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Contribution to inaccessibility as resource impact method: A base for sustainable resource management along the life cycle

J. Dewulf[a,b,*], A. Beylot[a], D. Monfort[a], F. Lai[a], J.Santillan Saldivar[a], Stéphanie Muller[a], F. Mathieux[c]

[a] BRGM, F-45060 Orléans, France
[b] Research Group Sustainable Systems Engineering (STEN), Department of Green Chemistry and Technology, Ghent University, Coupure Links 653, 9000 Ghent, Belgium
[c] Joint Research Centre, European Commission, Via Enrico Fermi 2749, 21027, Ispra, VA, Italy

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ABSTRACT

The goal of this paper is to present and demonstrate a proof of concept for a novel method that quantifies the impact of human activities that compromise the accessibility to the instrumental value of resources. It identifies ten key matrices along six life cycle stages. Starting from Time To Accessibility as a base, accessibility factors for resources are developed in function of the embedding matrix, scaled in between 0 and 1. The method provides value-based characterization factors for 45 resources as a Contribution To Inaccessibility - Life Cycle Impact Assessment (CTI-LCIA) method and involves price to capture the value. It points to hotspots along the life cycle (e.g. inaccessibility generation by storing in landfills and tailings deposits), the importance of process efficiencies, and the value of circular economy strategies. The latter is illustrated with a case study on four resources in a battery case study.

1. Introduction

In an era where the international community strives for sustainable production and consumption, being the Sustainable Development Goal number 12 of the ambition of the United Nations for 2030, sustainable management of natural resources is more than ever at stake. The issue of access to natural resources with a growing population is anticipated to become more and more crucial, especially regarding metal ores as these are the cradle of many recent technological developments, regarding the energy transition in particular since the UN Paris Agreement in 2015. Various international initiatives can be mentioned, e.g. the Green Deal in 2020 and the revision of the Renewable Energy Directive in 2021 in the EU, the Renewable Energy Act in 2021 and the measures under the Inflation Reduction Act in 2022 in the USA, and the 14th Renewable Energy Development five-year plan (2021–2025) in 2021 in China. The expected growth in demand of resources key in the renewable energy sector is impressive, e.g. the OECD anticipates a global metal demand of 20Gt in 2026, which is about 2.5 times the demand in 2011. When it comes to specific resources that are essential in batteries, an important technology in the transition, the expected growth is even higher with a growth by a factor of 5 and 25 by 2050 for cobalt and lithium in the EU, respectively (EC-JRC, 2020).

The Global Resources Outlook report (Oberle et al., 2019) shows that the first life cycle stages, so-called primary production with extraction and refining that transform natural resources into commodities, is a major contributor to global environmental impacts. As resources like metals are not really consumed but rather used, they have the potential to stay as metals within the further stages along the life cycle in the technosphere, whether they are commodities, manufactured into components, manufactured into new products, or in products at end-of-life (EOL). Hence it is vital that society maximizes the benefits of the extracted resources by keeping them as useful as possible and as long as possible. It is of no surprise that Circular Economy policies, e.g. the EU Action plan for the Circular Economy, have an important role to maintain the instrumental value of products, materials and resources within the economy, for as long as possible (EC, 2015). The instrumental value relates to their utility to humans (Sonderegger et al., 2017). Charpentier-Poncelet et al. (2022a) introduced an additional nuance to the notion of resources instrumental value by distinguishing the exchange value (i.e., the economic value in the technosphere) from the use value, both being part of the instrumental value of resources. Methods and tools that support a sustainable management of resources along the life

* Corresponding author.
E-mail address: jo.dewulf@ugent.be (J. Dewulf).

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cycle are indispensable in the current era.

Within environmental sustainability assessment methods, with Life Cycle Assessment (LCA) as one of the most advanced examples, it appears that the maturity to assess the impact on resources by human activities is not yet mature and not agreed upon. That is obvious from the UNEP SETAC task force work on recommendations of methods applicable to abiotic natural resources (Berger et al., 2020). Berger et al. (2020) refer to the exercise of the SUPRIM project on what now is the precise problem with resources (Schulze et al., 2020). The majority of the stakeholders appears to be mainly concerned about the instrumental value of resources for humans, with the technosphere as the main system of concern where resources should be kept available and where both primary and secondary supply chains are relevant. This clearly demonstrates that a classical cause-effect mechanism with the environment as key compartment is questionable when it comes to resources. Resources do not have only environmental but also economic relevance and are hence a so-called Area of Protection that cannot be solely situated in the environmental pillar of sustainability (Dewulf et al., 2015; Hackenhaar et al., 2023). The UNEP SETAC Life Cycle Initiative concluded that the instrumental value is central: the safeguard subject for "mineral resources" as defined by the Task Force "Mineral Resources" of the UNEP-SETAC Life Cycle Initiative is "the potential to make use of the value that mineral resources can hold for humans in the technosphere" (Berger et al., 2020).

The impact on resources in LCA has been characterized for more than 20 years by 'depletion' in the natural environment since the ADP method (Abiotic Depletion Potential) (Guinée and Heijungs, 1995). There is recently a new boost in developing resource impact methods. This new generation of methods addresses the loss of instrumental value of resources, requiring other flows to build upon impact methods. In the EDP method (van Oers et al., 2020), the environmental dissipation method, the loss of resources by emitting them into the environment is the cause to model impact on resources. Insights have grown that not only emissions to the environment but also transfers to certain stocks within the technosphere, i.e. to 'final sinks', deteriorate the instrumental value. Dewulf et al. (2021) elaborated the accessibility concept for resources, pointing to six human activities that compromise the accessibility of resources towards their instrumental value. Next to emitting, transfers of resources in wastes to landfills or downcycling of resources in by-products contribute negatively to resource accessibility. For the latter ones, the associated flows take place within the technosphere itself (technosphere flows) and challenge the LCA community where the inventory of flows (LCI: life cycle inventory) is mainly well established for elementary flows and not systematically 'designed' to develop impact models relying on technosphere flows. Nevertheless, recently a few attempts have been published to develop resource impact methods that capture transfers within the technosphere that compromise the accessibility of resources, like the JRC-LCI method (Beylot et al., 2020a, 2021), the JRC-LCI-BRGM method (Lai and Beylot, 2023) and the ADR/LPST method (Charpentier Poncelet et al., 2022b). Greffe et al. (2023) presented an instrumental value-based framework for assessing the damages of abiotic resources use. A learning from the recent methodological papers on resource impact is that the operationalization of the new generation of resource impact methods with current LCA software and associated LCI is challenging. Capturing systematically technosphere flows in function of resource impact should be enabled with inventories that systematically check resource flows with resource (or substance) flow analysis. Lai and Beylot (2023) concluded that full operationalization of their method depends on adequate mass-balanced LCI data inventories.

In the new generation of resource impact methods, the concept of decreasing accessibility is frequently formulated under the term 'resource dissipation'. Beylot et al. (2020b) stated that 'dissipative flows of abiotic resources are flows to sinks or stocks that are not accessible to future users due to different constraints'. The terminology can be debated as human activities that lead to resource inaccessibility do not have all the same degree of dissipation and hence do not exhibit the same level of irreversibility (definition of dissipation holds an irreversible character, according to Dewulf et al., 2021). The methods anyway are clearly on the right path with respect to impact on resources as they indeed cover human activities that compromise the instrumental value. Nevertheless, they are not yet the final answer. First of all, the methodologies are 'black and white' or 'on/off'. They do not discriminate between different degrees of resource inaccessibility contributions. The work of Dewulf et al. (2021) has made clear that some flows that compromise accessibility ("on") are more irreversible than others, e.g. flows to the environment versus flows to the hoarded stock. In that paper, the years of inaccessibility induced by the transfer has been proposed as a proxy indicator for the level of resource inaccessibility. Second and more fundamentally, there are clearly human activities that do not compromise the accessibility to the instrumental value but do even the opposite. For example, the instrumental value of a metal commodity, ready for manufacturing, is higher than within its initial ore body before extraction and refining. So these primary production life cycle stages can in principle be rather beneficial. The fact that processes create not only burdens or 'footprints', but also benefits or 'handprints', urges the sustainability assessment community to better quantify the positives of processes, beyond the typical 'functional unit' (Alvarenga et al., 2020).

Resources and the preservation of the access to its instrumental value have been considered in other contexts than primary production and life cycle assessment, for example with EOL processes in the context of a circular economy. There are various recovery strategies (R-strategies like recycling) that are intended to keep the accessibility of resources within the economy. Different recycling technologies can keep the resources in the economy but at different levels of quality or accessibility (Tonini et al., 2022). Tonini et al. (2022) argue that quality depends on technical characteristics of the recyclate, which results in a certain degree of virgin resource substitution. The term quality is used in a specific (technological) context, describing the features for a specific application, typically the application in the life cycle stage itself or in a subsequent one. In a more holistic view on sustainable resource management, one should look on effects on accessibility of resources not only at one particular life cycle stage such as EOL, but consider it systematically and more universally throughout the full life cycle. To the best of the authors' knowledge, there is not a methodology that captures resource accessibility or (universal) quality throughout a complete life cycle, although that would be a key asset in sustainable resource management.

The goal of this paper is to present and demonstrate a concept and a method that enable a better handling of resources, in particular mineral resources like metals, in sustainability assessment methods like LCA, starting from the recognition that the central role of resources is its instrumental value at the user. It proposes to quantify human actions in the life cycle of products that increase or decrease the access to the instrumental value of resources as resource impact. It develops a resource impact method based on the contribution to decreased or increased access to the instrumental value of resources or in short 'contribution to resource inaccessibility' or 'Contribution To Inaccessibility' (CTI) induced by a life cycle stage. To this goal, a stepwise elaboration is made. First, it builds the life cycle inventory in function of the goal, relying on a detailed resource flow analysis along a staged life cycle, with identification of key matrices in which resources are embedded. This base serves to model the impact of a certain life cycle stage in terms of an increase or decrease of resource accessibility (Section 2.1). Second, to enable the quantification of accessibility, accessibility factors of resources in key matrices is developed (Section 2.2). Third, it proposes a Life Cycle Impact Assessment method by quantifying the Contribution To Inaccessibility of all life cycle stages for multiple resources (Section 3). Finally, a demonstration of the methodology for batteries as case study is presented (Section 4). The paper ends with some discussion and future perspectives (Sections 5 and 6).

Important to mention is what is covered in this paper under 'resources'. Essentially, this paper intends to cover resources like metals and minerals that we derive from mineral resources, i.e. non-renewable resources with a stock character (Sonderegger et al., 2017). The life cycle of these resources starts with the extraction of these resources as 'natural resources' embedded in ore bodies as matrix. After extraction, resources are found in man-made matrices, such as commodities. They may leave the life cycle e.g. towards tailings deposits or towards the environment through emissions. This paper understands 'resources' not only in their natural form (natural resource in an ore body) but also in various man-made matrices, such as commodities or EOL products, and in poorly accessible stocks such as tailings and dispersed in the environment, albeit that their accessibility level is substantially different. This way, the understanding is in line with Berger et al. (2020) who included both primary and secondary resources under the area of protection 'Natural Resources', as all of them originate from nature. In the Supplementary Information (SI1), a set of definitions is presented for sake of a good understanding.

2. Contribution to inaccessibility of a resource by a life cycle stage

The development in this paper starts from the key problem with resources as identified in the SUPRIM project: human actions that compromise (or de-compromise) accessibility (Schulze et al., 2020). Resources are exploited for their instrumental value (Berger et al., 2020). Bringing in this latter insight, 'accessibility' put forward by the SUPRIM project can somehow be better specified, in the sense that it points to the 'accessibility to the instrumental value of resources'. In below, this will be named shorter as 'accessibility of resources' or simply 'accessibility'.

In a life cycle perspective, all processes or life cycle stages contain human actions that need to be evaluated in this context. A generic resource flow analysis with consistent mass balances is a solid starting point. The quantities of a resource entering and leaving a life cycle stage are the same but they enter and leave in different configurations or matrices (e.g. ore, product, emissions …), which may have different degrees of accessibility. Hence, depending on the change in configuration or matrix induced by the life cycle stage, i.e. outputs versus inputs, the life cycle stage can compromise (or increase) the accessibility. So based on the resource flow analysis per life cycle stage (essentially the LCI in LCA) in Section 2.1, the method to quantify the contribution to inaccessibility is built in Section 2.2 through the introduction of accessibility factors.

2.1. Contribution to inaccessibility of a life cycle stage relying on a detailed resource flow analysis

Along the life cycle, resources appear in different matrices, i.e. from ore body to EOL products, depicted in Fig. 1 in a generic staged way. In essence, life cycle stages alter the matrix in which a resource is embedded, e.g. extraction changes the embedding matrix "ore" into "concentrate" or "tailings". The idea of distinguishing resources in matrices is typically practiced in material flow analysis. It is essentially the matrix that facilitates or complicates the (further) exploitation of the instrumental value of the resource for the user: "concentrate" as matrix facilitates whereas "tailings" as matrix complicates it vis-à-vis "ore". In this context, the analysis represented in Fig. 1 points to ten relevant matrices along the life cycle. The ten matrices bring sufficient granularity to discriminate the exploitation of the instrumental value, while keeping it generic along the life cycle. The first set of processes, being the (primary) raw material acquisition and pre-processing (Zampori and Pant, 2019), is represented by two main stages: extraction and refining, resulting in resources in the form of tradeable commodities. It is supposed here that a natural deposit/ore becomes accessible once a mine is opened. Preceding steps such as geological exploration and mining feasibility steps are not integrated here. It is globally assumed that mining projects after a successful exploration phase take around 15 years (CSMO Mines, 2023). The manufacturing stage is split into two stages, component and product manufacturing. The delivered products, being products at beginning of use (BOU), are supplied to the use stage, where they leave later on as product at end of use (EOU) towards the EOL cycle stage. Implicitly, transport and distribution take place along the full value chain. Resources may leave the life cycle at various life

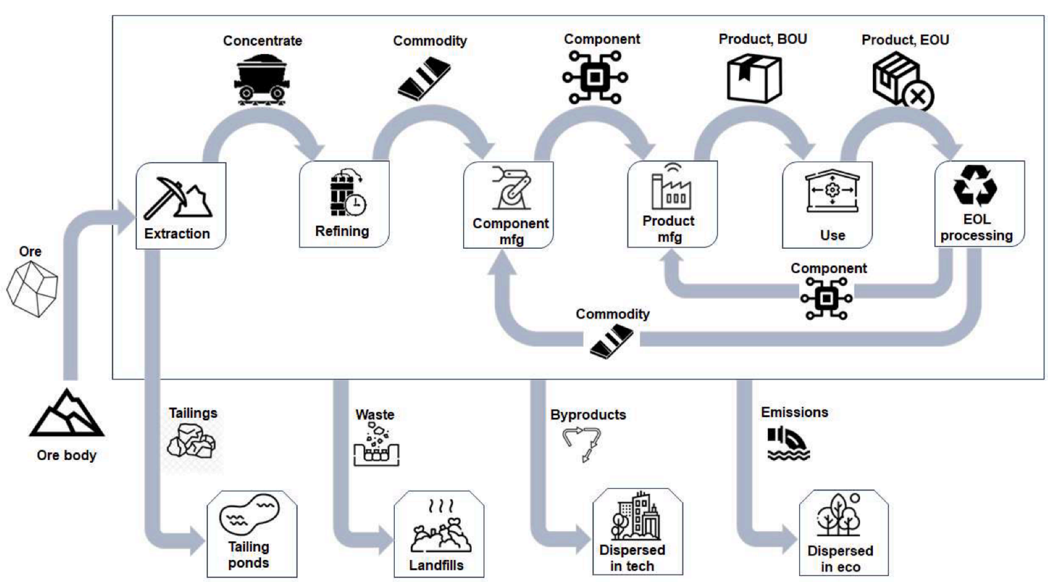

Fig. 1. Generic life cycle of a product employing resources embedded in ten key matrices: ore, concentrate, commodity, component, product at beginning of use (*Product, BOU*), product at end of use (*Product, EOU*), and in different losses along the value chain: tailings towards tailing ponds, waste sent to landfills, dispersed in the technosphere by downcycling into byproducts (dispersed in tech), and dispersed in the environment through emissions (dispersed in eco). Key life cycle stages of primary production are Extraction and Refining; key life cycle stages in manufacturing are component manufacturing (Component mfg.) and product manufacturing (Product mfg.); the Use is followed by the EOL (end-of-life) life cycle stage where resources in the end of use product can be recovered back as in component or as commodity by recycling, or eventually leaving and lost for the value chain. Note that other processes that impact accessibility like exploration, hoarding and abandoning with their respective stocks are not represented (cfr. Dewulf et al., 2021).

cycle stages and be sent to tailings and landfill deposits, and/or dispersed into the environment and technosphere. Dispersion in the technosphere typically happens with the recovery of the resource in byproducts where resources are utilized with a lower functionality (downcycling) and get dispersed, impeding its accessibility (Dewulf et al., 2021). Along the life cycle, resources appear in ten key types of matrices. Six out of them may be considered as 'useful' or accessible, with one being a natural matrix (ore body) and five being man-made: concentrate, commodity, component, product at beginning of use and product at end of use. Another set of four matrices hold the resource in rather inaccessible matrices: in tailings and wastes typically sent to tailings and landfill deposits, emissions sent to the environment, and by-product flows at the EOL that are downcycled and end in a dispersed stock in the technosphere. The further development requests a detailed resource flow analysis, meaning that a consistent quantification (mass-balanced) and specification (matrix-specified) life cycle inventory is to be built up.

Next, each life cycle stage, prior to the use stage, has the intention to deploy the instrumental value by increasing the accessibility of the resource to its instrumental value contained in the input: in principle it can have both an intended output, e.g. concentrate from the extraction process, and unintended outputs with lower accessibility, e.g. tailings sent to tailings deposits. These essential parts of the (life cycle) inventory will drive the impact of the life cycle stage with respect to its resource impact if the degrees of the entering and leaving mass flows can be characterized by an accessibility factor.

A consistent mass balance of a resource entering and leaving a life cycle stage in different matrices is presented in Fig. 2. After the supply chain life cycle stages, the resource in the product ready to use (beginning of use) gets its full instrumental value at the user. At the end of the use phase, the resource has lost its original instrumental value (or at least a substantial part) for the user to a level that the user considers that the product is at end of use, allowing the start of the EOL processing, neglecting eventual hoarding. The EOL processing may transform the resource embedded in the EOL product into different matrices; ideally it allows a next deployment towards the same high-value instrumental value through delivery of secondary raw materials (commodities) or components. Alternatively, the accessibility is jeopardized, e.g. by downcycling or landfilling. In Fig. 2, the masses $M_{i,j,p}$ and $M_{o,j,p}$ (kg) of a resource j entering and leaving the life cycle stage p are represented, with their respective level of accessibility, i.e. accessibility factor $AF_{i,j,p}$ and $AF_{o,j,p}$, scaled in between 0 and 1. M represents the mass of resource j under study, i the input of the resource within its respective matrix (as received from a preceding life cycle stage) delivered to the life cycle stage p (total number of sources: I) and o the output of the resource in its specific matrix from process p (total number of outputs: O). Part of the output may be sent to a following life cycle stage, or may get lost for the value chain, e.g. as emissions. All input and output streams are to be covered systematically whether they stay within the value chain or not.

Now the impact of the life cycle stage p on resource j can be quantified as its Resource Impact $RI_{j,p}$:

$$RI_{j,p} = CTI_{j,p} = \sum_{O}(M_{o,j,p}.AF_{o,j,p}) - \sum_{I}(M_{i,j,p}.AF_{i,j,p}) \quad \text{(Eq. 1)}$$

Where $CTI_{j,p}$ is the Contribution To Inaccessibility of resource j induced by life cycle stage p. The unit of the accessibility characterizing factor AF is kg accessible resource per kg resource (kg_{ACC}/kg). In case the life cycle stage deteriorates the accessibility by converting resources from quite accessible matrices (e.g. commodity) into quite inaccessible matrices (e.g. waste sent to landfill), $CTI_{j,p}$ becomes negative. Alternatively, if a highly efficient refining process fully converts a resource within a concentrate (lower accessibility) into a commodity (higher accessibility), then $CTI_{j,p}$ becomes positive.

2.2. Quantification of the level of accessibility of a resource in key matrices: accessibility factors

2.2.1. Selecting a universal base for accessibility factors: time to accessibility

Accessibility factors of a resource embedded in all kinds of matrices, either in an input stream ($AF_{i,j,p}$) or in an output stream ($AF_{o,j,p}$) need to be developed. Accessibility factors should represent the effort to make use of the full instrumental value of the resource, typically appearing in the final product delivered to the user. Ideally, there is a universal base like thermodynamics or economics that (1) links the resource in its specific matrix to the instrumental value; and (2) allows operationalization for resources in whatever matrix. To the best of our knowledge, this is not at hand. E.g. with respect to exploiting value or quality of resources embedded in EOL materials, other properties are used to characterize the accessibility than for example in primary production where e.g. ore quality properties are utilized (e.g. ore grade, mineralogy, particle size). Properties to characterize accessibility are typically sector-specific or 'life cycle stage'-specific, but not generic to describe the accessibility along the full life cycle.

This lack of ready-to-use life cycle-wide characteristics to establish life cycle-wide accessibility factors urges to seek for proxy metrics that have a universal nature allowing a vast employment. Dewulf et al. (2021) sought for indicators to express the inaccessibility level of

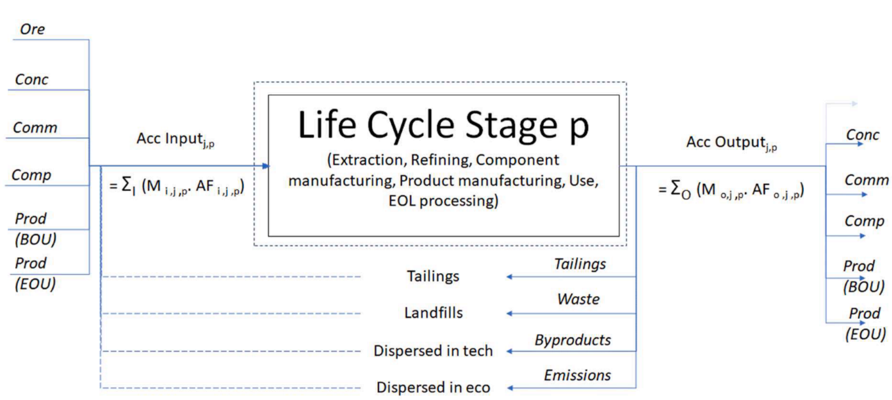

Fig. 2. Generic representation of flows of a given resource j through a life cycle stage p. Total input mass Σ_I ($M_{i,j,p}$) of a certain resource j is the sum of inputs embodied within respective matrices i (total number of input matrices: I) and is equal to total delivered mass output Σ_O ($M_{o,j,p}$) of a certain resource j in respective matrices (total number of output matrices: O). $AF_{i,j,p}$ and $AF_{o,j,p}$ represent the accessibility factors of the resource in its respective matrices in the incoming mass flow $M_{i,j,p}$ and outgoing mass flow $M_{o,j,p}$. The total amount of resource j entering and leaving the life cycle stage p expressed in accessible resources equals Acc $Input_{j,p} = \Sigma_I$ ($M_{i,j,p}$. $AF_{i,j,p}$) and Acc $Output_{j,p} = \Sigma_O$ ($M_{o,j,p}$. $AF_{o,j,p}$), respectively. For sake of completeness, all potential matrices are represented both at ingoing and at outgoing level, even if they may be hypothetical (represented by dashed arrows, e.g. sourcing from landfills).

resources embedded in rather inaccessible stocks. As a proxy, they proposed a quite universal characteristic having a meaning in a techno-economic context: time. The degree of inaccessibility of a resource in a matrix was quantified by the duration of inaccessibility, e.g. with best estimates of 65 years in landfills versus 500 years if emitted into the environment, based on data and expert knowledge. These years somehow present the best estimate of the time needed to (re-)access the instrumental value of these resources within a prevailing techno-economic context.

In a similar reasoning, one may define the Time To Accessibility (TTA) as a characteristic of accessibility of a resource within a certain matrix, i.e. time it may take to transform it from its matrix until its presence in the product, where it offers its instrumental value. This TTA is made up of the sum of the duration of the life cycle stages (DLCS: Duration of a Life Cycle Stages, in years) that are required to transform it. This means that next to the TTA proposed for inaccessible stocks like emissions into the environment, landfills, tailings and dispersed into the technosphere by downcycling, also TTA values have to be proposed for resources in more accessible matrices, such as ore bodies, concentrates, commodities, components, products at BOU and products at EOU, urging for a quantification of the DLCS of extraction, refining, component manufacturing, product manufacturing and EOL processing. In other words, how much time does it take to transform the resource contained in a certain matrix into a product as matrix, e.g. through component and product manufacturing to offer the instrumental value of a resource commodity? It can be understood that products at BOU offer the resources in a form at their instrumental value instantaneously, hence the TTA for products at BOU is zero. For resources in products at end of use (EOU), TTA is determined by the duration of the employed processes in the EOL life cycle stage, together with the durations of the subsequent life cycle stages to deliver the resource in a product ready for use. For example, if recycling is the key process in the EOL LCS, then it delivers secondary sourced commodities that need component and product manufacturing LCS to offer again the instrumental value.

2.2.2. Best estimates of duration of life cycle stages

To our knowledge, time required to convert a resource from one matrix into another matrix via a dedicated life cycle stage composed of a set of processes is not comprehensively documented. Moreover, it is obvious that there might be a large variety of the duration of a certain life cycle stage, e.g. component manufacturing. Indeed, the duration of the processes involved in a specific life cycle stage may depend on the envisaged resource and product, all being further dependent on the era and the geographical location, determining the involved techno-economic capabilities. In the next paragraphs, a first informed average estimate of the duration of the life cycle stages DLCS is envisaged with a lower and upper best estimate, this in function to further develop the CTI method, based here upon TTA as universal proxy for accessibility. The estimate is preferably based on data; alternatively experts have to be involved. In principle, it includes not only the processing time within the stage but also the associated logistics. The summary of the obtained DLCS values is represented in the Supplementary Information (SI2).

2.2.2.1. Duration of the life cycle stages extraction and refining. With respect to extraction, the S&P database (S&P Global Market Intelligence, 2023) has been examined for 9 resources: aluminum, copper, cobalt, lithium, gold, manganese, nickel, platinum and silver. These resources cover 51.7% of the economic value of resources recorded with production information in S&P Global Capital IQ. The duration of the extraction stage is the average time in between the start of the extraction, i.e. starting to get the instrumental value by extraction, and the effective extraction. The top ten producing mines have been selected for each resource for the year 2021 (except aluminum: 2016), this for sake of representativeness. The contribution of the mines have been weighted according to their production. It covers a range from 55 to 82% of the global production, except for those resources produced in a large number of somehow relatively small entities, i.e. for gold (13%), copper (25%) and silver (26%). It turns out that the average duration is 14.81 years, with a lower value of 8.06 (gold) and a higher value of 25.6 years (platinum). Details are provided in the Supplementary Information (SI3).

For the refining stage, there is no scientific document or database available to estimate the duration, this to the best knowledge of the authors. Experts at BRGM have been consulted to obtain a best estimate (Jacob and Touzé, 2023). Overall, the duration of the refining process is far shorter than extraction: the process can be run even within hours. However, the duration of refining is more determined by other factors, like transport which can be neglected in case of refining at the mining site, but can be weeks in case intercontinental transport is needed in between extraction and refining, eventually with delays for customs handling. Further on, the duration of the stockpiling can be significant before the processing as refining units may need a mix of concentrates at hand in order to make homogeneous feeds. From the various discussions, two months is considered as the best estimate of the refining life cycle stage, with a minimum best estimate of one week and a maximum best estimate of seven months.

2.2.2.2. Duration of the life cycle stages component and product manufacturing. With respect to the duration of component and product manufacturing, various sources but also expert knowledge have been consulted. For components like semiconductors, connectors, capacitors, resistors, surface mount and other inductive components, typical lead times are reported by Ultra Librarian (Ultra Librarian, 2023). Reported lead times are quite consistent with other sources (Supplychaindive, 2023; Fusionworldwide, 2023). An expert from industry (Leijen, 2023) was consulted, and an expert in logistics and supply chain management and production and service management was interviewed (Aouam et al., 2023) who reported a DLCS of typically 4 months with lower and upper estimates of 2.5 and 7 months respectively. Aggregating the information leads to a best estimate of 0.30 years with a lower best estimate of 0.20 years and an upper best estimate of 0.50 years.

The DLCS of product manufacturing is shorter when parameters like average production time (including logistics), material flow time and inventory turnovers are considered, leading to a DLCS best estimate of 2 months with lower and upper best estimates of 1 and 4 months, rounded to 0.15, 0.10 and 0.35 years, respectively (Aouam et al., 2023).

2.2.2.3. Duration of the life cycle stage end-of-life. With respect to DLCS of end-of-life, one should first understand what the involved processes are. Indeed, there are various EOL options that lead to recovery of resources within a circular economy perspective, such as recycling, reuse, refurbishment, repurpose etc. (Moraga et al., 2019). Obviously, only strategies that focus on the function, product, component or material, keep the accessibility of the resource substantially. The various recovery strategies may lead to different DLCS: recycling may take longer than refurbishment, for example. In the frame of this work, recycling back to commodities (secondary raw materials) is modeled as this is presumed to be the most prevailing EOL process that conserves the accessibility of the resource.

Recycling typically consists of preprocessing (collection, sorting, dismantling, separation) and the recycling processes themselves. A few European recyclers and recycler associations (Galloo, 2023; WEEE Forum, 2023) and public authorities (Préfet de Maine-et-Loire, 2020) were consulted. Taking into account the time at the preprocessing, transportation in between preprocessing and recycling plants which can be either rather regional (e.g. within the EU) or international, and the time at the recycling plant, the lead time typically varies in between 0.20 and 0.60 years, with an average 0.40 years.

2.2.2.4. Duration of the life cycle stages to exploit inaccessible stocks. With respect to the inaccessible stocks in tailings deposits, landfills, byproducts downcycled and dispersed in the technosphere and emissions release in the ecosphere, there are no current techno-economically feasible processes and according processing times to bring the resources back in the product value chain. However, Dewulf et al. (2021) investigated how long these resources may stay inaccessible, based on data and expert judgement. This duration of inaccessibility can be used to anticipate the typical duration it may take before there is economically viable technology that makes the resources again accessible after their transfer into these stocks. Hence, exploitation of resources in tailings and landfills is anticipated to happen 65 years after their deposition into these stocks, with 25 and 500 years the respective lower and upper best estimate. Resource exploitation from dispersed stocks is estimated to happen only after 500 years after their transfer to these stocks.

2.2.3. From duration of life cycle stages to time to accessibility and accessibility factors

2.2.3.1. From duration of life cycle stages to time to accessibility. To make a resource in certain matrix accessible, i.e. supplying it to the user in the form of a product offering its instrumental value, it requires multiple dedicated life cycle stages. The total time to accessibility (TTA) is made up of the sum of the duration of the life cycle stages (DLCS: Duration of a Life Cycle Stages, in years):

$$TTA = \sum_{I} DLCS_i \qquad \text{(Eq. 2)}$$

With i a life cycle stage (LCS) required to change the matrix from the initial one to the matrix product at BOU and I the total number of LCS required. To define the LCS required, the reader is simply referred to Fig. 1. For example, to make a resource in an ore body accessible, it takes 15.4 years in total, as it requires the LCS “extraction”, “refining”, “component manufacturing” and “product manufacturing” to convert a resource in an ore body into a resource in a final product ready for the user, with best estimates 14.81, 0.17, 0.30 and 0.15 years respectively. Resources in e.g. commodities or components are more accessible, with TTA of 0.45 and 0.15 years, respectively. Resources in EOU products, requiring EOL processing (recycling into commodities (secondary raw materials)) and component and product manufacturing towards full accessibility), require 0.85 years. For resources in (currently) inaccessible matrices like tailings deposits, landfills and dispersed in the technosphere and ecosphere, the TTA can be approached by the respective DLCS of their exploitation; the durations of the eventual subsequent life cycle stages like component and product manufacturing are negligible.

Based on the involved LCS, one can calculate the TTA for the ten key matrices; see Table 1. Apart from resources in products at beginning of use with TTA by definition 0 years, overall it appears that resources in commodities and components are most accessible with TTA less than 0.5 years; resources in concentrates and in products at EOU in between 0.5 and 1 year, and resources in ore bodies around 15 years. Resources in so-called inaccessible stocks are characterized by TTA of at least 65 years.

Making use of TTA has some key features for sustainable management of resources. First, processes that work towards offering the instrumental value to the user are acknowledged; e.g. primary production with extraction and refining reduces the accessibility from 15.4 (in ore) to 0.45 years (in commodity), whereas manufacturing stages bring the TTA down from 0.45 to 0 years. This is a core difference with classical depletion-based approaches to mineral resources in LCA. Second, the benefits of recycling strategies can be directly taken into account (not indirectly as per classical system expansion approach in LCA): recycling of EOL products into commodities reduces TTA from 0.85 to 0.45 years. Third, improving process efficiency is valued. If for example the primary production and manufacturing do not convert the incoming resource flow fully into the intended matrix (reducing the TTA), but convert a fraction into waste sent to landfills, then their operations may deteriorate the accessibility of a part of their input, quantifiable in TTA values. The TTA concept captures process efficiency by factoring in all outputs via their respective TTA, i.e. targeted ‘product’ outflows (accessibility gain) and the non-targeted output (accessibility loss).

2.2.3.2. From time to accessibility to accessibility factors. Starting from the development of TTAs, one can develop the contribution to resource impact by life cycle stages, that can be either positive or negative. With TTA varying from 0 to 500 years, a rescaling of the accessibility into a range from 0 (very inaccessible) to 1 (fully accessible) is proposed. This rescaling does not only ease the interpretation but also allows developing accessibility in terms of an ‘accessibility factor’ that can be multiplied with the mass of the resource in its respective matrix. By doing so, a certain mass of a resource in a quite inaccessible stock, e.g. wastes and emissions with TTAs of 65 and 500 years, could get an accessibility factor (AF: Accessibility Factor) close to 0 and a resource in a matrix with a TTA less than 1 year could get an AF close 1.

To this extent, various mathematical functions were tested. Finally, a generalized logistic function was utilized, similar as in the work by Santillan Saldivar et al. (2023), as this gave best shape to the intended rescaling features:

$$AF = A + \frac{K - A}{\left(C + Q.e^{-B.TTA}\right)^{1/v}} \qquad \text{(Eq. 3)}$$

By implementing the parameters $A = 1.8$, $K = 0$, $C = 1$, $Q = 0.5$, $B = 0.08$ and $v = 0.5$, resources in inaccessible matrices obtain AF below 0.01 and resources with TTA below 1 year obtain AF above 0.95. If the lower best and upper best estimates for inaccessible resources (25 years and 500 years) are utilized to set an AF of maximum 0.01, then the parameter B changes to 0.206 and 0.0103, respectively. AF is scaled to 1

Table 1
Lower best, best, and upper best estimates of Times To Accessibility (TTA, in years) of resources embedded in the ten key matrices, based upon the estimated DLCS (see SI2) of the involved LCS to make them fully accessible into the product providing the full instrumental value; upper best, best, and lower best estimate of the Accessibility Factors (AF) of resources in the ten key matrices, expressed in kg_{ACC}/kg. Conc: concentrate; Comm: commodity; Comp: component; BOU: beginning of use; EOU: end of use.

	TTA (yrs)			AF (kg_{ACC}/kg)		
	Lower best estimate	Best estimate	Upper best estimate	Lower best estimate	Best estimate	Upper best estimate
Ore	8.38	15.4	27.0	0.19	0.43	0.66
Conc	0.32	0.62	1.43	0.94	0.97	0.99
Comm	0.30	0.45	0.85	0.96	0.98	0.99
Comp	0.10	0.15	0.35	0.99	0.99	1.00
Product, BOU	0	0	0	1.00	1.00	1.00
Product, EOU	0.50	0.85	1.45	0.94	0.96	0.98
Tailings	25	65	500	0.00	0.01	0.22
Waste	25	65	500	0.00	0.01	0.22
Byproduct	500	500	500	0.00	0.00	0.00
Emissions	500	500	500	0.00	0.00	0.00

for a resource in product at BOU as matrix (TTA = 0 years), and 0 for a resource in the most inaccessible matrix, i.e. dispersed in the environment or technosphere (TTA = 500 years). The unit can be formulated as 'kg accessible resource per kg resource': kg_{ACC}/kg.

Based on TTA of resources in the ten key matrices, one can calculate the AF of resources in various matrices; see Table 1 and visualized in Supplementary Information (SI4). Matrices typically for the primary production sector exhibit AF from 0.43 for ore bodies, 0.97 for concentrates, and 0.98 kg_{ACC}/kg for commodities, demonstrating the resource accessibility gains the sector can make at 100 % process efficiencies. But, converting ore or concentrates into tailings or wastes result in compromising resource accessibilities ending up with 0.01 kg_{ACC}/kg. The manufacturing stage further increases the accessibility of resources in commodities (AF = 0.98 kg_{ACC}/kg) over components (AF = 0.99 kg_{ACC}/kg) towards products (AF = 1 kg_{ACC}/kg) for those quantities of resources that are effectively converted into the intended products. Within a circular economy perspective, resources in products at end of use still exhibit a substantial accessibility (AF = 0.96 kg_{ACC}/kg); it is detrimental to consider them as waste and send them to landfills by which their accessibility gets a substantial decrease with AF = 0.01 kg_{ACC}/kg.

3. Development of the contribution to inaccessibility life cycle impact assessment method (CTI-LCIA): from the impact by one life cycle stage on one resource to the impact by multiple life cycle stages on multiple resources

Based on the accessibility factors from Section 2.2 and the equation for $RI_{j,p}$ from Section 2.1, a Life Cycle Impact Assessment (LCIA) method can be proposed: CTI-LCIA (Contribution To (Resource) Inaccessibility–Life Cycle Impact Assessment method). It needs two further steps: it should couple individual LCS into a product system, and it requires the ability to handle multiple resources.

3.1. From one life cycle stage to a product system

Section 2.1 offered the resource impact of one single life cycle stage p on one particular resource j: $RI_{j,p}$. In case a LCA is executed for a product system that covers multiple LCS, e.g. cradle to gate or cradle to grave analysis for resource j, then the summation over all involved life cycle stages p (from the first LCS 1 to the last LCS P) results in a resource impact RI_j for resource j:

$$RI_j = \sum_P Resource\ Impact\ RI_{j,p} = \sum_P Contribution\ to\ Inaccessibility\ CTI_{j,p} \quad \text{(Eq. 4)}$$

or

$$RI_j = \sum_P RI_{j,p} = \sum_P CTI_{j,p} = \sum_P \left(Acc\ Output_{\ j,p} - Acc\ input_{\ j,p}\right) \quad \text{(Eq. 5)}$$

or

$$RI_j = CTI_j = \sum_P \left[\sum_O \left(M_{o,j,p}.AF_{o,j,p}\right) - \sum_I \left(M_{i,j,p}.AF_{i,j,p}\right)\right] \quad \text{(Eq. 6)}$$

Based on all respective input and output quantities of resource j ($M_{o,j,p}$ and $M_{i,j,p}$), the AF factors from section 2.3 ($AF_{i,j,p}$ and $AF_{o,j,p}$). The exercise might be simplified as several outputs from several stages p, $p+1, p+2$ … serve as inputs for stages $p+1, p+2, p+3$ …, nullifying the contribution to the resource impact as they are exchanged within the system boundaries of the product system; illustrated in the Supplementary Information (SI5). For example, if extraction and refining are both part of the system under study and extraction delivers ten Mt concentrate to refining, then the exchanged (accessible) mass does not appear at the system level as it is an internally exchanged flow. In the end, the RI_j of the life cycle under study will be determined by the net inflows (NI) and net outflows (NO) to the overall product system under study:

$$RI_j = CTI_j = \sum_P \left[\sum_{NO} \left(M_{no,j,p}.AF_{no,j,p}\right) - \sum_{NI} \left(M_{ni,j,p}.AF_{ni,j,p}\right)\right] \quad \text{(Eq. 7)}$$

Where $M_{no,j,p}$ and $M_{ni,j,p}$ are the externally sourced mass flows of resource j to the all LCS and the externally delivered mass flows of resource j from all LCS, respectively, with $AF_{no,j,p}$ and $AF_{ni,j,p}$ their respective accessibility factors. The 'n' in the subscript refers to the fact that these flows (and related AF) are part of the inventory that describes the "net exchange" of the product system.

3.2. From one resource to multiple resources: developing resource-specific accessibility factors

The analysis could be a base to quantify the damage to the safeguard subject for "mineral resources" as defined by the Task Force "Mineral Resources" of the UNEP-SETAC Life Cycle Initiative. Indeed based on the contribution to inaccessibility, it fits well as a quantification for the damage to "the potential to make use of the value that mineral resources can hold for humans in the technosphere". To that extent, multiple resources have to be analyzed together: a total set of resources J in order to have an overall resource impact CTI-LCIA for a certain product system, factoring in all respective resource impacts RI_j into an overall resource impact RI. Various options can be considered. First of all, all resources are equal in terms of their contribution to RI. This means that the contribution to RI of one particular resource j simply depends on the involved mass flows along the life cycle and the respective accessibility factors. However, some resources may be more valued than other resources: the same loss of accessibility may lead to more or less loss of instrumental value. One may think of a physical base, e.g. proven reserves, total of reserves and anthropogenic stock to differentiate AF per resource, expressing how the use of resources in a product system can affect the opportunities of future users to use resources (cf. Berger et al., 2020). However, these approaches are not directly and fully related to the instrumental value. Another base might be economics, e.g. costs or prices. Prices may be a way to give weight to the relative instrumental value of resources for humans (see Berger et al., 2020). In this work, the latter has been adopted as a base, similarly as in the JRC-LCIA method with long-term averaged prices as a base (50 years), utilizing copper as reference with an economic value of 3663.2 \$/t, expressed in dollar values of 1998 ($\$_{1998}$) (Ardente et al., 2023). This way, the value-based accessibility factor AF_V for a certain resource r is:

$$AF_V = \frac{Pr_r}{Pr_{Cu}}.AF_{Cu} \quad \text{(Eq. 8)}$$

With AF_{Cu}=AF from Table 1, and Pr_r and Pr_{Cu} the price of 1 kg of resource r and Cu (€/kg), respectively. The obtained AF_V factors are listed in the Supplementary Information (SI6) for resources in products at BOU. The element Au and the Platina Group Metals get an AF_V in the order of 10^3, the elements Be, Ga, Ge, Hf, In, *Re* and Tl in the order of 10^2, and Se, Ag, Ta and Te in the order of 10^1. At the other end of the spectrum, the elements N, K and S obtain an AF_V in the order of 10^{-2}. About two thirds of the resources (29/45) display an AF_V in the order of 10^{-1} and 10°. By multiplying a mass flow of r [kg r] with AF_V [kg_{ACC} Cu/kg r], one gets the mass flow r quantified in kg_{ACC} Cu.

The equations for the CTI-LCIA from Section 3.1 now simply have to be summed for all resources. Resource specific AF factors ($AF_{V\ i,r,p}$ and $AF_{V\ o,r,p}$) for all resources r (1, …,r, …R) with their respective accessibility factors in all supplied (total number of supplied flows: I) and delivered (total number delivered: O) flows to and from all life cycle stages p (1, …,p, …,P) can be used as characterization factors for all respective mass flows in the inventory ($M_{i,r,p}$ and $M_{o,r,p}$):

$$RI = CTI = \sum_R (R_{i,j}) = \sum_R \left[\sum_P \left(\sum_O (M_{o,r,p}.AF_{V\ o,r,p}) - \sum_I (M_{i,r,p}.AF_{V\ i,r,p}) \right) \right] \quad \text{(Eq. 9)}$$

With the consideration that life cycle stages are embedded in an overall product system, only net input (ni = 1 to NI) and net output (no = 1 to NI) flows with respective accessibilities ($AF_{V\ ni}$ and $AF_{V\ no}$) determine the resource impact of the product system:

$$RI = CTI = \sum_R \left[\sum_P \left(\sum_{NO} (M_{no,r,p}.AF_{V\ no,r,p}) - \sum_{NI} (M_{ni,r,p}.AF_{V\ ni,r,p}) \right) \right] \quad \text{(Eq. 10)}$$

This is visualized in the Supplementary Information (SI5). The calculation can be executed based on the AF and AF_V factors from Table 1 and the Supplementary Information (SI6) and with the LCI, offering the masses of resources entering and leaving the product system, which should be mass-balanced checked and matrix-specific.

4. Demonstration of the method for batteries as case study

In order to test and demonstrate the proposed method in a life cycle analysis context where resources have a relevant key role in the current energy transition, the application of metals in a vehicle battery was chosen: a LMO (lithium manganese oxide) battery. A full life cycle case study was evaluated, similar to the case studied by Lai and Beylot (2023) who tested their LCIA method. The base of the LCI is from ecoinvent (version 3.7), with three EOL scenarios tested: current performance with 5 % recycling rate, conservative future performance (40 % recycling rate) and optimistic future performance (80 % recycling rate). The reader is referred to Lai and Beylot (2023) for further details of the case study description.

The method could be tested for aluminum, copper, lithium, and manganese, with quantities in the battery equal to 41.5, 67.8, 2.47, and 35.4 kg respectively, for a functional unit of 1 LMO battery, offering a nominal capacity of 2.1 kWh over a service life of 100 000 km. For other resources the LCI does not provide a base with consistent mass balances. For the four resources, the LCS extraction and refining encompasses fourteen processes, the LCS component manufacturing three processes, and the LCS product manufacturing, product use and EOL are composed of one process each (See illustration in the Supplementary Information, SI7). The inventory is not suited to separate the LCS extraction and the LCS refining, so that the CTI-LCIA has been executed for Extraction and Refining as one merged LCS, resulting in a total set of five LCS.

The mass inputs and outputs in the inventory allow an easy calculation of the accessible masses entering and leaving each LCS, illustrated for Mn in Table 2. Two LCS contribute positively to RI: product manufacturing and especially extraction and refining, the latter with a gain of 11.51 kg_{ACC} Mn. This value is the result of the obtained 37.93 kg_{ACC} Mn in $LiMn_2O_4$ (39.1 × 0.97) ready for component manufacturing, and 0.23 kg_{ACC} Mn (22.9 × 0.01) in waste sent to tailings and landfills, starting from 26.66 kg_{ACC} Mn in ore (62 × 0.43). In case all Mn in ore would have been processed at 100 % efficiency, then a gain of 62.0 kg . (0.97–0.43) kg_{ACC}/kg = 33.48 kg_{ACC} Mn could be obtained. So apart from the CTI-LCIA within a LCA context, the methodology also unravels where future resource gains can be made by increasing process efficiencies.

The loss of accessible resources is due to (1) the LCS component manufacturing because of waste production that weighs heavier than the gain in accessibility by transforming commodities into components; (2) the LCS use as the instrumental value at EOL is lower than at BOU; and (3) mainly in the LCS EOL. In the latter process, 96% of the mass is lost as waste with a low AF of 0.01. Overall, the full life cycle results in a loss of 24.36 kg_{ACC} Mn.

In Table 3, the results for the four resources with three different EOL scenarios are represented. Similar trends are identified amongst the resources: gains in accessibility by extraction and refining, slight losses by component manufacturing, slight gains by product manufacturing, and some losses by the use phase. With respect to the different EOL scenarios, substantial reductions in accessibility losses can be achieved in the future conservative and optimistic scenarios. In the latter case, the full life cycle results in gains in resource accessibility: all LCS following extraction and refining do destruct 'only' 55.3 (Al) to 89.5 % (Mn) of the accessibility gains made by extraction and refining.

In order to test the CTI-LCIA for all resources simultaneously, the AF_V from the Supplementary Information (SI6) have been implemented, as illustrated in Fig. 3. Cu is the main contributor to the resource impact, because of the important quantities in combination with a relatively high AF_V. On the opposite, Mn contributes moderately to the RI because of its relatively low AF_V (= 0.187). The LCS product manufacturing (+2.01 kg_{ACC} Cu) and especially extraction and refining (+43.13 kg_{ACC} Cu) result in gains, whereas component manufacturing (-9.03 kg_{ACC} Cu) and use (-4.03 kg_{ACC} Cu) in losses. Remarkable is that future scenarios bring substantial changes: from -90.8 in the current EOL scenario over -57.0 in the conservative future to -18.32 kg_{ACC} Cu in the optimistic future scenario, resulting in an overall impact over the life cycle changing from losses in the current (-58.73 kg_{ACC} Cu) and the future conservative (-24.91 kg_{ACC} Cu) to gains in the future optimistic scenario (+13.77 kg_{ACC} Cu). This means that the resources left after this life cycle are in the end more accessible than before.

The method could be utilized to steer the economy in terms of conserving the access to the value of resources, i.e. keeping the same level of accessible resources after the life cycle as before: pursuing a break even with CTI=0. That implies a certain circular economy level, which in this showcase would require a recycling rate of 65.8 % for the resources.

Table 2
Mass balances for manganese per LCS (in kg), where ingoing masses (M_{in}, kg) and outgoing masses (M_{out}, kg) are provided with respective accessibility factors AF_{in} and AF_{out} (kg_{ACC}/kg); followed by the contribution to the resource impact per LCS: CTI = $\Sigma(M_{out}.AF_{out})$-$\Sigma(M_{in}.AF_{in})$; expressed in kg_{ACC} Mn (>0: gain; <0: loss). With respect to the outputs, a distinction is made in between the targeted output ($M_{out,t}$ with respective $AF_{out,t}$) versus the non-targeted output ($M_{out,nt}$ with respective $AF_{out,nt}$). Non-targeted outputs are losses like tailings and waste sent to respective deposits. With respect to LCS and involved matrix changes, the reader is referred to Fig. 1.

Life Cycle Stage	M_{in}	AF_{in}	$M_{out,t}$	$AF_{out,t}$	$M_{out,nt}$	$AF_{out,nt}$	CTI
Extr&Ref	62.0	0.43	39.1	0.97	22.9	0.01	+11.51
Comp mfg	39.1	0.97	35.4	0.98	3.73	0.01	-3.23
Prod mfg	35.4	0.98	35.4	1.00	0.00	0.01	+0.71
Use	35.4	1.00	35.4	0.96	0.00	0.01	-1.42
EOL	35.4	0.96	1.77	0.97	33.6	0.01	-31.93
Overall							*-24.36*

Table 3
Contribution to resource inaccessibility for Mn (kg_{ACC} Mn), Cu (kg_{ACC} Cu), Al (kg_{ACC} Al) and Li (kg_{ACC} Li) for the different LCS and the full life cycle, for three EOL scenarios: current, conservative future and optimistic future. With respect to LCS and involved matrix changes, the reader is referred to Fig. 1.

LCS	Mn	Cu	Al	Li
Extr&Ref	+ 11.51	+27.67	+21.52	+1.01
Comp mfg	-3.23	-6.18	-3.52	-0.23
Prod mfg	+0.71	+1.36	+0.83	+0.05
Use	-1.42	-2.71	-1.66	-0.10
EOL, current	-31.93	-61.16	-37.44	-2.23
EOL, cons. fut.	-20.00	-38.39	-23.49	-1.40
EOL, opt. fut.	-6.37	-12.34	-7.55	-0.46
Overall, current	*-24.36*	*-41.02*	*-20.27*	*-1.49*
Overall, cons. fut.	*-12.42*	*-18.26*	*-6.32*	*-0.66*
Overall, opt. fut.	*+1.21*	*+7.79*	*+9.62*	*+0.28*

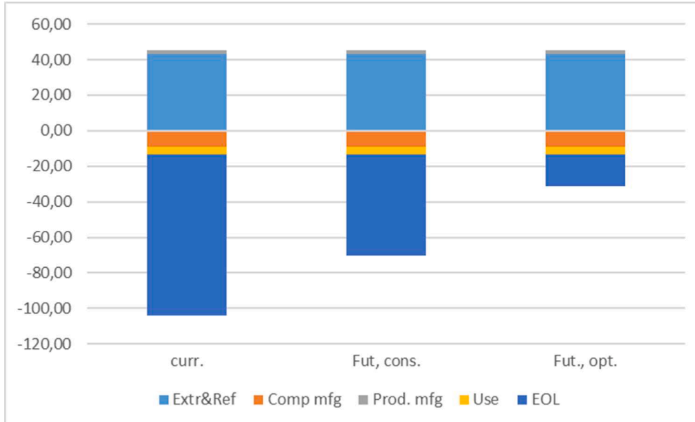

Fig. 3. Resource impact of different life cycle stages based (kg_{ACC} Cu) on four resources (Al, Cu, Li, Mn) in a battery application, with three EOL scenarios: current, future (conservative) and future (optimistic) (kg_{ACC} Cu). Extr&Ref: extraction and refining; Comp mfg: component manufacturing; Prod. mfg: product manufacturing; EOL: end-of-life. Positive values indicate reduction in inaccessibility (accessibility gains); negative values increase in inaccessibility (accessibility loss).

5. Discussion and perspectives

The resource scope, temporal scope and geographical scope of the developed CTI-LCIA method for individual resources and price-based aggregated resources started from the concept of accessibility developed by Schulze et al. (2020). It advanced conceptually in two ways. First, the accessibility of resources has been refined in terms of: 'accessibility to what?': accessibility to the instrumental value of the resources, enabling to introduce different levels of accessibility of so-called accessible resources (in ore, concentrate …) and of so-called inaccessible resources (in emissions, landfills …). Second, by introducing a scale of accessibility, the method overcomes the discussion on what temporal perspective to adopt, e.g. short (e.g. 5 or 25 years) or long term (e.g. 100 or 500 years): it relies on a continuous time scale from 0 to 500 years. It does keep a global perspective. However, the proposed method may be altered into more regional perspectives, e.g. by adopting prices dependant on the region of the world.

A key feature of the methodology is that it offers a method to compare the instrumental value of resources wherever you encounter them in the life cycle: from being a natural resource in a mine over intermediates like components to EOL products, but also for resources lost, like in emissions. Time has been used as a base to come up with accessibility levels for resources in different matrices. Other bases may be explored, e.g. of an economic nature. The developed method starts from the instrumental value which has a use value and an exchange value component. The development of the accessibility factors for resources in various matrices has been anchored around the use value specifically, i.e. when it is at the disposal to the user to exploit the use value and where the resource delivers its functionality; cfr. Greffe et al. (2023). On the other hand, when the resource-specific values have been developed, price has been used in the method development, which rather refers to the exchange value.

The method is developed by starting with mass balanced inventories with specification of the matrices in which the resource flows appear. Currently, LCI utilized in LCA are not systematically mass balanced. For the case study in this paper, the authors utilized the mass balanced flows for four resources, which already needed some substantial work starting from ecoinvent data; see the supplementary information of Lai and Beylot (2023). With respect to the specification of the matrix, the CTI-LCIA method is quite unique. Current LCIs do that only partially, not systematically. In some cases, classical LCI datasets like the ones in the ecoinvent database specify it in an indirect way, e.g. as 'extracted from ground', indirectly indicating that the resource enters the process in ore as matrix. In this sense, a new and more systematic nomenclature that specifies the matrices consistently may be suggested to be used in Life Cycle Inventory data sets, e.g. 'in ore', 'in concentrate', 'in commodity', etc. The main challenge most probably lies in the inclusion of matrix specification for resources exchanged within the technosphere Once the nomenclature have been adapted to the LCI databases, the integration to LCA softwares might be straightforward.

At a more technical level, the method relies on a mathematical function that translates TTA into AF, i.e. via a logistic function, as in Santillan Saldivar et al. (2023). Various other methods have relied on such an approach, e.g. the ADP and EDP method when it comes to resources. Next to testing alternatives to translate TTA into AF, also the utilized TTA may be further examined. However, the effect of further refinements, e.g. more granularity with respect to the duration of life cycle stages, e.g. distinction in between duration to manufacture one product versus another in function of the applications of the resources, may not fundamentally change the outcomes. Indeed, if one considers the effect the duration finally has on AF when lower best, best, and upper best estimates are analyzed, effects are limited (Table 1). Two exceptions may be identified. First, there is the LCS extraction: potentially this could be made resource-specific. However, data limitations do not enable to implement this refinement. A second potential refinement may be with tailings and waste sent to tailings and landfill deposits. Copper in landfills most probably has a better accessibility than selenium, for example. However, there is no further refined and accurate information available to do so, according to the knowledge of the authors; they relied on estimates by Dewulf et al. (2021). Also worth mentioning is that the LCS EOL have been modeled as recycling; other EOL strategies may change the AF factor at EOU, or even during the use phase, e.g. in case of refurbishment.

With respect to the interpretation of the results, the method can estimate if a life cycle stage contributes to gains or losses of accessibility. It can point to hotspots in the life cycle as typically done in LCA. On top of that, it can also be used in steering processes to conserve resource accessibility. Interesting is also to understand that especially primary production can have a substantial contribution to gains in accessibility (the 'handprint'), as learnt from the case study. However, analysis of the losses of accessibility of this life cycle stage, e.g. via tailings, should not be overlooked. Moreover, resource impact is only one of the midpoint or endpoint impact categories; primary production can go along with 'footprints' in other impact categories, e.g. because of emissions that lead to air and water pollution.

Although it is too early to grasp the possible applications, the method may be useful in policies addressing sustainable management of resources. It could potentially be a base to define targets in circular economy policies where setting targets is always a compromise of various interests. For example, the case study demonstrates that a recycling rate of 65.8% for batteries would be needed to conserve resources, being higher than the 50% material recovery level target for 2027 but lower than the 80% material recovery level target for 2031 for lithium, as mentioned in Article 71 of the recent proposal for a Regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020 (Council of the EU, 2023). The CTI could also help analyzing in the future the material recovery level targets of the battery regulation in regards to recycled content targets (e.g. for lithium in article 8 of the same regulation). As the method connects directly to resources, some reflection may be needed how to bring it into policies: it can be positioned in waste and circular economy policies, but also within environmental policies based on life cycle analysis (as impact category for resources), or even within criticality mitigation policies through steering towards enhancing physical access next to addressing geopolitical access constraints.

The CTI-LCIA should be complemented with methods that address other environmental impacts. The current CTI-LCIA can be simply positioned together with these other methods at the midpoint level. The method, with quantification in kg accessible copper, that has a midpoint nature, can simply be directed to endpoint level, by further translation in monetary values. With a value of $\$_{1998}3,663.2$ per ton of copper commodity (Ardente et al., 2023), an inflation of 1.86 since 1998 (inflationtool.com), and with a AF for copper as commodity 0.98 kg_{ACC}/kg Cu, the AF_{ACC} can be translated in $AF_{ACC,\$}$ as $\$_{2023}6.95$ at the endpoint level.

6. Conclusion

Relying on the insights that accessibility to the instrumental value is the key challenge, this paper has been able to present a novel resource impact method, CTI-LCIA, fitting into the new generation of impact methods. Similarly to the JRC-LCI or the ADR/LPST method, it emphasizes that flows within the technosphere are key with respect to the impact on the AoP natural resources. However, it fundamentally diverges from other methods in the sense that it measures losses ànd gains in instrumental value. This latter is a quite unit asset: it emphasizes that certain processes along the life cycle can be beneficial. This advocates for a paradigm shift in the sustainability assessment community, and in the LCA community in particular: one should not only seek for quantifying ‘burdens’ or ‘footprints’, but also develop methods that allow a better quantification of positive contributions of production and consumption chains in function of sustainable development.

Credit author statement

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

Disclaimer

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

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Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.107363.

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