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Exergy cost allocation of by-products in the mining and metallurgical industry

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ABSTRACT

In the mining and metallurgical industry, with each ore, products, by-products and wastes appear. Allocations among products when one or more by-products come about in a mining or metallurgical process are based either on tonnage or on commercial prices. Both ways of allocating costs entails disadvantages that are analysed in this paper. Besides a rigorous way to allocate costs among non-fuel minerals through the exergy replacement costs is proposed. Particularly, 33 different mineral deposit models where 12 coupled products are obtained have been analysed. Results show that the average difference between the economic approach and the exergy approach range from 0% to 30%. The highest difference is presented in metals such as copper, nickel and cobalt. Therefore, as a case study, exergy cost allocation was applied to copper and nickel production with its respective by-product (cobalt). The results suggest that if exergy replacement cost is applied, cost allocation values are similar to those obtained via the price indicator. This supports the idea that the exergy replacement cost is very close to the value society places on minerals. That said, contrarily to prices, exergy replacement cost does not fluctuate with external factors linked to market mechanisms but remains constant.

1. Introduction

The long-term availability of mineral resources is a key factor to satisfy human activities, technology and economic activity, including those metals that are generally not the primary production of mines, such as copper or nickel, but instead are mined as by-products during the mining of primary ores. In this regard, mining industry is confronted with the difficult and often rather complicated problem of assigning costs to their by-products and joint products, which have highly complex demand/supply and technology and investments requirements.

The availability of by-product metals depend on the available technology to recover those metals during or next the processing of host metal ores, as well as on the economic profit of by-product metal recovery. Mudd et al. (2013) proposed a set of parameters in order to evaluate by-product metal availability such as: (1) size and type of the by-product metal ore bodies; (2) the characteristics abundances of by-product metals in the host or hosts; (3) the typical recovery efficiencies for these by-product metals (mainly the different technologies used); and (4) models of the relative costs and benefits of by-product metal recovery. However, in the latter parameters there is a missing one related with energy consumption of by-product metals.

Otherwise, conventional Life Cycle Assessment (LCA) software usually performs allocations among products based either on tonnage or on revenue (commercial prices). Both ways entail many disadvantages, such as introducing subjectivity with price or underestimating burden for certain by-products when the tonnage is low. Specifically in the Ecoinvent database, the by-product allocation problem (the joint production of silver and lead, for instance) is undertaken by a subdivision of the sub-processes. The starting point for the estimation depends on the general profit expectations of the company, considering an arbitrary performance value of 10%. Hence, the allocation factors are based on revenue but these values are corrected by mass in order to keep up with the resource balance in the final commodity. Consequently, allocation methods are confronted with the difficult and often rather complicated problem of assigning costs to their by-products and joint products.

Furthermore, LCA uses computer software and database like Ecoinvent (Classen et al., 2007), which contains a very broad data on energy supply, resource extraction, raw material supply like chemicals, metals, explosives or water. However, most of such databases consider regional averages of environmental impacts associated with mineral processing, with arbitrary allocations among those

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Table 1
Cost allocation of Cu–Au–Ag deposits as a function of tonnage, price and ERC.

Deposit type	Porphyry Cu–Au				Cu skarn				Epith. quartz-alunite Au			
	Ton. [%]	Price [%]		ERC [%]	Ton. [%]	Price [%]		ERC [%]	Ton. [%]	Price [%]		ERC [%]
		1980	2006			1980	2006			1980	2006	
Copper	99.96	56.6	81.3	70.3	99.86	43.3	73.3	46.1	98.9	3.1	9.5	5.3
Gold	0.01	38	17.4	28.2	0.01	40.3	21.7	50.0	0.3	90	86.7	92
Silver	0.03	5.4	1.4	1.5	0.13	16.3	5	3.9	0.7	6.9	3.8	2.7

operations using raw materials, hydro, gas, coal or nuclear generated electricity, or those occurring in different countries, or even any variations from process to process. In this way, authors like Yellishetty et al. (2009) have conducted a critical review of existing LCA methods in the minerals and metals sector in relation to allocation issues related to indicators of abiotic resource depletion, concluding that LCA issues of minerals and metals need to be investigated further to get more understanding, to facilitate the future use of LCA as a policy tool in the mining sector and increase objectivity with more scientific validity.

Aware of this problem, the authors propose in this paper a new cost allocation factor based on the exergy of by-products. The final aim is to estimate the energy consumption and eventually economic, technology and environmental bearings of each commodity produced. The novelty introduced with respect to what is already being done in conventional Thermoeconomic analysis is that when non-fuel minerals come into play, allocation is carried out through the so called exergy replacement costs (ERC) instead of through chemical exergy. In this way, the scarcity factor of minerals is taken into account.

Particularly, this paper analyses 33 different mineral deposit models where 12 joint products and by-products are obtained. This models are described in tables (e.g. in Table 1 “Porphyry Cu–Au”, where the products are: copper, gold and silver). Additionally, as a case study, exergy replacement cost allocation is applied to copper and nickel production taking into account their respective by-products.

1.1. Mineral deposit models

A mineral deposit is a concentration of a mineral of sufficient size and grade that might, under the most favorable circumstances, be considered to have economic potential. Once the mineral deposit has been explored and is known to be of sufficient size, grade, and accessibility to be producible to yield a profit, it becomes an ore deposit. A mineral deposit model is the systematically arranged information describing the essential attributes (properties) of a class of mineral deposits (Cox and Singer, 1992).

A comprehensive study of average ore grades was undertaken by Cox and Singer (1992). In their study, a compendium of geologic models was presented, including 85 descriptive models identifying attributes of the deposit type and 60 grade-tonnage models giving estimated pre-mining tonnage's grades from over 3900 well-characterized deposits all over the world. The average grade ($\bar{x}_m$) of the different mineral deposits analyzed is calculated with Eq. (1), taking into account the tonnage (M) and ore grade (x_m) of each model and the number of deposits containing the mineral under consideration. Tables 1, 2, 4–6 and Tables A.10–A.18 are calculated with the mean average grade and tonnage of each deposit type.

$$\bar{x}_m = \frac{\int_0^M x_m dM}{\int_0^M dM} \qquad (1)$$

Such models will serve us to demonstrate why the allocation model presented in this paper is more suitable than conventional approaches using tonnage or economic values.

1.2. Joint products and by-products in the mining industry

Products produced at the same time are classified as joint products or by-products, generally driven by the importance of the different products to the viability of the mine (PWC, 2012). Distinctions are often made among main products that produce most of a mine's income, joint products that generate similar shares of the return and by-products that make minor contributions (Gordon and Tilton, 2008). The same metal may be treated differently based on differing grades and quantities of products (Hansen et al., 2009). Accordingly, the carrier element can in some cases be only the secondary material being recovered since the minor elements are of much higher economic value. The decision as to whether these are joint products or one is only a by-product is important as it may affect the allocation costs.

As previously explained, more than one metal is commonly produced by the same mining and refining processes. Metals such as lead and zinc are commonly found together; silver is often found with gold. These are only two examples of the many joint products that Nature provides. Each carrier commodity metal is associated in Nature (geology) by a distinctive mix of valuable minor elements. The latter has led to metallurgical processing being sharpened to effectively recover most elements economically (Verhoef et al., 2004).

By-products are known also as companion metals (Mudd et al., 2013) (e.g. cobalt, molybdenum, rhenium, selenium, germanium, gallium, tellurium and indium). Although these metals often have economic and technological importance, the economic driver for mining here is undoubtedly the major metal. Sometimes, by-products can be mined as target metals on their own if they occur in elevated concentrations (e.g. cobalt, bismuth, molybdenum, gold, silver, PGMs and tantalum) or if demand exceed the supply available.

2. Approaches to allocating joint cost

Cost allocation of mineral resources is not a simple task, due to the fact that it must be performed on the best possible reasonable basis. A systematic and rational basis of cost allocation should be applied when the costs of a product are not separately identifiable (PWC, 2012). Joint costs are the total of the raw material incurred up to the initial split-off point. The split-off point is the point at which the joint products become separated and identifiable. Joint cost allocation is based on the proportional values of the products at the split-off point. Separable costs, meanwhile, are those costs incurred after the split-off point and can be easily traced to individual products. For instance, if a given ore contains both iron and zinc, the direct material itself is a joint product. Since neither zinc nor iron can be produced alone prior to the split-off point, the related processing costs of mining and beneficiation, crushing, and splitting the ore are also joint costs (PWC, 2012).