The current work has brought forward a fairly comprehensive set of six human compromising actions: emitting, landfilling, tailing, downcycling/dispersing into the technosphere, hoarding and abandoning. It became equally clear that the associated inaccessibilities and degrees of inaccessibility are different. As there is no science or technology to measure and quantify the degree of inaccessibility thoroughly, a proxy was identified. This work made an estimate of the duration of the inaccessibility, sometimes based on quite reliable information, e.g. for hoarding, but in many cases on estimates with high uncertainty.

The work has also shown that the aforementioned compromising actions are not systematically considered in sustainable resource management at public bodies nor in the sustainability assessment toolbox. Nevertheless, it is obvious that current tools like MFA and to some extent LCA may be a good base to address resource (in)accessibility, although some further development is certainly needed. At public management, it turns out that the European Commission with its MSA studies has a good ground to address resource accessibility. The cobalt case study took advantage from the corresponding MSA study and allowed a quantification of five out of the six flows that impact accessibility of cobalt as a result of use within the EU.

Further on, the concept of accessibility and the identification and quantification of actions that compromise the accessibility may offer new potential for a better sustainable management of metals. Rather than measuring how much we keep in the loop by means of dedicated circular economy indicators, the current approach points to opportunities to do better by reducing compromising actions. The six actions identified demonstrate that the improvement of accessibility may require a multitude of actions across the value chain and along the full life cycle of materials: at the primary production, at the manufacturing, at the use and at the end-of-life management.

Finally, the elaboration of the concept with the EU cobalt case study can be seen as an eye-opener: 70% of extracted cobalt ends in inaccessible stocks. In other words, inaccessibility can lead to about a tripling of the environmental impact and costs associated with the virgin supply chain (see the cobalt case study), as this supply chain has to compensate for the generated inaccessibilities. Not only the generated inaccessibility is remarkable, but the associated surplus extraction of primary stocks to meet the continued growing demands brings economic, environmental and social consequences with it.

Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission.

Credit author statement

We prefer to not outline the single contribution of each author.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Terminologies: list of key terms in function of the development of the inaccessibility concept

Term	Definition	Reference
Abandoned Stock	Stock no longer functional, no longer at user or left in situ in case of infrastructure	Own definition
Abandoning	Leaving the material, usually for ever	Own definiton; contextualized from Cambridge dictionary
Accessibility	Ability to make use of a resource	Schulze et al. 2020a
Availability	Physical presence of a resource	Schulze et al. 2020a
Compromising action	Actions which lead to a problem	Schulze et al. 2020a
Concentrated	Present with a relatively high mass fraction	Own definition
Confined	Present within a relatively low area/volume; kept in a closed place	Own definition; contextualized from Cambridge dictionary
Dispersed Stock	Stock that underwent dispersion, i.e. stock in low concentration spread over larger areas/volumes	Own definition
Dispersed	Spread into relatively large area/volume	Own definition
Dispersion	Spreading of mass from areas/volumes of high to low concentration (Dispersive mass transfer, in fluid dynamics)	Wikipedia (https://en.wikipedia.org/wiki/Dispersive_mass_transfer)
Dissipation	Result of an irreversible process, here equivalent to dispersion: spreading of mass from areas/volumes of high to low concentration	Wikipedia (https://en.wikipedia.org/wiki/Dissipation)
Downcycling	Recycling of waste where the recycled material is of lower quality and functionality than the original material	Wikipedia (https://en.wikipedia.org/wiki/Downcycling)
Emitting	Transfer of mass from technosphere to ecosphere	Own definition, in line with LCA methodology
Flow	Mass flow rate	Brunner P.H. and Rechberger H. Handbook of Material Flow Analysis, 2nd Ed. CRC Press 2016.
Functional Stock	Stock that is fulfilling its designated function at the user, as part of a product-service system	Own definition
Hibernation	State of being asleep	Cambridge dictionary
Hoarded Stock	Materials at the user that are not part anymore of the functional stock	Own definition; contextualized from Cambridge dictionary
Hoarding	Keeping materials at the user that are not part anymore of the functional stock	Own definition; contextualized from Cambridge dictionary

(continued on next page)

(*continued*)

Inaccessibility	Lack of ability to make use of a resource	Schulze et al. 2020a
Landfilling	Getting rid of materials by buryiing	Own definition; contextualized from Cambridge dictionary
Landfills	Process of getting rid of materials by burying	Own definition; contextualized from Cambridge dictionary
Net Addition to Functional Stock	Flow of material into the functional stock	Own definition
Stock	The total amount of materials stored in a process	Brunner P.H. and Rechberger H. Handbook of Material Flow Analysis, 2nd Ed. CRC Press 2016.
Tailings	Materials left over after the process of separating the valuable fraction from the uneconomic fraction (gangue) of an ore	Wikipedia (https://en.wikipedia.org/wiki/Tailings)
Waste rock	Bedrock that has been mined and transported out of the pit but does (usually) not have metal concentrations of economic interest	Aquila Resources (http://backfortymine.com/)

Appendix 2. Background information on the MSA methodology and its utilization for the case study

A2.1. *Background information on the MSA methodology*

The reader is refered to the EC –JRC report on the material system analyses (MSA) specifications (EC, 2020c). In below, the general MSA scheme is presented in Fig. A2.1. The involved stocks and flows parameters are listed in Table A2.1.

A2.2. *Development of the calculation of the inaccessible stocks for the cobalt case study starting from the MSA*

A2.2.1. *Calculation of extracted materials and inaccessibilities of the primary supply chain of the stock within the EU*

The input to the stock in use is M3. Extracted materials and inaccessibilities stem from D1.1 within EU, but globally, this should be corrected with a factor M3/D1.1. However, as the EU is exporter of secondary raw materials for manufacturing, the global supply from primary origin is to be reduced; see further. This means that the factor becomes M3/(D1.1-fsec) = Fprod. This means that the global M2’ = M2 . Fprod and that

M2’ primary = M2primary . Fprod
D1.11’ = D1.11 . Fprod
D1.4’= D1.4 . Fprod
D1.5’=D1.5 . Fprod

M2(globally primary) comes from the market and is not only supplied from EU refining. This means that globally the amount of material refined material has to account for both the trade in the refining and manufacturing stages, and has to be recalculated by the factor Fprod.((D1.3-C1.2)+C1.1)/C1.1= Fprod.Fref. Hence the global flows C1.1’, C1.5prim’, C1.6prim’ and M1’ equals:

C1.1’= Fref. Fprod. C1.1
C1.5prim’= Fref. Fprod. C1.5prim
C1.6prim’= Fref. Fprod. C1.6prim
M1’= Fref. Fprod. M1

M1’ (M1) does not only rely on B1.2’ (B1.2) because of import of extracted materials. This means that globally the amount of extracted material needed has to account for the trade in the extraction, refining and manufacturing stages. This means that the flows of the extraction processes at global scale are a factor Fprod.Fref.(((C1.8+C1.3)-B1.3)+B1.2)/B1.2 = Fprod.Fref.Fex compared to the respective EU flows. Hence:

B1.2”= Fprod . Fex . B1.2’ = Fprod.Fex.Fref. B1.2
B1.4”= Fprod.Fex . B1.4’ = Fprod.Fex.Fref. B1.4
Global extraction = EXTR” = B1.2”+B1.4”= Fprod . Fex . (B1.2’+B1.4’) = Fpro.Fex.Fref. (B1.2+B1.4)

A2.2.2. *Inaccessibilities associated with the secondary value chain*

The functional stock within the EU leads to a net flow for EOL processing E1.6. However, the EOL processing within the EU also handles a net import F1.2+C1.4-F1.1 and a new scrap D1.5’. This latter one is negligible. This means that the inaccessibilities and delivered secondary raw materials

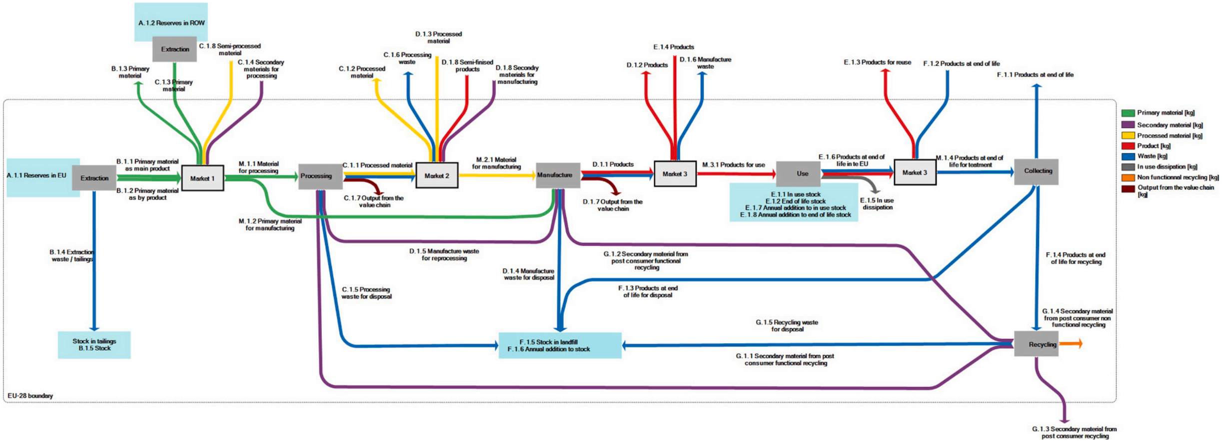

Fig. A2.1. General MSA flow scheme of a raw material in the EU.

from own use need to be corrected by a factor Feol = ((E1.6 + ((F1.2+C1.4)-F1.1) / E1.6:

M4' = M4 / Feol
G1.4' = G1.4 / Feol
G1.5' = G1.5 / Feol
C1.5sec' = C1.5sec / Feol
C1.6sec' = C1.6sec / Feol
F1.3' = F1.3 / Feol
G1.1' = G1.1 / Feol
G1.2' = G1.2 / Feol
G1.3' = G1.3 / Feol

The delivered secondary raw materials by the EU EOL processing, stemming from used products in the EU, G1.1'+G1.2'+G1.3', go to the secondary raw materials market where there is a net export C1.2-D1.9. Hence the flow to manufacturing from secondary origin from products used in the EU is higher than M2 secondary, i.e. a factor M2/ (M2+(C1.2-D1.9)). This means that the contributions to the EU manufacturing M2 increases by 15%, hence the virtual import ratio M3/D1.1 drops to M3/(D1.1-fsec) = M3/D1.1'.

A2.2.3. Inaccessibilities at the user: hoarding

In the elaboration of the MSA's, estimates were made on additions to end-of-life stock at user, i.e. hoarding. From the results with hoardings at different applications, a total of 1533 tonnes has been estimated.

From the final MSA, the Net Addition to the Stock (NAS) with user equals M3 - (E1.6+E1.5) = 12354 t. As we learn from the estimates that 1533 t are no longer function, it means that the Net Addition to the Functional Stock (NAFS) = 12354 – 1533 = 10 821 t. This means 87.6% functional and 12.4% non-functional at the user.

As the total stock at use E1.1 equals 334 134 t and if we assume a same ratio functional stock (FS) to total stock as NAFS/NAS of 0.876, this means a total FS of 292 701 t, next to 41 433 non-functional. This means an increase of both 3.7% in one year.

A2.2.4. Overall quantification of inaccessibilities

After implementation of the calculations, it can be calculated how much extraction is needed and how much inaccessibilities are generated, associated with the renewal and extension of the functional stock.

Extraction = EXTR = B1.2''+B1.4''= Fprod. Fex . (B1.2'+B1.4') = Fprod. Fex.Fref. (B1.2+B1.4)
Tailings:
TAIL = B1.4''= Fprod. Fex . B1.4' = Fex.Fref. B1.4
Landfilling:
From refining: C1.6'prim + C1.5'prim
From manufacturing: D1.4'
From EOL treatment: G1.5' + C1.6'sec + C1.5'sec + F1.3'
Hence:
LANDF = C1.6'prim + C1.5'prim + D1.4' + G1.5' + C1.6'sec + C1.5'sec + F1.3'
Downcycling:
At manufacturing: D1.11'
At EOL processing: G1.4'
Hence:
DOWN = D1.11' + G1.4'
Dissipative use:
DISS = E1.5
Hoarding:
HOARD = 1533 t; see above.

Overall, it means that extraction does not only provide the net addition to the functional stock, but equally compensates for generated inaccessibilities by tailings, landfilling, downcycling, environmental dissipation and hoarding:

INACCESS = TAIL + LANDF + DOWN + DISS + HOARD
EXTR = INACCESS + NAFS

A2.2.5. Final calculation

The abovementioned procedure has been implemented. A doublecheck of the global extraction between a calculation based on the modified MSA and with the overall mass balance EXTR = INACCESS + NAFS shows a gap less than 7%.

Final adjustment leads to the following scheme: 30% of the extracted materials are used to expand and renew the functional stock, and where 70% are compensating inaccessibility due to tailings (21.3%), landfilling (31.2%), downcycling (11.6%), dissipation (1.4%) and hoarding (4.3%).

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