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Gold from copper mining as a case study for allocation in life cycle assessment

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Abstract

Allocation in multi-output life cycle assessment (LCA) systems has been extensively discussed in literature. Common approaches to address allocation include system subdivision or expansion, physical cause-and-effect relationships, and distribution based on allocation factors such as product mass or revenue. In this study, we critically examine these allocation methods using the example of the Finnish copper–gold mine Kevitsa. We demonstrate that the prioritization of allocation methods prescribed by ISO 14044 is often inapplicable. We argue that this issue is partly rooted in the strong association of LCA with natural sciences, such as environmental science, toxicology, mathematics, and physics. This alignment frequently results in allocation choices that fail to reflect the benefit of the product system, as benefit is not an inherent property of a material but rather a subjective preference within the economic system. For illustration, we use CO_2 as a numerical example in one impact category, though allocation plays an equally important role across all impact categories. Moreover, we contend that for processes producing a primary product alongside valuable by-products, a case differentiation instead of a rigid hierarchy should be considered—a perspective not adequately captured by the current allocation standard. We advocate for a more transparent and comparable allocation framework in LCA that prioritizes the benefit of the product system over strict adherence to natural laws.

1. Introduction

A simple 18-karat gold ring weighing approximately 4 g contains about 3 g of pure gold. In some of the world's highest-producing gold mines, such as Olimpiada or Grasberg, the ore grades are typically around 2 g-Au t^{-1} ore. This implies that to produce a single gold ring weighing just four grams, small enough to be worn on a finger, approximately 1.5 tons of ore must be extracted. This figure excludes the additional overburden and gangue material that must also be moved. By contrast, to produce an equivalent mass of copper, only 0.5 kg of ore is required, assuming a copper grade of 0.6%. It is also common for mines to extract multiple metals simultaneously, such as copper and gold, making them multi-output operations. Around 10% of the gold production between 2018 and 2021 came from copper mining, i.e. mainly from porphyric deposits [1]. Furthermore, at least 44% of the global copper mining production is associated with gold [2].

The extraction of such a vast amount of rock for a small quantity of gold comes at a significant environmental cost. Large-scale mining operations necessitate the excavation of deep shafts or the creation of expansive craters, processes that require substantial energy inputs. Additionally, the extraction of gold often involves the use of toxic chemicals, such as cyanide or mercury. The process also demands considerable amounts of water and the use of explosives, further exacerbating the environmental impact.

In response to growing consumer awareness regarding the environmental and ethical implications of gold production, there has been an increasing demand for transparency in the origins and production methods of gold. The gold industry has responded to this trend, with jewelry companies offering 'green' or 'fair' gold, certified by various eco-labels.

One effective method for generating the data required to compare the environmental impacts of different mines and metals is life cycle assessment (LCA). LCA is a well-established methodology used to evaluate the environmental impacts associated with all stages of a product's life cycle. One widely recognized application of LCA is in the assessment of climate impacts, often expressed as CO_2-equivalents (CO_2eq).

SKARN Associates provides a comprehensive database that includes information on energy demand and climate impacts for more than three thousand mining assets producing various metals, including gold, copper, and nickel [3]. A closer examination of the SKARN database reveals that the same mining assets, such as Grasberg, exhibit higher total environmental impacts in the copper database compared to the gold database, with climate change impacts being approximately 1.4 times greater. This discrepancy is primarily due to the allocation methods employed.

Allocation in LCA refers to the process of distributing environmental burdens across the different products generated by a production system. For instance, if livestock farming is responsible for 9% of global greenhouse gas emissions, how should these emissions be apportioned among meat, milk, and leather [4]? Similarly, in metal production, whether from mining or recycling, production systems often yield multiple metals. Therefore, the analysis and application of allocation methods in multi-output systems are crucial for ensuring the accuracy and relevance of environmental assessments and sustainability strategies within the metals and mining industry [5, 6].

The problem, that is also responsible for the aforementioned curiosity in the SKARN database with different impact results for the same mine for different products, stems from the different ways of dealing with these multi-output systems. Different allocation methods have been debated since the 90s [7–11]. In 1997, LCA was standardized by DIN EN ISO 14040 and 14044.

The DIN EN ISO 14044:2021-02 (all references to ISO 14044 in this work, unless stated otherwise, refer to this version) defines three steps for co-product allocation. These steps are in ascending order solving of the system's multifunctionality by subdivision or system expansion. Allocation of unwanted in- and outputs to the specific causes of these outputs via physical laws. The last step, according to ISO, if the prior two have failed, is to allocate the environmental impacts based on distribution keys to the products.

The ISO 14044 is widely accepted as guidelines for allocation in the metals industry, as can be seen in a study by PE INTERNATIONAL on behalf of 16 different industry associations in the field of metals and mining [12]. Additionally, a study by Lai *et al* found that of 27 LCA studies in the field of metals and mining, economic allocation was most widely used, while only two studies used allocation methods not covered explicitly by the ISO 14044 [5]. Furthermore, the authors applied five allocation methods to a Cu–Zn–Pb–Ag mine. The study found that using production costs instead of product prices yields similar results, but they claim that this method might be more robust as it is not dependent on volatile economic prices.

Nuss and Eckelman highlight significant differences for many metals between mass and economic allocation, as well as the relatively low influence of different time spans used for moving-averages of the prices [13]. A review of LCA studies in the metals and mining industry by Santero and Hendry identified several areas of alignment, including allocation [6]. Their tables 1–3 present different allocation recommendations depending on the type of metal, data availability, and product mix. The authors argue that economic allocation captures the driver of the mine, which is making profit. This was also described more generally and not tailored for metals and mining by numerous other studies [14–16]. Many studies additionally suggest using economic allocation when the prices of the products are differing vastly [12, 14, 17–19]. In their case study, Fernandez *et al* applied four different allocation methodologies to an ironmaking process co-producing zinc and slag [20]. To demonstrate the practical implications of the allocation problem, the authors explain differences in the interests of co-product users and producers regarding their choice of allocation methods. They could not find an allocation method that is a good compromise for producers' and consumers' needs. Some studies commonly advocate for harmonizing allocation methods for co-products to achieve more comprehensive and reliable LCA results [5, 6, 20].

The authors of the presented paper share the view that the ISO standard, which remains widely used and frequently cited to justify allocation decisions in LCA, inadequately addresses the core issue of allocation—specifically, the challenge of assigning costs (e.g. environmental impacts) to benefits (e.g. products). The hierarchy of allocation methods recommended by the ISO standard prioritizes so-called 'physical allocation methods' over alternatives such as economic allocation. This prioritization likely reflects the influence of engineers and natural scientists within the LCA community and the ISO, who tend to favor a 'natural law' or, rather, an objective view [21, 22].

The following study does not seek to reach a definitive conclusion; rather, its objective is to provide a concise summary of the key methodological issues pertaining to economic allocation while also offering a comprehensive overview of the current state of the debate. Moreover, it looks at different allocation methods using the impact on climate change from copper–gold production as a prime example and tries to answer the following question: How do allocation methods in LCA, which aim to establish objective rules, represent product systems that are primarily operated for economic reasons (e.g. copper–gold mining), particularly given that economic benefit is not an inherent property of a material but rather a subjective preference within the economic system?

2. Materials and methods

2.1. Solving multi-functionality in LCA

In metals and mining LCA, it is common to encounter systems with multiple products. These systems include ores containing multiple metals that are extracted and refined by mines and smelters or electronic devices containing various metals that are recycled and refined from waste electrical and electronic equipment (WEEE). In these cases, the environmental impacts are jointly caused by all products, but often the aim is to determine the environmental impact of a specific product.

According to ISO 14044, the methods to address the multi-functionality of LCA systems are divided into three main steps. The first step, with its two sub-steps, aims to avoid allocation. The second step attempts to allocate impacts according to their specific causes. Step three involves allocating the impacts using different distribution keys among the products.

The first sub-step, known as subdivision, involves breaking down the product system into more granular process steps to assess whether allocation is necessary. If this approach does not resolve the allocation issue, ISO suggests moving on to system expansion. In this method, the outputs or functional units of the multi-output system are consolidated into a so-called product basket. This means that all the products, along with their specific production volumes, become part of a single functional unit, eliminating the need for allocation.

A peculiarity in comparative LCA is that this method is often extended in ways not explicitly described in the ISO standard. Since the product basket might not be comparable to other systems and LCAs, products from other systems are added or subtracted to match the functional unit. For example, if a smelter 'CN' produces 20 units of copper and two units of nickel, and the study is focused on copper, a common approach is to find another smelter 'N' that solely produces nickel. The environmental impacts of this nickel smelter 'N', scaled to two units of nickel, are then subtracted from the copper–nickel smelter 'CN', resulting in a hypothetical mono-output copper smelter producing 20 units of copper.

In step two, it is recommended to identify the causes or reasons behind the impacts and then associate these accordingly. This can be challenging, especially if there are overhead processes involved. However, in cases where specific emissions happen because of particular inputs, like in waste treatment, this method offers an optimal solution to allocate impacts (e.g. emissions) based on their specific causes (e.g. specific type of waste). ISO 14044 refers to this as 'physical relationships'. In LCA, this is often mistakenly equated with finding distribution keys based on physical parameters. Distributing the total environmental impacts of a product system to each product based solely on physical attributes, such as product mass or crustal concentration is frequently labeled as physical allocation [6, 23, 24]. However, this remains a distribution key and not a true physical cause-and-effect relationship, and therefore, it falls under the next step—step three.

If the previous methods are unsuccessful, ISO recommends step three—allocating the impacts between the products using distribution keys. The most common distribution keys in metals and mining are the weight share of each product relative to the total product weights (mass) or the revenue share of each product relative to the total product revenue (economic).

2.2. Case study: Kevitsa mine, Harjavalta smelter and Pori refinery

The Kevitsa Mine, operated by the Boliden Group, processes surface-mined sulfidic copper ore for pyrometallurgical treatment. The concentrate is transported by train from the mine to the Harjavalta smelter, which is around 900 km away. In Harjavalta, nickel matte and copper anodes are produced. The copper anodes are then transported by train (30 km) to the nearby copper refinery in Pori. There, cathode copper, gold, palladium, and platinum are produced. The mine and its associated refineries are operational at the time of this study (2024) [25]. The annual production comprises approximately 9 million tons of ore, yielding 19 kt of copper, 10 kt of nickel, 640 t of cobalt, 1.5 t of platinum, 1.1 t of palladium, and 650 kg of gold [26 suppl. VII.V]. A block flow diagram of the product system can be seen in figure 1.

A comprehensive LCA of the Kevitsa Mine system was previously developed and assessed by Fritz *et al* [26]. The life cycle inventory data was provided and assessed by the German Federal Institute for Geosciences (BGR) during a project from 2019 to 2022 and published in [26 suppl. VII]. Additionally, the inventories, assumptions, and results were reviewed by a panel with strong expertise in LCA, mining, and metallurgy during the project. This LCA has been expanded for the present paper to include the gold refining process at

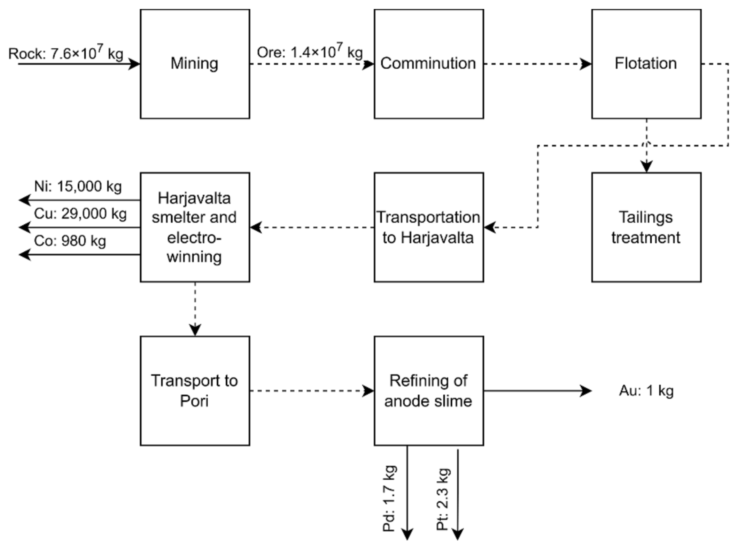

Figure 1. Block flow diagram for the production of 1 kg of gold from Kevitsa mine, Harjavalta smelter and Pori refinery.

the Pori refinery. In this paper, the LCA serves primarily as a case study to explore allocation methods and is therefore not discussed in exhaustive detail. Because allocation affects all impact categories, one exemplary category was chosen, and hence the presented study utilizes impacts on climate change in CO_2eq. The LCA was modeled and calculated in Brightway [27] and ecoinvent [28] using the environmental footprint 3.1 method [29].

2.3. SKARN database

To contextualize the results of this study for copper and gold, the SKARN database was utilized. Skarn Associates is a database provider dedicated to assisting the mining sector in mitigating its negative environmental impacts by providing strategic insights into energy usage, climate change, and water impacts across supply chains.

SKARN predominantly sources its data from mining company reports. The database internally ranks the confidence level of the data based on these reports. The highest confidence is assigned to mining companies that provide detailed reports on energy consumption, CO_2eq emissions, and production volumes. Lower confidence is attributed to assets that only report energy demand, requiring an estimation of CO_2eq, or where only historical data is available. Some assets are benchmarked, meaning that emissions and energy demands from similar assets are scaled according to production volumes. This study used the Q4 2022 (reference year 2020) version of SKARN's database, focusing on energy use and climate change data for copper and gold.

The gold database comprises data on approximately 480 gold mining assets. For these assets, the database includes information such as production volumes, total CO_2eq emissions, and energy demands, as well as specific CO_2eq and energy intensity per unit weight of gold. Additional information is provided on mining methods (e.g. open-pit, underground) and energy sources. For mines producing more than one product (multi-output systems), SKARN employs 'metal-equivalents' to allocate data per unit of gold, resulting in the same outcomes as economic allocation.

The copper database contains data on approximately 259 copper mining assets with similar types of information as found in the gold dataset. Some assets are included in both databases; however, as previously noted in the introduction (section 1), the total CO_2eq and energy demands for the same asset differ between the copper and gold databases. This discrepancy arises from a distinct method of impact allocation. According to SKARN, for mines producing gold within a base metal concentrate, all emissions associated with the freight, smelting, and copper refining of the concentrate are allocated to the primary metal in that concentrate (e.g. copper in a copper concentrate). Nonetheless, emissions from the refining of anode slimes derived from copper refining are calculated and included in the CO_2eq of gold. Since SKARN allocates one specific process, namely the copper smelting, solely to one product, namely copper, this method is, within this study, called process-specific allocation.

To enhance the comparability and contextualization of the results of this study's case analysis, certain modifications were applied to the SKARN database. Specifically, for all copper–gold mines, the total CO_2eq values from the copper dataset were compared with those from the gold dataset. Next, the higher total CO_2eq value from the copper dataset, including the emissions of the copper smelter, was selected. Using this value, both economic and mass allocation were performed based on the specific product volumes of each asset. This resulted in outcomes derived from three distinct allocation methods: the original process-specific allocation provided by SKARN, mass allocation, and economic allocation.

3. Results and discussion

3.1. Subdivision

Boliden reports annual metal production and associated CO_2eq emissions at the company level (organizational LCA, O-LCA), separated into categories for mines and smelters [25]. These emissions can be allocated to the metals produced, either by mass or by economic value. The metals produced by Boliden are zinc, copper, nickel, lead, gold, silver, and palladium. For the mines, mass allocation results in 0.87 kg CO_2eq per kg of metal. For the smelters, the mass allocation yields 0.23 kg CO_2eq per kg of metal. The total carbon footprint of the metals produced by Boliden is 1.1 kg CO_2eq per kg of metal. Note that not all the metals in the concentrate of the mines get produced by the smelter. Metallic cobalt, for example, is not a product of the Boliden smelters but only part of the ore concentrates of some mines. Hence, the smelters' CO_2eq do not get allocated to cobalt. Under economic allocation, the carbon footprint for some metals is increasing, e.g. gold with 10 000 kg CO_2eq per kg of gold. For other metals, the carbon footprint is decreasing, e.g. lead with 0.47 kg CO_2eq per kg of lead. The question of whether the carbon footprint is decreasing or increasing when transitioning from mass to economic allocation is contingent upon the relative product mass being higher or lower than the relative product revenue. The total specific CO_2eq for lead, copper, and gold (excerpt) mined at a Boliden mine (e.g. Kevitsa) and smelted at a Boliden smelter (e.g. Harjavalta) are as shown in table 1. The prices used are the ones that Boliden uses internally for their calculations [25]. More details on the calculation, containing all the metal products by Boliden, can be found in supplement I.

According to ISO 14044, the first step to avoid allocation is to subdivide the process into more granular components. On a first level, the O-LCA could be divided into different sites, i.e. mines, but this does not solve allocation, as each mine produces more than one product. Therefore, the subdivision needs to be even more detailed, looking at the process level within the mine sites. Figure 2 provides a schematic representation of subdivision on a process level, applied to the case study examined in this paper.

From the figure it can be seen that copper exits the system at an earlier stage of the product system, thereby avoiding the additional environmental impacts associated with subsequent steps in the production process, such as electrowinning for gold, silver, and PGMs.

However, despite this subdivision, allocation remains necessary in the context of copper–gold mining. This is a common situation in most LCAs within the metals and mining industry, as metals are often inseparable in various processes [6].

An additional benefit—or even a consequence—of subdivision is that the product system and its processes are understood in greater detail. The results of the subdivided system are presented in section 3.4.

3.2. System expansion

The Kevitsa mine, combined with the Harjavalta smelter and Pori anode slime refinery, serves as a prime example in this study. These facilities collectively produce 19 kt of copper, 10 kt of nickel, 640 t of cobalt, 1.5 t of platinum, 1.1 t of palladium, and 650 kg of gold [17 suppl. VII.V.]. In this context, expanding the system to include all these functions does not yield meaningful results, as the outputs are so specific to this mine that they would result in incomparable figures. This issue is prevalent across many mining operations, where each orebody and mine are unique in terms of product yield and composition. Unlike other production systems—such as those involving the co-production of chlorine and hydrogen—where product relationships are relatively consistent across different sites, mining operations are highly site-specific. The German cost accountant Paul Riebel argues that the cause lies in an entrepreneurial decision—such as the operation of a specific mine—and the effect is the resulting (co-) production with its associated combined cost structure [30]. He insisted on considering this structure as a whole rather than dividing it further, thus conceptualizing 'product baskets'. Riebel notes that all the allocation methods dividing the costs (environmental impacts) among the benefits may not accurately reflect the cause-and-effect, or in physics often called action-reaction, relationship between products and their environmental impacts. In economic terms, the environmental impacts (effects) occur during production, whereas the products (causes) are realized post-production [30]. This temporal discrepancy challenges the appropriateness of economic allocation, as it suggests that the effects precede the causes. Riebel further argues that the terms 'means' (impact) to an 'end' (product) would be better fitting.

In cases where system expansion by simply including the whole product basket in the functional unit is impractical, LCA practitioners typically adopt alternative strategies.

Table 1. Climate impacts for gold and copper on a company or factory level for Boliden; Prices according to Boliden 2024 [25].

Metal	Price	Allocation (mass)	Allocation (economic)
Unit:	(USD/kg)	(kg CO_2eq kg^{-1} metal)	
Lead	2	1.1	0.47
Copper	7.8	1.1	1.8
Gold	45×10^3	1.1	10×10^3

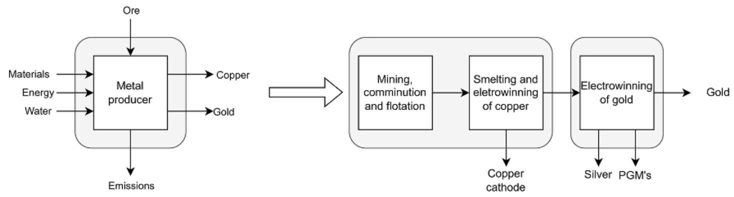

Figure 2. ISO 14044, step 1 (a) subdivision.

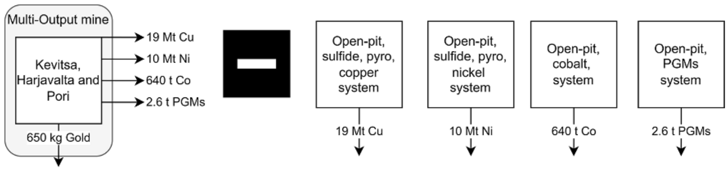

Figure 3. Solving the multi-functionality of a system by substitution.

One common approach in comparative LCA is to expand an alternative system of multiple products or to substitute certain products using alternative mono-output systems in such a way that the product weights in each product basket of the systems in comparison are the same. This method is often referred to as system expansion and substitution by LCA practitioners, which can easily be confused with step 1(b) of ISO 14044:2006, that does not explicitly talk about using alternative mono-output-systems to make the functional units more comparable [31]. For the case study here, this would involve substituting the production of palladium, platinum, nickel, cobalt, and copper in order to isolate the environmental impact of gold alone. However, this approach necessitates the use of mono-output systems; otherwise, the allocation problem re-emerges within the substituted models. In the metals and mining sector, this is frequently not feasible, as many products are not produced by mono-output mines [5]. Additionally, this approach is highly resource-intensive, as it would require detailed LCA data from five different mono-output mines to address our case.

The approach of system expansion and substitution has been subject to criticism, with some researchers arguing that it is merely a specific form of allocation rather than a true avoidance of allocation as intended by standards like ISO [15]. Essentially, this method shifts the issue from selecting appropriate allocation factors to the challenge of choosing suitable equivalence processes. Figure 3 provides a schematic representation of this approach as applied to the case study in this research.

Given the availability of the comprehensive databases SKARN, including CO_2eq for different mines with different product combinations, it was tested whether it might be practical to use substitution. However, an extensive review of the assets in the SKARN database reveals that it is not possible to identify mono-output mines for platinum and palladium—even when considering platinum and palladium together. Therefore, in the context of this study, system expansion and substitution do not adequately address the issue of multifunctionality.

3.3. Physical allocation

According to ISO 14044, if allocation cannot be avoided using step 1, then physical partitioning should be employed. This involves identifying physical relationships that represent changes in inputs and outputs. A well-known example of this approach is a waste incineration plant, where some emissions are directly caused by specific types of waste [21]. This method is often referred to as the '*polluter pays*' or '*cause-and effect*' principle [32].

Table 2. Climate impacts for gold and copper allocated by mass and revenue (economic) for the case study Kevitsa; Prices according to Boliden 2024 [25].

Metal	Price	Allocation (mass)	Allocation (economic)
Unit:	(USD/kg)	kg CO_2eq kg^{-1} metal	
Copper	7.8	8.1	3.6
Gold	45×10^3	8.9	26×10^3

In the context of the metal production system used as a case study here, it is not feasible to precisely attribute environmental impacts to specific metals, as the environmental impacts are caused by extracting the ores and are hence independent of the specific metals within the ore. This challenge is common among multi-output mines; for example, it is difficult to partition emissions resulting from blasting or the energy required for rock crushing, which affects all metals simultaneously.

3.4. Other relationships like mass or economic value

The final step, according to ISO 14044, if both step 1 and step 2 are not feasible, is to employ alternative relationships. The ISO standard cites economic allocation as one such example. Another prominent method, particularly in the metals and mining sector, is allocation based on mass or weight percentages of the products. Note that the latter is often confused with physical allocation falling under step two. According to Lai *et al,* these two methods—economic allocation and mass-based allocation—are the most commonly used approaches for allocating environmental impacts in LCAs of metallic products in the mining industry [5].

Table 2 shows environmental impacts for this study's copper–gold system, including scope 3 for the exemplary impact category of climate change.

When employing mass-based allocation, both gold and copper exhibit similar results, with CO_2eq emissions ranging between 8 and 9 kg per kg of metal. This method involves allocating the total emissions of a product system based on the mass percentage of each product and subsequently dividing by the specific product weights. Essentially, the specific emission per product weight for each product is equivalent to distributing the total emissions across the total product weight [23]. In this study, the observed divergence of 8.1 kg CO_2eq kg^{-1} Cu and 8.9 kg CO_2eq kg^{-1} Au can be attributed to the process described in section 3.1, where copper exits the product system at an earlier stage than gold.

However, this approach is problematic because the allocation of environmental impacts based on mass does not account for the fact that raw materials and associated environmental impacts often do not scale linearly with the mass of individual products but rather occur in conjunction.

Additionally, pure mass allocation does not address the issue of obsolescence: if a product becomes obsolete due to shifting market demands or technological advancements, it may be considered waste and thus should not bear any environmental burdens. For instance, the demand for cadmium, a by-product of zinc mining, declined due to environmental concerns since the 1960s and is now beginning to gain more popularity again in photovoltaic and battery technology, as noted in the keynote for the 2024 EcoBalance by Gavin Mudd [33]. Or for lead, another by-product of zinc mining, it is projected that demand will decrease significantly [34]. In such a scenario, would a zinc–lead mine continue to produce lead, and should any environmental impacts be allocated to lead production?

The system under investigation emits approximately 250 kt CO_2eq to produce 19 kt of copper, 10 kt of nickel, 640 t of cobalt, 1.5 t of platinum, 1.1 t of palladium, and 650 kg of gold. Within this system, copper is allocated the majority of the environmental burdens, accounting for 63% of the total, while gold is allocated only 0.0023% (mass allocation). This results in an emission of approximately 5800 kg CO_2eq for the production of 650 kg of gold. In contrast, the arithmetic mean for mono-output gold mines in the SKARN database (Q4 2023, reference year 2020) is 33 000 kg CO_2eq per kg of gold ($n = 128$). For 650 kg of gold, this equates to 21 kt CO_2eq. The significant discrepancy arises because, in multi-output systems such as the Kevitsa mine, the majority of the environmental impacts are allocated to copper, while in mono-output gold mines, all impacts are attributed solely to gold. Consequently, the Kevitsa production system, which generates additional metals such as copper, nickel, cobalt, and PGMs, exhibits a lower environmental impact per unit of gold produced. However, it remains uncertain whether this allocation reflects the true environmental impact of gold production.

Copper and gold exhibit a price differential of approximately 8 500 times. This raises several questions: Is gold being mined solely because of its mass, its abundance, or primarily because of its high price? At the Kevitsa mine, the principal mineral is pyrrhotite, which contains approximately 60%–65% iron. However, this iron is not included in Kevitsa's product portfolio, despite its substantial production volume. The reason for this exclusion is economic: the iron is not sold due to its lower value. This example illustrates, similar to the example of cadmium or lead becoming obsolete, that even in approaches where allocation is based solely on mass, without considering economic factors, the prices and economic value of the products still play a significant role. This leads to a fundamental question previously discussed in the context of mass allocation and obsolescence of products: Should the allocation be based on the outputs that can 'potentially' be utilized (e.g. due to their physical or chemical properties), or should it be based only on those that are actually used? The unwanted in- and outputs (e.g. burden) are always allocated to the wanted in- and outputs (e.g. benefit). The benefit in an economic system, which is the common framework when discussing mining and LCA, cannot always be measured by physical values, but rather with willingness to pay or, rather the market price.

This issue cannot be resolved 'objectively,' as it invariably relies on subjective evaluations of the products derived from the process. In natural systems, the geological formation of rocks and minerals results in a bundle of products generated as a unified whole. However, the 'Homo technicus' approach involves segmenting this system into subsystems and analyzing each subsystem individually. This segmentation introduces the allocation problem [21].

For example, in the Pueblo Viejo mine in the Dominican Republic, copper, silver, and gold are produced with a weight distribution of 85% copper, 13% silver, and 2% gold [35]. According to the allocation methods discussed, copper would bear the majority of the costs and environmental burdens associated with the Pueblo Viejo mine. This allocation approach, however, conflicts with the primary objective of the mining operation, which is to extract gold. Gold is the primary value-adding product and offers the greatest economic benefit. This is evident in the market valuation, where gold constitutes 94% of the total value, while silver accounts for 6% and copper contributes less than 1%.

An alternative allocation method that considers prices could be beneficial. In business economics, this approach is known as the '*ability-to-bear' principle* [32]. According to this principle, costs (or expenses) are distributed based on the value assigned to cost centers that, due to their market strength, are capable of 'absorbing' these costs.

Applying this principle to the Kevitsa mine, out of the total 250 000 tons of CO_2eq emissions associated with the production of all metals, approximately 28% would be allocated to copper (the second highest after nickel, which receives 37%), and around 6.9% would be attributed to gold. Consequently, this method significantly increases the specific impact for gold while only marginally reducing the specific impact for copper (see table 2).

From supplement II, it can be seen that based on rough estimations without precious metals Kevitsa, would have only been profitable in 2021 and 2022 (last row, last two columns from the left). Therefore, one could argue that for Kevitsa, the precious metals are not by-products but co-products [36]. The driver of the process is to make a profit based on the economic values of the products, which might not be achieved without the by-products [37].

Frischknecht argues that 'if economic and environmental aspects influence consumer choices, economic and environmental aspects should influence the determination of allocation factors for consumer goods as well' [15]. This perspective takes into account, the audience and the aims of LCAs by industry.

One often-said criticism of economic allocation is the fluctuating market prices affecting the validity and credibility of LCA results [14, 38]. The effect of fluctuating prices was analyzed with the annual, nominal prices from the World Bank's Pink Sheet [39]. Figure 4 shows the copper and gold prices as well as the copper-gold ratio based on the annual nominal prices. The graph below, figure 5, shows the same, but with a ten-year moving average applied as recommended by PE INTERNATIONAL [12]. This smoothing technique helps to 'control for price volatility that may occur in a single year' [13].

The copper-to-gold ratio is computed by dividing the market price per pound of copper by the market price per troy ounce of gold. This ratio is utilized by many economists as an indicator of various economic conditions [40]. In the context of LCA, this ratio is of interest as it provides insight into the potential uncertainty introduced into LCA results due to price fluctuations. Figures 4 (annual) and 5 (mov. avg.) show that the copper-to-gold ratio varies between approximately 70% and 40%, respectively. Hypothetically, if the production processes and associated environmental burdens of a mine remain constant over time, this variation suggests that LCA results could be subject to fluctuations of around 40% (based on the ten-year moving average).

Guinée *et al* counter the argument of price volatility by saying that the amounts of co-products produced in a multi-functional process will fluctuate per year, as will the prices of the products [37]. It was tried to check this statement, exemplary for the Grasberg copper–gold mine, based on the production figures for the Freeport Indonesia project by the annual reports from Freeport-McMoRan (2004–2024) [41]. It was found that the copper–gold production ratio fluctuates up to 60% for the time from 2000 to 2024, mainly influenced by the variance in gold production (relative standard deviation, RSD: 44%). Meanwhile, the variance of the amount of ore milled was rather low (RSD: 22%), indicating that process inputs like energy or explosives and thus the associated environmental impacts are also probably less fluctuating. It is

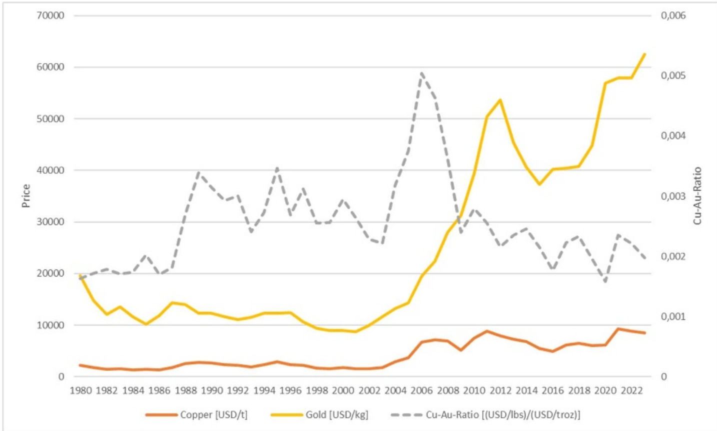

Figure 4. Copper and gold price as well as copper–gold-ratio from 1980 till 2023 (annual prices).

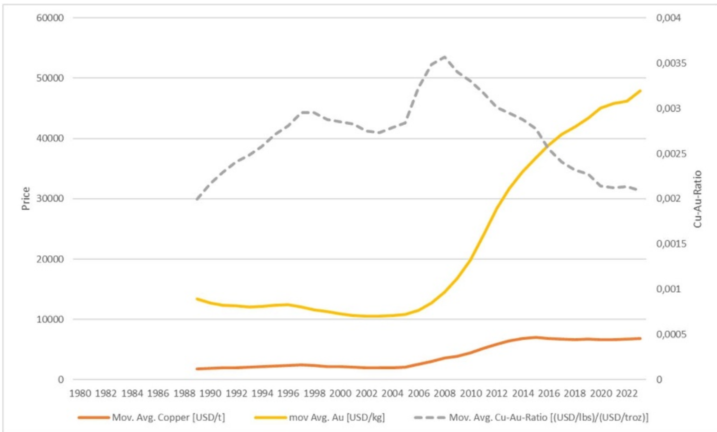

Figure 5. Copper and gold price as well as copper–gold-ratio from 1980 till 2023 (10 year mov. Avg.).

important to note that price fluctuations may be more pronounced for metals primarily used in industrial applications, such as copper, compared to those predominantly used as financial assets, like gold [40]. Gold is often described as a 'safe haven' asset [42], meaning its price tends to rise during economic crises as investors seek stability beyond currencies, banks, or stock markets [43]. In contrast, copper, being primarily an industrial commodity rather than an investment asset, may exhibit different price behavior during economic downturns.

It is important not to forget that only looking at the change of prices, assuming, that they do not influence the production itself, is not very realistic. Maximizing the output of products with high prices can influence physical flows like energy or mass consumption [14]. In mining, declining gold prices can lead to the suspension or closure of specific sections or entire mines [44]. There are examples, including in South Africa, where closed mines are reopened because of rising gold prices. As stated by Laurence *et al* 'gold mines never die; they just rest for a while' [45]. This is also in line with Huppes, who argues, that the value created causes the process, and if no value is created, then the process will stop and thus no environmental impacts will be created [16].

3.5. Process-specific allocation

As outlined in the introduction, the SKARN database employs an allocation method referred to as 'process-specific allocation'. In this approach, specific allocation rules are applied to one or more distinct processes within the production system. For instance, in the SKARN database, the environmental impacts associated with the copper smelting process are exclusively attributed to the primary metal present in the concentrate.

The results in table 3 indicate that switching from process-specific allocation to economic allocation results in a significant increase in the calculated CO_2eq for gold production, with an increase of more than

Table 3. Climate impacts of gold and copper for different allocation methods in the SKARN database for Cu–Au-mines only.

Metal	Process specific allocation	Allocation (mass)	Allocation (economic)
Unit:		(kg CO_2eq kg^{-1} metal)	
Copper	5.1	8.4	4.2
Gold	28×10^3	8.4	39×10^3

33%. In contrast, this change leads to a more modest decrease of about 15% in the CO_2eq for copper production (supplement III).

This allocation method by SKARN avoids categorizing copper–gold mining projects as outliers with disproportionately high environmental impacts within the gold production database. By attributing the smelting processes predominantly to copper, rather than gold, the calculated environmental burden for gold is reduced, thereby aligning these projects more closely with the most common gold production process, cyanidation, which do not involve smelting [46, 47]. If only the Cu–Au mines with copper as their primary metal are used, the carbon footprints would be ≈33 000 kg CO_2eq kg^{-1} Au using the process-specific allocation and ≈47 000 kg CO_2eq kg^{-1} Au using economic allocation.

Looking through an industry lens, this allocation approach might be rational. Through the gold industry lens, attributing the smelting process primarily to copper minimizes the environmental impact assigned to gold production, thereby preventing copper–gold mines from skewing the data in the gold production database. Since smelting is not a standard process in gold production, its exclusion from the gold lifecycle reduces the apparent CO_2eq burden. Conversely, through the copper industry lens, where smelting is a common and essential process, it might seem appropriate to assign the environmental impacts of smelting to copper output. This ensures that the environmental burden reflects the actual processes involved in copper production.

4. Conclusion

The purpose of the current study was to discuss the challenges of the different allocation methods in LCA for multi-output systems using CO_2eq of mining as a prime example.

This study has identified that subdivision does not resolve the allocation problem in LCA for the metals and mining industry. Breaking down the product system into smaller units or more granular steps does not effectively address multi-functionality, as metals occur together in many process steps as they are trapped together inside the ore or the WEEE. It is still always recommended to subdivide the system as far as possible, as some process steps may indeed not involve all metals and do therefore affect the allocation. Additionally, as the LCA practitioner subdivides the system, more and more knowledge of the system is gained, and the LCA gets more detailed.

System expansion is not particularly useful due to the heterogeneity of mines, making it difficult to derive meaningful results for the product basket from the LCA. Mines are too different in their operations and outputs to allow for a representative and coherent product basket as a functional unit, rendering the outcomes of such a system expansion less meaningful. The results are simply not comparable.

In LCAs the system expansion described in ISO 14044 is often extended by adding or subtracting mono-output processes of other product systems to or from the system under investigation in such a way as to have similar functional units. This is inherently complex, as it requires a comprehensive LCA for each by-product based on a mono-output system. This poses a practical challenge in the metals and mining sector since mono-output mines or even recycling facilities do not exist for several metals. Moreover, the arbitrary nature of choosing an allocation method is merely replaced by arbitrariness in selecting substitution systems.

In metals and mining, physical allocation based on the cause-and-effect principle is difficult to achieve because emissions cannot be precisely attributed and quantified for a specific product within the orebody or WEEE. It is frequently misunderstood that distributing environmental impacts by the percentage of physical parameters like mass or exergy to the products would be a form of physical allocation, but this is not a cause-and-effect relationship as described in the ISO.

Only the third step, which ISO 14044:2021-02 considers the last resort, is genuinely applicable in the metals and mining sector. Namely, the step of finding distribution keys to allocate the impacts to the products.

Allocating by weight percentage is unsuitable for a metal like gold, of such high economic value. Ores inherently contain more metals than are ultimately produced and sold, dictated by which metals are economically viable to extract. In the Kevitsa case study used within the presented paper, e.g. iron is the most abundant metal in the ore, but it is not a product of the mine. Consequently, even mass-based allocation implies an inherent economic value.

Economic allocation is frequently criticized due to price volatility, which is particularly significant for product pairs such as gold (as an investment) and copper (industrial use). The present paper shows that these influences can lead to fluctuation in environmental impacts of around 50%. Conversely, it was shown through the example of the Grasberg mine that the fluctuations in the annual production ratio between copper and gold can be comparable to those of prices.

A mine exists primarily to make economic profit. The costs of the products can only be borne by the metals with high enough market prices. But what if the market decides that a product is not needed anymore, the prices drop close to zero, and the product becomes obsolete? The question is, should the allocation be based on the outputs that can 'potentially' be utilized (e.g. due to their physical or chemical properties), or should it be based only on those that are actually used? Despite the shortcomings, we still consider economic allocation to be the best method for cases where several products with great product price variations exist.

Another way of allocating the costs, or, in the case of LCA, environmental impacts, might come from the mathematical scholar of cooperative game theory. The Shapley value is such a method that could help to fairly distribute the environmental impacts among the products. These mathematical models have already been discussed in the context of LCA [48–50], but there is no detailed study on using Shapley values for a fair distribution of multi-output allocation. Future studies should address this topic in the field of metals and mining.

The ISO standard does not address the question of benefits. In our modern world, benefits are determined primarily by market price today and, since the rise of neoliberalism, more than ever before. Metallurgists, mining engineers, or simply any natural scientists who have meticulously gathered and calculated precise technical data for their LCA models may be dissatisfied with allocation based on market prices. However, this perspective overlooks the realities of our economic systems. The ISO standard must recognize this and be adapted accordingly, not only by incorporating LCA experts from the natural sciences or standardization experts from engineering but also by including perspectives from business administration, economics, and the social sciences.

Accurate, transparent, and standardized LCA results are essential for informing policy and practice because they provide a reliable basis for decision-making. Policymakers and practitioners rely on LCA to evaluate environmental impacts, compare alternatives, and develop strategies for sustainable development. The high influence of allocation methods on the results, in combination with the lax rules for choosing the allocation methods, create a potential loophole that calls for better standardization. We call for clearer rules to allocate environmental impacts while implementing case differentiation instead of rigid hierarchies. Such measures can enhance transparency, consistency, and comparability across studies. A future focus on the benefits of product systems in the standardization of selecting allocation methods could be a way forward to ensure that LCA results best reflect the real world.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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