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Article

Integrating Industrial Ecology Thinking into the Management of Mining Waste

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Abstract: Mining legacies are often dominated by large waste facilities and their associated environmental impacts. The most serious environmental problem associated with mine waste is heavy metals and acid leakage through a phenomenon called acid mine drainage (AMD). Interestingly, the toxicity of this leakage is partly due to the presence of valuable metals in the waste stream as a result of a diversity of factors influencing mining operations. A more preventive and recovery-oriented approach to waste management, integrated into mine planning and operations, could be both economically attractive and environmentally beneficial since it would: mitigate environmental impacts related to mine waste disposal (and consequently reduce the remediation costs); and increase the resource recovery at the mine site level. The authors argue that eco-efficiency and resilience (and the resulting increase in a mine's lifetime) are both critical—yet overlooked—characteristics of sustainable mining operations. Based on these arguments, this paper proposes a framework to assist with identification of opportunities for improvement and to measure this improvement in terms of its contribution to a mine's sustainability performance.

Keywords: mining; metals; eco-efficiency; resilience; mine waste; sustainable development; Material Flow Analysis; industrial ecology; sustainable resource management

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1. Introduction

In our finite world the consequences of the continuously growing global demand for metals are becoming more and more concerning. It is common thinking that metal mining is by definition an unsustainable activity because of the non-renewability of its feedstock and many authors have raised the issue of resource depletion. Some have estimated the remaining years of supply for some of the commonly used metals [1–3]; others have talked about an upcoming "peak minerals" [4,5]; and global trends in ore grade decline have been observed [6].

Even though a mining operation cannot inherently be sustainable it is nonetheless crucial to identify areas of improvement in order to stimulate a positive change. In this context this paper raises the key question of what defines a "sustainable" mining operation, and the associated questions: what is currently unsustainable in mining practices and what would a more sustainable mining operation look like? In the first part of this paper the authors provide key elements of the answers by stating the most critical problems the mining industry is facing: the consequences of ore grade decline, a lack of economic viability, and increasing mining legacies.

The authors propose to view these legacies—in particular the giant mine waste deposits—as opportunities rather than an environmental and economic burden. In the second part the question is therefore addressed from a waste management angle and the paper investigates how a new approach to mine waste management could potentially improve a mine's sustainability performance. The authors argue that prioritising resource recovery and viewing waste as a future resource could potentially address all three critical problems stated previously.

In the third and final part the authors propose a framework based on the principles of industrial ecology. This framework aims at testing and assessing the hypothesis enounced in the second part, and eventually:

- Quantify the benefits of a recovery-oriented waste management system; and
- Identify external and internal incentives to facilitate a desirable change in mining practices.

2. The Challenge of Sustainable Mining

The sustainability challenge is multifaceted and multidimensional and the present paper does not intend to provide a comprehensive picture of such a complex problem. The aim is rather to give attention to a critical aspect of mining that has been mostly overlooked in the literature, namely the responsibility of the mine's operator to manage the finite resource in a sustainable way. The following section presents three interrelated facets to this challenge.

2.1. Economic Resource Depletion

The Club of Rome published "Limits to growth" in 1972, warning decision-makers about the consequences of exponential growth in a finite world. When the initial report was updated 30 years later, the system-dynamic analysis performed showed that abiotic resource depletion and the consequent increase in resource prices would become a major problem during the first half of the twenty first century [7]. Other studies support these conclusions [1,8].

Despite these results there is an ongoing debate about whether abiotic resource depletion rate is becoming critical. Gordon *et al.* [9] and other authors evaluate that there is still no immediate concern, although Gordon *et al.* [9] admit that human and natural limitations are likely to arise in the future. Hence, even though the question of physical depletion is not considered as crucial, the authors still acknowledge the growing constraints of resource use. This aspect was well-stated by the European Commission [10]: "at present the environmental impacts of using non-renewable resources like metals, minerals and fossil fuels are of greater concern than their possible scarcity".

This will become eventually a matter of physical *versus* economic depletion. Prior *et al.* [6] make this distinction, arguing that "physical depletion is not the primary determinant of a mineral's availability". Economic depletion, namely the moment when the costs of resource extraction compensate for its benefits, is a real issue that is likely to come sooner than physical depletion. Interestingly, economic depletion and physical depletion are not necessarily connected: according to Prior *et al.* [6] the social and environmental impacts of extraction "may stimulate a resource production peak that is completely unrelated to resource stocks".

Indeed, beyond the discussion on whether the forecasts for the remaining years of supply are correct, the reality of abiotic resources gradual exhaustion is already impacting the mining industry: the decline in ore grade and quality is the "visible symptom" [11] and results in increased energy demand [3], water use [12] and waste generation [13].

A number of studies show global trends in ore grade decline as well as a trend for more complex and finer-grained ore deposits [6,14,15]. As a result minerals are more difficult to extract and require more energy. The energy increase as a function of ore grade decline is even exponential [8,16]. Finally, a lower ore grade leads to lower mineral processing recovery rates, which implies higher metal losses to tailings [17].

The real problem of resource depletion is therefore the reduced accessibility of the resource, which results in increased environmental impacts and costs. Technological improvements have allowed for exploiting poorer and more complex deposits while keeping metal prices stable [9], but this might not be sufficient as the problem will tend to increase exponentially in the future [11]. Mining companies have been exploiting easily accessible, high-grade reserves in priority, often wasting lower-grade material (see the next section). This is not a sustainable strategy considering the global trends that require a long-term resource management strategy.

2.2. A resilience Problem

Adding to the resource depletion discussion is a seemingly conflicting trend of a lack of resilience in mining operations. Laurence [18] analysed one thousand mine closures that occurred in a 30-year period, and observed that only 25% of them closed after complete extraction of the ore. The remaining 75% were unplanned closures that resulted in valuable resource being left behind. This means that 75% of mining projects are not resilient and consequently not sustainable in the original sense of the word: not able to sustain their operations in time.

Having resilient operations is essential for sustainability, as the extractive industries cannot contribute to sustainable development if they cannot succeed economically or even survive. The Mining, Minerals and Sustainable Development research project [19] highlighted the "viability of the minerals industry" as the first of nine main challenges the mining industry is facing.

Moran and Kunz [20] proposed a maturity framework for sustainable mining operations and in that framework the final, most sustainable stage of maturity is "adaptable and resilient". Walker *et al.* [21] define resilience as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks". Adaptability is the ability of the system's actors to influence resilience. A resilient mining project is therefore able respond to external changes, one of the most common being a change in commodity prices [18]. Laurence's study shows that the mining industry is far from reaching that final stage of maturity.

Premature closures have negative consequences at all levels. At the social level, employees lose their jobs, and the subsidence of the local community is affected. The financial actors lose their investments. Unplanned closures lead to safety issues, poor rehabilitation and consequently unmitigated environmental impacts. And, above all, a premature closure does not consider either alternative land uses for the waste or the possibility to re-mine it in the future. What is left of the resource is most likely sterilised, that is to say rendered non-economic to extract.

This resilience problem shows how crucial the time perspective is in evaluating the sustainability of a mining project. Due to the non-renewability of its feedstock, it is physically impossible to prolong a mining activity forever. Hence, compared to many other industrial activities mine sites inherently have a shorter lifetime. However, mining operations can be prolonged and Laurence's results show that there is a great potential for improvement. A more resilient mine site would consequently have a longer lifetime, and would allow the complete extraction of the resource. This would potentially be beneficial at all levels: a stable local community, a well-planned rehabilitation and economic gains resulting from a more careful handling of the exhaustible resource.

2.3. Mining Legacies

According to Laurence's study [19] significant amounts of valuable material can be found on three out of four closed mine sites. Hence, in a global context of resource depletion, the mineral resource at the local level is not being recovered as efficiently as possible. This leads to the third aspect of the sustainable mining challenge: mine legacies. The unprocessed resource and all remaining rock deposits become waste and contribute to the environmental legacy after closure. However, mining legacies are present on every mine site and even resilient ones still generate significant amounts of waste. Defining mining legacies becomes even more difficult considering that the distinction between waste and valuable material is often blurry, as this section will show.

Hence, what are mining legacies? What kind of material is left behind on mine sites and is there a better way to make use of it? While mining operations are inherently limited in time, the environmental legacies they generate can last for hundreds of years or effectively in perpetuity. Yet, mine waste still contains significant amounts of valuable material, which may be economically recoverable now or in the future with new or emerging technologies.

This section investigates the content of mining legacies, focusing on the most important and problematic waste streams. It shows the main sources of metal losses at the mine site level, discussing how mine waste is generated and what factors define its quantity and composition. Understanding these processes is the first step in evaluating the potential for resource recovery from mine waste. Section 2.3.2 also shows a barrier for improvement at this level, pointing out the lack of available data surrounding mining legacies.

2.3.1. How is Mine Waste Generated?

There are three main processes in metal mining that generate waste: mining itself, which is the extraction of the ore from the ground; mineral processing, which produces a mineral concentrate out of the ore; and metallurgical processing which generates a refined metal out of the mineral concentrate (see Figure 1).

Mining is the first stage of the exploitation of a mineral resource. It can be defined as the extraction of material from the ground in order to recover the ore, which is the material of economic value.

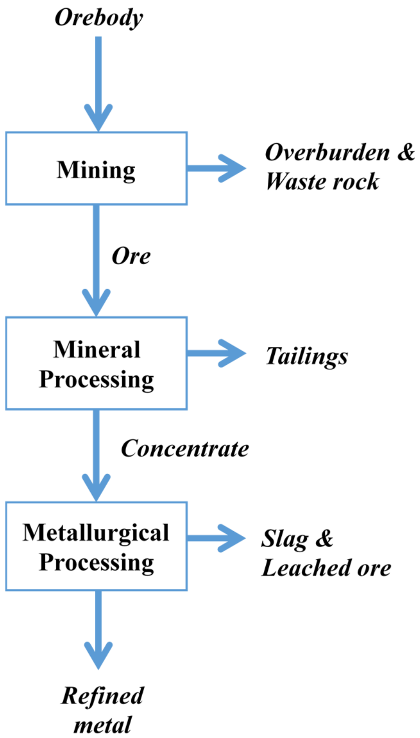

Figure 1. Schematic product and waste streams at a metal mine.

The aim of mineral processing, also called beneficiation or concentration, is to separate the valuable minerals contained in the ore from the gangue, which is the name given to the worthless material surrounding the minerals in the ore. This includes processes such as: crushing, grinding, flotation and gravity, magnetic or electrostatic separation.

Metallurgical processing is generally done in two different ways: hydrometallurgy and pyro-metallurgy, although electrometallurgy is another less common option [22]. Hydrometallurgy (or leaching) relies on the use of solvents to dissolve the wanted metals while pyro-metallurgy (or smelting) uses heat to break down the crystalline structure of the ore mineral. In both cases the chemical combination of the minerals is destroyed to release the metal in its pure form.

While hydrometallurgical processes are nowadays usually happening on the mine site, electro and pyro-metallurgical processes are mainly situated off-site [22]. The reason is that electro and pyro-metallurgical processes require much more energy and mine sites are typically located in remote areas where access to energy is expensive. However, there are other factors that determine where a metallurgical processing operation will be held. For example pyro-metallurgical processing generates sulfuric acid as a by-product while hydro-metallurgical processing is a net consumer of it. Therefore there is an incentive for these two operations to be combined [15].

It is also worth noting that in some cases of very high grades the ore can be directly sent to the refining stage without previous mineral processing, or with a very basic processing stage. This is sometimes the case for iron ore for example that can contain on average 60% iron [23].

Therefore, depending on the site, a mining company may perform only the mining stage, or it may include a mineral processing stage as well, and sometimes it can also have a refining plant. In a majority of cases however, a mine site performs the mining and mineral processing operations [22].

Three main types of waste are generated by these three activities (see Figure 1):

Overburden or Waste Rock

It is the material that covers or surrounds the ore body and that has to be removed in order to access the economical material. What distinguishes waste rock from ore, that is to say what is economical to extract and what is not, is the cut-off grade: under a certain mineral percentage the material will be treated as waste. The value of the cut-off grade will depend on all the factors that determine the costs of the overall mining operations. For example surface mining (in an open pit) is typically much cheaper than underground operations; as a result open cut mining can afford to have a much lower cut-off grade. Mineral extraction is scheduled and the cut-off grade is updated overtime to adapt to change in costs and metal prices to ensure an economically viable operation.

Tailings

Tailings are generated by the mineral processing of the ore. As a result of milling and flotation they are generally finely grained rocks in suspension in water. The ore grade will determine how much tailings are produced. For example, the mineral processing of 100 tonnes of copper ore with a 2% grade will roughly generate 98 tonnes of dry tailings, to which must be added the water content. The grade varies greatly from one metal to another.

Beneficiation processes are not 100% efficient in performing the separation between minerals and gangue: the mineral concentrate produced still contains a significant percentage of gangue and valuable minerals also end up in the waste stream. The mineral recovery rates will highly depend on the technology chosen and how adapted it is to the specificity of the ore (e.g., its mineralogy). However, metal recovery can and often needs to be adjusted in order to meet the desired concentrate grade. Recovery rates and concentrate grades are correlated as a more selective process will lead to a higher concentrate grade as well as a lower recovery rate, and consequently higher metal losses in tailings.

The concentrate grade is determined by the smelter contract and the smelter's benefits will depend on the metal prices. The optimum concentrate grade leading to maximum profit is typically higher in times of low metal prices, and *vice versa*. Consequently, a smelter contract designed in times of low prices would lead to more metal losses in tailings [17].

Slag and Leached Ore

Slag is the solid waste produced by pyro-metallurgical processing. Hydrometallurgical processing generates another significant waste deposit in mine sites: leached ore. After being crushed in the mill the ore is deposited as a heap leach pad and acid runs through it to extract the wanted metal. When the remaining ore's grade is considered to be uneconomical the operations end and the leached ore is left as waste.

More generally, inefficiencies in mineral characterization, extraction, processing, *etc.* generate metal losses throughout the life of the mine, from exploration to closure. In all cases several factors (mineralogical, technological, managerial, *etc.*) make the difference between ore and waste, and hence determine the amount and the composition of the mining legacies. These factors influence the costs and revenues of the operations and economic considerations eventually determine the final decision.

The extent of the problem is multiplied when one considers the complexity of mineral ores and the diversity of elements they usually contain. Indeed ore deposits usually contain several kinds of metallic minerals, and some valuable non-metallic minerals are often associated (e.g., fluorites and barytes). However, they may not be present in sufficient amounts for their extraction to be economic, or their extraction simply does not align with the company's strategy.

When these minor minerals are found in the concentrate, they are considered as impurities by metallurgists and are rejected in the slag. The same happens to a larger extent in poly-metallic ore mines where several elements are present at economic levels. In this case separate concentrates are sometimes produced for each metal extracted and "a valuable metal in the "wrong" concentrate will be considered as impurity" [17].

When metallurgical processing and mineral processing are performed by different companies, a contract between the two defines the quality of the concentrate and fixes its price. In particular, the contract sets acceptable levels of impurities and a minimum grade for the concentrate. Sometimes however, a smelter may extract more than one metal out of the concentrate and will pay for these additional metals if they are present above a certain grade, also set in the contract. This is typically the case for precious metals such as gold and silver found in copper concentrates [17].

In conclusion, even though the mineralogy of the ore deposit sets the basis for how a mining project can be executed, the difference between ore and waste, or between valuable material and impurities, is eventually determined by human factors. Mining companies adapt to the ore deposit and choose the technologies to be used, design the process flow sheet and plan the entire mine project in order to eventually maximise their profit. This makes the system also subject to human error and one can question the success of current strategies given the lack of resilience exposed earlier, and speculate on whether metal losses could partly be avoided.

2.3.2. Mine Waste and Mining Legacies

Avoiding metal losses and preventing mine waste is of critical importance. This section considers the extent of mining legacies, how essential it is to mitigate mine waste generation as well as a current barrier for improvement, namely a general lack of reporting.

Lottermoser [22] estimated that the global mine waste deposit was in the order of several hundred billion tonnes, covering an area of one hundred million hectares. Metal mine waste generation in particular would be currently averaging 15 billion tonnes per year. This is ten times larger than global municipal waste generation, which was estimated to be 1.3 billion tonnes in 2012 [24].

To put these numbers into perspective, the total amount of mine waste is the same order of magnitude as the materials moved by geological processes, such as oceanic crust formation, soil erosion, *etc.* [22]. Lottermoser concludes that "the Earth is getting increasingly shaped by mine wastes rather than by natural geological processes".

Furthermore, mine waste generation has been growing exponentially and this trend is likely to continue in the future [25], though Bringezu [26] pointed out that it could be partially offset by other factors such as the growing trend for underground mining. Indeed, underground mining generates less waste rock than open cut operations because, other than the relatively small amounts of rock excavated for access tunnels and shafts, only ore is excavated.

Mining is by far the industry that generates the most waste. Coal mining is the largest, followed by metal mining industries together with the industrial minerals industry [22]. Extraction and production of clay, sand and gravel generally produce much less waste.

Waste generation varies significantly between metals. This depends mostly on the ore grade that is directly related to the amount of tailings produced. Lottermoser [22] stated that for every tonne of metal ore extracted, at least a tonne of solid waste is generated, but often the amounts of waste are orders of magnitude greater.

Estimating the total amounts of metals lost in mine waste as well as total volumes is subject to uncertainties because of a lack of available data. Indeed, the way mine waste data is reported is mostly inconsistent and incomplete. In the "Global Reporting Initiative" (GRI), a voluntary initiative established by the United Nations in 1997, mine waste is reported under the category "EN23" [27] which encompasses the "total weight of waste by type and disposal method". The same applies to the metallurgy industry and slag is to be reported the same way. The guidelines therefore do not encourage companies to distinguish between different kinds of waste or to report their composition.

Worse, data on waste rock is mostly inexistent. Waste rock generation from mining activities is called a hidden flow [28]. Brattebø *et al.* [28] define hidden flows as material flows that do not enter our economic system. Indeed, when thinking about the global human footprint one first thinks of all the material consumed by our society: consumer goods, infrastructure, food, fossil fuels, *etc.* However, at the basis of all human activities significantly larger movements of materials are happening: the excavation of overburden in order to extract abiotic resources, but also the excavation of materials for infrastructure (roads, buildings, *etc.*), and soil erosion due to agriculture and forestry (more generally the extraction of biotic material). These movements remain mostly unquantified because they are hidden flows and do not have economic value.

Furthermore, if not managed properly, mine waste can generate significant pollution, mostly through the form of acid mine drainage (AMD). It is considered to be a major source of water pollution in countries that have historic or current mining activities [29] and one of the major environmental challenges the mining industry is facing worldwide [25]. AMD is the oxidation of sulfide minerals in the presence of water and oxygen. It results in water acidification and heavy metals solubilisation that are both highly detrimental for the surrounding environment when the contaminated water then slowly leaches from the waste dump.

The leaching rates and the long-term effects of AMD are difficult to estimate. Adding to the lack of data on mine waste amounts, mining legacies are mostly unquantified. In addition, they remain long after their corresponding mines close, which makes it difficult to penalise the people who were financially responsible.

A minimum of 50,000 recorded abandoned mines in Australia is to be added to the 550 operating mines [30]. In the case of an abandoned mine the local government becomes responsible for assessing the risks and prioritising the sites that need the most maintenance or rehabilitation. The first step in managing abandoned mine sites is to make an inventory. Sometimes this first step is not even achieved and, in Australia, one of the most resource-rich countries, the Northern Territory does not have such inventory [30]. In the other states, inventories are mostly up-to-date, but do not provide much detail on the sites except for their localisation.

Adding to this are the regular reports of tailings dams accidents. Hudson-Edwards *et al.* [25] estimated that over 70 major dam failures have occurred around the world since 1970. The International Commission on Large Dams reported about 230 accidents in the second half of the twentieth century [31] and the WISE Uranium project reported 112 accidents between 1960 and 2014 [32]. The magnitude of accidents varies significantly, from a minor seepage to a major dam collapse.

Azam and Li [33] reviewed the tailings dam failures occurring during the last hundred years and investigated both the cause of the accident and the social, economic and environmental impacts it generated. The concerning result is that for a great majority of accidents the total amounts of contaminants released remains unknown.

Finally the spatial occupancy of mine waste is an important impact to consider. Mine waste covers 100 million hectares [22] and the land occupied is rendered unusable in the long term. The Fraser Institute [34] identifies two main environmental-impact categories: the several contamination paths to the surrounding environment and the "loss of productive land". Reid *et al.* [35] argue that land use should be one of the most important impact categories to consider in environmental impact assessments applied to mining.

In conclusion, mine waste is problematic for various reasons and improvements in mine waste management are necessary. Mitigating, controlling, or even understanding mine waste generation faces a major barrier: mining companies typically do not monitor the waste they generate and the composition of mine waste thus remains largely unknown. This prevents opportunities to make a better use of the waste, extract further material from it or even reduce its generation. However, an alternative waste management oriented towards resource recovery could potentially mitigate environmental impacts, which is what the next section will explore. This paper will now develop a potentially more beneficial scenario that addresses the three sustainability challenges exposed in this first section: resource depletion, lack of resilience and mining environmental legacies.

3. A Potential Solution

3.1. A Preventive and Recovery-Oriented Waste Management

According to Laurence [18] the International Council on Mining and Metals (ICMM) principles "ignore one important dimension that distinguishes mining from all other activities: a focus on the mineral resource itself". Ayres *et al.* [15] confirm that the current economic models used in designing a mine project "do not take into account energy or material resource depletion or thermodynamic constraints" . Fonseca *et al.* [36] reach the same conclusion in their assessment of five other promising sustainability frameworks: "what seems to be driving those frameworks is less the need to preserve minerals for future generations and more the need to ensure performance improvements in connection with some environmental, social and economic areas". *A priori*, there is nothing wrong about addressing the triple bottom line, except if it is done in a short-term perspective. The concerning context of resource depletion shows how important it is to adopt a long-term perspective.

Just like any other sector the mining industry requires infrastructure and labour to operate and needs to address its pollution mitigation objectives while creating positive value for a wide range of stakeholders in order to contribute to sustainable development. However, unlike most other sectors, the mining industry extracts a non-renewable resource out of the ground and the challenge is to exploit this resource "in a sustainable way" [18].

A wide range of valuable components is left behind in mine sites in the various waste deposits and, interestingly, the AMD occurring from waste deposits is partly due to the presence of these valuable components. Several authors have highlighted this fact and argued that further extraction of these elements would offer two advantages: recovering value out of the waste and mitigating environmental impacts. Lottermoser [22] states that "if innovative alternatives to current waste disposal practices are pursued and if wastes are recycled or reused, then waste disposal problems are eliminated." Dold [37] also insists on this double benefit and adds that pollution mitigation also results in cost reduction and thus both aspects can be economically desirable. Lottermoser [38] adds that mine waste recycling ideally "creates financial assets, slows consumption of natural resources, limits waste production, encourages innovation and local industries, creates jobs and teaches responsibility for the environment shared by all".

For Wills [17] mine wastes and in particular tailings still contain significant amounts of valuable metals and constitute a potential future resource. The author adds that the cost of tailings reprocessing can sometimes be lower than that of processing ore, because tailings have already been extracted and ground. However, extracting minerals from mine waste may also require additional inputs and related costs due to the low concentration of materials and possibly a more complex mineralogy [8]. Resource recovery from low-grade ore or very low-grade ore may not be economically or environmentally desirable.

In spite of these concerns, the global trend of ore grade decline may require the mining industry to adapt to lower-grade material and it is worth investigating how viewing mine waste as a potential future resource and managing it accordingly would be beneficial. Dold [37] provides a good visual description on how handling the waste as low grade ore or very-low grade ore in a recovery-oriented waste management would contribute in optimising resource extraction and mitigating AMD (Figure 2). In Figure 2, the low-grade stockpile can be processed after the higher-grade material, and ultimately the very-low grade material when the economics become favourable. Meanwhile an appropriate storage facility collects the leachate and prevents it from contaminating the surrounding environment. Pit lake water may also be treated to recover metals and prevent further contamination.

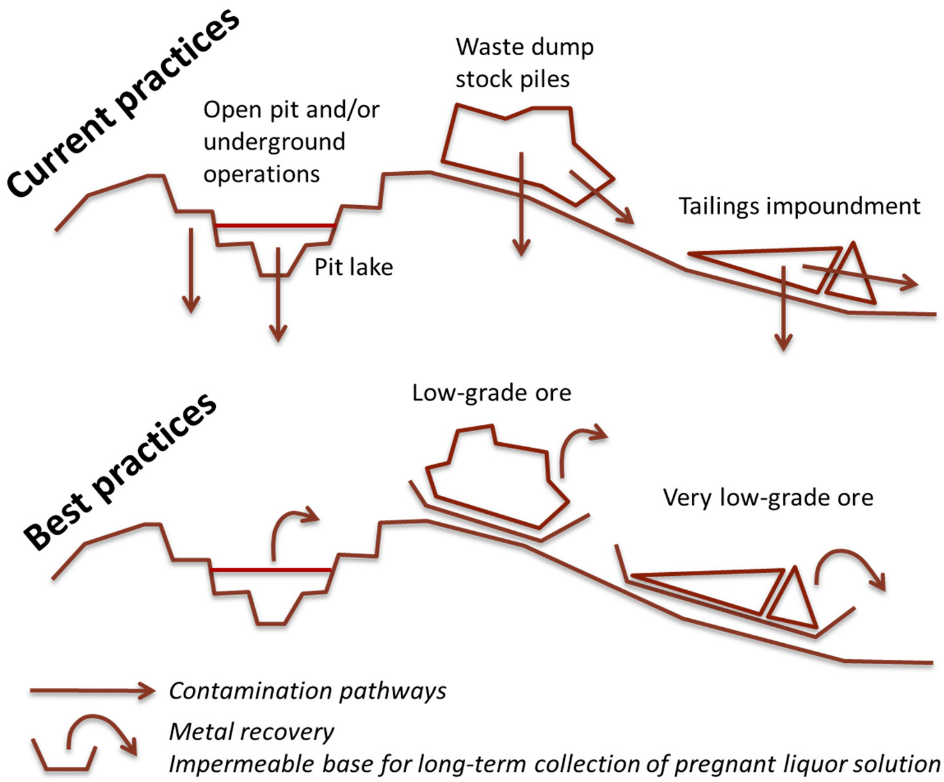

Figure 2. Current mine waste management practices versus a metal recovery oriented waste management. Adapted from Dold [37].

Such a mine site would handle and process an increased amount of material and consequently extend its lifetime. It could also potentially increase its resilience, as Folke *et al.* [39] insist on the link between resilience and diversity. A recovery-oriented mine waste management system would diversify the operations on site by processing material from various deposits, using different technologies and extracting different types of minerals. For instance, a mine extracting several valuable elements will be less sensitive to a drop in prices of only one element. However, such a hypothesis needs to be tested.

3.2. A New Pyramid of Priorities for Mine Waste Management

Dold argues that mine waste should be viewed as a potential future resource and consequently proposes an alternative way to handle mine waste. This alternative approach can be illustrated by building a new hierarchy of priorities for mine waste management. The waste management hierarchy "Reduce-Reuse-Recycle-Dispose" sets general guidelines for waste management that prioritise waste prevention, *i.e.*, waste reduction, over waste reuse and recycling, final disposal in landfills being the least desirable option. This hierarchy has been used for mine waste in the 2012 waste management plan for the Rasp mine in Broken Hill, Australia [40]. However, this hierarchy was primarily developed for municipal solid waste as guidelines for consumer behaviours. Some authors have pointed out its limitations when applied to other types of waste [41,42]. In particular, mine waste differs from post-consumer waste in many ways and the pyramid presented in Figure 3 is more adapted.

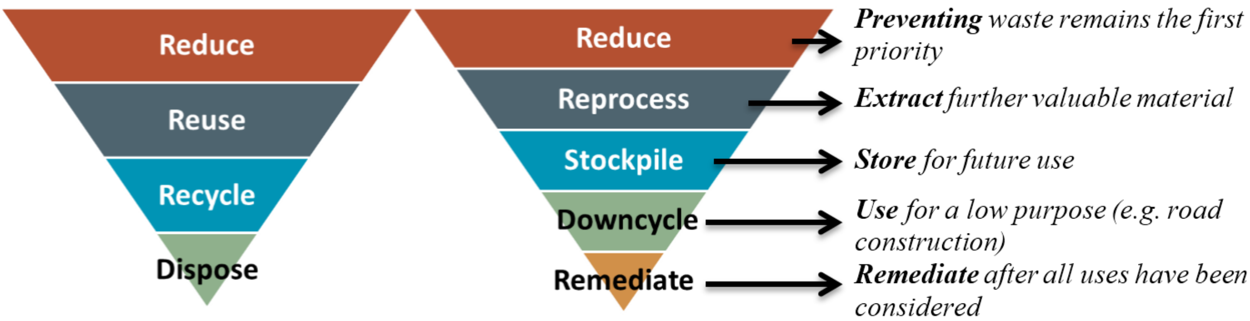

Figure 3. General waste management hierarchy (**left**); new hierarchy for mine waste management (**right**).

The proposed mine waste management pyramid still places waste prevention at the top of the priority list. It is however then followed by the reprocessing option, which allows recovering part of the valuable materials left in the waste. Stockpiling can occur when there is a need to wait for more favourable economics and until reprocessing becomes a profitable activity. When the valuable elements left in the waste are considered unrecoverable then the waste may be used for another purpose, such as on site void backfilling, or sold as road construction material. Depending on the purpose the waste may have to be proven inert and non-hazardous. This option is rated lower on the priority list as it results in the definitive loss of all remaining valuable components. Finally, remediation and site rehabilitation may happen after all other options have been considered.

However, these five options do not exclude each other and perhaps the use of an inverted pyramid can be misleading. For instance, remediation is a necessary step and needs to be addressed in all mine sites. However, if done too early it could result in sterilising the remaining resource. The new hierarchy places the priority on resource recovery while simultaneously making use of the waste. All five options may be combined in order to optimise the economic gains and mitigate the environmental impacts. This optimisation also needs to take into account the external inputs (energy, chemicals, machinery, *etc.*) required to perform the different actions.

Such a mine waste management approach requires a long-term perspective, especially because of the stockpiling possibility. Ayres [15] acknowledges that in many cases part of the waste rock deposits is low grade ore that has been stored intentionally in anticipation of future rise in prices. Stockpiling is already a common practice. However, the mine may cease its operations before the prices rise, which relates to the issue of resilience in an economically unstable environment.

The previous section showed how, in current mining operations, many factors determine whether a material is treated as waste or not. It can be unfavourable economics in the form of low prices or high costs, inefficient processing due to technological limitations and mineralogical factors [22], or more broadly personal management decisions [37] and the overall corporate strategy (e.g., high-grading). Policies and regulations also have an influence in providing incentives or discouraging further resource recovery. Some of these factors, if not all, may have prevented the optimisation of extraction at the time of mining but they may change and become favourable in the future.

Two questions arise from the previous discussions: is this alternative waste management approach as attractive as it looks? That is to say, does it: reduce the environmental legacies, increase resource recovery and favour economic resilience? And if it is, why has it not been more broadly applied in practice and what incentives could stimulate a positive change? The next section describes a framework aiming at answering these two questions.

4. The Framework

4.1. Three Scenarios to Compare

A recovery-oriented waste management approach at the mine site level could potentially provide an adequate answer to the challenges presented in the first section: optimise resource recovery while mitigating environmental legacies and increasing resilience. However, this hypothesis needs to be tested and verified, and a framework needs to be developed to assess the benefits of such management in a comprehensive way, as well as identifying the factors that could trigger change. Before presenting the proposed framework we will first explain the situation by distinguishing three cases (Figure 4):

- Scenario A: a traditional mine produces a certain amount of mineral concentrate P1 while generating an environmental impact E1 during its entire life cycle. After closure the mine legacies generate an additional environmental impact E1′.
- Scenario B: a traditional mine, a certain time after its initial closure is re-opened. The new mine operator decides to re-mine the waste deposits. This second operation leads to an additional production P2 and its related environmental impact E2. In between the two operations, the waste is deposited in the traditional way without planning for future extraction. Examples of case B can be found in practice, such as the large Australian mine sites Kalgoorlie and Mount Morgan.
- Scenario C: an innovative mine site is operated with a planning for future recovery as described earlier. It operates during a certain period, longer than in scenario A and without discontinuation as in scenario B, to produce a final amount of P3 while generating a certain environmental impact E3.

In this study the ratio P/E is defined as the eco-efficiency of the mining project. This production-environmental burden ratio reflects direct environmental impacts generated on site (pollution due to toxic waste generation, greenhouse gas emissions due to fuel consumption, *etc.*) and indirect environmental impacts embedded in energy and material use (e.g., the materials used to build the process plant were extracted from another mine, transportation in and out of the mine site also generates greenhouse gas emissions, *etc.*). Thus eco-efficiency is also linked to the economic aspect; the cost of inputs to the operations. It is a relevant indicator that ensures resource recovery (*i.e.*, production) is not favoured at the expense of the environmental footprint and indirect resource use.

Scenario B provides an enhanced resource recovery compared to scenario A. It however requires additional inputs and generates an additional environmental impact while in parallel treating the legacy from project 1, *i.e.*, preventing E1′. To compare these two scenarios the advantages and disadvantages need to be evaluated in a quantitative manner.

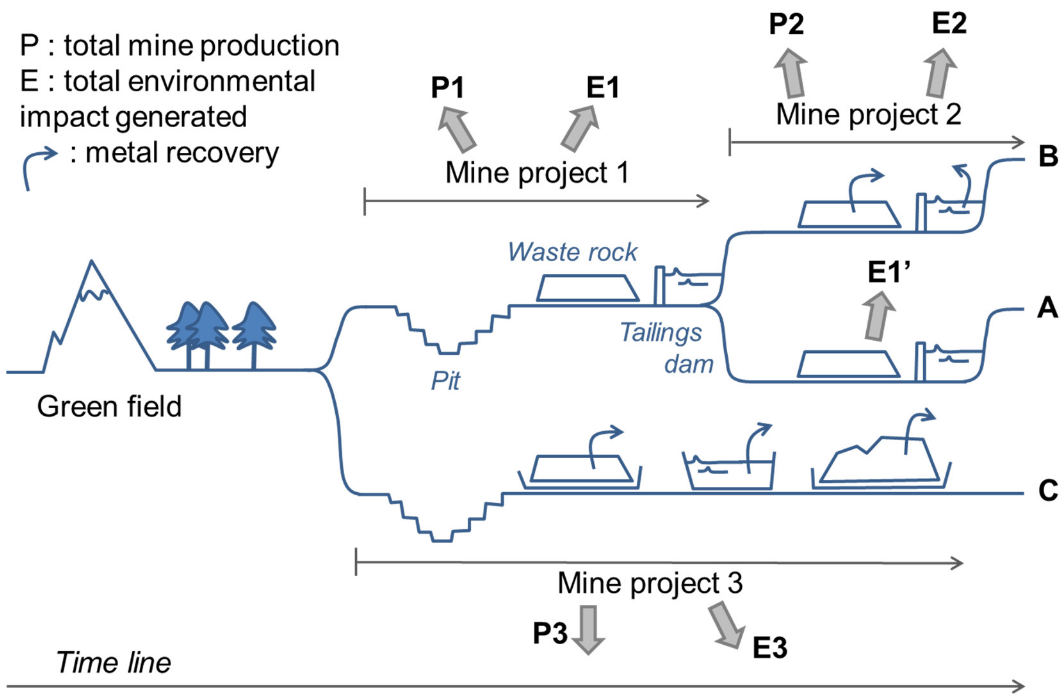

Figure 4. Distinguishing three scenarios to be compared. Notes: Scenario **A**: traditional mining; scenario **B**: re-mining; scenario **C**: "sustainable" mining.

Comparing scenario B and scenario C is more complex. E3 could potentially be smaller than E1 + E2—the total environmental impact generated by scenario B—as better planning and the continued activity allowed for a cleaner disposal of the low-grade material. Furthermore, the discontinuation between mine projects 1 and 2 may result in abandoned infrastructure that could have been reused if it had been properly maintained. The new infrastructure carries embedded environmental impacts that contribute to E2. P3 could also potentially be higher than P1 + P2 as a consequence of this better planning and the resulting efficiency improvements and cost savings. Also, project 2 initially needs a prospection stage in order to determine the composition of mine waste, while project 3 has monitored its low-grade stockpiles.

How can the three scenarios be compared and to what purpose? Scenarios A and B are both real cases and represent current practices. The eco-efficiency of project 2 can be assessed using a real case study and compared to the alternative case of "doing nothing" as in scenario A. A quantitative analysis based on onsite data collection can be performed. In particular, this analysis can determine two aspects of the problem stated above: the increased resource recovery (production over total resource in the ground) and the environmental legacies, *i.e.*, how the legacies from project 1 are addressed and what new legacies project 2 generates (see Section 4.2).

However, scenario C is a hypothetical scenario and cannot be the subject of a quantitative analysis. Furthermore, there are no conventional approaches to measure resilience [43]. Scenario C can however be studied in a qualitative manner and be used to investigate the two other parts of the research questions: the factors that influence project 3's resilience and the incentives that could facilitate a desirable change (see Section 4.3).

4.2. Quantitative Analysis (Scenarios A and B)

The difference between scenarios A and B is the re-mining stage. The quantitative analysis aims at determining whether mine waste re-mining is indeed beneficial with regards to the recovery of the mineral resource and the environmental performance. It is clear that a waste re-mining project would enhance the resource recovery at the mine site level. However, how would it affect the environmental footprint?

In scenario B, project 2 adds to the industrial activities on site and contributes to increasing the mine site's environmental footprint. However, and possibly the main argument in favour of scenario B is that project 2 is taking place on a site already heavily impacted by industrial activities rather than being implanted in another "green field". Thus project 2 is not responsible for the initial impact that turned the green field into a brown field. Furthermore, re-mining virtually prevents the opening of another mine.

Hence, minimising the mine site's overall environmental impact (E) is not the goal. The goal is to minimise the environmental impact embedded in metals, that is to say maximise the eco-efficiency (P/E). The eco-efficiencies of scenarios A and B may be compared:

$$\frac{P1 + P2}{E1 + E2} > \frac{P1}{E1 + E1'} \quad (1)$$

A mining project's eco-efficiency, and in particular its environmental footprint, may be calculated through the use of system-modelling tools such as Life Cycle Analysis (LCA) or Material Flow Analysis (MFA). A Material Flow Analysis at the mine site level would involve mapping of all material flows within the system, understand where metal losses occur and which processes are the most energy and material intensive. The Eurostat guidelines for Economy-Wide MFA or any similar methodology may be used [44]. MFAs usually do not connect material flows with environmental impacts. However, they can be coupled with LCAs to reach that goal.

In a Life Cycle Analysis the practitioner performs an inventory of the emissions of all processes occurring over the mine's life cycle. Processes are hence associated to their environmental impacts. LCA background data also allow accounting for indirect emissions occurring outside the mine site. However, while LCA presents a great potential to assist the mining industry in identifying areas of improvement, it may also suffer from methodological limitations as it is a standardized tool that has rarely been applied at the mine site level [14]. More research is needed to address these limitations and research efforts may benefit from practical case studies.

4.3. Qualitative Investigation (Scenarios B and C)

The qualitative analysis aims at comparing scenarios B and C and identifying incentives that can encourage a change towards scenario C. What distinguishes scenario C from scenario B is the planning stage. The preventive mine waste management system is to be planned in the early stages of the mining project. According to McLellan *et al.* [45] this is the only way to minimise mine waste. Indeed, in order to prevent and not only reprocess the waste once it has been generated, or mitigate its environmental impact, critical decisions are to be made upstream. For example, the cut-off grade determination will directly influence the amount and composition of waste rock.

The qualitative investigation targets the decision-making process and the factors that influence it. This can be done on three different scales that ensure the issue is dealt with in a comprehensive way.

4.3.1. Three Main Scales of Investigation

Laurence [18] argues for the need to focus on the mine site level in order to understand the factors and the practices that influence its resilience. Practices vary significantly and from one mine to another the resource may be managed sustainably or unsustainably. However, sustainable resource management is an issue that needs to be addressed over a wide range of scales [20]. A framework that considers the progress that the mineral industry is making towards sustainability requires a higher scale than the mine site level.

Hilson [46] distinguishes three main dimensions: technical, managerial and political, which illustrate well the different scales for such a framework (Figure 5). While the "technology and efficiency" scale represents what is implemented in practice at the operational level, it is mainly the result of the decisions taken at the management level. The management culture on the other hand is influenced by the political and regulatory context.

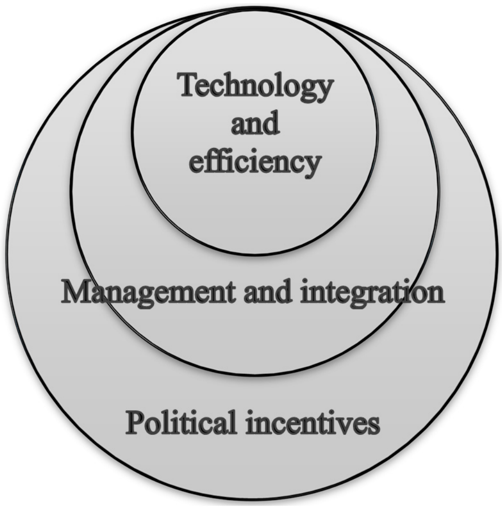

Figure 5. A three-scale qualitative framework.

Technology and Efficiency

Technological innovation may play a role in increased metal recovery rates (process efficiency) and eco-efficiency. For example, the Hall-Héroult and Bayer processes, the only available pathway to produce aluminium, are notoriously inefficient and energy consuming [47,48] despite aluminium being a relatively abundant metal. Research could potentially identify alternative technologies that would reduce wastage significantly. More generally, pre-concentration methods such as differential blasting may be added prior to the mineral processing plant and enhance metal recovery [49].

However, technological innovation is not sufficient and several authors have insisted on the need for innovation at a system level [50]. Moran and Kunz [20] emphasize that the improvement in several individual indicators does not automatically represent an improvement in the overall system. Efficiency can be improved not only by specific technological improvements but also by systemic innovation, which involves the planning and the management levels. The systemic approach also ensures a connection between the operational and managerial levels.

Management and Integration

Moran and Kunz [21] define four dimensions by which a mine site can be integrated and connected: by its value chain, its life cycle, by the spatial dimension, and by flows of information.

At the value chain level resource recovery may potentially be improved by changing the terms of the contract between the concentrator and the smelter. At the spatial level synergies with other businesses can be stimulated. For example a mine site could develop a partnership with a wastewater treatment company that would recover metal from mine wastewater [51].

At the life cycle level planning for recovery and anticipating a future use for the waste are necessary. Collaboration between mining disciplines (as well as with non-mining disciplines such as biochemistry, chemistry, hydrology, ecology) may allow innovative ideas to be integrated across the mine's life cycle [52]. This connects with the information dimension, where Moran and Kunz [20] emphasize the importance of policies, either governmental or corporate, as well as formal or informal networks within the company. Collaboration and exchanges of information between professionals need to be enhanced to find common ground. Interdisciplinary considerations should become dominant in all decisions [20]. The lack of data on mine waste also shows how monitoring mine waste would be helpful to achieve more sustainable mining operations. More generally Mitchell *et al.* [53] argue that companies can improve their performance only if they manage to gather and analyse the data on their operations.

The management team may make use of analytical industrial ecology tools such as Life Cycle Analysis or Material Flow Analysis in order to identify options for improvement and develop a strategy to enhance the local efficiency. LCA and MFA are system-modelling tools and thus enable innovation at a system level. LCA may be applied either to the life cycle of mining operations or to a metal product's value chain, relating to the first and second dimensions defined by Moran and Kunz [20]. MFA allows mapping the flows within spatial boundaries and may be used to understand better information flows (third and fourth dimensions).

This second scale is where the operations are integrated into the bigger picture and synergies with other actors are identified. Moran and Kunz [20] argue that integrating and connecting the different components in the mining system leads to resilience. This integration, aiming at multidisciplinary collaborations and system improvements, is critical to enable progress towards more sustainable operations. It is designed to "strengthen the inter-linkages between operations and their surrounding environment and community" [20] in order to satisfy all stakeholders. Finally, political incentives can influence managerial decisions into implementing sustainable practices and thus set the "rules of the game".

The Role of Policies

Policies can influence and provide the right incentives to change business practices. They are particularly important in the present context as resource recovery is not *a priori* the mining companies' concern. Mining companies have a commitment to shareholders to generate profits and, while efficiency measures and a longer life time might result in increasing benefits, nothing forces the operator to extract more than what it judges economically desirable. Mining companies have no obligation to make the most out of the resource they own and reprocessing waste is not part of their core business. Furthermore, the natural resource is not a purchased input and is therefore not included in productivity calculations [54].

Countries on the other hand are more concerned with the long-term accessibility of the national resources than corporations. Furthermore, local or provincial governments become responsible for the legacies of abandoned mine sites. An improved resilience at the mine level results in the mining company having sufficient time and the means to implement its planning for closure appropriately, which would remove the burden from the government. Dobbs *et al.* [55] point out various ways in which governments would gain in building stronger partnerships with the mineral industry and could result in improved resource extraction being a key goal of mining companies.

According to Bringezu [56], an improvement in process efficiency would result in reducing metal prices, which would consequently increase material consumption. For Bringezu, this is the reason why it is necessary to look at the overall performance of a country and not only at the mine site level. Resource-rich countries need to provide incentives that enhance resource recovery from a specific deposit.

Hilson [57] investigates the barriers and enablers available to apply cleaner production practices. The author identifies policies as of prime importance and so does Ehrenfeld [58]. Legislative efforts can however be counter-productive when they change too frequently, are inconsistent, or fail to take a holistic approach. Ehrenfeld [58] also underlines that regulations tend to narrow down the spectrum of options for businesses while they could instead encourage change by opening new opportunities. Despite that, when appropriately determined, political instruments have the potential to encourage technological and systemic innovation.

5. Conclusions

This paper questioned what sustainability and especially sustainable resource management means at the mine site level. The authors argue that a sustainable mine is, above all, a mine that:

- Recognises the scarcity of the non-renewable resource by optimising extraction and minimising the amounts of valuable materials in the waste stream;
- And is able to provide long-term social and economic stability to its stakeholders by prolonging and diversifying its operations. This means being resilient to economic changes.

These two aspects are interrelated since, for instance, a more careful extraction would require more time and workforce; and social and economic stability could potentially come from the diversification in activities and operations as a result of enhanced resource recovery.

A new perspective to mine waste management is then presented as a potential solution to the sustainable mining challenge. Such management should include a planning for future material recovery and consequently the handling of the waste as a potential future resource. This could include notably the collection of leachate from impermeable storage facilities. The technical aspects are not investigated; rather the paper presents an emphasis on how this new approach could be integrated across the mine’s life cycle in order to reduce waste generation at earlier stages.

Sustainable management of resources and a prevention-oriented waste management system account for collateral inputs and outputs to the operations: water and energy use, infrastructure requirements, environmental burden. Enhanced metal recovery should not produce an unacceptable increase in these flows. This is why the authors propose the use of systemic and quantitative tools such as Material Flow Analysis to assess the benefits of increased metal recovery and identify a threshold of acceptability for the consequent increase in environmental impacts. The system boundaries for such an analysis need to be determined carefully.

In addition to setting the ground for a quantitative analysis the authors finally propose a qualitative investigation of the non-technical factors that could influence such a change in waste management practices. Three main levels are defined to frame this investigation as factors can be technical, managerial or political. The next step will be to apply this framework on a set of case studies, and analyse the results to propose the necessary conditions, such as policy changes or incentives for innovation, that would be required to unable such a framework to be practically implemented.

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Author Contributions

This paper and the literature review it is based on have been written and developed by Éléonore Lèbre as part of her Ph.D. project. The advisory team is composed of Glen Corder (principal advisor) and Artem Golev (secondary advisor).

Conflicts of Interest

The authors declare no conflict of interest.

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