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A Multi-Criteria Decision Model for the Assessment of Sustainability and Governance Risks of Tailings Dams

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The Brumadinho tailings dam collapse in 2019 killed hundreds and caused extensive damage to the surrounding area, including long-lasting environmental damage. Yet, this catastrophic event also triggered numerous proposals and activities to increase transparency related to environmental, social and governance (ESG) risks and sustainability in a broader context. Recently, several studies have proposed indicator-based approaches, but they generally lack a coherent aggregation and analysis of trade-offs and synergies between different sustainability criteria. Against this background, the current study seeks to create a global sustainability comparison of tailings dams at a country level, by combining harmonized data from multiple input sources through an iterative, multi-stage process. First, a comprehensive set of criteria and indicators is established that includes, among others, the impact on the environment, accident risks, and socio-political and governance aspects. Second, a dedicated Multi-Criteria Decision Analysis (MCDA) framework based on an outranking sorting approach (i.e., ELECTRE-TRI) is developed. Third, the evaluation system is applied to 43 countries that experienced at least one tailings dam failure since 1970, providing fact-based and transparent decision support to stakeholders and policy makers.

Keywords: Tailings Dam, Risk Assessment, Sustainability, Governance, Multi-Criteria Decision Analysis.

1. Introduction

Mines and associated mineral processing plants produce two types of output, which are categorized as economic or non-economic. The latter refers to tailings that are mostly comprised of waste, and make up 97% or more of total ore processed (Adiansyah et al. 2015). In 2016, it was estimated that the mining of minerals and ores produced about 8.8 billion tonnes of tailings, of which 46% are attributable to copper (Oberle, Brereton, and Mihaylova 2020).

Tailings dams are large earth-fill embankments that hold back mining operations refuse. This refuse can range in composition from solid rocks and dirt to a slurry of processing water and sludge (e.g. coal ash). The contents of the tailings dams depend on the type of ore and the stage of mining producing the waste. Tailings dams are intended to retain and isolate these wastes indefinitely.

Tailings dams may be built across river valleys, or as curved as well as multi-sided dam walls on valley sides; this latter design facilitates drainage. On flat or gently sloping ground, lagoons are built with walls on all sides of the impoundment. Three potential methods are commonly employed to construct a tailing dam (Wills and Finch 2016).

The first is the upstream method, where the centerline of the dam moves upstream into the pond. It has the advantages of low costs and the speed with which the dam can be raised by each successive dike increment. However, due to the speed in construction, previously deposited slimes do not have time to solidify, thus the tailing dam is more prone to failures (van Zyl 2014).

In the downstream method, the dam wall is raised, the centerline shifts downstream, and the dam remains founded on coarse tailings. This method ensures the static and seismic safeness of the dam (Mohd. Azizli, Tan Chee, and Birrel 1995). However, large amounts of sand required to raise the dam wall, which substantially increases the building costs in the early stage of operation (Bowker and Chambers 2015).

Lastly, the centerline method is a variation of the downstream dam, where the dam crest remains in the same horizontal position as the dam wall is raised. It requires smaller volumes of sand fill to raise the crest to any given height. However, attention is needed to ensure that unstable slopes do not develop temporarily because the dam can be raised faster compared to the downstream method.

Until recently, very little information about mine tailings dams was available publicly, and these facilities only received high public and media attention after catastrophic events. An analysis of accidents for the last more than 100 years showed a decreasing trend of failures, especially since the 1970s, but at the same time there is a higher incidence of failures with more severe consequences (Bowker and Chambers 2015). These failures coincide with an increase in mine waste due to fast-growing demand of many minerals for the energy transition, while ore grades are declining (Rana et al. 2021).

Table 1. Most severe tailings dam accidents since 1970. NA = Not Available.

Year	Country	Tailings released (million m^3)	Fatalities (Number)
2015	Brazil	**45**	19
2014	Canada	**24.4**	0
2012	Philippines	**13**	0
1992	Philippines	**80**	0
1982	Philippines	**28**	0
2020	Myanmar	NA	**126**
2019	Brazil	12	**300**
2008	China	0.19	**254**
1985	Italy	0.2	**269**
1972	USA	0.5	**125**

Table 1 lists the most severe events since 1970, in terms of the amounts of tailings released and the numbers of fatalities, respectively, based on a compilation of data from various sources (see chapter 2 for details).

The initial consequences of a failure are the loss of life and devastation of the surrounding area, including settlements and the natural landscape. Beyond these immediate impacts, failures can also leave a centuries-long environmental impact, including the contaminatin of water, sediment, and soil with toxic substances (e.g., heavy metals) (Kossoff et al. 2014).

In 2019, the tailings dam at an iron mine in Brumadinho, Brazil burst, which led to the release of 12 million m^3 of iron mining wastes and killed 300 people, making it the worst tailings dam disaster in the country's history (Silva Rotta et al. 2020; Owen et al. 2020). Similar accidents have also occurred at fossil power plants like the one in Kingston (Tennessee, USA) in 2008 that released 4.1 million m^3 of coal ash slurry. This highlights the equally destructive potential of coal ash ponds (Santamarina, Torres-Cruz, and Bachus 2019).

The typical causes of tailings dam failures include poor construction, poor management, and unexpected load on the dam caused by a natural phenomenon, such as extreme precipitation, earthquake, etc. (Azam and Li 2010; Davies, Martin, and Lighthall 2000; Kossoff et al. 2014). Historically, countries have not regulated tailings dams well. As a result, many tailings dams fall unnoticed into, and remain in, disrepair (e.g. the Kingston dam), until an accident occurs (AECOM 2009). On the other hand, the Brumadinho dam was closely observed and monitored, but it failed three years after closure, which is contrary to the expectation that geotechnical structures become more stable over time (Santamarina, Torres-Cruz, and Bachus 2019). Therefore, the authors of this study concluded that this indicates the existence of potential gaps in the scientific understanding of tailings facilities and failures, due to time-delayed triggers. Another recent review recommended: (1) to improve international collaboration in safety, (2) to ensure a sound understanding of fundamental geotechnical engineering, physics, and science, and (3) to integrate new insights in future operational practices (Clarkson and Williams 2020).

The Brumadinho tailings dam failure triggered diverse stakeholder activities, in order to establish and implement a framework for a sustainable approach to mine tailings management and reporting. This includes a wide range of guidelines, standards and regulatory requirements (MAC 2019; ICMM, UNEP, and PRI 2020). However, there is usually a shortage of information on the cost of environmental and social externalities (Burritt and Christ 2021). Furthermore, institutional investors have a strong interest for increased transparency and public disclosure of environmental, social and governance (ESG) risks of their investments (Innis and Kunz 2020). The Global Tailings Portal is an example of a successful initiative that established a group of investors and funds, which control more than 13 trillion USD of assets (The Church of England Pensions Board et al. 2019). Despite such industry and multi-stakeholder driven initiatives, it is the responsibility of national governments to develop standards to overcome structural governance challenges (Franken and Schütte 2022).

The impacts of mine tailings are assessed with different sets of indicators that measure sustainability in various contexts and at different scales. These include the United Nation's Sustainable Development Goals (SDG), the Global Reporting Initiative, Social Life Cycle Assessment (SLCA), and ESG risks, among others (Lèbre et al. 2019; Mancini and Sala 2018). However, these indicator-based studies often lack a coherent aggregation and analysis framework that builds upon established Multi-Criteria Decision Analysis (MCDA) methods. Therefore, this study follows the principles and approaches outlined in Hirschberg and Burgherr (2015) and Siskos and Burgherr (2022).

The overarching goal of this research is a global sustainability comparison of tailings dams at the country level, considering ESG risks and focusing on governmental responsibility. The following specific objectives are addressed:

- Inclusion of environmental indicators, based on Life Cycle Assessment (LCA).
- Evaluation of tailings dam accident risk, using quantitative data from historical events.
- Development of a transparent and consistent MCDA framework that facilitates interaction between the analysts and stakeholders.

2. Approach and Methods

The main goal of the proposed methodological framework is the sorting of the alternatives (i.e., countries) into different categories of performance. To identify the most suitable MCDA method for our problem, the MCDA Methods Selection Software (MCDA-MSS) was used (Cinelli et al. 2022). Based on this process, the ELECTRE TRI Multi-Criteria Decision Aid method (Yu 1992) was selected, which additionally provides the possibility to account for and handle pseudo-criteria (Roy and Skalka 1984). Specifically, the modelling of a criterion as a pseudo-criterion, adds the benefit of assigning strong and weak preference relationships, as well as indifference between two alternatives. These preference relationships are especially suitable for numerical criteria, in which small differences do not cause significant or any change in their value.

2.1. The ELECTRE TRI Method

For the application of the ELECTRE TRI method it is required to build a set of different profiles $\underline{b}_h$, which correspond to fictitious actions (criteria vectors), equal to the number of different performance categories (C) minus one. These are assessed and fixed by the decision maker (DM), so that each profile represents the boundaries between two consecutive categories (Figueira, Mousseau, and Roy 2016).

Let us call C_1 the worst category and C_k the best one. Thus, the set $C = \{C_1, C_2, \dots C_h, \dots, C_k\}$ denotes the set of all categories, where C_{h+1} is preferred to C_h, for $h = 1,2, \dots, k-1$. The sorting of an action $a \in A$ to a category C_h results from the comparison of a to category profiles $\underline{b}_1, \underline{b}_2, \dots, \underline{b}_{k-1}$, which delimit the upper and lower limits correspondingly to the categories C_h and C_{h+1}, $h = 1,2, \dots, k$ (see Fig. 1).

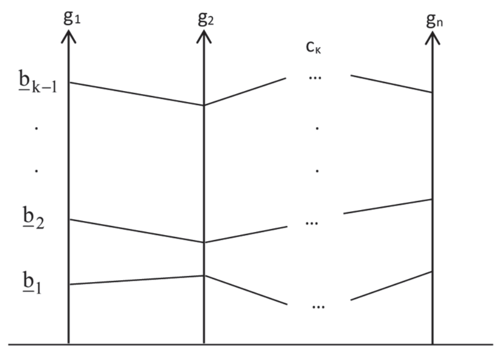

Fig. 1. Definition of sorting categories via category profiles.

The comparison of an alternative a, under evaluation, with a profile $\underline{b}_h$, is performed with the aid of outranking relations, $aS\underline{b}_h$ or $\underline{b}_h Sa$, assessed through the ELECTRE III method, and by building certain credibility indices (see Greco, Ehrgott, and Figueira 2016). Then, a sorting algorithm is implemented (optimistic or pessimistic) to assign the set of alternatives A into the k performance categories. More details on the application of the aforementioned sorting algorithms and the mathematical foundations of the ELECTRE TRI method can be found in Yu (1992) and Roy and Bouyssou (1993).

3. ESG Risks Indicators for Tailings Dams

The sustainability performance of tailings dams across countries is evaluated, based on a comprehensive set of ESG risk indicators. Towards this direction, a literature search was conducted to compile an overview of previously used indicators. The framework proposed by Adiansyah et al. (2015) assigned indicators to the classical three sustainability dimensions (i.e., environmental, economic and social), complemented by a regulation dimension that covers legislative and governmental procedures. The works of Mancini and Sala (2018) and Tayebi-Khorami et al. (2019) group indicators into six impact areas and five key areas, respectively. Finally, there are studies that categorize indicators according to ESG risks (Lèbre et al. 2020; 2019; Owen et al. 2020), focusing on individual tailings facilities, which requires adequate spatial resolution of indicator data. In a second step, the feasibility of the collected indicators for the present global evaluation is assessed and complemented by additional indicators, covering a broad range of ESG risks relevant for tailings dams.

In total, this study provides an evaluation of 43 countries, which have suffered at least one accident at a tailings facility, during the period 1970-2021. For this purpose, a global database of tailings dam failures was compiled, using the following primary information sources: the TSF failure data table (Bowker and Chambers 2015), the chronology of major tailings dam failures (WISE 2022), the world mine tailings failures (Bowker 2022), and the Energy-related Severe Accident Database (ENSAD) of the Paul Scherrer Institute (PSI) (Kim et al. 2018).

The final indicator set consisted of 12 indicators that were equally distributed among the ESG risk dimensions, and could be quantified for all 43 countries analyzed. Table 2 shows the countries, according to the World Bank classification by income level as of 1 July 2021 (World Bank 2022). The indicator system is summarized in Table 3 and described in detail in the remainder of this chapter.

Table 2. Countries by World Bank income level.

Income level	Countries
High	Australia, Canada, Chile, Finland, France, Germany, Hungary, Israel, Italy, Japan, New Zealand, Portugal, Spain, Sweden, UK, USA
Upper-middle	Armenia, Brazil, Bulgaria, China, Guyana, Kazakhstan, Mexico, Montenegro, Namibia, North Macedonia, Peru, Romania, Russia, Serbia, South Africa, Turkey
Lower-middle	Angola, Bolivia, Ghana, India, Laos, Myanmar, Philippines, Ukraine, Zambia, Zimbabwe
Low	Liberia

Table 3. Overview of the indicator system to assess the sustainability performance of tailings dams in 43 countries.

Dimension	Indicator name
Environment	Mine Tailings Toxicity
	Biodiversity & Habitat Index
	Terrain Ruggedness Index
	Land Cover Diversity
Social	Indigenous People
	Social Vulnerability
	Political Stability
	Accident Risk
Governance	Political Participation
	Ease of Doing Business
	Control of Corruption
	Mining Contribution Index

For each indicator the following information is provided: indicator name, measurement unit, preference scale (decreasing “D” or increasing “I” indicate a better performance for lower or higher indicator values, respectively), a short description and the primary data source.

The **environment** dimension comprises four indicators that relate to toxicity, natural ecosystems, topographic variation and land cover.

- **Mine Tailings Toxicity [CTU]; D**: this indicator measures the toxicity of copper mine tailings (in comparative toxic units, CTU) per kilogram of copper produced in mines contributing more than 0.5% of annual copper production. Due to limited data availability for Life Cycle Assessment (LCA) of mine tailings, a recent study on global sulfidic copper tailings was used (Adrianto, Pfister, and Hellweg 2022). For other areas of concern, like water pollution, air quality, climate change from energy use, and resource consumption, data quality at a country level is insufficient.
- **Biodiversity & Habitat Index [Score]; I**: the Environmental Performance Index (EPI) consists of 11 issue categories (Wendling et al. 2020). The Biodiversity and Habitat issue category assesses countries' actions towards retaining natural ecosystems and protecting the full range of biodiversity within their borders. It is measured with seven sub-indicators (https://epi.yale.edu/epi-results/2020/component/bdh).
- **Terrain Ruggedness Index [m]; D**: this indicator indicates how jagged or flat the terrain of a country is on average, measured in metres of elevation difference. Terrain ruggedness contributes to slope instability, erosion and challenging structural and foundation conditions, which are some of the main identified sources of past tailings dam failures. High terrain ruggedness signifies topographic variations and heterogeneity of landslide formations, which can make tailings dam design more challenging. Here the dataset published by Nunn and Puga (2012) is used, which is available here: https://diegopuga.org/data/rugged/.
- **Land Cover Diversity [Score]; I**: Land cover 'snapshots' for a given year provide evidence against which conversions can be evaluated (Haščič and Mackie 2018). The habitat diversity of a country is measured by the Gini-Simpson Index, based on 11 land cover types that are available from OECD statistics: https://stats.oecd.org/Index.aspx?DataSetCode=LAND_COVER#.

The indicators in the **social** dimension integrate different societal aspects, as well as a new indicator that expresses the accident risk of tailings dams.

- **Indigenous People [%]; D**: in a mining context, the distinctive cultures and ways of life of indigenous people are particularly at risk, resulting in higher levels of poverty, marginalization, discrimination, etc. (Garnett et al. 2018). This indicator provides the percentage share of a country's area held or used by indigenous people and communities. Data is available at LandMark (Dubertret and Wily 2015).
- **Social Vulnerability [Score]; D**: it consists of three social and cross-cutting indicators of the Fragile States Index that is published annually by the Fund for Peace (Fund for Peace 2017). The country values are the sum of the individual indicator scores. A higher value indicates that the society in a country is more vulnerable, and thus generally less capable to deal with the consequences of a tailings dam failure.
- **Political Stability [Percentile Rank]; I**: the political stability and absence of violence/terrorism indicator is part of the World Bank's Worldwide Governance Indicators (WGI). It assesses perceptions of the likelihood that the government will be destabilized or overturn by diverse unconstitutional or violent means (Kaufmann, Kraay, and Mastruzzi 2010). The WGI project website provides data for over 200 countries, since 1996: http://info.worldbank.org/governance/wgi/.
- **Accident Risk [%]; D**: the tailings dams accident risk at a country level is calculated, based on historical events. For this purpose, different impacts (i.e. release, runoff, fatalities) are assigned to five severity classes, with their values increasing in equal steps from 5 to 25, assigning higher weight to more severe impacts. Impacts are then combined and expressed as a relative ratio of the maximum possible risk.

The indicators of the **governance** dimension reflect the political and regulatory environment, as well as the importance of the mining sector in a country's economy.

- **Political Participation [Score]; I**: this indicator is part of the Economist Intelligence

Unit's (ECU) index of democracy. It includes nine indicators that are measured via public opinion surveys (mainly the World Values Survey) and experts' assessments (The Economist Intelligence Unit 2020).

- **Ease of Doing Business [Score]; I**: this index represents the conduciveness of the regulatory environment to start and operate businesses. The distance to frontier score captures the gap between an economy's performance and a measure of best practice across all indicators of the index (World Bank 2020).
- **Control of Corruption [Percentile Rank]; I**: it belongs to the World Bank's World Governance Indicators (WGI), and is a composite governance measure that captures the extent public power is used for private gains (Kaufmann, Kraay, and Mastruzzi 2010). The current and historical data (since 1996) are available at: http://info.worldbank.org/governance/wgi/.
- **Mining Contribution Index [Score]; D**: this is a composite index of four indicators, each capturing different aspects of mining's contribution to national economies. It includes mineral and metal export contribution, change in mineral and metal export contribution, mineral production value, and mineral rents as a percentage of GDP (ICMM 2020).

4. Conclusions and Outlook

This study proposes a transparent and cohesive evaluation system to comprehensively assess the sustainability performance of tailings dams at a country level. With regard to its contribution to the scientific literature, this work developed two new indicators to measure the toxicity of mine tailings, based on Life Cycle Assessment, and to calculate the accident risk of tailings dams. Moreover, the indicator-based approach is combined with an MCDA sorting framework to assign countries to different sustainability performance categories.

Despite several recent initiatives, the limited publication of primary data and the derived ESG risks for tailings dam facilities pose a serious multidimensional problem. In particular, it hampers public trust in the industry, authorities and political decision makers. Hence, the proposed framework attempts to overcome this barrier because it incorporates the preference information of stakeholders and uses an iterative and interactive process to systematically evaluate trade-offs and synergies between different ESG risks and how they affect overall sustainability. Furthermore, it provides a technical tool for institutional investors (e.g., pension funds, insurers and sovereign wealth funds) to better take into account the diverse facets of sustainability, which is crucial for illiquid assets, such as infrastructures.

The next steps of this ongoing research effort concern the actual application of the framework, including (1) the implementation of a user-friendly procedure for preference elicitation, (2) collection of real-world stakeholder input, (3) benchmarking of the countries, and (4) analysing and ensuring the stability of results by incorporating a robustness control methodology.

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