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Evaluating resource efficiency at major copper mines

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ABSTRACT

Resource efficiency is both, a scientific concept in sustainability assessment and a policy concept that aims to achieve maximum extraction of resource materials from a mineral deposit at minimum waste production. Presently, established proxies for resource efficiency use weight-based measures of a system's materials consumption However, such proxies are not directly applicable to mining operations. This study introduces a new method and associated techniques for the evaluation and quantification of resource efficiency in mining operations. This approach considers intensities in land, water, energy and mineral deposit consumption (i.e. specific resource consumption to produce one unit of output). Applying this new methodology, resource intensities have been assessed and quantified for 22 major copper mines. Results have allowed relative ranking of these mines in terms of resource efficiency. This work also demonstrates that deposit properties and its geographic location impact on resource efficiency. Consequently, political measures, needed to promote resource efficiency in mining, should focus on region-specific aspects and the properties of the mined ore deposit.

1. Introduction

Resource efficiency is a concept that focuses on the responsible consumption of natural resources. In a policy context, the concept aims to use the planet's limited natural resources in a sustainable manner, while minimising the negative impacts of resource usage on the environment (European Commission, 2011). However, a broadly accepted definition of "resource efficiency" has not yet been established (Huysman et al., 2015). In general, resource efficiency evaluates the relationship between a systems resource input and its (beneficial) output. Ratios of input and output, such as resource intensities or (their reciprocal values) resource productivities, are commonly used as measures of efficiency. The output of a production system is a product or service, which can be measured using physical or monetary metrics. Expressing the input of natural resources in physical metrics (e.g. weight or volume) is a well-established approach.

The suitability of metrics and indicators depends on the chosen system boundaries and research perspective (e.g. global, domestic, company or product). As a provisional lead indicator for comparing resource efficiency of countries, the EU uses Gross Domestic Product (GDP) divided by Domestic Material Consumption (DMC), while admitting the need for developing more suitable indicators (European Commission, 2011). The DMC approach aggregates different materials based on their mass, which represents the use of implicit weighting (equal importance of mass). To overcome this arbitrary weighting, environmental weighting of material consumption has been proposed (van der Voet et al., 2005). The World Resources Forum discusses the development of a resource efficiency index of nations considering materials, water and land indicators combined by explicit weighting (Tukker et al., 2015). In the manufacturing industry the assessment of resource efficiency is frequently associated with energy and material efficiency (e.g. Kitajima et al., 2015; VDI, 2016), following the rationale that reducing material consumption will reduce stress on natural resources in the upstream supply chain.

In mining, resource intensities such as water and energy intensities are established indicators to characterise resource efficiency. In the literature, intensities for copper mining (Northey et al., 2013) as well as for gold and uranium mining (Mudd, 2010) have been reported. A growing database on the energy consumption in the comminution of gold and copper ores allows benchmarking of this isolated process while incorporating grind size and ore grades (Ballantyne and Powell, 2014).

Expressing resource intensities separately by category of natural resources or individually for certain processes provides a good overview of different dimensions and drivers of resource efficiency, but it does not allow a ranking of entire mines, unless there is a real dominance relationship. A generally accepted index on resource

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efficiency in the mining industry has yet to be established. The aim of this project is to develop a method for aggregating an index on resource efficiency, allowing a ranking of mines or technical design alternatives within a mining operation, based on a single score. The calculation method needs to be comprehensible and easily accessible, in order to be widely recognised. Additionally, it should enable mining companies to derive operational objectives from the calculated scores.

2. Method development

The method used in this study assesses the relative efficiency of mines by comparing them to other mines that produce the same main metal commodity. The study considers extraction and mineral processing activities, as those processes are typically performed on site. Thus the mine site defines the system boundary of this assessment. A concentrate is usually the first tradable product in the process chain. Consequently, this material was set to be the standard output. Allocation adjustments were made to incorporate differing forms of products (e.g. cathodes) and by-products. As mining takes place at the beginning of a product's life cycle, the perspective can be classified as "cradle-to-gate".

Resource efficiency indicators used in this work focus on direct inputs. The major advantage of input orientation is its increased measurability, when compared to concepts focusing on subsequent outcomes (impacts) in the causality chain (Geibler et al., 2016). According to the framework presented by Huysman et al. (2015) this approach can be classified as "resource efficiency at flow level". The primary benefits of the mining process are considered to be proportional to the amount of valuable content in the products (e.g. metal content in concentrate). Physical mine production was used instead of product value for two reasons. Firstly, mine production is a more constant measure, while product value changes significantly during economic cycles in commodity prices. Secondly, it enables the application of the indicators in further modelling like life-cycle assessment.

The method developed in this study combines technical indicators, which are publicly available, with expert opinions (panel method with explicit weighting) on the relevance of each resource category. The indicators considered are based on inventory flows, as these are accessible, measurable, almost uniformly understood worldwide and well-established in the mining industry. The method stops modelling at an early midpoint and does not examine environmental impact categories or the stress on natural resources, thus leaving such considerations of further effects to the panel judgement. When considering more than one criterion weighting is unavoidable, while explicit weighting is superior to implicit weighting (Huppes et al., 2012).

The general structure for aggregating an index is presented in the information pyramid in Fig. 1. The primary raw data are derived from measurements usually carried out by or on behalf of the mining company. Processing these data yields annualised inventory flows. Information disclosed in sustainability reports is usually on the level of inventory flows or on the level of mathematically manipulated inventory flows, which makes them indicators.

For the numerical aggregation of resource intensity indicators, the Analytical Hierarchy Process (AHP) was applied. It is an established technique for multi-criteria decision making (MCDM) for complex problems (Velasquez and Hester, 2013), which has been broadly applied in environmental analysis of mining operations (e.g. Fukuzawa, 2012; Rikhtegar et al., 2014; Shen et al., 2015). It helps to structure and analyse a problem, by breaking it down to simple pairwise comparison judgements and tests on the consistency of the judgement. The general principle and the mathematical background of AHP can be found in Saaty and Vargas (2012). As the aim of the study was to evaluate resource efficiency in mining, resulting in a ranking of mines, there is no direct decision making associated with the analysis (i.e. choosing the most resource efficient mine for sourcing of copper concentrate). However, the ranking of mines provides a basis to support further decision making.

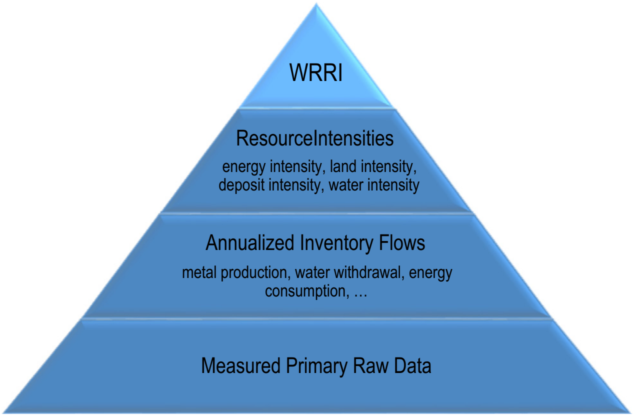

Fig. 1. Information pyramid for evaluating resource efficiency (WRRI = Weighted Relative Resource Intensity).

In this study, resource intensity RI_{ij} of a mine i in resource category j has been defined as the quotient of resource consumption RC_{ij} over metal production P_i (Eq. (1)). Metal production in the scope of this assessment refers to metal content in concentrate. For polymetallic mines metal equivalents of the primary metal are applied, using allocation by long term (e.g. 5 years) economic values.

$$\frac{RC_{ij}}{P_i} = RI_{ij} \tag{1}$$

Resource intensities (RI), which are measured in diverse physical metrics, require normalisation in order to yield compatible values (on a common scale). Normalised RI are obtained by dividing the specific RI by the weighted arithmetic mean of RI over all mines $i = 1,\ldots,n$, as seen in Equation (2)). This normalised value can be considered to be the relative resource intensity $RI_{ij,rel.}$, expressed in percent of the peer groups' average value. The weighted arithmetic mean is obtained by weighting RI by mine production. Taking mine production into account for weighting, sets the average of total production as the benchmark, thus reducing sensitivity of the results towards the incorporation of additional (small) mines into the scope of the assessment.

$$RI_{ij,rel.} = \frac{RI_{ij}}{\overline{RI}_j} \tag{2}$$

$$\overline{RI}_j = \frac{\sum_{i=1}^{n} RI_{ij} * P_i}{\sum_{i=1}^{n} P_i} = \frac{\sum_{i=1}^{n} RC_{ij}}{\sum_{i=1}^{n} P_i} \tag{3}$$

The score of the index, which is denoted as Weighted Relative Resource Intensity (WRRI), is the sum of the relative resource intensities multiplied by their respective weighting factor w_j. Based on AHP, the weighting factors are derived from the principle eigenvector of a pairwise comparison matrix. As they are normalized, the weighting factors sum up to one.

$$WRRI_i = \sum_j w_j * RI_{ij,rel.} \tag{4}$$

$$\sum_j w_j = 1 \tag{5}$$