# Linkage of impact pathways to cultural perspectives to account for multiple aspects of mineral resource use in life cycle assessment

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ABSTRACT

Important advances have been made to define the multiple impact pathways relating mineral resource use to the area of protection (AoP) natural resources in life cycle assessment (LCA). Yet, the link between stakeholders' interests and the aspects relevant to resource use as addressed by existing impact assessment methods has so far only marginally been explored. This article proposes to go beyond the case-specific determination of stakeholders' interests (and the associated selection of impact assessment method) by defining multiple groups of different values based on cultural perspectives, in order to determine the corresponding relevant impact pathways and assessment methods.

Relying on the Cultural Theory and related potential development scenarios, we identify socio-economic objectives and resource management strategies that fit the egalitarian, individualist and hierarchist perspectives. Our analysis reveals that different aspects of resource use may be most relevant to assess for each perspective since they pursue different socio-economic objectives. Egalitarians are expected to prioritize the long-term availability of geological stocks for future generations by keeping extraction flows to a minimum to reach global sufficiency, and individualists, to safeguard their short-term accessibility to resources by managing their supply risk. Hierarchists are likely to aim to maximize the value obtained from resources globally, and could thus focus on addressing dissipative flows. Building on this analysis, we provide a proposal for a more holistic assessment of the impact pathways linked to mineral resource use using existing LCIA methods, and identify ways forward for method developments to come.

## 1. Introduction

### 1.1. Context

Life cycle assessment (LCA) is a well-suited method to estimate the environmental impacts of products and services. Multiple impacts pathways link life cycle inventory (LCI) data (extraction and emission flows) with midpoint impact categories, which may then be translated into endpoint damage on three so-called areas of protection (AoP): human health, natural environment (or ecosystem quality), and natural resources (European Commission et al., 2010). The scope and definition of the AoP natural resources has been increasingly studied in the past years (Dewulf et al., 2015; Drielsma et al., 2016b; Sonderegger et al., 2017; Sonnemann et al., 2015). Notably, the Life Cycle Initiative, regrouping numerous LCA scientists and experts (Berger et al., 2019; Frischknecht and Jolliet, 2016), worked on improving the definition of the AoP. Recently, its Taskforce on mineral resources (henceforth, "MR taskforce") completed an extensive review of all of the life cycle impact assessment (LCIA) methods addressing mineral resource use (Sonderegger et al., 2020). The authors identified several aspects related to mineral resources which may be relevant to consider within the AoP natural resources: depletion, dissipation, the changing quality of

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mineral resources and its consequences, the economic externalities of their extraction, the consumption of exergy or emergy embedded in resources, as well as availability or accessibility issues due to physico-economic scarcity, geopolitics and socio-economic aspects of supply risk (Berger et al., 2020; Sonderegger et al., 2020). Furthermore, they defined the safeguard subject for mineral resources in the AoP as *"the potential to make use of the value that mineral resources can hold for humans in the technosphere"* and have identified the damage as *"the reduction or loss of this potential caused by human activity"* (Berger et al., 2020). The authors also identified seven potential questions a practitioner may want to answer to related to different resource aspects, and made recommendations regarding the most suitable LCIA methods available to address each of these questions.

### 1.2. Challenges and objectives

Addressing the multi-faceted aspects related to mineral resources altogether and structuring the impact assessment in the AoP remains challenging. While the MR taskforce determined the aforementioned questions and recommended appropriate LCIA methods addressing them, they did not determine how to address multiple aspects associated with mineral resource use altogether. Moreover, most of the methods suggested or recommended by the MR Taskforce quantify midpoint impacts rather than endpoint damage, suggesting that identifying and measuring the endpoint damage is uneasy. An underlying problem seems to lie within the definition of resources, consistently referring to their value for humans, with no specification of which value, nor which humans, are referred to. A review of existing definitions by Beylot et al. (2020b) showed that, in the common anthropocentric perspective, resources have typically been defined based on their intrinsic value or utility for humans, since their functions answer specific needs or more generally contribute to human well-being. The definition of mineral resources as proposed by the MR Taskforce makes no exception. In addition, the related safeguard subject refers to their accessibility for humans globally rather than to their intrinsic value in the environment (Berger et al., 2020; Schulze et al., 2020). Yet, while resources are defined as being of utility or of value to humans *in general*, or globally, they are in fact only beneficial to those accessing and making use of the value they have *for them*. This was made evident in the recent enthusiasm for critical materials assessments (European Commission, 2020; Graedel et al., 2015; Sonderegger et al., 2015) and relatable risk-based assessment methods developed for LCA (Bach et al., 2019, 2016; Cimprich et al., 2019, 2018; Gemechu et al., 2016).

In this light, the safeguard subject as defined by the MR taskforce may be interpreted differently depending on which group of humans is referred to (both regionally and temporally) as well as which are their objectives, leaving a wide margin to subjectivity when assessing the impacts of mineral resource use on the AoP natural resources: What is the value of resources? Who should have access to resources and their value? How should they be managed through space and time? Answering such questions inherently involves value judgements. Consequently, the impact mechanisms relevant to practitioners also depend on what they value. For such reasons, the MR Taskforce recommended methods that may be used by LCA practitioners depending on the questions they wish to address. Yet, while LCA is a value-based tool implying decisions on what is to be safeguarded in space and time, the link between the problematic to be addressed during impact assessment and the often implicit value choices and assumptions undermining each LCIA method's model are not self-evident (Finnveden, 1997; Hellweg et al., 2003). Moreover, it is arguably of crucial importance to align the impact assessment of mineral resource use with objectives, since the *potential to make use of the value of resources* inherently depends on the planning of the mineral supply and resource management accordingly with objectives such as those embodied in UN sustainable development goals (SDG) (Ali et al., 2017; Schandl et al., 2016; UNEP, 2017; Wackernagel et al., 2021). For instance, the Swiss ecological scarcity method integrates policy objectives in their impact assessment model (Frischknecht and Büsser Knöpfel, 2013).

Hofstetter (1998) stated that all modelling choices made in LCA should be consistent with a single world view, and defended that the Cultural Theory (Thompson et al., 1990) is relevant for such modelling decisions. The widely used ReCiPe method (Goedkoop et al., 2013; Huijbregts et al., 2017) and the underlying eco-indicator99 method (Goedkoop and Spriensma, 2001) build on cultural perspectives as defined in the Cultural Theory. These cultural perspectives, or archetypes, represent different lenses through which humans may see the world and value things, nature and people around them or afar in space and time (Hofstetter, 1998). Out of five perspectives, the individualist, egalitarian and hierarchist ones are particularly fit for the LCA decision making context (Hofstetter, 1998). In the ReCiPe and eco-indicator99 methods, the selection of impact methods to assess the impacts of mineral resource use is made easier for the practitioner, since subjective assumptions and choices underlying the selection of relevant impact mechanisms and time horizons are attributed to specified cultural perspectives. Yet again, a single impact pathway is proposed to account for the impacts of mineral resource use in these methods, providing a limited representativeness of the cultural perspective for the AoP natural resources.

The main objectives of this work are to define mineral resources and their value in the context of life cycle approaches, to identify resource management strategies in line with different socio-economic objectives proper to the individualist, egalitarian and hierarchist perspectives, and to identify and link relevant impact pathways to the AoP natural resources under these three perspectives. To address these challenges, we first propose a comprehensive definition of the value of mineral resources relevant to life cycle perspective approaches such as LCA, and identify the beneficiaries of this value (section 2). Secondly, building on the notion that different resource management strategies may be used to pursue different social and economic objectives respective to different cultural perspectives, we propose a linkage between cultural perspectives and concrete strategies (section 3). The developments proposed in section 3 allow identifying impact mechanisms that may be most relevant to each perspective (section 4). As a result, we come up with a proposal on how impact pathways and the corresponding LCIA methods can be sorted based on the cultural perspective(s) that they best represent (section 5). In this way, we provide initial guidelines to address mineral resource use in a more comprehensive way in LCA under different cultural perspectives. We discuss our key findings in section 6.

## 2. Mineral resources and their value

The MR taskforce defined mineral resources as "*chemical elements (e.g., copper), minerals (e.g., gypsum), and aggregates (e.g., sand), as embedded in a natural or anthropogenic stock, that can hold value for humans to be made use of in the technosphere*" (Berger et al., 2020). These correspond to the resources identified within box A of Fig. 1, which are studied in this article. A complementary description of the different mineral resources identified in the figure is provided in the Supplementary materials.

The potential functions in the technosphere may be obtained through current or future transformation activities in the economy and have a potential value for human beings at some point in time. From the classic utility theory upon which are based modern economics, two different meanings can be distinguished for the word "value": "[it] *sometimes expresses the utility of some particular object, and sometimes the power of purchasing other goods which the possession of that object conveys. The one may be called* value in use*; the other,* value in exchange" (Stigler, 1950, citing Smith, 1937). Generally, only does a *value in use* obtained through human activities has an *exchange value*, although some *use values* are also provided directly by nature (Marx, 1867). The former refers to products and services obtained in the economy, while the latter refer to direct functions obtained from ecosystems (i.e. ecosystem services).

It is thus useful to distinguish between the economic *exchange value* and the *use value* of mineral resources. We henceforth refer to the

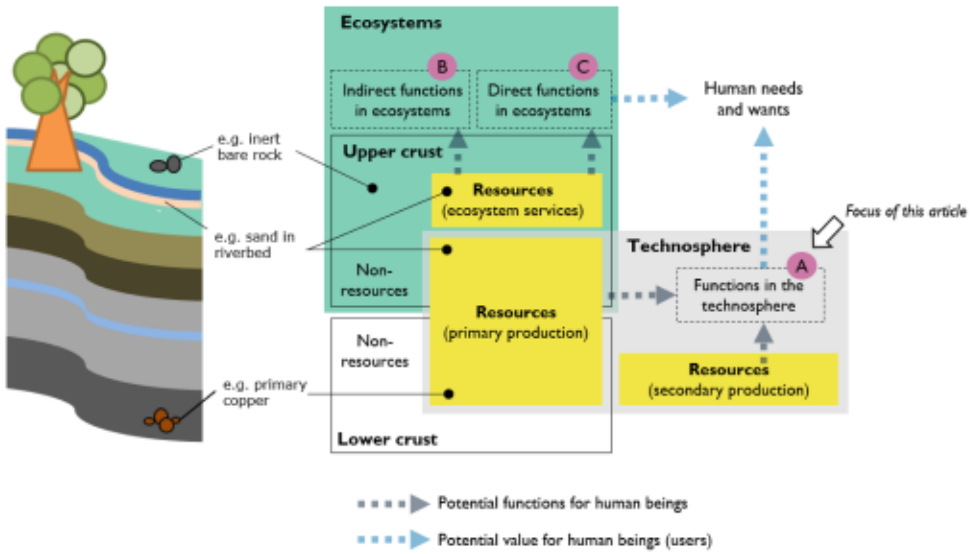


**Fig. 1.** Identification of mineral resources providing functions in the technosphere (A) and ecosystems (B and C)

exchange value as an *economic value*, and retain the terminology for *use value*. In this article, the use value specifically refers to the experiential value that may be accredited to the functions of final products when the final consumer makes use of them. For an exhaustive coverage of what the final products may include, we refer readers to the description of the *household's actual consumption*, resulting from the expenditure of households, governments and non-profit institutions serving households (NPISHs), as proposed by Lequiller and Blades (2007). Put briefly, final consumption includes all final products and services whose use values fulfill human needs and wants, such as household appliances, public and private infrastructure, etc. The economic value is usually represented by the price obtained in exchange of a good on a market; it may be reinvested in other capital (e.g. infrastructure) or distributed amongst different stakeholders (e.g. to a state through taxes, to employees through salaries, to shareholders, etc.).

### 2.1. *Value chain of mineral resources*

In general, the different mineral resources are found in nature in low concentrations, and deposits containing higher concentrations are geographically dispersed (Blomsma and Tennant, 2020). Therefore, they require more or less intensive transformation before they can provide use values to humans. Primary resources are extracted, beneficiated and refined in most cases, then usually sold to a third party for further transformation. The economic value of these primary mineral resources, i.e. their rent, is typically shared between the extractive industries and the resource's owner (often a nation) through various taxing schemes (Bulearca et al., 2012). Refined mineral resources are manufactured into more complex materials (e.g. alloys) and components (e.g. hard disk drives), which themselves only provide a use value as part of broader product systems (e.g. aircrafts and computers) (Blomsma and Tennant, 2020; Greenfield and Graedel, 2013). Like primary (and secondary) resources, intermediate goods may be traded for their economic value, but have no use value for final consumers on their own. The transformation of mineral resources into materials and semi-products provide the successive intermediaries with new properties, generally increasing their economic value.

The economic value generated along value chains does not represent the finality of value chains: they are meant to supply consumers with final products whose use value answer their needs and wants. It is therefore the demand for use values of products that drives production systems, and eventually allows organizations to capitalize on the surplus economic value generated along supply chains. Thus, as the last step of the value chain, products and services are purchased by final consumers in order to fulfil their needs and wants. The economic value of products generally reflect the final consumers' willingness to pay for them, based on the perceived use value they may get from them in their respective context (Le Gall-Ely, 2009). Henceforth, we distinguish between the economic value of the mineral natural capital (accessed through exploration, extraction and refining processes), the economic value of supply chains (e.g. employment, rents, taxes, financial capital, etc.), and use values. Fig. 2 illustrates examples of potential supply chains and applications making use of the mineral chalcopyrite and its elemental constituents regardless of their economic feasibility.

One same mineral resource may be used in various supply chains, each of them generating different values for potentially different users. The quality of the resource may have implications on which applications it is fit for (Stewart and Weidema, 2005). For example, while chalcopyrite is generally economically extracted for its copper content, some applications could make use of the mineral as such, such as sensor electrodes for the detection of natural hydrogen peroxide (Wang et al., 2018). The elements it contains can be used both as pure single elements (e.g. copper in electrical wires), or as composite materials (e.g. steel used in a boiler). In addition to the multiple potential states that may be valued for one same mineral, multiple characteristics could be of use for each of them. For instance, pure copper can be used for its conductivity as part of wires or electronic devices, or for its resistance to corrosion as part of copper pipes. The functions of final products result from the characteristics of resources or materials they are composed of, of the labor put to contribution in their manufacturing including energy, as well as the different capitals (i.e. manufactured, human, social and financial capitals) that are required to transform them along value chains. In LCA studies, functions are typically reported as the functional unit of a product or process, and do not refer to economic values nor use values they generate.

### 2.2. *Beneficiaries of the value of mineral resources*

The physical availability of geological reserves of mineral resources does not guarantee their technico-economic accessibility for humans (Drielsma et al., 2016b), and even less so their accessibility for one specific group of humans. Indeed, the economic value held by primary resources is only accessible to those that can legally operate locally or abroad while having the indispensable pre-accumulated capitals to do so. These include the financial capital required to invest in new projects (e.g. exploration and building infrastructure), the manufacturing capital required for extraction and transformation, the human capital in the form

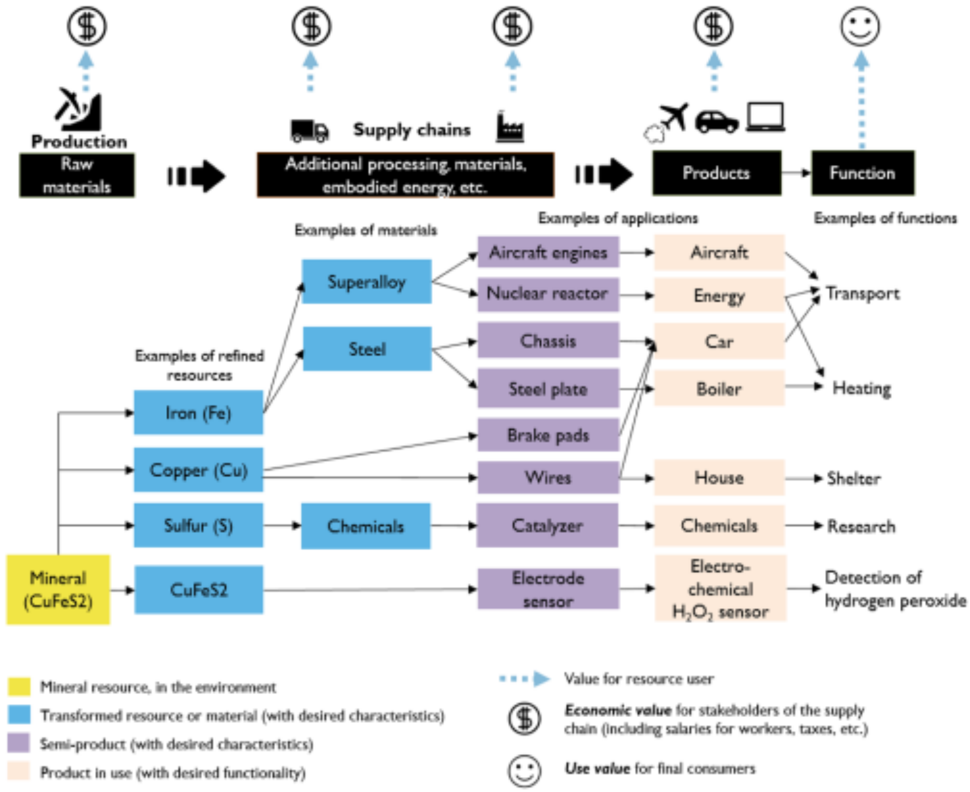


**Fig. 2.** Potential supply chains making use of the mineral chalcopyrite (CuFeS2) to generate economic and use values

of knowledge and skills (e.g. breveted metallurgical process and trained personnel), and the social capital (including favorable geopolitical relationships and the social license to operate locally). For instance, environmental, social and governance risks may have an incidence on which resources are accessible in different regions, as such risks can disrupt the opportunities to explore for ore bodies and the feasibility of subsequent mining operations (Ali et al., 2017; Kerr, 2014; Lèbre et al., 2019; Northey et al., 2018). Generally, the main stakeholders for the economic value of primary raw materials are nations possessing resources, as well as extractive industries aiming to generate socio-economic benefits from extracting and processing them. This economic value may be an important support to a territory's socio-economic activities and to its development (EITI, 2019; IIED, 2002; Wall and Pelon, 2011). While Graedel and Cao (2010) found out that the production and processing of primary resources

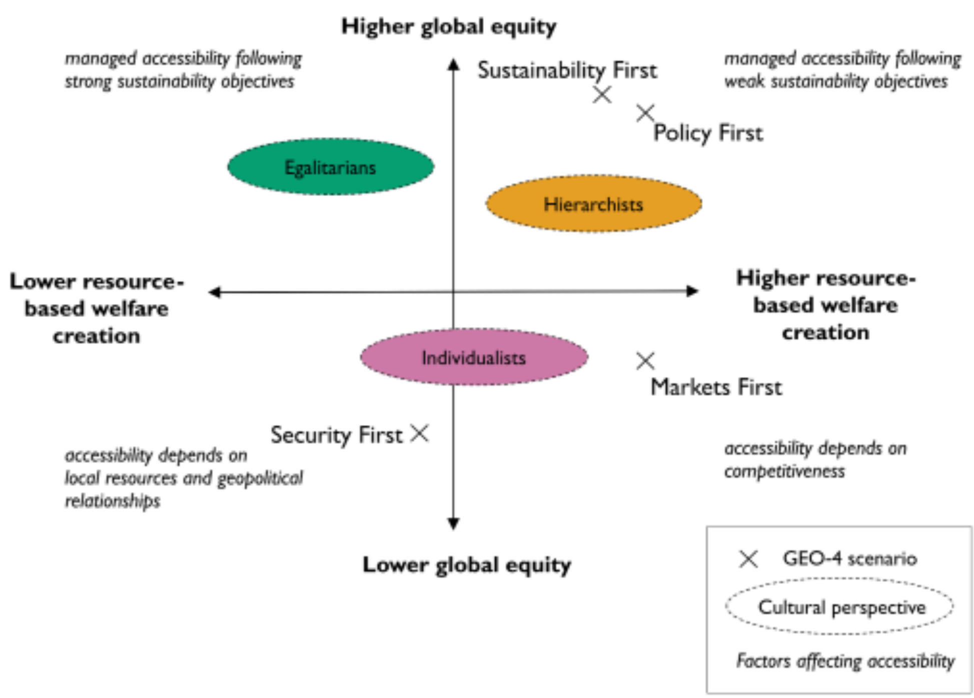


**Fig. 3.** GEO-4 scenarios and cultural perspectives distributed over four quadrants with regards to the expected interregional equity in the accessibility to resources and the global resource-based welfare creation

**Table 1**

Egalitarian, individualist and hierarchist cultural perspectives and their respective relevant geographical scales and time scopes, as well as archetypal views of resource use and their corresponding socio-economic objectives, political strategy archetypes, and preferred resource management strategies.

| Cultural perspective archetypes | Time horizon of interest (Hofstetter, 1998) | Geographical scope of interest | GEO-4 Scenario (UNEP, 2007) | Socio-economic objective | View of mineral resources (Adapted from Hofstetter, 1998) | Political strategy archetype | Resource management strategy |
|---|---|---|---|---|---|---|---|
| **Egalitarian** | Long term > short term | Global (Hofstetter, 1998) | Sustainability First (with an emphasis on environmental protection & sufficiency) | Equitable opportunities for future generations | Resources are depleting: they should be used with parsimony and their value should be preserved for future generations. | *Social justice through sufficiency* | Minimal consumption for global sufficiency, following strong sustainability principles |
| **Individualist** | Short term > long term | Organization | Security First or Markets First | Optimized opportunities for the organization | Resources are vital to the organization. Their access should be secured to maintain the activity. | *Business as usual: survival of the fittest* | Secure resource supply to sustain economic activity & increase competitiveness |
| | | National | Security First or Markets First | Optimized opportunities for the nation | Resources are vital to the nation. Their access should be secured to maintain the national economic activities. | *Business as usual: make my country great again* | Secure resource supply to sustain economic activity & increase competitiveness (e.g. strategic stockpiling & trade agreements), maximal consumption and efficiency<br>-<br>*Markets First:* Liberal policy & economic planning<br>*Security First:* Prioritizing local industry & employment (including military) |
| | | Global | Markets first; however might be non-applicable: see section 3.2 | Optimized opportunities for the current generation | Resources are abundant and vital to the global economy. The access to resources should be secured to increase global economic activities. | *Business as usual* | Deregulation & free markets lead to increasingly widespread resource use |
| **Hierarchist** | Short term = long term | Global (Local vs global outcomes) (Hofstetter, 1998) | Sustainability First or Policy First (with an emphasis on global welfare) | Enhanced opportunities for current & future generations | Resources are scarce but needed for sustainable development. They should be managed equitably globally and across generations. Use should be optimized to maximize global welfare. | *Social justice through cooperation and development* | Sustainable development through controlled resource use, improved technique and cooperation (e.g. circular economy & high resource productivity in developed countries, international cooperation to sustain socio-economic development of lower income countries) |

is rather independent from nations' development, it can be observed that most of the world's largest mining companies operating worldwide are of Australian, British, American, Canadian, Russian, South African, Chinese or Hong Kong ascendance (PwC, 2019), suggesting that there is a relatively high concentration of capital shared between these organizations and their respective stakeholders. These organizations all emanate from relatively advanced developing countries or developed countries with a long history of mining activities, except for China which has quickly caught up in this millennium, largely relying on its important reserves (cf. USGS, 2020).

Like extractive industries, the transformation industries also generate socio-economic benefits from their activities. Some economies are specialized in generating surplus economic value from the transformation of resources into products along global value chains, such as those in eastern Asia, Western and northern Europe and the US (The World Bank, 2020). In general, it appears that developed nations and organizations within, which rely on extensive pre-accumulated capitals as well as favorable geopolitical relationships, are more competitive than low- and mid-income countries, and therefore have a greater access to resources traded on international markets (Wackernagel et al., 2021). Coherently, Graedel and Cao (2010) showed that there is a rather high correlation between the level of development and of competitiveness of nations, and the intensity of their resource transformation and use.

The concentration of economic value generation from both natural capital and transformation activities within developed countries leads to an increased accessibility to the use value of final products (including public and private infrastructure) for organizations and citizens of these same countries. Indeed, they generate more GDP per capita, and citizens within generally have a greater purchasing power than those of low- and mid-income countries (UNEP, 2017, 2016). For instance, Nakajima et al. (2018) and Watari et al. (2020) showed that the consumption and accumulation of metals is much larger in developed countries and in China than in other countries. China may indeed be considered to be on par with developed countries in terms of industrial potential given the current competitiveness of its supply chains, the extent of its infrastructure, and its increasingly important involvement in global economic activities in the past two decades (The World Bank, 2020; World Economic Forum, 2019).

## 3. Resource management strategies in line with cultural perspectives

The current trends of the accessibility of resources and their value as described in the previous section may be desirable for some, and less for others. In this section, we propose plausible resource management strategies in line with socio-economic objectives suitable to the individualist, hierarchist and egalitarian perspectives. Their respective objectives and corresponding resource management strategies are theorized following the Cultural Theory as interpreted by (Hofstetter, 1998), established future world scenarios of the UN Environmental Programme (UNEP, 2007), and complementary literature. Four 'GEO-4' scenarios have been defined: Markets First, Policy First, Sustainability First, and Security First, as presented in the chapter 9 of the Global Environment Outlook (GEO) report (UNEP, 2007). Each scenario represents a potential avenue of how current social, economic and environmental trends could unfold along different development paths depending on different policies and societal choices. In the Markets First scenario, international trade is deregulated in order to pursue a flourishing global economy, giving most place to the private sectors. The similar *Yale Market World* scenario (Elshkaki et al., 2018) implies an increasingly widespread use of resources whose deposits are not even distributed geographically. In the Sustainability First scenario, public and private organizations and nations cooperate to address social and environmental concerns at the global scale. This scenario entails an increase in resource consumption for developing countries to build up their infrastructure (Elshkaki et al., 2018; UNEP, 2017). In the Policy First scenario, similar goals to the Sustainability First scenario are pursued, but are enforced by highly centralized policies rather than emerging from a natural cooperation between the different actors. Markets are heavily regulated as to ensure that goods and services are not provided at the expense of key ecosystem services and overexploitation of non-renewable resources. In the Security First scenario, nations prioritize their own security and economy with small regards to other nations. More details on the four scenarios are provided in section S3 of the Supplementary materials.

In the next three subsections, we further interpret the egalitarian, individualist and hierarchist perspectives with regards to which GEO-4 scenario(s) might appeal to them the most given the socio-economic goals they are inclined to pursue, and consequently which resource management strategy they may tend to prioritize. The perspectives are attributed to organizations, nations or global scales. Fig. 3 presents the key determinants for the following analysis. The results of the analysis are summarized in Table 1. Complementary information and justifications underlying the rationale for linking specific resource management strategies to cultural perspectives are provided in sections S3 and S4 of the Supplementary materials.

The placement of elements on the graph is only indicative in order to compare between scenarios and perspectives. They do not refer to quantified metrics. The hierarchist perspective is best embodied in the Policy First and Sustainability First scenarios; the individualist perspective, in the Security First or Markets First scenarios (depending on upmost local interests: security or commerce); and egalitarian perspective, in none of the scenarios.

### 3.1. *Egalitarians*

Egalitarians value the long term over the short term, and are mostly interested in the global and long-term survival of the human population, with a minimal amount of burden shifting to future generations (Hofstetter, 1998; Huijbregts et al., 2017). They also view ecosystems as fragile and sensible to human interventions (Mamadouh, 1999; Thompson et al., 1990), and hence could argue that maintaining their integrity is primordial to support human life in the long run as they cannot be replaced (see Norton, 2002). Moreover, they are risk-adverse and view resources as prone to depletion (Hofstetter, 1998), accordingly with the pessimistic fixed stock paradigm (Tilton, 1996). Thus, the development scenario for egalitarians could align on strong sustainability principles, entailing the protection of irreplaceable ecological functions that contribute to human welfare, i.e. deemed to be critical natural capital (Ekins et al., 2003; Pelenc and Ballet, 2015). Hofstetter also noted that the egalitarian perspective closely aligns on strong sustainability principles (cf. Hofstetter, 1998, p. 68-69).

While we estimate the egalitarian strategy would focus on preserving the integrity of ecosystems rather than on a concerted mineral resources management, it can be expected that global social equity would be at the heart of an egalitarian resource management strategy. Therefore, we consider that egalitarians will favor a parsimonious access to resources combined with an efficient use in order to meet human needs globally, i.e. aiming for global sufficiency rather than local welfare. Hence, egalitarians may opt for a resource management strategy that reduces present consumption in the high-income countries, and favor an equitable access to resources required for the global long-term sufficiency in developing ones (cf. Figure S4 in the Supplementary materials). Accordingly, the political strategy archetype for egalitarians could be branded *social justice through sufficiency*.

### 3.2. *Individualists*

Individualists position themselves before others, both in space and time (Hofstetter, 1998). Thus, they are likely to aim for a maximal profitability for the current generation and locally. They are optimistic about technological developments and the capacity of future generations to adapt, and believe resources to be abundant (Hofstetter, 1998). Therefore, securing the organization's or nation's welfare and maximizing its profits in the short or midterm is expected to be of upmost importance to individualists.

At the organizational or national scale, individualists could incline to the Security First or Markets First scenarios depending on their upmost interests. If projected at the global scale, it can be estimated that

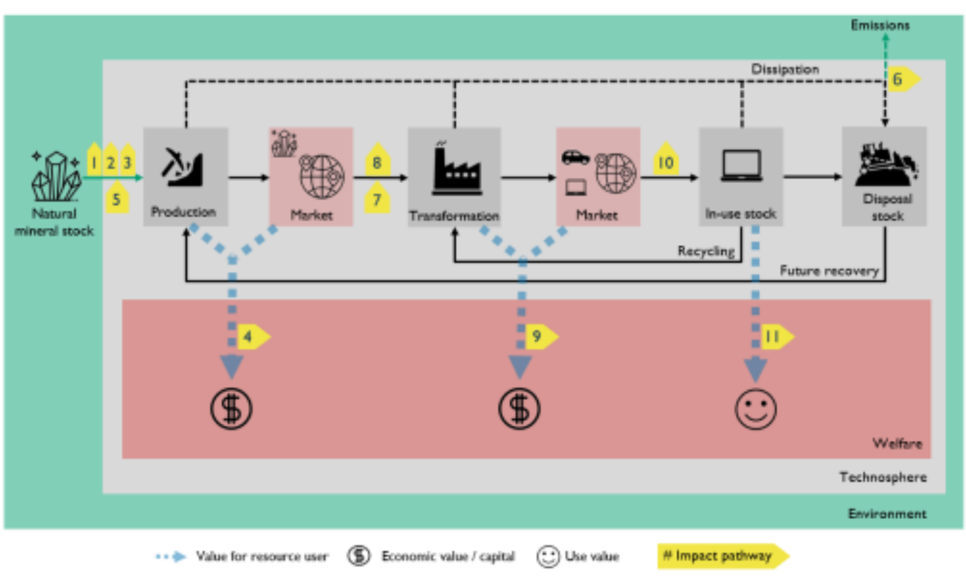


**Fig. 4.** Resource stocks and flows and their economic values and use values along supply chains, as well as eleven potential impact pathways linked to the AoP natural resources

individualists would aim to generate high resource-based welfare for the current generation. Still, one should note that the individualist perspective is inherently hardly compatible with global assessments as the interests of each subgroup are self-centered and primarily valued over that of others. We therefore estimate that individualists would most favor management practices that secure their own resource supply by means of economic and technological competitiveness, and that favor trade agreements, stockpiling, geopolitical relations, lobbying, etc. It can be observed that the individualist take on resource use is the most related to the current patterns on the accessibility to resources presented in section 2.2. Therefore, the political strategy archetype for individualists is branded *business as usual*.

### 3.3. Hierarchists

In a way, hierarchists may be thought of as a middle ground between the egalitarian and the individualist perspectives. They favor a fair and positive outcome for both current and future generations globally, and are optimistic on technological adaptation to sustain human welfare (Hofstetter, 1998). Hence, it can be estimated that hierarchists would attempt to maintain a balance between the development of the manufactured environment and environmental protection that tend to increase human welfare through space and time, i.e. by promoting the development of lower income countries while sustaining welfare in industrialized countries. Such development strategy generally aligns with weak sustainability principles, which contrasts with strong sustainability as it promotes technological progress as a means for human development and welfare, based on the assumption that natural capital can essentially be substituted with manufactured capital (Bullock, 2017; Ekins et al., 2003). Hofstetter also noted that the hierarchist perspective generally aligned with weak sustainability principles (-cf. Hofstetter, 1998, p. 68-69). This perspective is most compatible with UNEP's Sustainability First and Policy First development scenarios, that generally embody the 17 sustainable development goals (SDGs) of the UN (UN, 2015, 2012). Pursuing a global socio-economic development is commonly in line with propositions of the UN (see e.g. UN, 2018), UNEP's International Resource Panel (IRP) (see e.g. UNEP, 2017; IRP, 2019) and the World Bank (see e.g. The World Bank, 2020). Coherently, UNEP's Life Cycle Initiative is currently working on integrating SDGs in the life cycle sustainability assessment framework (Life Cycle Initiative, 2020).

The political strategy archetype for hierarchists could thus be branded *social justice through cooperation and development*. Balancing short-term development goals such as SDGs with longer-term sustainability objectives requires maintaining a balance between the socio-economic benefits of the production and consumption patterns and their environmental externalities. Strategies such as increasing resource productivity, circularity and efficiency are most typical when it is attempted to decouple resource consumption from human well-being. Nonetheless, it may imply to take smart decisions when weighting the benefits of these strategies with their own externalities (Allwood and Cullen, 2012; Pauliuk, 2018; Reuter et al., 2019).

## 4. Identification and classification of impact pathways

In this section, we systematically identify potential impact mechanisms and related LCIA methods addressing the impacts of mineral resource use on the AoP natural resources, building on the works of the MR Taskforce (Berger et al., 2020; Sonderegger et al., 2020). We also propose complementary pathways associated with the potential to make use of the economic and use values under a life cycle perspective, as seen in section 2. We then set-up a method allowing evaluating how well impact pathways fit cultural perspectives.

### 4.1. Existing impact pathways and associated LCIA methods

The MR Taskforce has identified seven aspects of mineral resource use that may be addressed with existing LCIA methods, in addition to which the taskforce proposed that dissipation should be considered (Berger et al., 2020). From these, we identified seven impact pathways that are related to making use of the value of resources (impact pathways #1-7, presented in Fig. 4 and Table 2 below). We considered that the pathway based on thermodynamics was not relevant. Moreover, we identified LCIA methods that may be relevant to assess each impact pathway, partly based on the recommendations of the MR Taskforce. Each of these methods are described in section S5 of the Supplementary materials.

Depletion (impact pathway #1) and dissipation (#6) both represent a reduction of the accessibility of mineral resources for future generations, that may reduce their potential to make use of the economic and use values of these resources. The former (#1) may be addressed with the ADP ultimate reserves method (van Oers et al., 2002; van Oers and Guinée, 2016) or the Crustal scarcity indicator (Arvidsson et al., 2020), and the latter (#6) with the Joint Research Centre's suggested approach (Beylot et al., 2021, 2020a), as well as the environmental dissipation potential (EDP) (van Oers et al., 2020), average dissipation rate (ADR) or lost potential service time (LPST) methods (Charpentier Poncelet et al., 2021c). The current over-extraction of mineral resources (impact pathway #2), the lowering ore quality (impact pathway #3), as well as the improper reinvestment of economic gains from the sale of mineral resources (impact pathway #4) may all lead to a reduced potential to make use of their economic value. Impact pathway #2 may be addressed with the Future Welfare Loss method addressing the lost economic value caused by unsustainable over-extraction (Huppertz et al., 2019); #3, with the surplus cost potential (SCP) method (Vieira et al., 2016); and #4, with the LIME2 endpoint method (Itsubo and Inaba, 2012). We considered the SCP method to be conceptually more relevant than the surplus ore potential (SOP) method (Vieira et al., 2017) regarding developments proposed in this article. Finally, global or regional short-term supply risk (impact pathways #5 and #7, respectively) may affect current resource users' potential to make use of the economic and use values of mineral resources. Impact pathway #5 addresses the mid-term physico-economic scarcity of mineral resources (Berger et al., 2020), and may be addressed with the ADP economic reserves method (van Oers et al., 2002; van Oers and Guinée, 2016). Impact pathway #7 represents short-term supply risk linked with geopolitical and socio-economic aspects (Berger et al., 2020), which can be addressed at the national scale using the GeoPolRisk method (Cimprich et al., 2019,2018; Gemechu et al., 2016) or at the global scale using the ESSENZ method (Bach et al., 2019, 2016).

### 4.2. Additional impact pathways

Accessing and using resources do not guarantee an optimal value creation amongst potential users over the life cycle of resources. The performance of resource-based welfare creation for their users can therefore be evaluated, as it influences the potential to make use of the economic and use values of mineral resources. It could include an evaluation of the current sustainability of the management and distribution of mineral resources amongst potential users (e.g. nations or supply chains) (impact pathway #8) and the efficiency of economic value creation along supply chains (#9), as well as the sustainability of the management and distribution of products amongst potential users (#10) and the efficiency of use value creation linked with the use of products for final consumers (#11). The assessment of impact pathways #8-11 should differ depending on each cultural perspective's socio-economic objectives. No existing LCIA method addresses these impact pathways. The eleven identified impact pathways are identified in Fig. 4 in relation to the flows of resources or values they may apply to.

### 4.3. Classification method for linking impact pathways with cultural perspectives

The relevance of impact pathways to the different cultural perspectives is evaluated with three criteria: the geographical scope, the temporal scope, as well as the implicit beliefs (e.g. capacity of future generations to adapt) and associated response (resource management strategy) underlying the pathway. We evaluated relevance with a four-grade scale (none/very low, low, medium and high). For example, we evaluated long-term depletion not to be relevant to individualists because they are not interested in the long term and tend to believe in their capacity to obtain ever more resources (or substitute depleted ones) thanks to technological solutions. The filled out evaluation grid is provided in section S4 of the Supplementary materials. Impact pathways that are evaluated with a none/very low for at least one criterion were considered not to be most relevant for that cultural perspective. We here acknowledge that, while we attempted to remain as objective as possible, our evaluation may have involved some degree of subjectivity, which could be a limitation of our study. Results and analysis are described in the next section.

## 5. Linkage of impact pathways with cultural perspectives

In the three sub-sections below, we discuss impact pathways that were evaluated to be most relevant to each cultural perspective. Results are synthetized in Table 2 and Fig. 5.

**Table 2**
Aspects of mineral resources and the related impact mechanisms most relevant to egalitarians, individualists and hierarchists

| Cultural perspective archetype | Relevant aspects of mineral resources | Question related to the impacts of mineral resource use (adapted from Berger et al., 2020) How do I quantify the… | Impacting flows (or other resource aspect, identified with an asterisk) | Potential impact mechanisms and damage | # impact pathways (fig. 4 and 5) | Potential LCIA methods (building on Berger et al., 2020) | Importance of the pathway with regards to the cultural perspective (low, medium, high) |
|---|---|---|---|---|---|---|---|
| **Egalitarian** | Preserve resources for future generations | … contribution of a product system to the depletion of mineral resources? (Berger et al., 2020) | Extractive flows | Extraction leads to depletion, reducing the future accessibility of resources, resulting in a lost potential for future generations to make use of the use value of mineral resources | 1 | ADP ultimate reserves, Crustal scarcity indicator | High |
| | | … contribution of a product system to the inaccessibility of mineral resources due to dissipation? | Dissipative flows & Hoarded and abandoned resources* | Dissipation (as well as hoarded and abandoned resources; cf. Dewulf et al., 2021) leads to the inaccessibility of resources, resulting in a lost potential to make use of the use value of the dissipated mineral resources | 6 | EDP, JRC suggested approach, ADR and LPST | Low-medium |
| | Efficiency of the use of resources with regards to pursuing global long-term sufficiency | … contribution of a product system to externalities (use value and economic value) in relation to mineral resource use, considering egalitarian socio-economic objectives? | Extractive flows | Current extraction leads to diminishing ore grades and increasing costs, resulting in a reduced potential to make use of the economic value of mineral resources | 3 | SCP | Low-medium |
| | | | Extractive flows | Current over-extraction of geological resources leads to lower total economic rent over time, resulting in a lost potential to make use of the economic value of mineral resources | 2 | Future Welfare Loss | Low-medium |
| | | | Inefficient resource use with regards to egalitarian socio-economic objectives* | Unequitable distribution of mineral resources and products, resulting in a lost potential for other potential users to make use of the economic value and use values of mineral resources | 8, 10, 11 | N/A | 8, 11: Medium 10: Low-medium |
| **Individualist** | Continuous accessibility to resources (organizational, national or global) | … potential accessibility issues for a product system related to short-term geopolitical and socio-economic aspects? (Berger et al., 2020) | Supply disruption/ supply risk* | Supply risk may generate an inaccessibility to resources (supply disruption), resulting in a lost potential to make use of the economic values of resources (also use values at regional or national scale) | 7 | Country or organizational level: GeoPolRisk Global level: ESSENZ | High |
| | Maximal supply & economic activity for | … potential availability issues for a | | Supply risk may generate an | 5 | ADP economic reserves | Low (if global scope deemed relevant) |

(*continued on next page*)

**Table 2** (*continued*)

| Cultural perspective archetype | Relevant aspects of mineral resources | Question related to the impacts of mineral resource use (adapted from Berger et al., 2020) How do I quantify the… | Impacting flows (or other resource aspect, identified with an asterisk) | Potential impact mechanisms and damage | # impact pathways (fig. 4 and 5) | Potential LCIA methods (building on Berger et al., 2020) | Importance of the pathway with regards to the cultural perspective (low, medium, high) |
|---|---|---|---|---|---|---|---|
| | current generation (global) | product system related to mid-term physico-economic scarcity of mineral resources? (Berger et al., 2020) | Supply disruption/ supply risk* | inaccessibility to resources (supply disruption), resulting in a lost potential to make use of the economic and use values of mineral resources | | (However, mid-term assessment according to MR taskforce) | |
| | Efficiency of the use of resources with regards to local short-term welfare | … contribution of a product system to externalities (use value and economic value) in relation to mineral resource use, considering individualist socio-economic objectives? | Inefficient resource use with regards to individualist socio-economic objectives* | Inefficient resource use limits the total amount of welfare generated for the current generation, resulting in a lost potential to make use of the economic and use values of mineral resources | 9, 11 | N/A | 9: Low at global scale, medium at national scale, high at organizational scale 11: Low to high (depending on nation's developmental state) |
| **Hierarchist** | Continuous accessibility to resources for sustainable development | … contribution of a product system to the inaccessibility of mineral resources due to dissipation? | Dissipative flows & Hoarded and abandoned resources* | Dissipation (as well as hoarded and abandoned resources; cf. Dewulf et al., 2021) leads to the inaccessibility of resources, resulting in a lost potential to make use of the economic and use values of resources | 6 | EDP, JRC suggested approach, ADR and LPST | High |
| | | … potential availability issues for a product system related to mid-term physico-economic scarcity of mineral resources? (Berger et al., 2020) | Supply disruption/ supply risk* | Mid-term supply risk may generate an inaccessibility to resources (supply disruption), resulting in a lost potential to make use of the economic and use values of mineral resources | 5 | ADP economic reserves | High |
| | Efficiency of the use of resources with regards to pursuing global welfare through development | … contribution of a product system to the (economic) externalities of mineral resource use? (Berger et al., 2020) | Extractive flows | Current over-extraction of geological resources leads to lower total economic rent over time, resulting in a lost potential to make use of the economic value of mineral resources | 2 | Future Welfare Loss | Low-medium |
| | | | | Current extraction leads to diminishing ore grades and increasing costs, resulting in a reduced potential to make use of the economic value of mineral resources | 3 | SCP | Low-medium |
| | | | | Insufficient re-investments of economic rent of resources, resulting in a lost potential to make use of the economic value of mineral resources | 4 | LIME2 endpoint | Low-medium |
| | | … contribution of a product system to externalities (use value and economic value) in relation to mineral resource use, considering hierarchist socio-economic objectives? | Inefficient resource use with regards to hierarchist socio-economic objectives* | Inefficient use of resources and sharing of economic activities along supply chains (e.g. unsustainable supply, non-cooperative distribution of resources and value chains, etc.), resulting in a lost potential to make use of the economic and use values of mineral resources | 8, 9, 10, 11 | N/A | 8: High 9, 11: Medium-high 10: Medium |

### 5.1. *Impact pathways most relevant to egalitarians*

Given their socio-economic objectives, egalitarians are more likely to esteem the use value of resources than their economic value generated along value chains. Nonetheless, they may look forward to an equitable distribution of the economic value generated from mineral natural capital globally (impact pathways #2 and 3). Moreover, given their aversion for risk-taking, their prioritization of equal opportunities for future generations, and their general alignment with strong sustainability principles, one aspect of mineral resource use that might appeal most to egalitarians is the depletion of long-term geological stocks (impact pathway #1). The total amount of resources that may be accessible in the long term accordingly with the egalitarian perspective could tend to be seen as relatively small in comparison to the total geological availability (cf. discussion in Drielsma et al., 2016). Hence, the most precautionary depletion assessment could consider a small fraction of the crustal content as a proxy for the total long-term resource accessibility. As endpoint damage, it could be attempted to quantify the lost potential use value for future generations related to the depletion of reserves. We here specify that egalitarians may only consider mineral resource use to be impactful to the AoP natural resources when it feeds product system's whose use values answer wants beyond sufficiency.

The wasteful use of resources, embodied in the concept of dissipation (cf. Beylot et al., 2020b; Zampori and Sala, 2017), could also be addressed by egalitarians as it may reduce the accessibility of resources for future generations (impact pathway #6). It would be relevant to take a long-term scope (e.g. 500 years) into account. The impact assessment of dissipative flows could thus be linked to a lost potential to make use of the value of resources over time, as proposed in the LPST method (Charpentier Poncelet et al., 2021c). Finally, egalitarians could aim to assess the unequal interregional accessibility to resources and their economic values and use values, resulting in an unequal accumulation of resources and capital, as briefly described in section 2.2 (impact pathways #8, 10 and 11).

### 5.2. *Impact pathways most relevant to individualists*

Given their socio-economic objectives and their focus on the short term, individualists are inclined to secure their own access to resources and to their values. Individualist organizations or nations may primarily attempt to secure their access to resources in order to generate economic value for their stakeholders (e.g. employees, shareholders, governments collecting taxes, etc.) and secure their accessibility to use values. If ever individualists are thought of at the global scale, it could be considered that they would attempt to maximize the current generation's welfare through uncontrolled production and consumption, with few regards to burden shifting to future generations. Therefore, it seems that supply risk methods would be of upmost interest to individualists (impact pathways #5 and 7).

As individualists aim to maximize their welfare regardless of burden shifting to future generations, they may also aim to maximize the efficiency of resource use, i.e. by maximizing the economic value and use values that is generated with a limited amount of accessible resources at once (impact pathway #9 and 11). Although it was not suggested by the MR Taskforce to address this specific aspect of resource use, the ESSENZ method also aims to measure the national resource efficiency. However, in the LCA context, measuring resource efficiency should rather be done at the product or organizational scales, since only these may be subject to LCA studies. No existing LCIA method measures resource efficiency at such scales. Still, some indication on resource efficiency can be calculated at the inventory level using existing approaches such as the Material Input per Service Unit (MIPS) (Liedtke et al., 2014). It could thus also be attempted to measure the efficiency of resource use of a product system in relation to the (economic) value generated by the functional unit in LCA.

Finally, the dissipation of mineral resources could potentially be a relevant aspect of the individualist assessment, especially for the scarcest or most critical ones. Nonetheless, individualists may consider that humans will be able to obtain ever more resources despite decreasing ore grades (e.g. for copper, see Gorman and Dzombak, 2020,

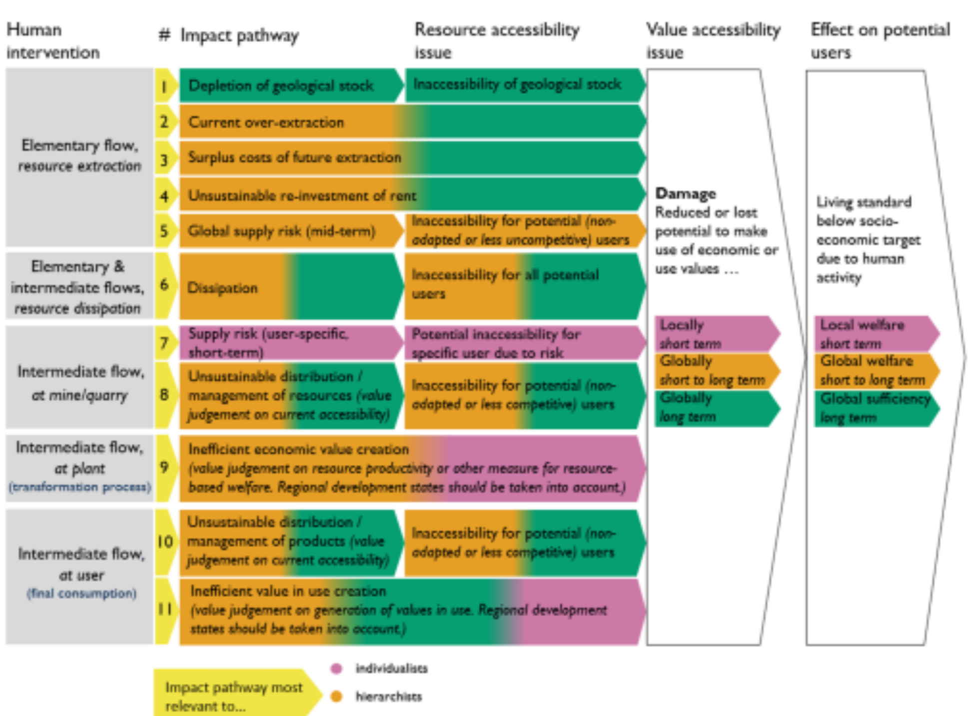


**Fig. 5.** Potential impact pathways related to mineral resource use, and the cultural perspectives they are most relevant to. The value accessibility issue is adapted from the definition of damage of Berger et al. (2020).

and Kerr, 2014), thanks to exploration and technological development. They may therefore estimate that dissipation is not so much of an issue to deal with. Therefore, if ever dissipation is assessed under the individualist perspective, it could tend to only account for the short-term dissipation of mineral resources for which there is a local supply risk (e.g. critical materials). We stress that some attention should be spent on establishing coherent development scenario and timelines when setting impact mechanisms between dissipation and the AoP natural resources under this perspective, alike for other perspectives.

### 5.3. *Impact pathways most relevant to hierarchists*

Hierarchists believe in the contribution of the man-made environment to increase human welfare; yet, they also acknowledge resources to be rather scarce and should be used efficiently. Given their inclination for concerted solutions to pursue global development, they are likely to aim for a secured accessibility, efficient use, and equitable sharing of mineral resources with regard to sustainability objectives (cf. section 3.3). A continuous access to both primary and secondary resources is required to support economic activities in high-income economies as well as the socio-economic development of low or middle income countries (Bringezu, 2015; UNEP, 2017, 2016).

In this light, one aspect of mineral resource use evaluated to be highly important to hierarchists is dissipation (impact pathway #6). Indeed, dissipation goes against the global objective of a more circular economy and increases the reliance on primary extraction, therefore putting pressure on geological stocks and compromising the accessibility of resources for future generations (Charpentier Poncelet et al., 2021c). Besides LCIA methods addressing dissipation, circularity indicators could also be relevant to consider as a positive image of dissipation methods (see e.g. Ellen MacArthur Foundation, 2019; Glogic et al., 2021; Niero and Kalbar, 2019). Moreover, given the general optimism of hierarchists regarding technological developments, they may consider that parts of the flows that have been made inaccessible today (e.g. resources stored in landfills or tailings) will become accessible again in within the timeframe relevant to their assessment (see e.g. Dewulf et al., 2021 and discussion of Charpentier Poncelet et al., 2021a). While such assumptions could possibly be implemented in dissipation-oriented methods, it should be kept in mind that impact assessment should provide signals and advices pointing towards sustainable technologies rather than assume it will happen by itself (Steen, 2006).

Regarding the accessibility to geological stocks, hierarchists could also be interested in the global mid-term supply risks linked with the depletion of mid-term reserves (impact pathway #5). For the endpoint damage assessment linked with potential accessibility issues (linked with dissipation and/or depletion), it can generally be expected that hierarchists would attempt to prevent the dissipation of resources that generate most economic and use values, that can hardly be substituted by other resources, and/or those most sensible to become depleted in the short to mid term. Therefore, dissipation methods could be complemented with depletion, economic and/or substitution models to measure the endpoint damage on the AoP natural resources. For example, methods such as the anthropogenic extended ADP (AADP) (Schneider et al., 2015, 2011) could provide useful information on the global scarcity of resources to be matched with dissipation rates as measured with the ADR method.

Additionally, hierarchists would aim to generate sustainable value from the extraction (impact pathways #2-4), transformation and use of mineral resources (impact pathways #8-11). They could aim to increase the efficiency of resource use with regards to pursuing sustainability objectives in a cooperative way amongst organizations and nations, accordingly with the Sustainability First or the Policy First scenarios. For example, they could assess the sustainability of the sourcing of raw materials (see e.g. conflict-free minerals: Young, 2018), or the efficiency of the re-investment of the rents into local sustainable development (see e.g. the *Breaking New Ground: Mining, Minerals and Sustainable Development* report: IIED, 2002, and the Extractive Industry Transparency Initiative: EITI, 2019). Yet, addressing such aspects of resource use fall outside of the traditional LCA framework, and we leave these aspects open for discussion and future developments to come.

## 6. Discussion and conclusions

Resources and values are two sides of the same coin and hence cannot be assessed dissociated one from another: managing the accessibility to resources determines which potential users may benefit from their economic value and use value. Depending on one's cultural perspective, different management strategies may be established because they pursue different socio-economic objectives (cf. Table 1). Consequently, different aspects related to mineral resource use may be most relevant to each of them (cf. Table 2). Our analysis allowed identifying eleven potentially relevant impact pathways, but more may be needed to cover different socio-economic objectives for each perspective. Out of these, seven may be most relevant to egalitarians, three to individualists (which vary based on the geographical scope of their assessment), and nine to hierarchists, as identified in Fig. 5.

The classification of impact pathways by cultural perspective and their association with existing LCIA methods (Table 2) may orientate the selection of LCIA methods to be used by practitioners depending on their beliefs and on what they value (i.e. which cultural perspective fits them best; cf. sections 3 and S3 of the Supplementary materials). The classification helps ensuring a more holistic coverage of the potential impacts related to mineral resource use fitting a specific view of the world. It also proposes a generic hierarchisation of the impact pathways for each perspective in such a way that it may provide some indications for weighting if ever multiple impact pathways are addressed altogether in one same LCIA method to assess the impacts of mineral resource use on the AoP.

We noted that existing LCIA methods may be used to address impact pathways 1 to 7. However, aside the Future Welfare Loss, SCP and LIME2 endpoint methods, LCIA methods considered for this analysis only allow quantifying midpoint impacts. Also, impact pathways 8 to 11 are not addressed by existing methods. Interestingly, they could be thought of as relevant only in the context of social or economic assessment, or in the englobing Life Cycle Sustainability Assessment (LCSA) (Dewulf et al., 2015). Yet, while these pathways may originate from flows that are not addressed within the traditional environmental LCA framework, we have demonstrated that they also relate to the safeguard subject defined by the MR Taskforce and hence may deserve consideration. These impact pathways involve value judgements on the current accessibility to resources depending on socio-economic objectives considering regional needs. Indeed, the effects of an inaccessibility to mineral resources for different potential users depends on their specific socio-economic context, and it could be needed to assess these in an analogous way to the regional vulnerability when assessing the impacts of water use linked to the AoP human health (Boulay et al., 2011).

For instance, mineral resources that are used in the upmost optimal way considering specific cultural socio-economic objectives may be considered as having no impact under that same cultural perspective's assessment (impact pathways #8-11). Conversely, resource use may be perceived as impactful under some perspectives when they allow to fulfill *excessive* wants, where *excessive* depends on the perspective. Therefore, socio-economic objectives should be kept in mind if ever LCIA methods are to be developed. Addressing impact pathways #8-11 might therefore involve contribution analyses of supply chains, including processes and products, to the local or global welfare through the economic value and use values they generate. The developments proposed in this article reinforce the relation of the AoP natural resources to socio-economic rather than strictly environmental considerations, which is required if resources are to be managed appropriately under a given world view.

Many flows to be characterized are not elementary flows, which was also highlighted as a challenge to overcome for supply risk methods (Berger et al., 2020). Nonetheless, some of the studied LCIA methods already aim to quantify flows in the technosphere (intermediate flows or economic values), while their characterization factors so far apply to extraction flows: it is the case for the ADR, Future Welfare Loss, LIME2 endpoint, LPST and SCP methods. This trend puts forward the necessity to delve into intermediate flows if it is attempted to assess the damage on the AoP natural resources exhaustively, because it is where the mineral resource-based value (as defined for the AoP natural resources) happens.

We propose that all of the LCIA methods should be linked to an endpoint damage considering economic and use values for specific users, although we acknowledge that quantifying such values may be challenging. Following this proposal, additional developments would be required to assess resource accessibility issues, value accessibility issues, and eventually effects on potential users, as depicted in Fig. 5. Indeed, it can be noted that existing impact pathways link the effect of water shortages to regionalized aspect of human welfare (i.e., human health) (Boulay et al., 2011). The economic value of resources on markets could be used as a proxy to estimate the lost economic value, as suggested by the JRC to estimate the lost economic value due to dissipated flows (Beylot et al., 2020a). However, market prices are unlikely to represent the actual economic value generated along supply chains, and even less so to represent the use value. Moreover, price may only partly take into account other relevant information such as the scarcity and substitutability of resources (Ecorys, 2012; Henckens et al., 2016). Thus, alternative approaches measuring the value-added of metal flows in specific regions or globally (e.g. based on input-output tables: see Beylot and Villeneuve, 2015 and EXIOBASE3: Tukker et al., 2018) could provide a more exhaustive assessment of the economic value of resources as defined in this paper. At this time, methodological developments are needed to combine dissipation and depletion methods with economic value, use value, and/or substitution evaluations. Finally, a joint assessment of damage including the values obtained from ecosystems would be necessary to take into account the different cultural perspectives holistically.

Methodological choices underlying LCIA methods within a given perspective should be consistent. For example, there has been numerous discussions on the most relevant geological stock to safeguard (Drielsma et al., 2016b; Pradel et al., 2021; Steen, 2006; van Oers and Guinée, 2016), and we here suggest that the stock and LCIA model in question should match with the cultural perspective's view of technological development and its tolerance for risk. For instance, the assessment of depletion under the egalitarian perspective could consider the total amount of accessible resources in the long term to be better represented by the reserve base or economic reserve of each element, as assessed with the ADP reserve base and ADP economic reserves methods, rather than ultimate reserves. Furthermore, the same reference stocks should be utilized for the assessment of other impact categories (e.g. for depletion and surplus cost) in order to remain consistent amongst the multiple impact pathways under a given perspective.

Additional topics that may deserve further attention for method development were identified throughout our analysis. Characterizations factors could be calculated differently for different mineral resources under different perspectives, depending on the functions they may have for humans in the technosphere. For example, technology metals may be more valuable to hierarchists than to egalitarians. In a similar way, individualists could rely on supply risk (or criticality) assessments that take the current economic importance of resources into account (see e.g. Graedel et al., 2012 and Sonnemann et al., 2015). Moreover, the measurement of dissipative flows may also become part of supply risk assessments (Helbig et al., 2020), since dissipative flows may increase the industry or a nation's dependence on the supply from third parties. For the opposite (yet complementary) reason, recycling was integrated in the GeoPolRisk method (Santillán-Saldivar et al., 2021). Finally, it could be useful to improve the definition of impact pathways with regards to sustainability objectives such as SDGs, as undertaken by the Life Cycle Initiative (2020).

As concluding thoughts, we would remind that LCA is a value-based tool dedicated at supporting design and engineering decisions in the industry, at communicating the environmental profile of products, and at supporting policy-making: it can be expected that professionals or policy-makers in organizations making use of LCA are typically interested in generating resource-based socio-economic value in the short term, which rather fits the individualist or hierarchist perspectives. Preserving the geological stocks, especially for the long term, is not much relevant in either's agenda (Drielsma et al., 2016a). Moreover, challenges awaiting humanity in light of on-going environmental changes and the ever-increasing needs of the still growing global population, as articulated in the SDGs, make it more difficult to defend the egalitarian paradigm today than it was a few decades ago. This situation has led to the development of multiple resource indicators, that were here associated to different impact pathways and cultural perspectives in order to provide guidance to life cycle assessment practitioners when deciding which LCIA methods may be used altogether to assess the impacts of mineral resource use depending on what they value.

## CRediT authorship contribution statement

**A.C.P:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization. **A.B.:** Conceptualization, Writing - review & editing. **P.L.:** Conceptualization, Methodology, Investigation, Writing - review & editing, Visualization. **B.L., S.M., J.V., G.S.: Writing - review & editing.**


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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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## Supplementary materials

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