FROM DISASTER RESPONSE TO NEW TECHNOLOGICAL PRODUCTS: A SYSTEM THINKING APPROACH TO TRANSFORM DAM TAILINGS INTO CERAMICS

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ABSTRACT: *DISASTERS REPRESENT A SEVERE DISRUPTION OF THE FUNCTIONING OF A SOCIETY, RESULTING IN HUMAN, MATERIAL, ECONOMIC AND ENVIRONMENTAL LOSSES – WHICH LEAD TO AN ARGUMENT IN FAVOUR OF MITIGATION AND PREPAREDNESS ACTIVITIES. CONCERNING POTENTIAL CAUSES OF DISASTERS, ONE OF THE WORLD´S MOST SIGNIFICANT PROBLEMS IS THE RESIDUE FROM MINING ACTIVITIES AND WASTE FROM INDUSTRIAL PROCESSING. FOR EXAMPLE, THERE ARE CIRCA 8,400 MINES IN OPERATION AND 800 MINING DAMS IN BRAZIL, WITH 449 OF THEM INCLUDED IN THE NATIONAL DAM SAFETY POLICY. DESPITE THIS, THE BRAZILIAN GOVERNMENT HAS ADVANCED IN VARIOUS ACTIONS IN FAVOUR OF THE 5R CONCEPT AND ALSO IN TECHNOLOGIES TO USE SUCH RESIDUE. THEREFORE, THIS RESEARCH AIMS TO DISCUSS THE ECONOMIC, SOCIAL, AND ENVIRONMENTAL IMPACTS OF DEVELOPING A TECHNOLOGICAL PRODUCT BASED ON MINING TAILINGS. THE RESEARCH ADOPTS A SYSTEM THINKING APPROACH BASED ON CAUSAL LOOP DIAGRAMS (CLD), REPRESENTING THE CURRENT SITUATION AND THE PROPOSED BUSINESS STRUCTURE WITH A NEW PRODUCT DEVELOPED BASED ON DAM TAILING. THE MODEL PROPOSED IN THIS WORK ILLUSTRATES THE PATH TO THE TRANSFORMATION OF DAM TAILINGS, REUSING AND REPURPOSING IT INTO GLASS-CERAMIC MATERIALS, PROPER TO FLOORING ON POPULAR HOUSES OR PUBLIC FACILITIES. FUTURE RESEARCH INVOLVES A PROPOSAL TO QUANTIFY THE RELATIONSHIP BETWEEN THE CLD VARIABLES AND THE USE OF RENEWABLE ENERGY SOURCES.*

KEYWORDS: *SUSTAINABLE DEVELOPMENT, DISASTER, TECHNOLOGICAL PRODUCT*

1. INTRODUCTION

Disasters represent a severe disruption of a society's functioning at any scale due to hazardous events interacting with conditions of exposure, vulnerability, and capacity, leading to human, material, economic, and environmental losses (UNDDR, 2025). The traditional focus on disaster response has been questioned in several calls for greater attention to disaster mitigation and preparedness (SCHREVE and KELMAN, 2014). The United Nations and several stakeholders claim that, for every dollar invested in disaster mitigation and preparedness, society could have saved several dollars in the disaster aftermath (HEALY, MALHOTRA, 2009). Besides these economic perspectives, it is also fundamental to consider that it is difficult to measure human suffering (SHAO et al., 2020) and environmental impact (MATA-LIMA, 2013), which adds another perspective on the potential for reducing disaster impacts.

Concerning potential disaster causes, one of the world's most significant problems involves the impact on the industry's operation (OLIVEIRA et al., 2020). A practical example is the residue from mining activities and the corresponding waste from industrial processing (BOWKER and CHAMBERS, 2025). Indeed, Brazil recently faced two major disasters resulting from mining dam collapses in the cities of Mariana and Brumadinho, highlighting an imbalance between economic, social, and environmental dimensions. Palu and Julien (2019) indicate the following causes for those two disasters: embankments built with material from mining activities residues; multi-stage raising of the dam (to increase storage capacity); lack of regulations and design criteria; continuous need of monitoring to ensure the dam stability; and high cost of maintenance after the mine closure. After these disasters, the Brazilian government improved sector control, with the register of circa 8,400 mines in operation and 839 mining dams, with 449 of them included in the National Dam Safety Policy, which means that they are higher than 15 meters, with volume greater than 3 million cubic meters and/or receives hazardous waste (BRASIL, 2020).

From a sustainable approach, there are several potential alternatives to industrial waste based on a 5R concept that involves reducing, redesigning, recycling, reusing, and repurposing (FONSECA, 2000). In Brazil, the National Solid Waste Plan (BRAZIL, 2020) has already presented positive and realistic impacts on several aspects of the 5R concept, including the economic, territorial and environmental ones. Another example is Law 14,260/2021 (BRAZIL, 2021), which is also known as the Recycling Incentive Law (LIR), which is an initiative that promotes the strengthening of recycling in Brazil through tax incentives.

Considering the complexity and imbalances between economic, social, and environmental dimensions in the mining sector, as well as the potential contributions of 5R concepts and associated laws in Brazil, this research aims to discuss the economic, social, and environmental impacts of developing a technological product based on mining tailings. This research focuses on discussing cause-and-effect relationships through casual-loop diagrams (CLD) based on the System Dynamics methodology (STERMAN, 2000). The CLD proposed in this work argues for the transformation of dam tailings into glass-ceramic materials, which can be adopted by communities near the current dams, promoting territorial development while at the same time reducing the risk of disasters and promoting economic benefits to the companies, even using tax grants as considered by the Law 14,260/2021 registered in Brazil (2021).

Following this introduction, the second section presents theoretical background on business models, dam risk and safety, and new products. The third section presents the methodological approach adopted in this research. The fourth section presents the results, focusing on the CLD, and outlines the current scenario of the mining sector and the proposed scenario. Last, the fifth section provides the final considerations.

2. THEORETICAL BACKGROUND

2.1. Sustainable business models

A Sustainable Business Model (SBM), or Business Model for Sustainability (BMS), "is a framework for how organisations create, deliver and capture value based on sustainable development principles. Rather than a traditional business model that is focused solely on profit, an SBM can help organisations to tackle sustainability challenges" (LEEDS, 2024). This will occur through the profitable operation of the entire enterprise and requires addressing a range of aspects, including ecological and social ones. Within its framework, companies can evolve their products and processes in a positive direction, contributing to the planet (LEEDS, 2024).

Specifically concerning sustainability, Bocken et al. (2014) presented three SBM archetypes: Technological, Social, and Organisational, which may serve as a basis for analysing and measuring companies' innovation capacity (AWAN and SROUFE, 2022). These can be integrated with the Business Model Canvas (BMC), as proposed by Osterwalder and Pigneur (2010), a standard methodology used to analyse a business plan, emphasising innovation. It includes some typical blocks: Key Partners, Key Activities, Key Resources, Value Proposition, Customer Relationships, Customer Segments, Channels, Cost Structure, Revenue Streams, and Sustainability.

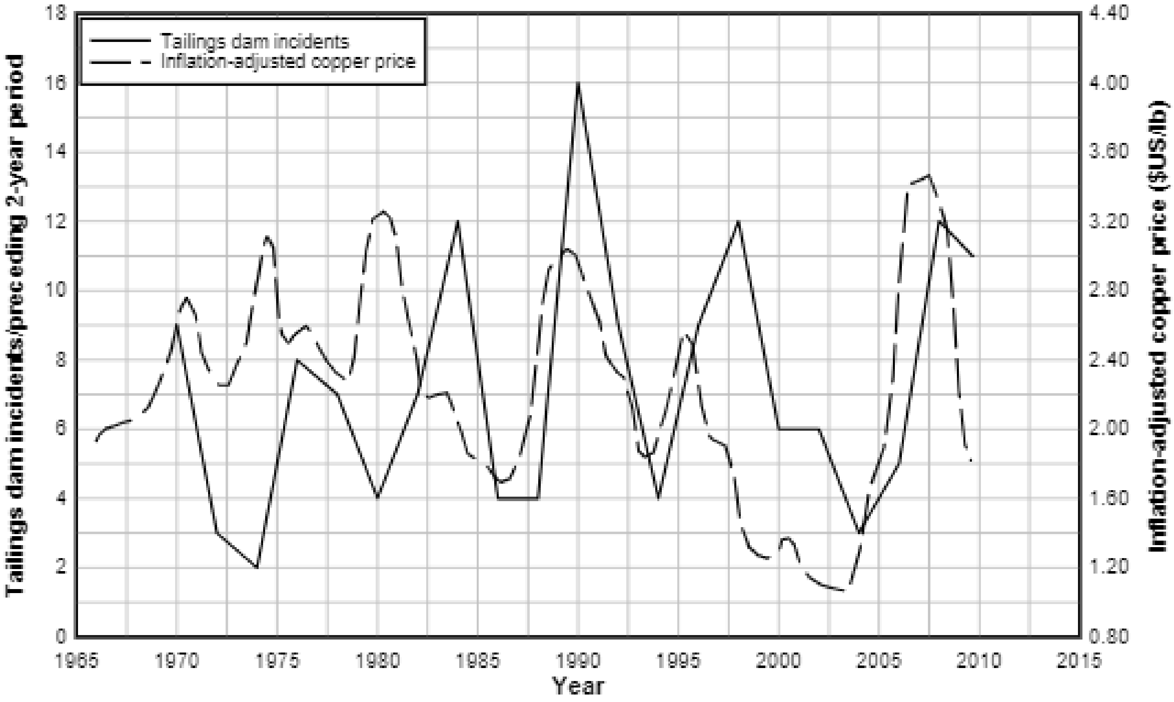
Considering an enterprise as a collective accomplishment, collaborative governance and the strengthening of cooperation networks are opportunities for territorial development, as is the expansion of public policies' roles in supporting sustainable business. In this context, for instance, Zaoual (2006) proposes that territoriality is not only a physical space; it also has a social dimension and dynamics, encompassing a set of knowledge, practices, and identities that shape productivity and social dynamics. It is also used by various social agents whose practices and relationships lend it specific meanings. According to Da Silva (2009) and Xavier et al. (2024), the production of territory is directly linked to forms of territoriality, which express how social groups occupy, organise and attribute functions to space. The territory and collective memory of a social group are deeply connected. If, on the one hand, the territory carries and transmits the symbols that establish perpetuity in the shared memory of individuals, on the other hand, this collective memory is fundamental in establishing and maintaining the connection of the group with its territory. Both elements – territory and memory – are inseparable in the formation of the group's identity, continuously affecting each other (NETO, 2021).

2.2. Disaster risk and safety of dam tailings

Considering a dam and tailing perspective, Davies and Martin (2009) explained a corresponding relationship between the elevation and reduction of prices and, consequently, the tendency towards dam failure. On the one hand, the authors indicate that price elevation leads to: a) urgent licensing procedures (inappropriate technologies); b) urgency of execution procedures (design and construction failures); c) rising capital and operating costs and debt; d) qualitative and quantitative depletion of reserves (quantitative increase in waste, effluents, and tailings). On the other hand, the price reduction leads to pressure to reduce operating costs. Consequently, there is a clear trend of higher-scale disruptions in the post-boom, as observed in Figure 1.

Considering the economic nature of the mining sector and the constant fluctuations in prices, a disaster management approach suggests that it is only a matter of time before the subsequent dam failures occur. Therefore, a mitigation approach and reduction of dams and tailings is vital.

Figure 1 - Adjusted copper price and tailings dam incidents.



Source: Davies e Martin (2009).

2.3. Technological products made of tailings

Recent research has investigated the transformation of tailings into glass-ceramic materials as a known process using a sequence of grinding, melting at high temperatures, and casting, followed by heat treatment for the crystallisation of new phases into the vitreous matrix (FONSECA et al., 1995, 1996, 2004). Several studies indicate that, after undergoing this process, all elements, including metals, are transformed into a solid and inert material, which is forever immobilised (GILLIAN, 1992).

A series of tests were carried out to optimise the melting and crystallisation conditions of vitreous parts, based on the Differential Thermal Analysis (DTA), using different heating rates (5°C/min, 10°C/min. and 20°C/min) as well as distinct particle-size fractions of vitreous material (diameter ranges from 425mm to 300mm; 149mm to 125mm; 44mm to 37mm; and less than 37mm.

These analyses show that the Tc of 850 °C is not affected by the decrease in particle size of the vitreous material, confirming that the phenomenon has mainly bulk characteristics - volumetric crystallisation, as shown in Figure 2. Otherwise, in the event of surface crystallisation, the Tc would be significantly reduced, as the driving force of the phenomenon is the surface area.

To verify the immobilisation of metals, the glass-ceramic material was subjected to leaching and solubility tests according to Brazilian legislation (ABNT, 2004a, 2004b), and the obtained results met the specifications (ABNT, 2004c) to classify the material as non-hazardous. The monthly production of the glass ceramic material required to absorb 15,000 tons of tailings generated in Três Marias is estimated to be 200,000 m². In the Brazilian market, which is the third-largest in the world in terms of stoneware consumption and production, reaching 690 million m² in 2017, this amount represents less than 0.4% of the total volume (FONSECA, 1995). The materials developed used only mining waste stored in dams.

Figure 2 – Glass (left) and glass-ceramic (right) pieces obtained from the tailings.

Source: Fonseca (2019).

The following stage is to evaluate the economic feasibility of the process and sale of this material on the market. Preliminary studies to estimate the production costs of this material, using the ceramic flooring and coating industry as a parameter, indicate that it will be affordable to offer a product with comparable qualities to porcelain stoneware and granite, at competitive prices, as presented by ANFACER (2029). The glass-ceramic manufacturing process and costs are like the stoneware products, making it possible for glass-ceramic products to be offered to the market at competitive prices, since 1t of tailing, with the investment of 80 Dollars on manufacturing costs, produces 18m^2 of glass-ceramic, yields 160 Dollars gross sales revenue (at wholesale prices).

3. RESEARCH METHODOLOGY

The "System Thinking Perspective" focuses on illustrating cause-and-effect relationships of a complex system through CLD (STERMAN, 2000). The key components of a CLD are: Nodes (Variables), Arrows (Edges, positive and negative), and Feedback Loops that can be subclassified as Reinforcing Loops (R) and Balancing Loops (B). In the CLD, each variable is represented by a node, and the cause-and-effect relationships between them are depicted using directional arrows known as edges (STERMAN, 2000). These arrows illustrate how a change in one variable affects another, providing viewers with a comprehensive understanding of the system's behaviour over time. In simpler terms, it helps to see how different parts of a system interact to create behaviours, whether positive or negative. Positive causes/interactions are identified by blue arrows and a "+". Negative causes/interactions are identified by red arrows and a "-". Two traces crossing an arrow means a "delay" in the process.

The creation of CLD begins with defining the system and key variables; after that, the relationships between them are mapped, and their interdependencies are identified. The next step is to determine the feedback loops and finally test and validate the CLD. Therefore, the integration among variables related to social and environmental risks (both endogenous and exogenous), as well as the company's supply chain activities, potential consequences, and the implementation of strategies, is presented in the CLD.

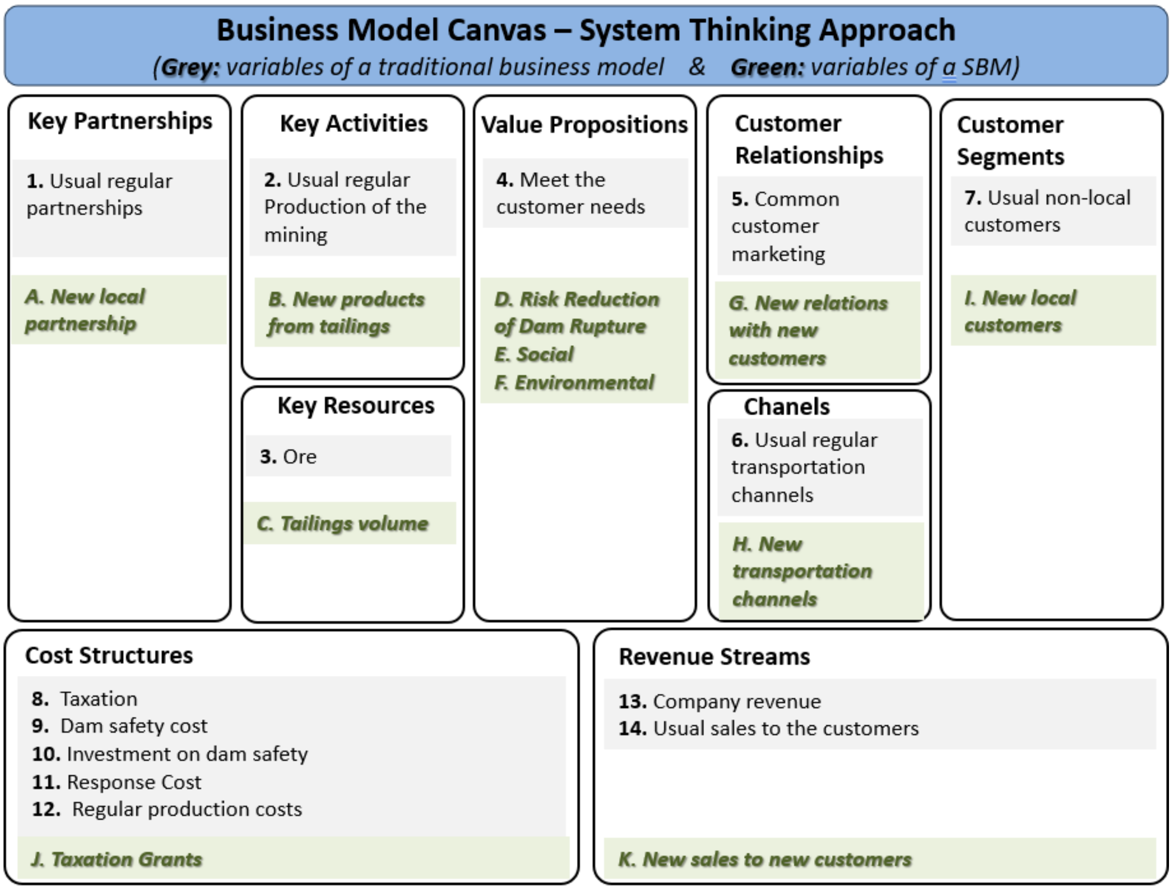
Our analysis uses some of the variables previously presented in Section 2. Then, some hypotheses about these relationships are defined as a synthesis of the insights to support decision-makers interested in the economic, social, and environmental dimensions (Fonseca et al., 2019) in developing a new product based on mining tailings.

4. RESULTS

Figure 3 presents a BMC containing a representative set of initial variables numbered from 1 to 14 (some of which were previously outlined in Section 2). Figure 4 also presents the results of a systematic perspective on the 5R, including the development of technological products made from dam tailing and disaster risk reduction, which leads to the inclusion of more variables, ranging from “A” to “K”. The variables 1 to 14 of this BMC are transformed into a CLD, as depicted in Figure 5.

For each of the 14 “variables” several loops can be identified. For the sake of conciseness (and diagram readability), just some of the “Reinforcing Loops R#” (sequence of all “+” or all “–“interactions) and some of the “Balancing B#” (whenever having at least one “+” or “–“among interactions) loops were indicated.

Figure 3: BMC containing the set of Variables considered in the CLD development.



Business Model Canvas – System Thinking Approach
*(**Grey:** variables of a traditional business model & **Green:** variables of a SBM)*

Key Partnerships
1. Usual regular partnerships
A. New local partnership

Key Activities
2. Usual regular Production of the mining
B. New products from tailings

Key Resources
3. Ore
C. Tailings volume

Value Propositions
4. Meet the customer needs
D. Risk Reduction of Dam Rupture
E. Social
F. Environmental

Customer Relationships
5. Common customer marketing
G. New relations with new customers

Chanels
6. Usual regular transportation channels
H. New transportation channels

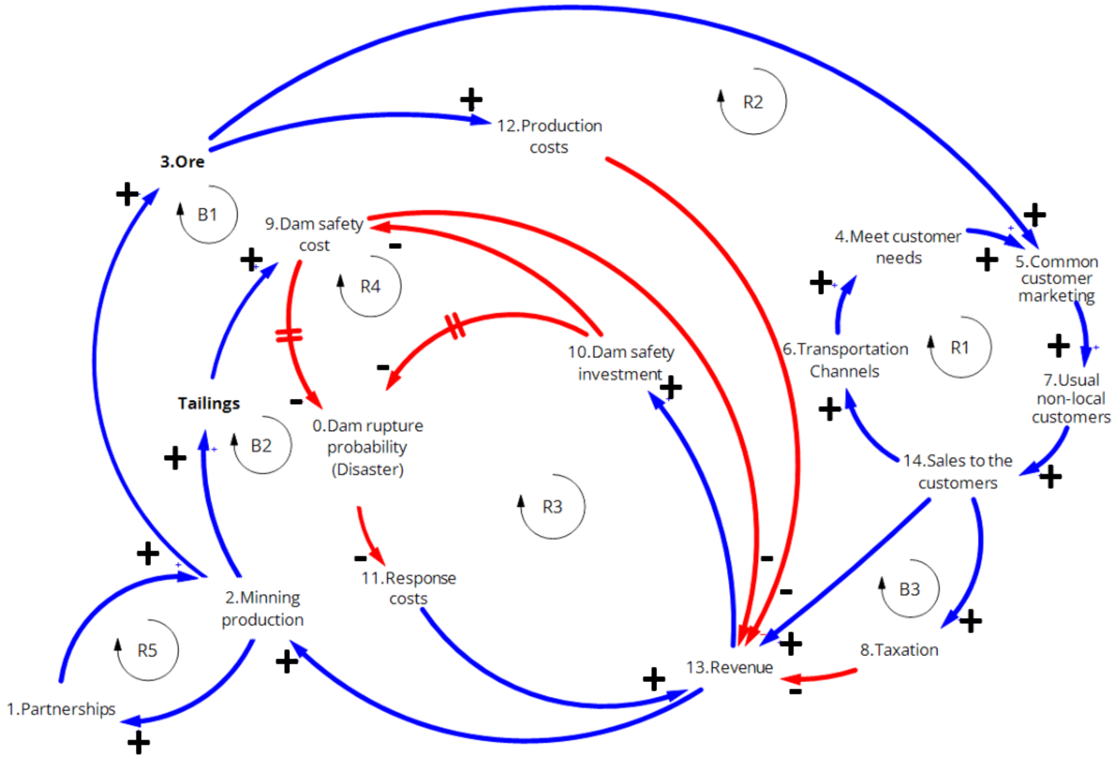
Customer Segments
7. Usual non-local customers
I. New local customers

Cost Structures
8. Taxation
9. Dam safety cost
10. Investment on dam safety
11. Response Cost
12. Regular production costs
J. Taxation Grants

Revenue Streams
13. Company revenue
14. Usual sales to the customers
K. New sales to new customers

Source: Drawn by authors themselves.

Figure 4: CLD for the traditional approach - no reuse of tailings.



Source: drawn by authors.

For instance, for the variable "4. Meet customer needs", one of the possible loops is "5. Common customer marketing, 7. Usual non-local customers, 14. Sales to the customers, and 6. Transportation Channels". This loop is called "R1" and is assumed to be a "reinforcing loop". Table 1 presents, for the sake of conciseness, only the loops indicated in Figures – which register loops for 8 out of the 14 variables depicted in Figures 4 and 5. Taking the B1 for behaviour analysis, in synthesis, the "2. Minning production" leads to more ore and more revenue (if "12. Production costs" does not compromise it), which is a good situation. Nevertheless, the "2. Minning production" results also in more "tailings". This variable generates three loops, one of which, called B2, includes "Tailings, Dam safety cost, Dam rupture probability (Disaster), Response costs, Revenue, Minning production". This B2 loop might lead to a bad situation: the dam rupture and a disaster (with all the "territorial" impact and its associated costs).

Table1: CLD loops.

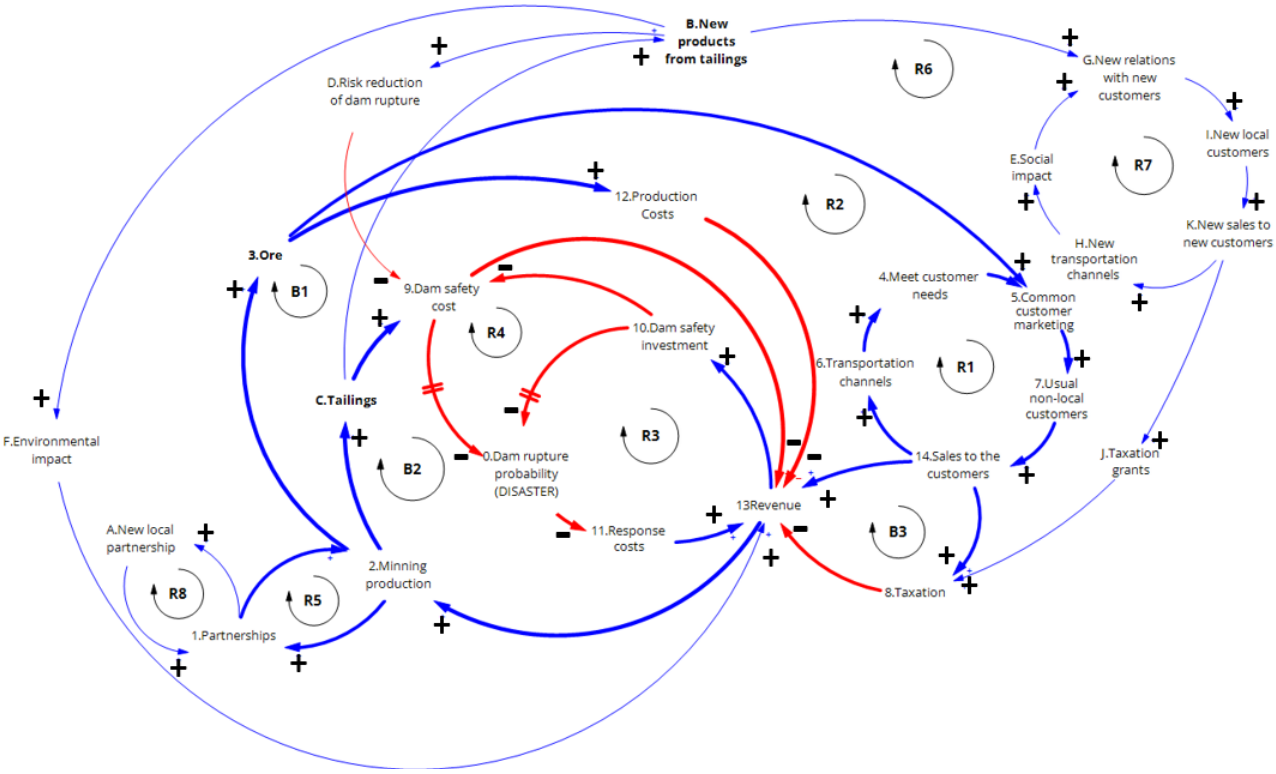
Loop	Variables Sequence	Loop Description	Source
R1	4.Meet customer needs 5.Common customer marketing 7.Usual non-local customers 14.Sales to the customers 6.Transportation Channels	This loop corresponds to the fulfilment of the value proposition: "Meet customer needs".	Section 2.1
R2	3.Ore 5.Common customer marketing 7.Usual non-local customers 14.Sales to the customers 13.Revenue 2.Minning production	This loop addresses the typical sequence of common ore mining production and revenue.	Section 2.2
R3	13.Revenue 10.Dam safety investment Dam rupture probability (Disaster) 11.Response costs	This loop corresponds to the typical relation among the revenue, costs and investments made to reduce the disaster probability.	Section 2.2
R4	13.Revenue 10.Dam safety investment 9.Dam safety cost Dam rupture probability (Disaster) 11.Response costs.	This loop corresponds to the typical costs and investments made to reduce the disaster probability.	Section 2.2
R6	B.New products from tailings F.Environmental impact 13Revenue 2.Minning production C.Tailings	This loop includes a typical 5R action in the process, featuring the "New products from tailings" variable, which reduces environmental impact and generates additional revenue from tailings.	Sections 2.2 and 2.3
R7	E.Social impact G.New relations with new customers I.New local customers K.New sales to new customers H.New transportation channels	This loop represents a typical consequence of 5R action in the process, including new relations with new customers, new local customers, new sales perspectives and so forth.	Sections 2.2 and 2.3
B1	2.Minning production 3.Ore 12.Production costs 13.Revenue	Typical sequence for producing ore and its corresponding revenue.	Section 2.2
B2	13.Revenue 2.Minning production Tailings 9.Dam safety cost	This loop might lead to a bad situation: the dam rupture and a disaster with all the subsequent impacts.	Section 2.2
B3	13.Revenue 2.Minning production 3.Ore 5.Common customer marketing 7.Usual non-local customers 14.Sales to the customers	Typical sequence for marketing association with revenue.	Section 2.2

Source: Drawn by authors.

Therefore, it is necessary to reengineer the system, including additional loops that incorporate some effective 5R strategies, as presented in previous sections, since sustainability, territoriality, and economic development are essential parameters to consider. Additionally, leveraging this in our favour, we have the use of Law 14.260 (BRASIL, 2021), which grants "tax incentives" and fosters projects that stimulate the circular economy. Their use of a systemic perspective, focusing on the "rethink, refuse, reduce, reuse, and recycle" approach, leads to the inclusion of more variables, as presented in the BMC of Figure 4, in the green background, and labelled from "A" to "K".

Figure 5 presents the reengineered system, where thick lines and arrows represent legacy (old) components, and thinner ones define new relationships. This resulting CLD includes both old and new variables, totalling 20 variables (1 to 14 + A to F). New key variables and resources involve "new products from tailings", handling "tailings volume", reducing "dam rupture probability", and so forth.

Figure 5 – Reengineering the System, the System Thinking Approach – Reusing Tailings.



Source: drawn by authors.

The current proposal has the potential to increase revenue by reusing tailings as a new product, contributing to the reduction of uncontrolled tailing disposal. The "Taxation grants" also save resources for better investments, which in turn reduces the risk of dam rupture, response costs, and company losses. This also provides a strong motivation for companies and local communities, fostering sustainability and the 5R cycle.

It is essential to recognise that the "Balancing Loops" work to stabilise the system, counteracting changes and maintaining equilibrium. These "Balancing Loops" act as harmful feedback mechanisms, preventing the system from spinning out of control.

5. FINAL CONSIDERATIONS

Disasters represent a severe disruption of a society's functioning, resulting in dramatic losses. Therefore, the traditional disaster response approach has been questioned by several parties, who request improvements to the entire process. Nevertheless, despite the universal claim on the importance of mitigation, few organisations turn it into action. One of the world's biggest potential disaster causes is the residues from mining activities and waste from industrial processing. In Brazil, we have more than 449 mining dams included in the National Dam Safety Policy. Consequently, it is essential to adopt a better management model for this waste, following the 5R approach. Therefore, this research aims to discuss the economic, social, and environmental impacts of developing a technological product based on mining tailings.

This work developed two CLDs to illustrate synergies and cause-and-effect relationships within this complex system. The first CLD corresponds to the traditional approach, with no reuse of tailings, and the second CLD represents a 5R approach, reducing, redesigning, recycling, reusing, and repurposing the tailings The proposed model leads to the transformation of dam tailings into glass-ceramic materials, a known process reusing tailings to repurpose it into a vitreous matrix, where elements are transformed into an inert material, proper to be used as a flooring material in, e.g., popular houses or public constructions.

Perspectives and future work include a methodology to quantify the relationship between the CLD variables, as well as the use of renewable energy sources as part of the overall process of reusing, repurposing, and obtaining new products.

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