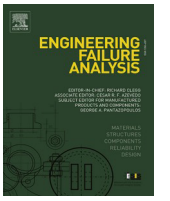
Engineering Failure Analysis 132 (2022) 105934

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal



Economic and financial consequences of process accidents in Brazil: Multiple case studies

Rodolfo Sapata Gonzalez, Raíssa Aparecida da Silveira Rossi, Luiz Gustavo Martins Vieira *

Faculty of Chemical Engineering, Federal University of Uberlândia, Uberlândia, Brazil

ARTICLE INFO

Keywords:
Industrial accidents
Economic-financial impacts
Mariana dam disaster
Brumadinho dam disaster
Fire accidents

ABSTRACT

Along with the advancement of process industries, there has been an increase in process safety accidents (as defined in the 1970s), which often cause deaths and damages to properties, communities, the environment, and the local economy. Process safety management (PSM) and legislation that can minimize dangerous incidents due to the failure of process operations are still insufficient in Brazil. Thus, this work aims to quantify the economic and financial consequences of three different process safety accidents using a case study methodology. The two first cases reflect extreme situations of accidents involving ruptures in tailings dams, which were used to store wastewater generated during ore processing (Mariana and Brumadinho). The Mariana dam disaster caused about 40×10^6 m^3 of mining waste to be released, covering ~1500 ha. The accident had a significant impact on the environment and economy throughout the Doce River Basin, resulting in a loss of US$5.28 billion. The Brumadinho disaster resulted in 270 deaths and 11 missing people, as well as severe environmental damage and property loss. Thirteen million cubic meters of tailings were released, damaging a 270-hectare region, and contaminating the Atlantic Forest natural reserves and the Paraopeba River. The total estimated cost, including production losses, fines, and damages, is US$13.48 billion. The third case is the fire at the Santos port terminal (São Paulo) caused by Ultracargo, which highlights the need for PSM policies and legislation because fire accidents are common in Brazil. Only the Port of Santos experienced at least one major fire case per year from 2013 to 2020. The fire spread to six storage tanks, consuming ~30,000 m^3 of fuel, resulting in a US$91.91 million loss for the company. The fire burned for nine days, causing delays in shipments, and a 4.3% reduction in agricultural exports during that period. Industrial process accidents, regardless of the severity of the accident or the type of product handled, have consistent economic and financial impacts on companies and the surrounding regions where they operate. This study exposes Brazil's vulnerability in terms of process safety control and product storage. Therefore, Brazil has the opportunity to explore this topic further.

Introduction

Several catastrophic accidents have occurred in industries around the world over the decades, and accidents continue to occur

* Corresponding author.
E-mail address: luizgustavo@ufu.br (L. Gustavo Martins Vieira).

https://doi.org/10.1016/j.engfailanal.2021.105934
Received 26 April 2021; Received in revised form 18 November 2021; Accepted 21 November 2021
Available online 24 November 2021

despite advances in process safety management (PSM). To reduce the number of safety accidents in process industries, safety measures that comply with regulatory standards are critical. Developed countries have already established laws, regulations, and standards that aid risk reduction strategies, which comprise design, installation, risk analysis, accident investigation, inspection, management of change, maintenance, procedures, training, and human factors [1–3]. However, Brazil has flaws in its process safety regulations, and does not ensure that safety standards are implemented properly.

Process industry accidents can have a detrimental financial impact on companies and regional economies in addition to the impact on health and surrounding environments. Table 1 presents the top 20 losses in the oil and gas industry due to process accidents since 1978 [4].

Table 1 shows the historical loss records, which highlight the negative impacts that process accidents can have on an industry, and the importance of hazard identification activities since risk improvements aimed at preventing accident recurrences are commonly based on past experiences.

This study aims to explain how an accident caused by process failure can result in economic and financial impacts. This paper presents an analysis of the economic and financial impacts of three distinct process industry accidents: the Mariana dam disaster, the Brumadinho dam disaster, and the Ultracargo fire. The case studies might assist the Brazilian entrepreneurs and government in comprehending the losses incurred as a result of the vulnerability associated with a safety control in process industries. This study is novel in that it uses quantitative analysis to provide new insights on how to improve PSM in Brazil in order to minimize not only the number of accidents but also the severity of the consequences.

1. Research methodology

A case study is an empirical technique for investigating a phenomenon and its context in a real environment. Explanatory research gathers facts, analyzes them, interprets them, and identifies their causes. This method aims to create hypotheses for logical deduction by expanding generalizations, structuring, and defining theoretical models [5,6]. This study used the explanatory-object methodology, which uses a bibliography to identify and analyze the causes of a certain event using multiple and integrated case studies. Thereafter, qualitative and quantitative analyses of the chosen cases were conducted to answer the question of interest: “How can a process failure cause an accident that has economic and financial consequences on companies and the regions in which they operate?” [5,7]. Process safety accidents are a relevant part of the current Brazilian reality that draws attention to the economy of Brazil’s industrial sector. The multiple cases study can support the central idea of the research by connecting empirical data to the question of interest. Since the impacts were still affecting several niches, data gathering ended in December 2020.

Research project

The research is divided into five sections: (1) issues raised by the case study, (2) propositions, (3) units of analysis (the cases), (4) data binding to the propositions, and (5) criteria for interpreting the findings [5].

The following propositions guided the study and assisted in the discovery of relevant evidence [5]: (i) A process incident causes property damage (damage in equipment, infrastructure, and products); (ii) in many cases, the impacts of an accident reach neighboring communities, affecting their economic activities; (iii) the impacts of an accident (environmental impacts and deaths/injuries) create a

Table 1
The 20 largest losses in the oil & gas industry [4].

THE 20 LARGEST LOSSES 1978–2017				
Date	**Plant Type**	**Event Type**	**Country**	**Property Damage (US$ M)***
07/06/1988	E&P OFFSHORE	Explosion, Fire	United Kingdom	1960
01/11/2017	Refinery	Fire	United Arab Emirates	1000
10/23/1989	Chemical	Vapor Cloud Explosion (VCE)	United States	1520
06/08/2009	E&P OFFSHORE	Plant Shutdown	Norway	910
03/19/1989	E&P OFFSHORE	Explosion, Fire	United States	900
03/15/2001	E&P OFFSHORE	Explosion	Brazil	850
09/25/1998	Gas Processing	Explosion, VCE	Australia	810
04/24/1988	E&P OFFSHORE	Blowout	Brazil	760
09/21/2001	Fertilizer	Explosion	France	730
06/25/2000	Refinery	Explosion, Fire	Kuwait	720
05/04/1988	Chemical	Explosion	United States	690
01/19/2004	Gas Processing	Explosion, Fire	Algeria	690
04/01/2015	E&P OFFSHORE	Fire	Mexico	690
05/05/1988	Refinery	Explosion, VCE	United States	670
03/11/2011	Refinery	Explosion, Fire	Japan	650
04/21/2010	E&P OFFSHORE	Explosion, Fire	United States	640
07/27/2005	E&P OFFSHORE	Explosion, Fire	India	520
11/14/1987	Chemical	Explosion, VCE	United States	520
12/25/1997	Gas Processing	Explosion	Malaysia	510
02/04/2011	E&P OFFSHORE	Plant Shutdown	United Kingdom	500

*Inflated to December 2017 values.

negative image, which may reduce investor interest and the company's market share; (iv) process accidents disrupt businesses, affecting production and logistics; and (v) fines are imposed on the company for failures in industrial processes.

Three units of analysis were chosen: (1) The case of the rupture of the tailings dam in Mariana (November 2015), which is a critical event that favors the confirmation of the propositions because it was assumed that all companies in the manufacturing sector could suffer process accidents; (2) the case of the rupture of another tailings dam in Brumadinho (January 2019), which is similar to the first one and reinforces the PSM vulnerability in Brazilian industries; and (3) the 2015 fire in the fuel tanks at the Santos port terminal, which was chosen because fire events are common and can reach several industries and sectors. This accident occurred in one of Brazil's most important ports, and the fact no one was killed or injured shifted the focus of the analysis to the economic and financial issues. The cases have different probabilities and severities. The fuel tank fire is an incident that involved a typical petrochemical plant and a common process safety accident called boiling liquid expanding vapor explosion (BLEVE). Conversely, the cases involving tailings storage can be considered part of an entire ore refining process that comprises various operations (tailings transportation, feeding, and drainage), and can be categorized as a loss of containment that has the potential to cause harm, not being limited to those facilities covered by the Occupational Safety and Health Administration (OSHA) PSM Standard [8]. Our proposed analysis exposes the effects on the economy, regardless of the company size and the industrial sector. These components help to explain how a process failure accident can result in economic and financial impacts.

2. Theoretical framework

2.1. PSM and economic–financial impacts

The Center for Chemical Process Safety (CCPS) has developed a PSM model that identifies, assesses, and controls risks in processes. The pioneering model is built on four solid bases that support the 20 pillars (Fig. 1) that are required to develop a satisfactory PSM model [9].

The CCPS releases publications based on benchmarking data collected from its members. This work used combined data from the benchmark survey to provide conclusive evidence that systematic process safety implementation provides four essential benefits that can be divided into two categories (qualitative and quantitative benefits) [7]. The qualitative benefits are corporate responsibility and business flexibility. A positive public perception of a corporation enhances its image and brand, making it more attractive to employees, communities, governments, regulatory agencies, insurers, and investors [7]. These benefits have an indirect relationship with the economic and financial growth of corporations. However, the measurement of these effects will not be the focus of this paper.

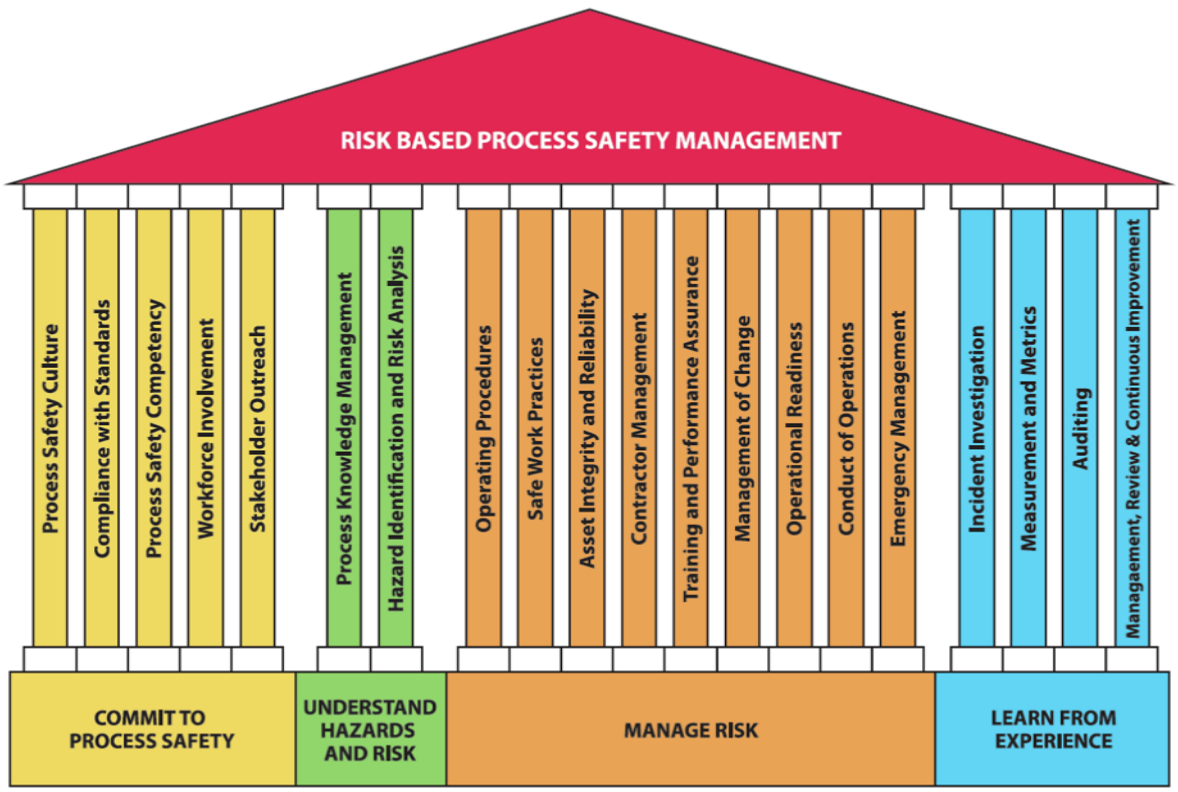


Fig. 1. PSM Model Developed by Center for Chemical Process Safety CCPS [9].

The first quantitative benefit is risk reduction since a successful PSM program can significantly reduce accidents and the high costs associated with their impacts. Process accidents that disrupt normal business activities have a direct impact on a company's share price because of liability losses and even criminal charges [7,9]. Fig. 2 shows the impact of these accidents on the share prices of companies in four different industries in four distinct countries. As can be observed, there is an immediate decrease in the share prices.

The second quantitative benefit is called sustainable value, and it is based on operational reliability after PSM implementation because well-controlled and reliable processes result in increased productivity and quality [7,9]. Fig. 3(a) depicts the benefits of PSM implementation on company reliability, including performance indicators such as productivity improvements, maintenance and production cost reductions, investment necessity reductions, and insurance cost reductions [7]. Fig. 3(b) shows the representativeness of the total value for each indicator in Fig. 3(a).

PSM tools and technology enhance value through preventive and predictive maintenance work, which ensures plant stability. An equipment breakdown or failure can trigger issues since several safety incidents are related to process instabilities and unscheduled shutdowns. In summary, a robust PSM system can enhance businesses by increasing profitability and shareholder value, which is closely linked to corporate image and trust from investors, politicians, regulators, activists, and the press [7,9].

In Brazil, there are still some gaps in the application of PSM concepts. An increase in production and productivity could already indicate some improvements in the Brazilian economy because of a lack of improvement in Brazil's productivity.

2.2. PSM in Brazil

Although there is no specific regulation for PSM in the Brazilian legislation, there are norms that contain some elements of this management model. Regulatory Standard No. 20 (NR-20), a Ministry of Labor regulatory standard, is the regulation that mostly resembles the theme, with a focus on flammable and combustible products [10], as shown in Table 2.

At times, NR-20 could be superficial. In terms of the pillars of safe work practices, NR-20 does not include nonroutine jobs, and some other pillars are not even mentioned in the Brazilian standard, such as management of changes, which is one of the major contributing factors in many catastrophic events in industries [11]. In addition, NR-20 is only used for combustible and flammable materials, leaving other industries outside of the PSM practices and more susceptible to accidents. Table 3 shows some Brazilian Ministry of Labor standards that could be applied to any industry segment and their similarities with the CCPS model.

As can be observed, the Brazilian legislation does not cover most topics relating to process safety. Owing to the absence of specific Brazilian legislation, some Brazilian industries operate under international standards and regulations because they understand the importance of the topic and the possible impacts. However, the absence of regulation limits companies' approach toward PSM, enabling a relatively high occurrence of process safety accidents and losses.

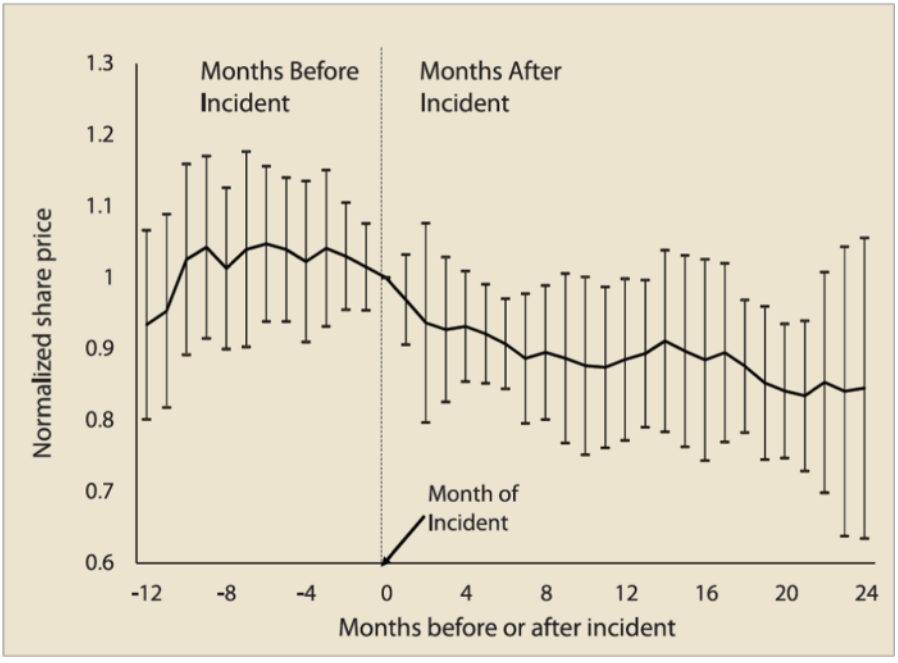


Fig. 2. Impact of process accidents on companies' share prices in four countries (Germany, India, Japan, and USA) and four industry sectors (chemical, petroleum, pharmaceutical, or utilities) normalized to the applicable country's stock market sector index [9].

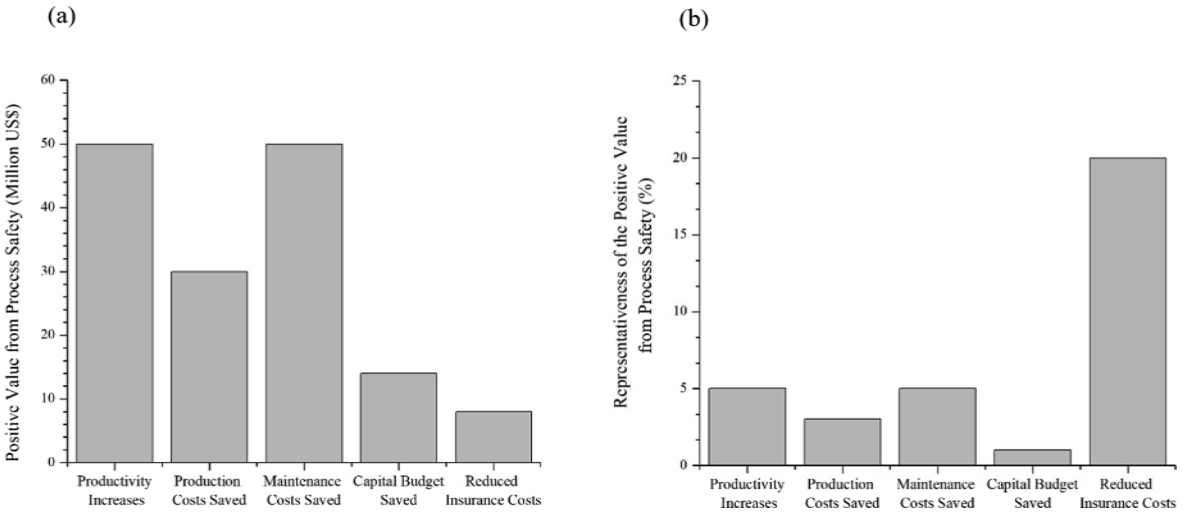


Fig. 3. Companies' gains related to the reliability after the PSM implementation (a) and representativeness in percentage for each indicator. Adapted from CCPS Report [7].

Table 2
Comparison between the PSM model of CCPS [9] and the Brazilian NR-20 [10].

PSM-CCPS	NR-20 (Flammable and Combustible Materials)	
1	Process Safety Culture	–
2	Compliance with Standards	–
3	Process Safety Competency	–
4	Workforce Involvement	–
5	Stakeholder Outreach	–
6	Process Knowledge Management	Design and Installation Handbook
7	Hazard Identification and Risk Analysis	Risk Analysis
8	Operating Procedures	Operational Safety
9	Safe Work Practices	Control of Ignition Sources
10	Asset Integrity and Reliability	Maintenance and Inspection of Assets
11	Contractor Management	Contractors
12	Training and Performance Assurance	Training of Workers
13	Management of Change	–
14	Operational Readiness	–
15	Conduct of Operations	–
16	Emergency Management	Emergency Response Plan
17	Incident Investigation	–
18	Measurement and Metrics	–
19	Auditing	–
20	Management Review and Continuous Improvement	–

2.3. The economy in Mariana and Brumadinho counties

The State of Minas Gerais is dependent on mining activities, which account for approximately 6% of its gross domestic product (GDP) [12]. Mariana County is located in the southeastern portion of the iron quadrangle, about 100 km from Belo Horizonte (capital of Minas Gerais), and the development of mining activities has boosted the local economy since the end of the last century [13]. During the 1970s, three major mining companies, Samarco, Samitri and Vale, inspired an intense urbanization process in the region. The main activity is iron ore extraction, which accounts for 60% of national production. Bauxite, manganese, gold, and quartzite are among the other minerals mined in the region [14]. Before the accident, Mariana had a GDP per capita of US$36663.98 in 2014 (the tenth highest in the state, which comprises 853 municipalities) [15]. The mining industry provided 85% of the county's income and employed the most citizens, accounting for 23.5% of the working population.

Brumadinho, which is located in the metropolitan region of Belo Horizonte, is another example of a county that flourished with the ore mining sector, which accounted for 60% of its income, producing a GDP per capita of US$16,080.08 in 2017 [16]. According to the National Mining Agency (ANM), Brumadinho's mining income in 2018 was US$17.16 million per annum before the dam rupture event, and the Feijão mine produced 8.5 million tons of iron ore annually, which was equivalent to 2% of Vale's iron ore production [17]. In addition to mining, tourism is another sector that contributes to the municipal's revenue. The tourist attractions are related to cultural and ecological tourism, such as extreme sports parks and historical sites, which include buildings from the seventeenth century

Table 3
Comparison between the PSM model of CCPS [9] and the standards from the Brazilian Ministry of Labour.

PSM-CCPS	Brazilian Standards (Besides NR-20)	
1	Process Safety Culture	–
2	Compliance with Standards	–
3	Process Safety Competency	–
4	Workforce Involvement	NR 5 - Internal Accident Prevention Commission (CIPA)
5	Stakeholder Outreach	–
6	Process Knowledge Management	–
7	Hazard Identification and Risk Analysis	–
8	Operating Procedures	–
9	Safe Work Practices	–
10	Asset Integrity and Reliability	NR 13 - Boilers and Pressure Vessels
11	Contractor Management	–
12	Training and Performance Assurance	–
13	Management of Change	–
14	Operational Readiness	–
15	Conduct of Operations	–
16	Emergency Management	–
17	Incident Investigation	–
18	Measurement and Metrics	–
19	Auditing	–
20	Management Review and Continuous Improvement	–

[18]. The Inhotim Institute in Brumadinho is the headquarters of Brazil's major contemporary art museums and is considered one of the largest open-air museums in the world, with an area of 140 ha comprising forests (biomes of the Atlantic Forest and the Cerrado) and botanical gardens. Immediately after the accident at the Feijão mine, there was an 80% decrease in tourist numbers, which took eight months to normalize [19,20].

2.4. Samarco and Vale

Samarco is a multinational company and a joint venture between Vale and the Anglo-Australian BHP Billiton, two of the three largest mining companies in the world. Samarco has two operational units for iron ore extraction and has operated in the Brazilian mining sector for 42 years. The company had an annual turnover of US$3.24 billion and was the country's tenth-largest exporter in 2014, the year before the Mariana incident. Samarco produced 24.9 million tons of iron ore in 2015 and had an annual income of US $2.01 billion [21,22].

Vale was founded as a state-owned company in 1942; however, it was privatized in 1997. The company operates in 30 countries and is one of the largest global mining enterprises, with operations in mining, steel, logistics, and energy. It generated an average income of US$35.3 billion per annum in 2017 and 2018, before the Brumadinho accident [23,24].

2.5. The Doce River Basin and the Paraopeba River

The Doce River Basin route spans 888 km (Fig. 4) and serves an estimated population of 3.5 million people living in 225 municipalities (200 in the State of Minas Gerais and 25 in the state of Espírito Santo), including Mariana. Agriculture, agribusiness, and electric power generation are all important components of the local economy. The basin has a rich biodiversity, with 98% of its area placed within the Atlantic Forest, one of the world's most important and threatened biomes [25].

The Paraopeba River is 510 km long, with a basin area of 12,000 km^2 (Fig. 5) and a population of 1.3 million inhabitants. It is one of the most important tributaries of the São Francisco River, which is one of the most important watercourses in South America [26]. The Paraopeba River supplies water to approximately 53% of the population of the metropolitan region of Belo Horizonte. Mineral exploration, automobile industry, beverage production, hydroelectric generation, livestock, and agriculture are among the prominent economic activities settled in its basin [27].

2.6. Tailings dams in Brazil

Tailings dams are used to store wastewater generated during ore processing, which is a process of separating valuable mineral materials from the sterile fraction that has no commercial value. This process usually requires a large amount of water, which is contaminated by tailings and chemicals, and is commonly stored in dams. The mud, which is composed of water, silica, and minerals, has no value. However, because of environmental issues, it must be stored rather than discarded. The dams are made of compacted soil or rock blocks with waterproofing and drainage mechanisms [28,29].

Brazil has 846 mineral tailings dams. However, only 432 are regulated by the National Dam Safety Policy of the National Mining Agency (ANM). Among the 432 tailings dams, 51 are considered high risk, while 47 are currently in a state of emergency. There are 368 tailings dams in the State of Minas Gerais, where the two dam accidents addressed in this paper (Marina and Brumadinho) occurred, and 38 of them are declared to be in an emergency state [30,31]. According to the historical data presented in Table 4, other dam-

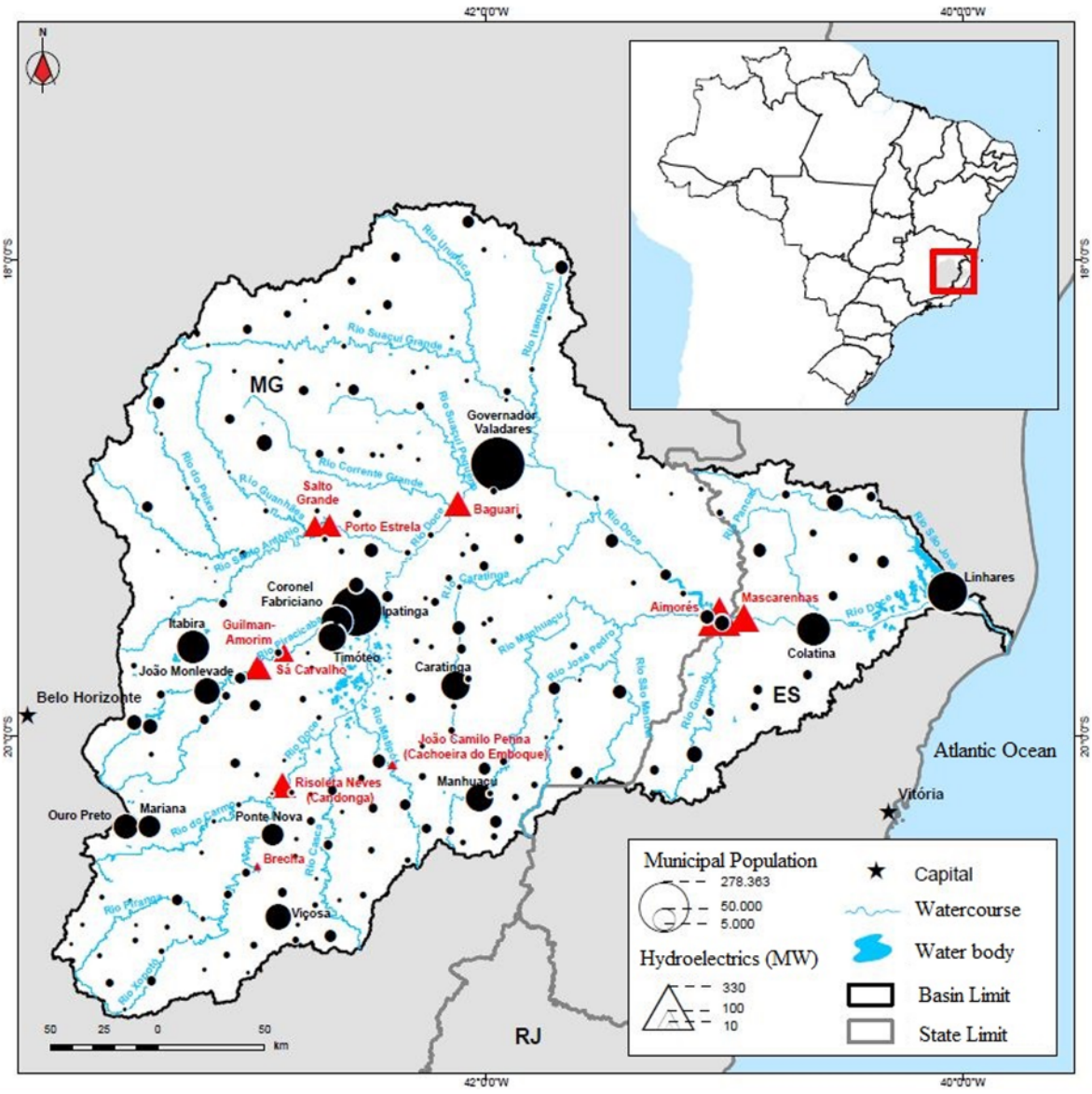


Fig. 4. Location of the Doce River Basin [25].

related accidents have occurred in Brazil [25]. The mining sector had several learning opportunities that could have prevented the Mariana and Brumadinho accidents. The incident investigation pillar of the PSM model is considered one of the main opportunities for preventing new and worse accidents.

2.7. Santos port terminal

The Santos port terminal is the most important port complex in Latin America, with a large and diverse operational capacity. The port has a 16-km pier extension, a total usable area of 7.8×10^6 m^2, 55 marine terminals, and 66 mooring berths. There are warehouses for several types of products, including chemicals and fuel storage tanks. The Santos port terminal is connected to vast roads and rail networks, ensuring continual flow of load to the country's major consumers and producers [32]. The port is closely linked to the Brazilian export market, accounting for approximately one-third of all foreign trades in Brazil. In 2019, the Santos port terminal handled about 28% of all Brazilian business transactions (US$111.8 billion) [33]. Fig. 6 depicts the volume of goods moved through the port in the last three years, as well as its share of movement compared to other Brazilian ports in 2019.

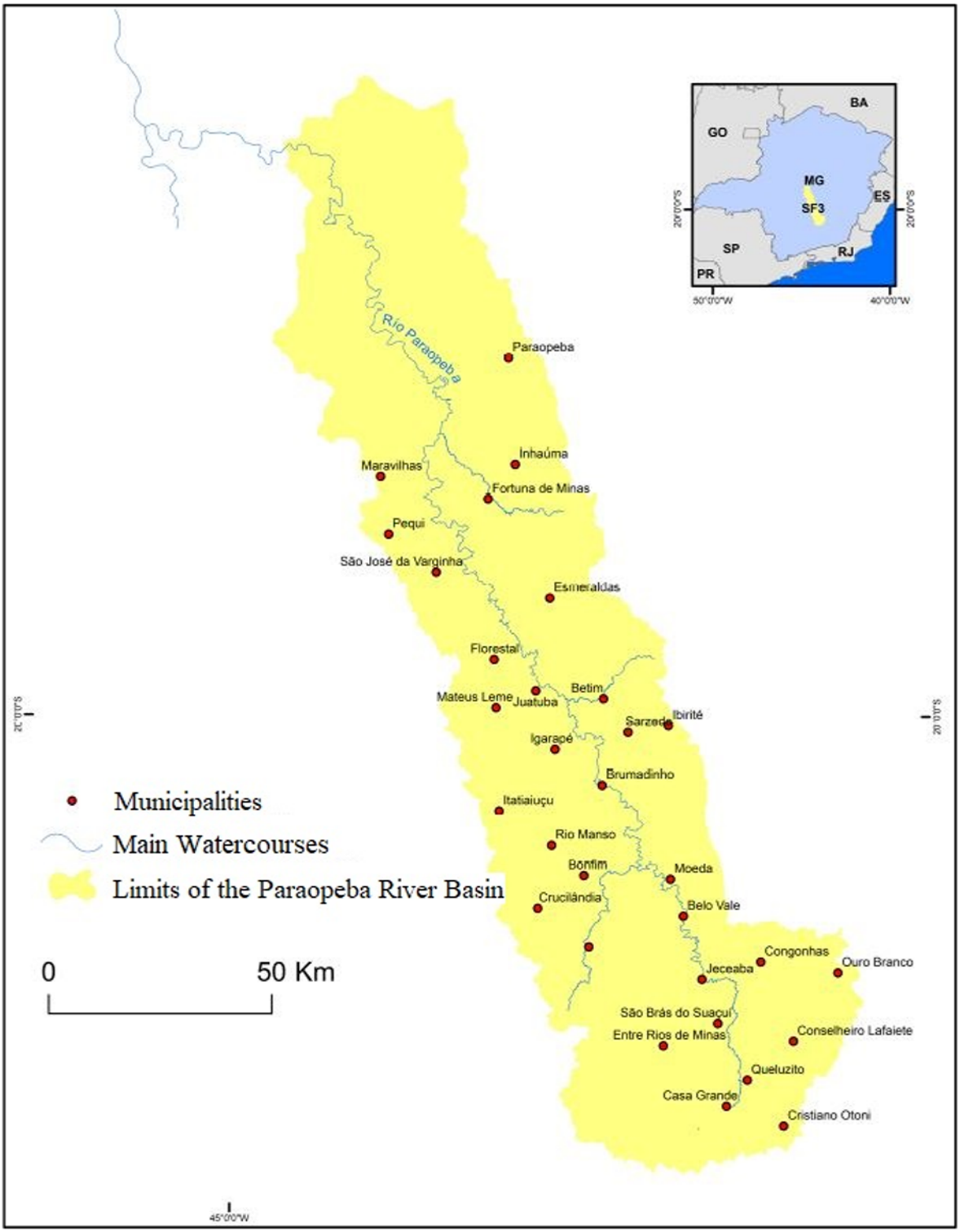


Fig. 5. Location of the Paraopeba River Basin [26].

2.8. Ultracargo

Ultracargo is part of the Ultra Group, one of Brazil's major business groups. Ultracargo is the largest provider of bulk liquid storage in the country, handling products such as fuels, corrosive liquids, vegetable oils, and chemicals. It also has other six port terminals

Table 4
History of accidents involving tailing dam ruptures in Minas Gerais [25].

Year	Site	Number of Victims	Volume of Tailings (m^3)
1986	Itabirito	7	350.000
2001	Nova Lima	5	600.000
2003	Cataguases	0	1.400.000
2008	Miraí	0	2.000.000
2014	Itabirito	3	not estimated
2015	Mariana	19	34.000.000
2019	Brumadinho	270*	13.000.000

*Confirmed deaths until December 2020.

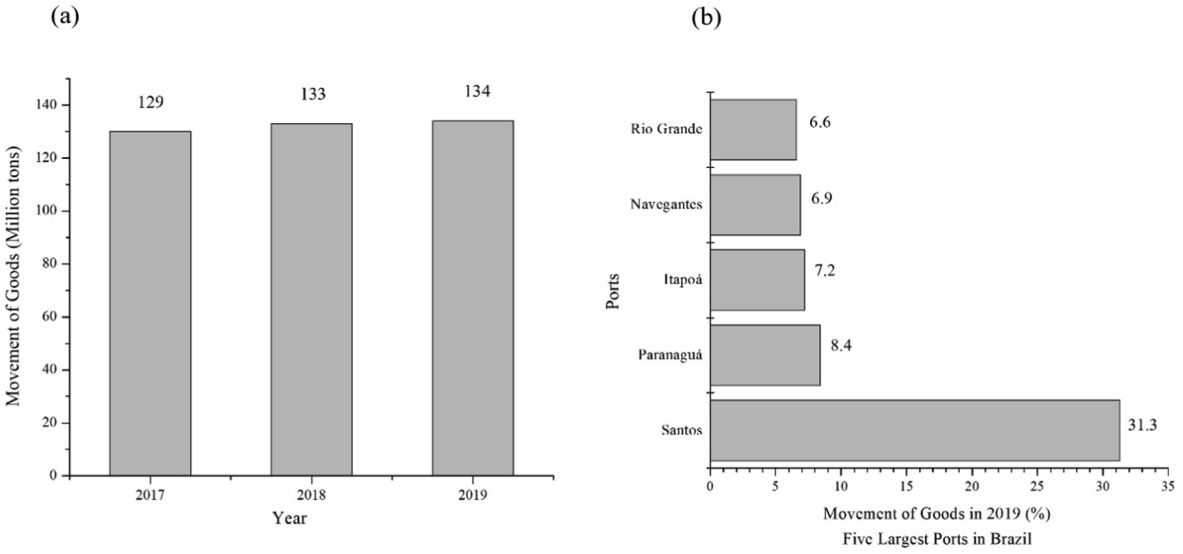


Fig. 6. Movement of goods at the Santos Port Terminal in the last three years (a) and its share of movement in comparison to other four Brazilian ports in 2019 (b) [33].

throughout the country in addition to Santos. The company has 176 tanks in the Santos port terminal, with a total storage capacity of about 307,000 m^3, which is equivalent to 36% of the company's total storage capacity [34]. In 2019, Ultracargo reported US$33.01 million in earnings before interest, taxes, depreciation, and amortization (EBITDA), and the Ultra Group reported US$22.68 billion in net revenue [35].

3. Development of case studies

Similarly, the impacts of each of the three cases were examined using the CCPS report [7], which explains the benefits of a well-implemented PSM program. The average exchange rate for the period during which each amount was generated was used to convert reais to dollars. As determined in the study methodology, the case analysis continued until December 2020 since the litigation processes were still ongoing and facts were constantly updated.

3.1. Mariana dam disaster

The Fundão tailings dam burst on the afternoon of November 5, 2015 (Fig. 7). The dam is part of the Germano mining complex in Mariana (Minas Gerais), which is owned by Samarco. The collapse caused a mud wave of 900 m and an estimated overflow of 40 million m^3 of mining waste into the Doce River Valley, killing 19 people [36,37].

The flow destroyed Bento Rodrigues, a Mariana district with approximately 600 residents, causing a massive environmental disaster (Fig. 8a). It is classified as one of the worst tailings dam accidents in history [25,39]. Iron, silica, and other particulates in the mud reached 680 km of water bodies, transporting waste materials to the outfall of the Doce River on the Atlantic Ocean in the state of Espírito Santo (Fig. 8b). The flood reached a part of the vegetation and substrate, worsening the damage in the river headboard and compromising water supplies in nine cities.

The mud hit four hydroelectric dams along the Doce River that retained part of the tailings. A total of 2,200 ha of land was inundated, causing severe social, economic, and environmental damages [25,42]. Every municipality in the region suffered the impacts. Agriculture, livestock, fishing, and energy sectors had their economy and ecosystems affected.

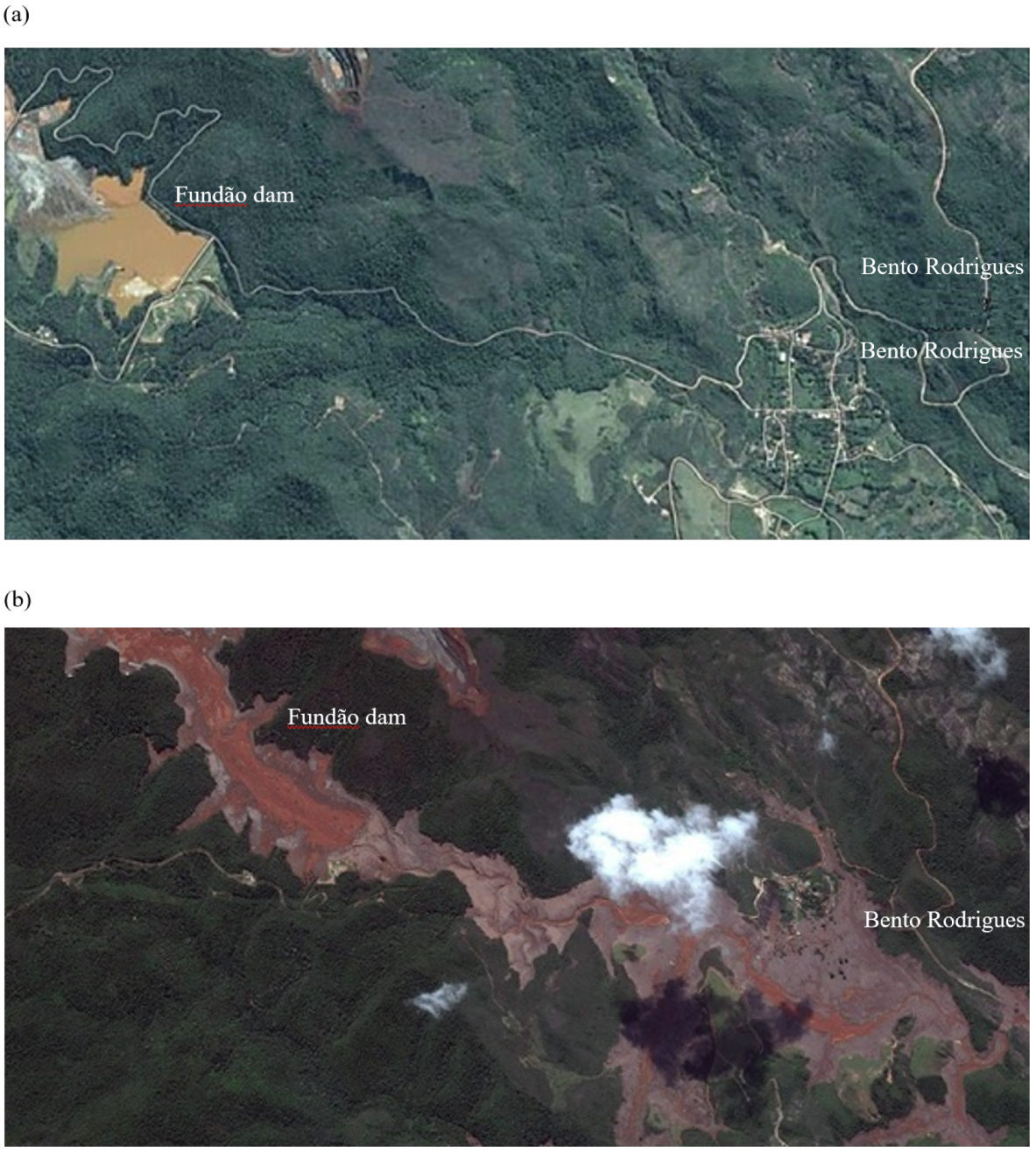


Fig. 7. Images of the region before (a) and after (b) the rupture of the Fundão dam [38].

The Federal Prosecutor's Office investigated the main possible causes of the Fundão dam collapse. During the investigations, it was discovered that the company had admitted to severe risky situations over the years, from the beginning of operations until the dam's rupture. A malfunction of the main internal drainage devices of the system and water accumulation were discovered during an inspection carried out in December 2008. It was acknowledged in 2009 that landfill debris was being transported and that this was causing erosion. Despite knowing about the liquefaction risks and the necessity to reinforce the dam structure, Samarco continued to operate and fill the dam while a new drainage blanket was installed to replace its original design [36,37]. A temporary project to setback the left abutment was carried out in 2012 to repair the dam while continuing operations. This project shortened the beach width of the dam to 60 m at the left abutment, which did not comply with the lower safety limit of 200 m required to maintain the draining characteristics of the sands (200 m of beach width). This resulted in saturated contracted tailings (slimes) settling in areas where they were not supposed to be [36]. In 2013, Samarco discovered the formation of cracks and waterlogging in one of the dam bases. Subsequently, without a license from the regulatory agencies, the dam was supplied with tailings from another Vale mining unit,

(a)

(b)

Fig. 8. The burial of Bento Rodrigues (a) and the moment when the mud reaches the Atlantic Ocean (b) [40,41].

which accounted for approximately 27% of the total tailings in the dam between 2008 and 2015, causing the dike level increase. The drainage problems persisted in 2014, as did issues relating to the dam being raised over slime, which allowed the sands to loosen (liquefaction potential). The dam's collapse was caused by a combination of these factors. The invasion of slimes and a change in the original design may have blocked the drainage, creating a zone of potential weakness that affected the dam's stability. The loose sand may have caused lateral extrusion, implying a stress change in the overlying sands, which triggered the liquefaction process and caused the dam to burst. According to Report 994/2016 elaborated by the Secretariat of Professional and Technological Education (SETEC), it is common knowledge that a large number of accidents involving embankment dams (such as the Samarco case) are caused by a lack of control during operation and drainage problems [37]. Small earthquakes (average magnitude of 2.2 Mw) at the time of the rupture may have accelerated the already well-advanced failure process [36]. The emergency plan was not followed when the collapse began, and the surrounding communities were reached, resulting in several victims and 19 deaths. According to the report of the Federal Prosecutor's Office, a risk analysis conducted in 2011 recommended the reallocation of neighboring communities, which was not done.

Since the investigation is still ongoing, it is not possible to state a definitive cause. However, based on the Federal Prosecutor's Office report [37], and Fundão tailings dam review panel [36], a root cause analysis using the fault tree technique [43] was developed to establish a possible scenario that summarizes the facts in chronological order (Fig. 9).

Fig. 9 attempts to approach the event in detail in order to understand the accident and identify the failures that disclose the most likely root causes for the Fundão dam rupture. The major root causes could be connected to a lack in the application of some PSM elements, such as process safety culture, process knowledge management, stakeholder's outreach, hazard identification and risk analysis, management of change, operational readiness, and emergency management. The probability or impact of the accident would have been lessened if a well-implemented PSM program was practiced in conjunction with systematic regulatory agency inspections.

3.1.1. *Economic–financial impacts of the Mariana dam disaster*

The direct and quantitative impacts of this accident followed the same course as the mud, while the indirect and qualitative impacts were proportional to how the news and images of the event spread around the world. Almost five years after the accident, billions of dollars have been spent to assess and alleviate the impacts of this catastrophic event, which resulted in the closure of Samarco. In 2015, Samarco reported a negative EBITDA of US$1.77 billion compared to the positive EBITDA of US$1.55 billion it reported in 2014, the year before the Mariana accident. Samarco made an average net profit of US$1.45 billion per year between 2011 and 2014. The company has only lost an average of US$2.28 billion per annum since the accident, totaling US$11.40 billion (2015–2019) [21–22,44–49]. The stock market was the first to show evidence of the companies' (Samarco, Vale, and BHP) loss of confidence. On the day after the accident, the shares of Vale and BHP decreased by 7.5% and 2.35%, respectively, reaching their lowest market value since

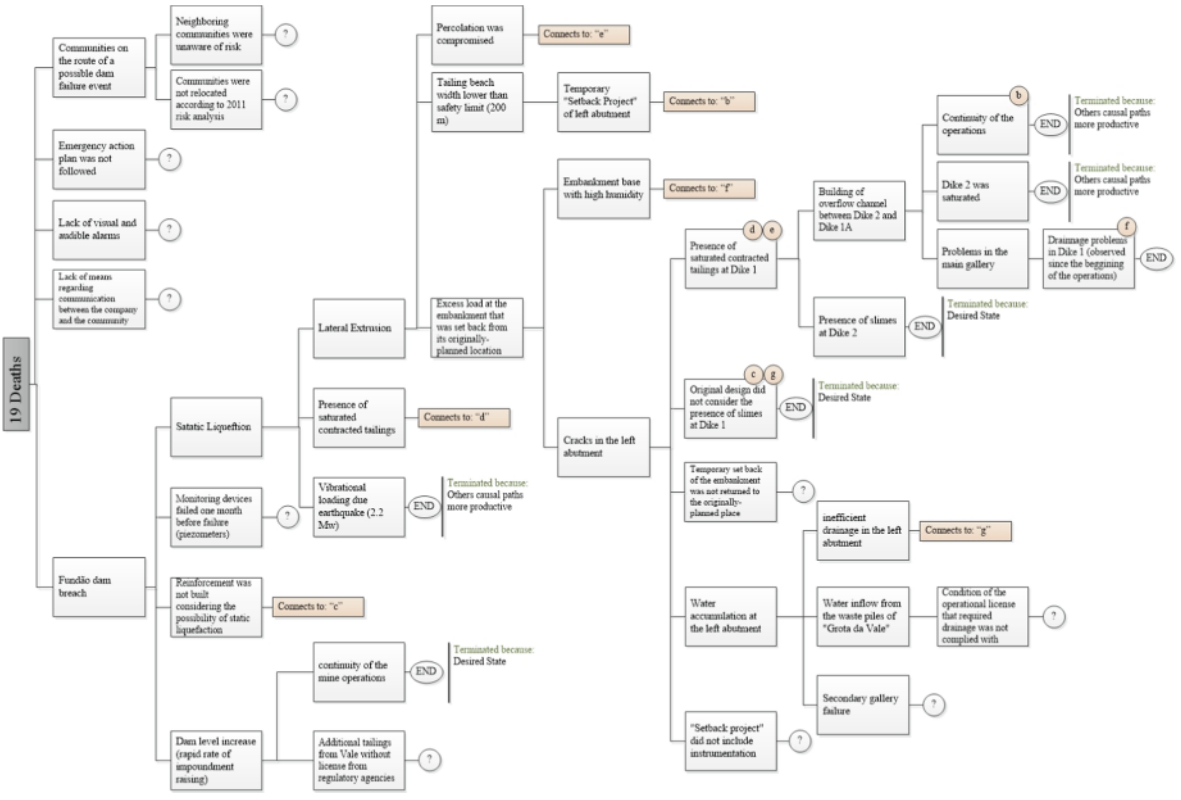


Fig. 9. Fault tree for the Fundão dam rupture in Mariana (a possible root cause analysis).

the accident. FitchRatings, an American credit rating agency, downgraded the prospects of Samarco from BBB to BB− [50]. Despite the marketing efforts of the companies to demonstrate corporate responsibility, public trust was lost because of the accident. There were impacts on the iron ore market in 2014 since Samarco was the second-largest iron ore pellet producer [51]. The product's value increased from US$40.50 at the end of 2015 to US$48.30 in the first quarter of 2016, and its price in the international market continued to rise throughout the year [52]. The event itself sparked speculation, affecting the direction and strategy of this industrial branch.

The impacts were felt not only by the company but also by the economy in the region, which had the lowest royalty income at the time of the accident, affecting the revenue of both the county and the state. Since mining activities account for about 90% of Mariana's income, the fall in tax revenues crippled the local economy and jeopardized most of the newly created job positions in the city. The surrounding cities of Ouro Preto, Mariana, and Catas Altas experienced a royalty (compensation for mineral resource exploitation) shortfall of approximately US$2.44 million per month [53,54]. Agriculture, fishing, and the use of water for human consumption were prohibited in the Rio Doce Basin to prevent any harm to human health because of metal contamination. Currently, the water can be used for animal consumption and irrigation, but fishing activities are still prohibited [55,56]. The agricultural sectors experienced revenue losses because of the destruction of agricultural areas and pastures. The tourism industry lost revenue because of the mud that reached beaches in the Atlantic Ocean and caused mistrust in water quality. The energy sector also suffered the effects of the accident. Three of the Doce River's four hydropower plants (UHE), with a combined generation capacity of 610 MWh, had their activities temporarily halted. The Baguari and Aimorés plants resumed operations in March and May 2016, respectively. However, UHE Risoleta Neves (capacity of 140 MWh) has remained inactive five years after the accident. Samarco is still draining the tailings at this power plant, in violation of the Tailing Management terms, which should have been ended by July 2018 [57,58]. UHE Risoleta Neves was the first hydroelectric plant to absorb the mud, and it acted as a barrier, retaining approximately 10.5 million m^3 of the tailings and reducing the impacts on other regions. Table 5 summarizes the qualitative and economic impacts.

The accident had a serious impact on the two quantitative benefits of PSM implementation (risk reduction and sustainable value). The accident caused 19 deaths, resulting in compensation for the families. Property damage spread beyond the company's site, destroying the whole village of Bento Rodrigues and its surroundings, including vehicles, houses, commercial facilities, streets, and bridges. Apart from the loss of market share, there were costs associated with business interruption due to Samarco's operations in Mariana being immobilized after the accident. The company obtained the corrective operational license (LOC) in September 2019. Five years after the Mariana accident, in December 2020, the company gradually resumed operations, beginning with 26% of its production capacity [59]. The litigation and fines by the federal government, the Brazilian environmental agency (IBAMA), and the governments of Minas Gerais and Espírito Santo sum up to US$5.28 billion. Table 6 summarizes the values relating to the impacts.

3.1.2. Environmental impacts relating to the Mariana dam disaster

According to IBAMA's technical report, the environmental damages included 663.2 km of polluted watercourses that reached the Atlantic Ocean, causing several beaches to be temporarily closed. A total of 1469 ha of riverine vegetation, including Permanent Preservation Areas (PPAs), was destroyed. Since the watercourses were silted, the mud altered the composition of the flora and fauna, resulting in habitat fragmentation. The river is being monitored, and the recovery process is still in progress [64].

3.2. The Brumadinho dam disaster

On January 25, 2019, a rupture occurred at the Feijão dam, resulting in the second major mining tailings disaster in Brazil in less than four years (Fig. 10).

Vale is in charge of the dam, which is located in the Feijão stream region in Brumadinho, Minas Gerais. Thus far, the breach has caused serious environmental damages and property losses; it has also resulted in 270 deaths and 11 missing people so far. A total of 13 million m^3 of tailings was spilled, affecting a region of approximately 270 ha (Fig. 11). The mud reached a section of the remaining Atlantic Forest and the Paraopeba River, which had ore concentrations over the permitted limit after the accident [66,67]. More than

Table 5
Summary of the qualitative and economic impacts of the Mariana dam disaster.

Qualitative Impacts		
Impact Category	**Evidence that supports the Impact**	**Reference**
Production cost increase*	Negative EBITDA	[21–22]
Productivity Loss*	Net profit losses	[44–49]
Perception of risk	Loss of market value	[50]
Poor corporate Image	Loss of public trust (FitchRatings depletion)	[50]
Economic Impacts		
Impact Category	**Evidence that supports the Impact**	**Reference**
Macroeconomic impact	Rise of the iron ore price	[52]
Impact on the state economy	Droop in the royalty incomes	[53,54]
Impact on several sectors of the local economy	Agriculture, fishing, tourism, and energy generation were affected	[55–58]
	Unemployment increase	[55–58]
	Loss of local infrastructure	[55–58]

* Although these impacts are considered quantitative by the CCPS study [7], this paper has not enough information to quantify them. Thus, for the article's didactic purposes, these impacts are here considered to be qualitative since they demonstrate indicatives that an impact has occurred.

Table 6
Quantitative impacts of the Mariana dam disaster.

Impact Category	Impacts	Value (million US $)	Reference
Deaths	Indemnities [a]	13.69	[60]
Property Damage	Damaged dams (fixed asset loss)	62.16	[22,46]
	Village of Bento Rodrigues and two other municipalities	475.52	[61]
	Damage to UHE Risoleta Neves and other infrastructure caused by the event	491.52	[61]
Business Interruption	Halt off the company's activities [b]	1.45	[21,44,45]
Litigation	Recovery, conservation, and monitoring actions for the entire affected environmental area	873.68	[61]
	Management and communication costs related to the assistance and repair actions regarding the damage	512.05	[61]
	Mineral Waste Management	394.31	[61]
	Aid for displaced families	533.33	[61]
	Actions to mitigate socio-economic impacts	732.27	[61]
	Aid to economically dependent families of Doce River	1008.68	[61]
Fines	IBAMA (fines from Nov.-2015 to Dec.-2020)	99.64	[62]
	Government of MG (SEMAD)	59.10	[63]
	Government of ES	0.36	[63]
	Total	**5277.76**	

[a] Value estimated by the author based on the reference [60].
[b] Estimated by the author based on the average profit between 2011 and 2014.

270 people were directly affected by the violent mudflow, and specimens of wild and aquatic fauna and flora perished because of the flood. Mariana and Brumadinho's outcomes have added Brazil to the list of major tailings dam disasters that have caused deaths, economic losses, and serious environmental damage.

Anomalies at the Feijão dam reinforced and increased the recognized but uncontrolled risk from 2017 until the rupture. The dam had already displayed clear signs of collapse in the last two years leading up to the rupture, posing an unacceptable risk of breakdown. According to the International Commission on Large Dams (ICOLD) [69], the main causes of embankment dam failure (which are common in mining companies such as Samarco and Vale) include (1) overflow, which accounts for 31% of the primary cause, and 18% of the secondary cause, and is usually caused by heavy rain; (2) internal erosion in the dam body, which accounts for 13% of the primary cause, and 5% of the secondary cause (it generally occurs as a result of infiltration due to drainage failures); and (3) foundation problems, which account for 5% of the primary cause, and 12% of the secondary cause. It occurs when the ground conditions are insufficient to withstand vigorous attempts.

At the end of 2017, the Feijão dam experienced drainage and internal erosion issues, resulting in a safety factor (the ratio between resistance and demanding efforts) of 1.06 in the stability analysis for liquefaction, which was below the lower safety limit of 1.3. The reports of Vale from 2017 and 2018 revealed a safety factor below the minimum acceptable value and an annual failure probability above the maximum suitable for internal erosion and liquefaction failure modes [65]. At the beginning of 2018, the company announced the installation of deep drains (considered a long-term action) as an attempt to increase the safety factor (SF). Hydraulic stress occurred during the installation of the 15th drain, causing cracks and severe internal erosion at the dam. Thus, the deep drain installation was halted. Owing to these problems, the dam's water drainage pumps remained inoperative for 35 days before the accident, allowing water to infiltrate the tailings during a period of excessive rainfall in January. Similar to that of the Fundão dam in Mariana, the most probable failure mechanism of the Feijão dam in Brumadinho was liquefaction [65].

It is worth noting that a new Federal Ordinance [70] was enacted to establish minimum criteria for the safety management of mining dams after the Mariana accident. According to investigations by the State Prosecutor's Office of Minas Gerais, the company changed the SF operational limit, and provided incomplete information to regulatory agencies, resulting in noncompliance with a contingency plan that should have been implemented as soon as the factor was discovered to be below the acceptable limit in 2017. The mudflow was abrupt and violent, covering the region in just a few seconds and making the escape and rescue of hundreds of people almost impossible. There were no effective mitigation measures (such as protective barriers and watercourse deviations) that could minimize the damage caused by the breach [65]. A possible scenario was devised (based on the report of the State Prosecutor's Office of Minas Gerais) to identify the root causes of this accident, similar to the Mariana case. A fault tree diagram was used to summarize the facts (Fig. 12).

Historical data and specific process studies connected to PSM offer opportunities to prevent new and worse accidents in this regard. At least nine pillars of the PSM model developed by CCPS, including process safety culture, standard compliance, stakeholder outreach, hazard identification and risk analysis, asset integrity and reliability, operating procedures, management of change, the conduct of operations, and emergency management, were seriously affected by the Brumadinho accident.

3.2.1. Economic–financial impacts of the Brumadinho dam disaster

Vale lost US$1.64 billion in the first quarter of 2019 because of the accident compared to a profit of US$1.59 billion in the same period of 2018. The impacts of the Feijão dam rupture caused Vale to record its first-ever negative EBITDA (−US$652 million in the first quarter of 2019) [71]. Vale's shares on the US Stock declined by 8% the day after the rupture, whereas it declined by

Fig.10. Rupture of the Feijão dam in Brumadinho [65].

approximately 20% in Brazil. The mining company lost more than US$17.77 billion in market value. The impact caused the biggest loss in the history of the Brazilian stock market in a single day [72]. Similar to the case of Samarco, FitchRatings downgraded Vale's rating from BBB+ to BBB− [73,74] because of the high costs of repairing the damage caused by the disaster. Despite the company's robust financial condition, the accident raised concerns, mostly because it occurred just over three years after the collapse of Samarco's tailings dam in Mariana, demonstrating a loss of public trust (an impact that is related to process safety). Vale's iron ore production cost was US$1.2/ton higher in the first quarter of 2019 than in the last quarter of 2018 because of the non-dilution of fixed costs after the Brumadinho halt [71]. The price increase caused the shares of other miners in the international markets to rapidly increase, with BHP's shares increasing by 2.36% and Anglo American's shares increasing by 2.46% in January 2019 [75].

Many agricultural areas were affected owing to the loss of property, vehicles, and crops, harming the region's economy. Loss of animals, such as cattle and poultry, was also experienced by the local farmers. The local economy was shut down for a few days while waiting for the civil defense to liberate the region. The hotel sector, which is mainly driven by local tourism, was also affected; some establishments had all of their reservations canceled. The region's economy was severely affected. Vale now provides emergency assistance to citizens who lost their jobs because of the Feijão dam rupture. Farmers in the region are currently attempting to resume their activities in Brumadinho. Those who did not have their properties directly ruined by the mud were hampered either by a lack of water to irrigate the crops or by consumers who stopped buying regional products out of suspicion of contamination. Production in the mining industry declined by 25.4% compared to its level in 2018, with an industrial aggregate product declining (−2.6%) in the year to date. The volume of transport services in the railway and storage sectors was also affected because they are strongly associated with the flow of ore production in the region [76,77]. The gross added value of transport in Minas Gerais decreased by 2.2% in 2019 compared

Fig. 11. Brumadinho region after de accident [68].

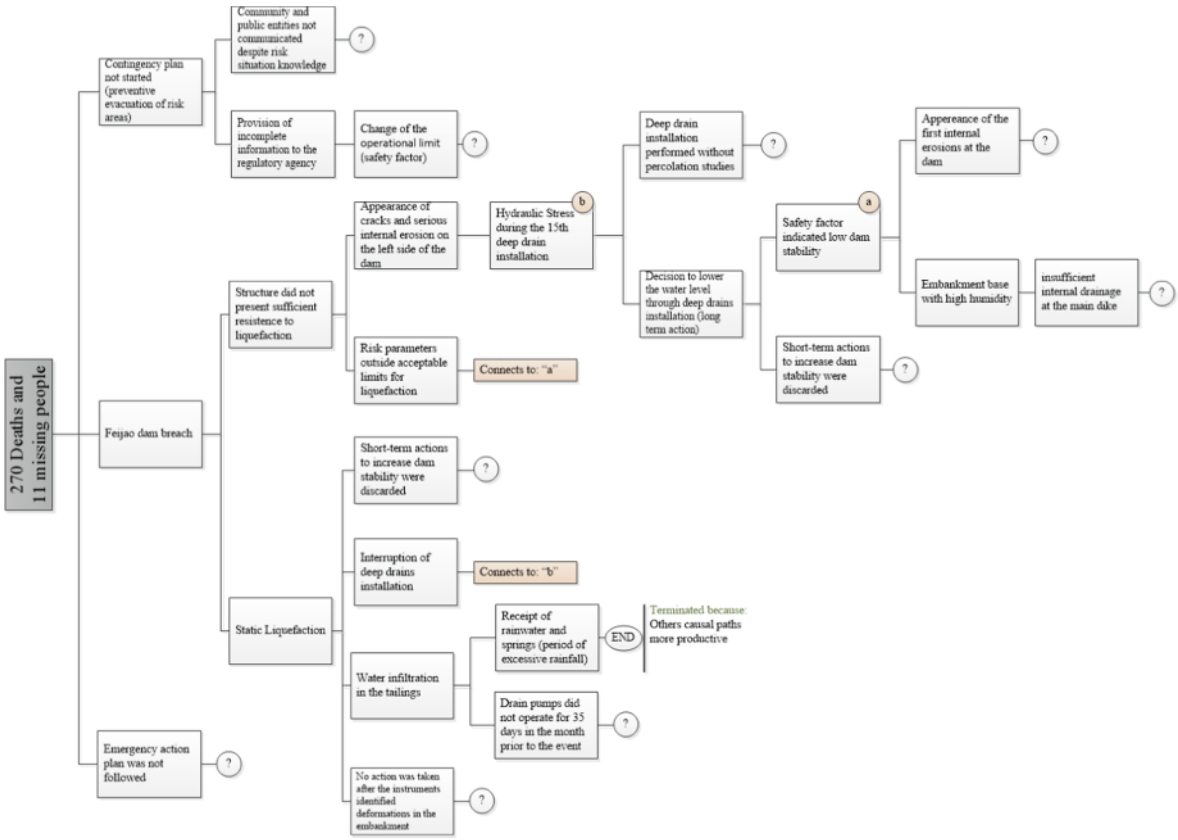


Fig. 12. Fault tree for the Feijão dam rupture in Brumadinho (a possible root cause analysis).

to that in the previous year. The exports also declined, albeit less sharply than the production, possibly because of stock sales [12]. The stoppage of several mining units after the Feijão dam rupture in Brumadinho caused a downturn in the mining industry in Minas Gerais. During the second quarter of 2019, some Vale mines had their operations temporarily suspended because of this incident [12]. Vale's report for the second quarter of 2019 revealed a 19% decrease in iron ore production in the southeast system operational complex (Itabira, Minas Centrais, and Mariana), and a 47.6% decrease in that in the southern system (Paraopeba, Vargem Grande, and Itabirito) compared to the level in the previous quarter. Some of its mining complexes were halted for 90 days during the second quarter of 2019 [12]. Table 7 summarizes the qualitative and economic impacts of the Brumadinho dam disaster.

Many variables, such as compensation for victims, the cost of reconstructing the affected area, and the negative impact on the company's image, should be compiled to estimate the quantitative impacts. The accident caused 270 deaths, and the affected families were compensated. The company's plant was damaged, resulting in business interruption. The mud destroyed many agricultural areas in Brumadinho municipality as well as the native vegetation, resulting in litigation and fines from the federal government, the IBAMA, and the Minas Gerais government. Vale incurred a financial impact of US$4.95 billion owing to provisions for compensation programs and agreements, provisions for decommissioning or decharacterization of tailings dams, expenses incurred directly related to Brumadinho, production loss, and shutdown expenses. If the financial impact of Brumadinho was excluded, the company's income would have been US$3.31 billion in the first quarter of 2019, similar to the result in the same period in 2018 [71,78]. The company's debt increased by 10% in March 2019 compared to the level in December 2018 owing to a US$1.84 billion fee to meet the obligation to keep funds available to assist Brumadinho victims. Table 8 presents values connected to the impacts of the Brumadinho dam disaster, similar to that of the Mariana dam disaster.

3.2.2. Environmental impacts relating to the Brumadinho dam disaster

At least 272 ha were destroyed when the dam in Brumadinho ruptured. The mining waste wreaked havoc on the native Atlantic Forest vegetation and PPAs. The mudflow reached the Paraopeba River, leaving a death trail in the region's fauna and flora. The mudflow buried everything in its path, including parcels of biomes, accesses, forests, and cultivation areas, until it reached the confluence of Ribeirão Ferro-Carvão and the Paraopeba River, which had its turbidity, color, and metal content altered. There was a disruption in water abstraction to supply human populations and restrictions on its use for multiple activities, resulting in economic losses in agriculture, livestock, fishing, tourism, commerce, energy generation, etc. The terrestrial fauna habitats were destroyed, and natural conditions were completely altered, culminating a scenario of complete environmental degradation. The soil and water underwent physical and chemical changes, resulting in the extermination of terrestrial and aquatic animals. The dam rupture in Brumadinho destroyed social and economic activities, causing harm to the citizen's health, safety, and well-being [65,69].

The Paraopeba River is currently recovering. Vale is in charge of two water treatment units as well as drainage of the tailings from the silted section of the river. The company maintains 90 sampling points to monitor the water quality [80,81].

3.3. Fire event at the Santos port terminal

On April 2, 2015, six fuel tanks of the Ultracargo Company, which stores products such as fuels, vegetable oil, and chemicals in the Santos port terminal (Santos, São Paulo), caught fire (Fig. 13), causing a few explosions. The smoke could be seen from several cities in the region, and the entrance to the Santos port by the Anchieta Highway had to be shut down. Six of the site's 176 tanks, each with a capacity ranging from 100 to 10,000 m^3, were affected by the fire, which spread over an area of approximately 184,000 m^2 [34].

The fire lasted nine days, consuming the entire stock of foam-forming liquid in the country. About 200 people worked nonstop to extinguish the flames, with assistance from the brigades of private companies in the port, civil defense, navy, army, and air force. The temperature in the area reached 800 °C, and more than 7 billion liters of water were used to cool the area. After the fire was extinguished, the fire department had to monitor the tanks to prevent autoignition [82].

According to the Federal Prosecutor's Office investigation, the fire started after a fuel transfer pump ruptured. The pump was

Table 7
Summary of the qualitative and economic impacts of the Brumadinho dam disaster.

Qualitative Impacts		
Impact Category	**Evidence that supports the Impact**	**Reference**
Production cost increase*	Negative EBITDA	[72]
Productivity Loss*	Net profit losses	[72]
Perception of risk	Loss of market value	[72]
Poor corporate Image	Loss of public trust (FitchRatings depletion)	[73,74]
Economic Impacts		
Impact Category	**Evidence that supports the Impact**	**Reference**
Macroeconomic impact	Rise of the iron ore price	[75]
Impact on the state economy	Droop in the Gross Additional Value	[12]
Impact on several sectors of the local economy	Local business, agriculture, fishing, tourism, and the transport sector were affected	[12]
	Unemployment increase	[12]
	Loss of local infrastructure	[12]
	Temporary activities suspension of other mines	[12]

* Although these impacts are considered quantitative by the CCPS study [7], this paper has not enough information to quantify them. Thus, for the article's didactic purposes, these impacts are here considered to be qualitative since they demonstrate indicatives that an impact has occurred.

Table 8
Quantitative impacts of to the Brumadinho dam disaster.

Impact Category	Impacts	Value (million US$)	Reference
Property Damage	Decomissioning of dams	1855.00	[71]
	Volume Loss	290.00	[71]
Business Interruption	Halt off the company's activities	160.00	[71]
Litigation	Agreement with Union and Governments of MG	8494.89	[76]
	Indemnities for deaths and aid for displaced families	2600.00	[77]
Fines	IBAMA	56.35	[78]
	Government of MG	23.67	[79]
	Total	**13479.91**	

turned on incorrectly after a power outage. The pump's discharge and suction valves were both closed, causing the pump to operate in a closed circuit with a combustible material for a while. The pump and the combustible material overheated, resulting in an explosion called BLEVE. The fire spread to the first flammable material storage tank. At that moment, the foam-feeding system of the tank was down, and the brigade members had difficulty accessing the room to retrieve the protection equipment, causing a delay in fighting the fire, and the fire-fighting system did not supply sufficient water flow and pressure. All these factors led to the collapse of the first tank. Subsequently, the fire spread to the other five tanks, causing one of the biggest fires in the country [85,86]. A root cause analysis was developed in the same manner as in the previous cases, and a possible scenario was summarized, as shown in Fig. 14.

By enlisting the bases and pillars of the PMS model involved in this event (process knowledge and management, hazard identification and risk analysis, operating procedures, safe work practices, operational readiness, and emergency management), it is clear that a process safety program can assist in preventing or mitigating serious impacts, potentially generating value sustainably for the companies that implement it.

3.3.1. Economic–financial impacts of the fire event at the Santos port terminal

The company's operation was reduced from 715,000 m^3 in 2014 to 655,000 m^3 in 2015 because of the accident. The unavailable part of the terminal accounted for 185,000 m^3, which represents 55% of Ultracargo's capacity in Santos, and 23% of the company's total capacity [87]. The company's EBITDA rapidly declined from US$71.16 million in 2014 to US$ 7.92 million in 2015, before returning to US$49.38 million in 2016 [88]. The company's noncompliance with laws and standards that allow for a safe process had a severe negative impact on its image. In 2015, the company proposed an investment of US$ 35.94 million to modernize the terminal safety measures, adequacy, and maintenance of the existing infrastructure. In 2016, Ultracargo's total investment went from US$7.31 million to US$22.81 million [89,90] to prevent more accidents that could result in financial impacts and loss of public trust.

Regarding the port activities, trucks were prohibited from entering the port through the right bank, causing all terminals on that side to shut down operations [91]. The fire disrupted the operations of several companies. Brasil Terminal Portuário lost 20 mooring ship windows, failing to embark about 20 thousand containers, which is equivalent to 25% of the terminal's monthly capacity. At T-Grão terminals, shipment operations were severely reduced. Normally, 20,000 tons are loaded every day. However, during the fire, the volume dropped to 10,000 tons per day. There were also fines associated with shipping loading delays and importer deadlines. The port had its standard movement normalized only a month after the accident, which affected the Brazilian trade balance [92,93]. Since the Port of Santos drains the equivalent of 25% of the trade balance, the nine-day fire resulted in a 4.3% reduction in the volume of agricultural goods exported [91,94], which represented a decrease of 17.5% compared to the level in April 2014. Soy, ethanol, sugar, cellulose, and meat exports were particularly affected by shipping delays. The city's mobility was hampered by a traffic jam on the highway leading to the port terminal, resulting in the loss of perishable products. Companies near the accident region had to suspend their activities for safety reasons. Even after the situation had stabilized, there were economic impacts because such an incident implies a loss of international trust. Brazilian companies may lose investors and competitiveness because of the lack of infrastructure [92]. Table 9 shows the qualitative and economic impacts.

The fire consumed approximately 34,000 m^3 of ethanol and gasoline, which represented 4% of Ultracargo's total capacity in Brazil or 10% of Ultracargo's capacity at the Santos terminal. To put out the fire, US$9.14 million (426,000 L) was spent on foam-forming liquid [91]. The company's activities at the Santos terminal were suspended until the end of 2015 because of the accident, which affected the company's business. Products, production, and infrastructure, including tanks and equipment, were all lost. The average storage of Ultracargo decreased by 8% compared to the storage level in 2014, mainly because of the partial unavailability of the terminal [89]. Liquid effluents dumped in Santos' estuary, mangroves and lagoons adjacent to the port, and gas emissions in the atmosphere all resulted in fines (US$4.87 million) [91]. In May 2019, the company signed a code of conduct agreement, committing to assist over 2000 fishermen and their communities by investing in infrastructure and professional qualification (totaling approximately US$20.5 million) [95]. Table 10 shows the quantitative consequences.

3.3.2. Environmental impacts relating to the fire event at the Santos port terminal

A large amount of toxic smoke with a strong stench and substances harmful to public health was visible from miles away, and soot was spread around the accident site. The fire also caused a significant change in water quality because large amounts of water contaminated with oil derivatives had to be drained into the Santos estuary. The chemicals decreased the amount of dissolved oxygen and raised the water temperature, killing 9 tons of fish from 142 distinct species [97,100].

Fig. 13. Fire in the fuel tanks of Ultracargo at the Santos Port Terminal [82–84].

4. Conclusion

A successful PSM program can assist companies in increasing production, decreasing maintenance and production costs, decreasing investment requirements, and decreasing insurance costs in addition to increasing public trust and market share. In contrast to these benefits, this study exposes Brazil's vulnerability to process accidents, and demonstrates how process accidents can cause several economic and financial impacts in addition to human and environmental consequences. The mining cases in Mariana and Brumadinho

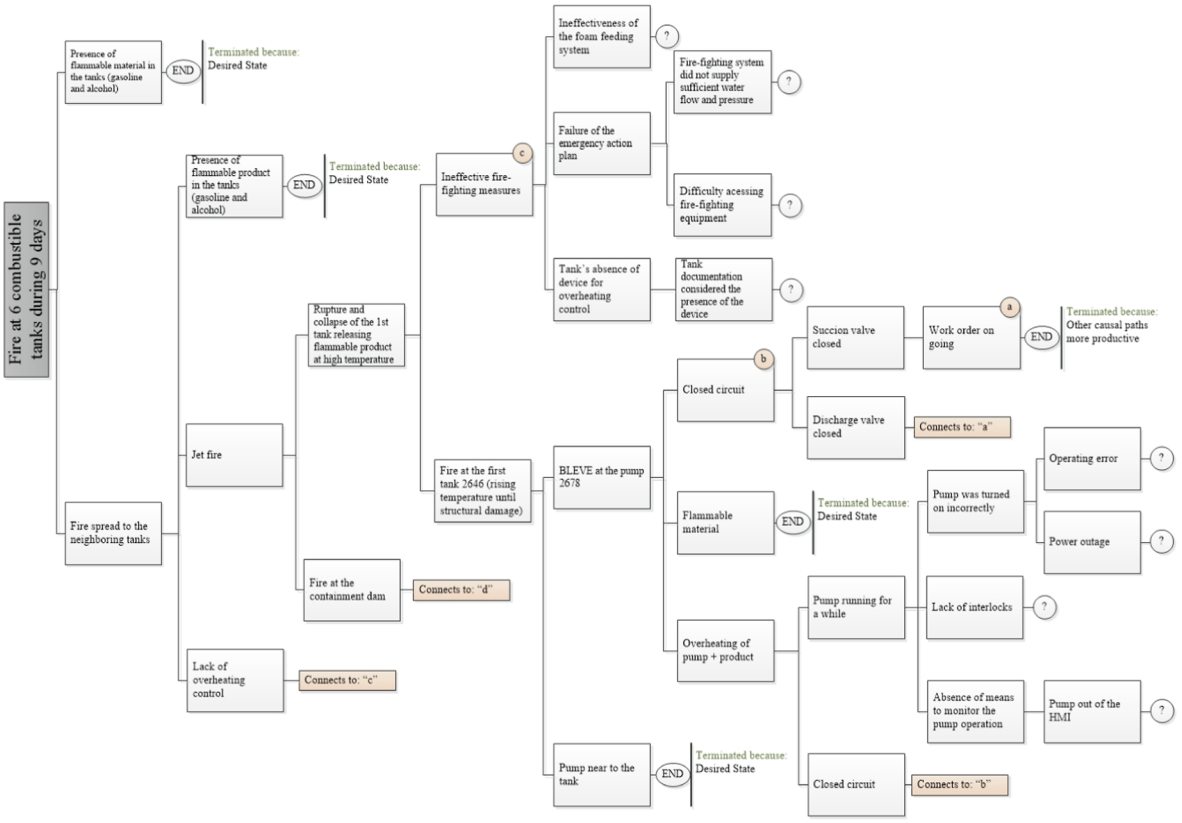


Fig. 14. Fault tree for the fire event at the Santos Port Terminal (a possible root cause analysis).

Table 9
Summary of the qualitative and economic impacts of the fire event at the Santos Port Terminal.

Qualitative Impacts		
Impact Category	**Evidence that supports the Impact**	**Reference**
Production cost increase*	Negative EBITDA	[88]
Productivity Loss*	Reduction of the company's operation	[87]
Poor corporate Image	Increase in the infrastructure and safety measures investments to prevent other accidents	[89,90]
Economic Impacts		
Impact Category	**Evidence that supports the Impact**	**Reference**
Impact on the country economy	Reduction in the volume of agricultural goods exported	[91,94]
Macroeconomic impact	Halt of the port terminals and in the highway that gives access to the port of Santos	[92,93]
	Loss of perishable products	[92]
Impact on several sectors of the local economy	Local business, fishing, and the transport sector were affected	[92]
	Loss of infrastructure	[92]

* Although these impacts are considered quantitative by the CCPS study [7], this paper has not enough information to quantify them. Thus, for the article's didactic purposes, these impacts are here considered to be qualitative since they demonstrate indicatives that an impact has occurred.

exposed the extreme and actual situation of Brazilian tailings dams that are not on the radar because they do not handle combustible or explosive materials. These two cases have a total financial impact of at least US$18.76 billion, with global ramifications. The third case, the fire at the Port of Santos, is one of the most common cases regarding safety-related issues (fires, smolders, and explosions (FSE)). Only the Port of Santos experienced at least one considerable fire case per year between 2013 and 2020. This fact reveals Brazil's deficiency in the prevention of process accidents.

Brazil has the opportunity to improve its legislation and develop the PSM field to lessen the risk of negative consequences such as the ones described in this paper. Regardless of the legislation, the subject is important in order to avoid negative economic and financial consequences for either the industries or the neighboring region. Brazil, in collaboration with its industries, must develop a more robust safety program that can contribute to a safer future for the country.

Table 10
Quantitative impacts of the fire event at the Santos Port Terminal.

Impact Category	Impacts	Value (million US$)	Reference
Deaths	There was no deaths	–	–
Property Damage	Fuel tanks and infrastructure [a]	1.52	–
	Product loss (gasoline and alcohol)	13.71	[96]
Business Interruption	Trucks outage	30.46	[92]
	Ship loading delay	20.00	[92]
	Reduction in goods trading	no estimated	
Litigation	Agreement with the Federal Public Ministry to compensate the damage caused by the accident and assist affected fishing communities [b]	20.50	[97]
Fines	Santos City Hall	0.85	[98]
	CETESB	4.87	[99]
	Total	**91.91**	

[a] Value estimated by the author.
[b] Negotiation still in process. Values could be up to US$ 913 million.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] I. Animah, M. Shafiee, Application of risk analysis in the liquefied natural gas (LNG) sector: an overview, J. Loss Prev. Process Ind. 63 (2020) 103–980.
[2] C. Zhu, J. Zhu, L.i. Wang, M.S. Mannan, Lessons learned from analyzing a VCE accident at a chemical plant, J. Loss Prev. Process Ind. 50 (2017) 397–402.
[3] M.J. Jafari, H. Mohammadi, G. Reniers, M. Pouyakian, F. Nourai, S.A. Torabi, M. Rafiee Miandashti, Exploring inherent process safety indicators and approaches for their estimation: a systematic review, Loss Prevent. Process Industries 52 (2018) 66–80.
[4] Marsh Report, The 100 Largest Losses 1978-2017 - Large Property Damage Losses in the Hydrocarbon Industry. Marsh & McLennan Companies. 25 ed., 2018.
[5] R.K. Yin, Study Research - Design and Methods - Applied Social Research Methods series, 4 ed., SAGE Publications, California, 2009.
[6] M.A. Marconi, E.M. Lakatos, Fundamentos da Metodologia Científica [Fundamentals of Scientific Methodology], 5 ed., Atlas, São Paulo, 2003.
[7] CCPS, (Center for Chemical Process Safety), of the American Institute of Chemical Engineers, The Bussines Case for Process Safety, 2 ed., Aiche Industry Technology Alliance, 2006.
[8] American Petroleum Institute Guide to Reporting Process Safety Events Version 3.0. ANSI/API Recommended Practice 754, Process Safety Indicators for the Refining and Petrochemical Industries, 2016.
[9] CCPS, (Center for Chemical Process Safety), of the American Institute of Chemical Engineers, The Bussines Case for Process Safety, 4 ed, Aiche Industry Technology Alliance, 2018.
[10] NR 20 - Segurança e Saúde no Trabalho com Inflamáveis e Combustíveis [Regulatory Standard - Safety and Health at Work with Flammables and Fuels]. Portaria SIT n° 308, February 2012.
[11] F. Gambetti, A. Casalli, V. Chisari, V. Rico-Ramirez, Why sometimes may be neglected management of change, Chem. Eng. Trans. 31 (2013) 553–558.
[12] Relatório Anual - Fundação João Pinheiro, A Economia de Minas Gerais em 2019 [The Economy of Minas Gerais in 2019] - Estatística & Informações - Indicadores Econômicos, Belo Horizonte, 2020.
[13] R. Cymbalista, P.M. Cardoso, O Plano Diretor de Mariana - MG: A difícil articulação entre planejamento urbano, patrimônio histórico e atores políticos [The Master Plan of Mariana - MG: The difficult articulation between urban planning, historical heritage and political actors]. I Congresso De Direito Urbanístico, São Paulo, 2006.
[14] P. Gracindo Junior, Mariana - Da Cidade Patrimônio a Cidade Partida. Patrimônio e Memória [From the Heritage City to the Broken City. Heritage and Memory], Universidade Estadual Paulista (UNESP) – CEDAP, Assis, 2007.
[15] Cidades de Minas Gerais, Economia de Maria [Economy in Mariana]. Data from Brazilian Institute of Geography and Statistics - IBGE, 2019, http://www.minasgeraismg.net/cidades/mariana#clima-de-mariana-mg, [Online; accessed 10-Aug-2020].
[16] PIB de Brumadinho [Gross Domestic Product of Brumadinho]. Data from Brazilian Institute of Geography and Statistics - IBGE, 2020, https://cidades.ibge.gov.br/brasil/mg/brumadinho/panorama, [Online; accessed 10-Aug-2020].
[17] Diário do Comércio , Impactos da tragédia de Brumadinho na economia [Impacts of the Brumadinho tragedy on the economy], 2019, https://diariodocomercio.com.br/economia/brumadinho-perde-60-da-arrecadacao-com-tragedia, [Online; accessed 18-Aug-2020].
[18] Instituto Estadual de Florestas [State Forestry Institute], Parque estadual da Serra do Rola-Moça, http://www.ief.mg.gov.br/component/content/198?task=view, [Online; accessed 18-Aug-2020].
[19] Globo G1, Instituto INHOTIM, um dos maiores museus a céu aberto do mundo, completa 13 anos em Brumadinho [Inhotim Institute, one of the largest open air museums in the world, turns 13 in Brumadinho], 2019, https://g1.globo.com/mg/minas-gerais/noticia/2019/10/12/instituto-inhotim-um-dos-maiores-museus-a-ceu-aberto-do-mundo-completa-13-anos-em-brumadinho.ghtml, [Online; accessed 23-April-2020].
[20] Arts and culture Google, INHOTIM, https://artsandculture.google.com/partner/inhotim?hl, [Online; accessed 23-April-2020].
[21] SAMARCO - Relatório da Administração e Demonstrações Financeiras [SAMARCO Annual Report], 2014, https://www.samarco.com/wp-content/uploads/2016/08/2014-Relatorio-da-Administra-o-e-Demonstra-es-Financeiras.pdf, [Online; accessed 20-Aug-2020].
[22] SAMARCO - Relatório da Administração e Demonstrações Financeiras [SAMARCO Annual Report], 2015, https://www.samarco.com/wp-content/uploads/2016/08/2015-DFs_portugues_final_07062016.pdf, [Online; accessed 20-Aug-2020].
[23] VALE S.A., About us, http://www.vale.com/brasil/EN/aboutvale/Pages/default.aspx, [Online; accessed 20-Aug-2020].
[24] VALE. S.A, Desempenho da VALE [Financial Report, Performance of VALE], 2018, http://www.vale.com/PT/investors/information-market/quarterly-results/ResultadosTrimestrais/Vale_IFRS_4Q18_p%20final.pdf, [Online; accessed 20-Aug-2020].
[25] Agência Nacional de Água, Ministério do Meio Ambiente, Encarte Especial sobre a Bacia do Rio Doce - Rompimento da barragem em Mariana/MG conjuntura recursos hídricos no Brasil [Ministry of the Environment -, Report on the Doce River Basin - Dam rupture in Mariana], 2016.
[26] O Comitê da Bacia Hidrográfica do Rio Paraopeba (CBH), Paraopeba River (SF3), MG [Paraopeba River Basin Committee], 1999, https://cbhsaofrancisco.org.br/comites-de-afluentes/cbh-do-rio-paraopeba-sf3-minas-gerais/, [Online; accessed 20-Aug-2020].

[27] Plano de Recursos hidricos, Rio Paraopeba [Water Resources Plan - Paraopeba River Hydrographic Basin], https://www.pdrhparaopeba.com/contexto, [Online; accessed 20-Aug-2020].
[28] S.K. Haldar, Mineral Exploration - Principles and Applications, 2 ed., Elsevier, 2018.
[29] ICOLD Report - Bulletin 99 - Dam Failures, Statistical Analysis, Commission Internationale des Grands Barrages, Paris, 1995.
[30] Agência Nacional de Mineração – Ministério de Minas e Energia, Relatório Anual de Segurança de Barragens de Mineração 2019 [National Mining Agency - Ministry of Mines and Energy, Annual Mining Dam Safety Report 2019], 2020.
[31] Agência Nacional de Mineração – Ministério de Minas e Energia, Relatório Semanal de Barragens de Rejeito [National Mining Agency - Ministry of Mines and Energy, Weekly Tailings Dams Report], Juny 2020.
[32] Porto de Santos Institucional [Institutional Port of Santos], http://www.portodesantos.com.br/institucional/o-porto-de-santos/, [Online; accessed 26-Aug-2020].
[33] Porto de Santos, Relatorio Annual [Annual Report of the Port of Santos], http://www.portodesantos.com.br/wp-content/uploads/2020/06/relatorio-anual-2019-versao-final2.pdf, 2019, [Online; accessed 26-Aug-2020].
[34] ULTRACARGO Institutional, http://www.ultracargo.com.br/, [Online; accessed 26-Aug-2020].
[35] GRUPO ULTRA - Relatorio Integrado [ULTRA GROUP Annual Report] 2019, http://www.ultra.com.br/Ultra/relatorio/2019/Relatorio Integrado 2019.pdf, [Online; accessed 26-Aug-2020].
[36] Report on the Immediate Causes of the Failure of the Fundão Dam, Fundão Tailings Dam Review Panel, 2016.
[37] Ministério Público Federal, IPL n.° 1843/2015 SRPF/MG; Autos n.° 38.65.2016.4.01.3822 (Busca e apreensão); Autos n.° 3078-89.2015.4.01.3822 (Medida Cautelar); IPL Polícia Civil - MG 1271-34-2016.4.01.3822; IPL Polícia Civil - MG 1250-24.2016.4.01.3822; Procedimento Investigatório Criminal (PIC) - MPF n.° 1.22.000.003490/2015-78; Procedimento Investigatório Criminal (PIC) MPF n.° 1.22.000.000003/2016-04 [Federal Prosecution Office - Criminal Investigative Procedure] 2018, http://www.mpf.mp.br/mg/sala-de-imprensa/docs/denuncia-samarco, [Online; accessed 31-Aug-2020].
[38] Globo Época, Fotos de satélite mostram o antes e o depois da tragédia em Mariana [Satellite photos show the before and after of the tragedy in Mariana], https://epoca.globo.com/tempo/noticia/2015/11/fotos-de-satelite-mostram-o-antes-e-o-depois-da-tragedia-em-mariana.html, 2015, [Online; accessed 18-November-2020].
[39] G.P.N.A Belchior, Responsabilidade Civil por Dano Ambiental e o Caso Samarco: Desafios à Luz do Paradigma da Sociedade de Risco e da Complexidade Ambiental [SAMARCO case and the Civil Liability for Environmental Damage], RJur Fortaleza. 13(2016) 10-30.
[40] Hoje em dia, Satélite da Nasa mostra imagens da lama na foz do Rio Doce, no Espírito Santo [NASA satellite shows images of the mud at the mouth of the Rio Doce, in Espírito Santo], https://www.hojeemdia.com.br/horizontes/sat%C3%A9lite-da-nasa-mostra-imagens-da-lama-na-foz-do-rio-doce-no-esp%C3%ADrito-santo-1.346481, 2015, [Online; accessed 19-November-2020].
[41] Agência Brasil, Tragédia de Mariana: Vale pagará US$ 25 milhões a investidores nos EUA [Mariana's tragedy: Vale will pay US$ 25 million to US investors], https://agenciabrasil.ebc.com.br/geral/noticia/2020-02/tragedia-de-mariana-vale-pagara-us25-milhoes-investidores-nos-eua, 2020, [Online; accessed 19-November-2020].
[42] SAMARCO, Understand the collapse, https://www.samarco.com/en/rompimento-de-fundao/, [Online; accessed 31-Aug-2020].
[43] D. Kritzinger, Fault tree analysis, BS EN 61025. In Aircraft System Safety, Vol. 3, 2017. https://doi.org/10.1016/B978-0-08-100889-8.00004-0.
[44] Relatório anual SAMARCO, Relatório Da Administração e Demonstrações Financeiras [Samarco Annual Report], https://www.samarco.com/wp-content/uploads/2020/12/2012-Relatorio-da-Administra-o-e-Demonstra-es-Financeiras.pdf, 2012, [Online; accessed 02-December-2020].
[45] Relatório anual SAMARCO, Relatório Da Administração e Demonstrações Financeiras [Samarco Annual Report], https://www.samarco.com/wp-content/uploads/2020/12/2013-Relatorio-da-Administra-o-e-Demonstra-es-Financeiras.pdf, 2013, [Online; accessed 02-December-2020].
[46] Relatório anual SAMARCO, Relatório Demonstrações Financeiras [Samarco Annual Report], https://www.samarco.com/wp-content/uploads/2021/01/Samarco_DFs-2016-versao-portugues-050917-final.pdf, 2016, [Online; accessed 02-December-2020].
[47] Relatório anual SAMARCO, Relatório Demonstrações Financeiras [Samarco Annual Report], https://www.samarco.com/wp-content/uploads/2020/12/Demonstracoes-Financeiras.pdf, 2017, [Online; accessed 02-December-2020].
[48] Relatório anual SAMARCO, Relatório Demonstrações Financeiras [Samarco Annual Report], https://www.samarco.com/wp-content/uploads/2020/12/Samarco_Demonstracoes-Financeiras-2018-vf.pdf, 2018, [Online; accessed 02-December-2020].
[49] Relatório anual SAMARCO, Relatório Mensagem da administração, relatório dos auditores independentes e demonstrações financeiras [Samarco Annual Report] https://www.samarco.com/wp-content/uploads/2020/12/Samarco_Demonstracoes_Financeiras_2019.pdf, 2019, [Online; accessed 02-December-2020].
[50] Fitch Ratings, Fitch Downgrades Samarco to 'BB-'; Rating Watch Evolving, https://www.fitchratings.com/research/corporate-finance/fitch-downgrades-samarco-to-bb-rating-watch-evolving-01-12-2015/dodd-frank-disclosure, December 2015, [Online; accessed 04-November-2020].
[51] Valor Internacional, Miner Samarco invests in iron ore pellet production to raise sales, https://www.valor.com.br/international/news/3505636/miner-samarco-invests-iron-ore-pellet-production-raise-sales?print=1, 2014, [Online; accessed 04-November-2020].
[52] Index Mundi, Preço Mensal do Minério de Ferro [Iron Ore Monthly Price] https://www.indexmundi.com/pt/pre%C3%A7os-de-mercado/?mercadoria=min%C3%A9rio-de-ferro&meses=180, [Online; accessed 05-November-2020].
[53] Estado de Minas, Economia, Dependente da mineração, Minas vive paradoxo após tragédia ambiental em Mariana [States of Minas Gerais, Economy - Dependent on mining, Minas Gerais lives a paradox after the environmental tragedy in Mariana, http://www.em.com.br/app/noticia/economia/2015/11/20/internas_economia,710096/dependente-da-mineracao-mg-vive-paradoxo-apos-tragedia-ambiental-em-m.shtml, 2015 [Online; accessed 05-November-2020].
[54] Governo de Minas Gerais, Avaliação dos efeitos e desdobramentos do rompimento da Barragem de Fundão em Mariana-MG [Government of Minas Gerais, Report Evaluation of the effects and consequences of the Fundão Dam rupture in Mariana-MG], Secretaria de Estado de Desenvolvimento Regional, Política Urbana e Gestão Metropolitana, http://www.agenciaminas.mg.gov.br/ckeditor_assets/attachments/770/relatorio_final_ft_03_02_2016_15h5min.pdf, 2016, [Online; accessed 05-November-2020].
[55] Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio) - Ministério Do Meio Ambiente, Balanço de ações após tragédia de Mariana [Ministry of the Environment, Actions after Mariana tragedy], http://www.icmbio.gov.br/portal/ultimas-noticias/20-geral/8545-icmbio-faz-balanco-de-acoes-apos-tragedia-de-mariana, 2016, [Online; accessed 06-November-2020].
[56] Estado de Minas Gerais, Tragédia em Mariana: pescadores do Rio Doce aguardam julgamento na Inglaterra [Tragedy in Mariana: Rio Doce fishermen await trial in England], https://www.em.com.br/app/noticia/gerais/2020/07/31/interna_gerais,1171931/tragedia-mariana-pescadores-rio-doce-aguardam-julgamento-inglaterra.shtml, 2020 [Online; accessed 06-November-2020].
[57] S.A.S. Sobrinho, Influência dos barramentos nas alterações da qualidade das águas do rio doce antes e após o rompimento da barragem de rejeitos de fundão [Influence of dams on changes in the quality of freshwater waters before and after the rupture of the Fundão Tailing Dam], Instituto de Ciências Biológicas - Programa de Pós-graduação de Especialização em Gerenciamento de Recursos Hídricos - Universidade Federal de Minas Gerais – UFMG, 2018.
[58] Agência Brasil, SAMARCO e Renova atrasam dragagem de usina; multa soma R$ 46 milhões [SAMARCO and Renova delay dredging the plant; fine totals R $ 46 million], 2020, https://agenciabrasil.ebc.com.br/geral/noticia/2020-02/samarco-e-renova-atrasam-dragagem-de-usina-multa-soma-r-46-milhoes, [Online; accessed 06-November-2020].
[59] SAMARCO, A retomada da empresa [The resumption of the company], https://www.samarco.com/en/retomada/, [Online; accessed 04-November-2020].
[60] Folha de São Paulo, Justiça determina indenização de R$ 2,5 milhões para família de vítima não encontrada em Mariana [Justice determines compensation of R $ 2.5 million for family of victim not found in Mariana], Justiça determina indenização de R$ 2,5 milhões para família de vítima não encontrada em Mariana - 20/10/2019 - Cotidiano - Folha (uol.com.br), 2019, [Online; accessed 16-March-2021].
[61] Monitoramento do Programa 1-32, Misnistério Público Federal, Caso SAMARCO, Novembro de 2019, http://www.mpf.mp.br/grandes-casos/caso-samarco/documentos/relatorios-ramboll/pg21_folder_nov2019.pdf, [Online; accessed 04-April-2021].
[62] Ministerio do Meio Ambiente, IBAMA, Rompimento da Barragem de Fundão: Documentos relacionados ao desastre da Samarco em Mariana/MG, [Ministry of the Environment, Disruption of the Fundão Dam: Documents related to the SAMARCO disaster in Mariana/MG], http://www.ibama.gov.br/recuperacao-

ambiental/rompimento-da-barragem-de-fundao-desastre-da-samarco/documentos-relacionados-ao-desastre-da-samarco-em-mariana-mg, 2020, [Online; accessed 04-April-2021].
[63] El Pais, IBAMA e governos de MG e ES aplicaram 68 multas, que totalizam 552 milhões de reais [IBAMA and the governments of MG and ES applied 68 fines, totaling R$ 552 million], https://brasil.elpais.com/brasil/2017/08/08/politica/1502229456_738687.html, 2017, [Online; accessed 10-April-2021].
[64] Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis – IBAMA Diretoria de Proteção Ambiental, Impactos ambientais decorrentes do desastre envolvendo o rompimento da barragem de Fundão, em Mariana, Minas Gerais - Laudo Técnico Preliminar[Brazilian Institute of the Environment and Renewable Natural Resources - Environmental impacts resulting from the disaster involving the disruption of the Fundão Dam in Mariana], DIPRO Coordenação Geral de Emergências Ambientais – CGEMA, Brasília– IBAMA, 2015.
[65] Ministerio Publico de Minas Gerais, Procedimento Investigatório Criminal n.° MPMG-0090.19.000013-4 - Inquérito Policial n. PCMG-7977979 - Distribuição por dependência à Medida Cautelar Criminal n.° 0001819.92.2019.8.13.0090 [District Attorney of Minas Gerais, Criminal Investigative Procedure], Brumadinho, January 2020.
[66] Comitê da Bacia Hidrográfica do São Francisco, Um ano após o rompimento da barragem em Brumadinho, rejeitos começam a ser retirados e legislação federal segue inalterada [One year after the dam burst in Brumadinho, tailings start to be removed and federal legislation remains unchanged], https://cbhsaofrancisco.org.br/noticias/novidades/um-ano-apos-o-rompimento-da-barragemem-brumadinho-rejeitos-comecam-a-ser-retirados-e-legislacao-federal-segue-inalterada/, 2020 [Online; accessed 06-November-2020].
[67] Agência Brasil, IBAMA, Ibama: tragédia de Brumadinho devastou 133 hectares de Mata Atlântica [Brumadinho tragedy devastated 133 hectares of Atlantic Forest], https://agenciabrasil.ebc.com.br/geral/noticia/2019-01/ibama-tragedia-de-brumadinho-devastou-133-hectares-de-mata-atlantica, 2020[Online; accessed 06-November-2020].
[68] Globo G1, Após desastre de Brumadinho, mais de mil pessoas largam casas e estão sem previsão de retorno [After Brumadinho disaster, more than a thousand people leave houses and are not expected to return], https://g1.globo.com/mg/minas-gerais/noticia/2019/03/14/apos-desastre-de-brumadinho-mais-de-mil-pessoas-largam-casas-e-estao-sem-previsao-de-retorno.ghtml, 2019, [Online; accessed 18-November-2020].
[69] ICOLD, Bulletin 121, Tailing Dams-Risk of Dangerous Occurrences, Commission Internationale des Grands Barrages, Paris. France, 2001.
[70] Portaria DNPM n 70389 de 17 de maio de 2017-Segurança de Barragens [DNPM Ordinance 70389, May 17, 2017 - Dam Safety], file:///C:/Users/raiss/Dropbox/Rody/Artigo%20para%20Journal/Material%20de%20Estudo/portaria-no-70389-de-17-de-maio-de-2017-com.pdf, [Online; accessed 02-Nov-2021].
[71] VALE S.A., Desempenho da Vale no Primeiro Trimestre de 2019 - 1T19 [VALE Annual Report First Quarter of 2019], 2019.
[72] Jornal Nacional, Preços das ações da Vale caem 20% após tragédia de Brumadinho [Vale Stock prices go down 20% after Brumadinho tragedy], https://g1.globo.com/jornal-nacional/noticia/2019/01/28/precos-das-acoes-da-vale-caem-20-apos-tragedia-de-brumadinho.ghtml, 2019, [Online; accessed 10-November-2020].
[73] Fitch Ratings, Fitch Afirma Ratings 'BBB+'/'AAA(bra)' da VALE [Fitch Affirms Vale's 'BBB +' / 'AAA (bra)' Ratings], https://www.fitchratings.com/research/pt/corporate-finance/fitch-afirma-ratings-bbb-aaa-bra-da-vale-perspectiva-estavel-25-06-2018, 2018, [Online; accessed 10-November-2020].
[74] Fitch Ratings, Fitch Afirma Ratings Grau de Investimento da Vale [Fitch Affirms Vale's Investment Grade Ratings], https://www.fitchratings.com/research/pt/corporate-finance/fitch-affirms-vale-investment-grade-ratings-removes-negative-watch-09-09-2019, 2019, [Online; accessed 10-November-2020].
[75] Jornal Estadão, Caos Financeiro Avança em Minas Gerais [Financial chaos advances in Minas Gerais], https://economia.uol.com.br/noticias/estadao-conteudo/2018/07/16/caos-financeiro-avanca-em-minas-gerais.htm, 2018, [Online; accessed 10-November-2020].
[76] VALE S.A., Fato Relevante - VALE informa sobre Acordo Global para Brumadinho, Escopo do Acordo Global [Press Release - VALE informs about Global Agreement for Brumadinho, Scope of the Global Agreement], http://www.vale.com/PT/investors/information-market/Press-Releases/ReleaseDocuments/20210204%20-%20Acordo%20Global_FR_p.pdf, 2021, [Online; accessed 10-April-2021].
[77] Valor Economico, Reparação de Brumadinho é prioridade número 1, reitera presidente da VALE [Repair of Brumadinho is priority number 1, reiterates VALE's presidente], https://valor.globo.com/empresas/noticia/2020/12/02/reparacao-de-brumadinho-e-prioridade-numero-1-reitera-presidente-da-vale.ghtml, 2020, [Online; accessed 10-April-2021].
[78] Ministerio do Meio Ambiente, IBAMA, IBAMA multa VALE em R$ 250 milhões por catástrofe em Brumadinho (MG) [Ministry of the Environment, IBAMA fines VALE R $ 250 million for catastrophe in Brumadinho (MG)], http://www.ibama.gov.br/ultimas-2/1879-ibama-multa-vale-em-r-250-milhoes-por-catastrofe-em-brumadinho-mg, 2019, [Online; accessed 10-April-2021].
[79] Agencia Brasil, VALE paga multas ao governo mineiro, mas questiona cobranças do IBAMA [VALE pays fines to the Minas Gerais government, but questions IBAMA charges], https://agenciabrasil.ebc.com.br/geral/noticia/2020-01/vale-paga-multas-ao-governo-mineiro-mas-questiona-cobrancas-do-ibama, 2020, [Online; accessed 10-April-2021].
[80] VALE S.A., Balanço da reparação [Repair Balance], http://www.vale.com/brasil/PT/aboutvale/servicos-para-comunidade/minas-gerais/atualizacoes_brumadinho/SiteAssets/reparacao/docs/Balanco Reparacao Vale dezembro 2019.pdf, 2019, [Online; accessed 11-November-2020].
[81] VALE S.A., Monitoramento das águas do rio Paraopeba será auditado e passará para a tutela do Igam [Monitoring of the waters of the Paraopeba River will be audited and will be under the authority of the Igan], http://www.vale.com/brasil/PT/aboutvale/news/Paginas/monitoramento-das-aguas-do-rio-paraopeba-sera-auditado-e-passara-para-a-tutela-do-igam.aspx, 2019, [Online; accessed 12-November-2020].
[82] Globo G1, Bombeiros anunciam fim do incêndio que atingiu Santos, SP, durante 9 dias [Firefighters announce end of fire that hit Santos, SP, for 9 days], http://g1.globo.com/sp/santos-regiao/noticia/2015/04/bombeiros-apagam-incendio-que-atingiu-santos-sp-durante-9-dias.html, 2015, [Online; accessed 12-November-2020].
[83] Instituto de Pesca de São Paulo, Incêndio no bairro Alemoa, em Santos, Relatório técnico a pedido do Ministério Público Federal [Fire in the Alemoa neighborhood, in Santos, Technical report at the request of the District Attorney], https://www.pesca.sp.gov.br/instituto/centro-de-comunicacao/noticias/737-incendio-bairro-alemoa-santos-instituto-pesca-emite-relatorio-tecnico-pedido-ministerio-publico-federal, 2015, [Online; accessed 18-November-2020].
[84] Globo G1, Ministerio Publico Federal denuncia ULTRACARGO por poluição causada por incêndio que durou 8 dias [Prosecution Office denounces ULTRACARGO for pollution caused by fire that lasted 8 days], https://g1.globo.com/sp/santos-regiao/noticia/mpf-denuncia-ultracargo-por-poluicao-causada-por-incendio-que-durou-8-dias.ghtml, 2018, [Online; accessed 18-November-2020].
[85] Globo G1, Ministerio Publico divulga laudo e pede multa de R$ 3,6 bilhões por incêndio na ULTRACARGO [District Attorney publishes report and asks for a R$ 3.6 billion fine for fire at ULTRACARGO], http://g1.globo.com/sp/santos-regiao/noticia/2016/11/mp-divulga-laudo-e-pede-multa-de-r-36-bilhoes-por-incendio-na-ultracargo.html, 2016, [Online; accessed 16-November-2020].
[86] Ministério Público do Estado de São Paulo, Grupo de atuação especial de defesa do meio ambiente [São Paulo District Attorney, Special group for the defense of the environment], GAEMA - núcleo III, Baixada Santista, Portaria n° 28/2015, April 2015.
[87] ULTRACARGO, Ano atípico exigiu engajamento e mobilização sem precedentes de toda a companhia para enfrentar e superar os desafios [Atypical year required unprecedented engagement and mobilization for the entire company to face and overcome challenges], http://www.ultra.com.br/Ultra/relatorio/2015/pt/ultracargo.html, 2015, [Online; accessed 16-November-2020].
[88] Relatório Anual GRUPO ULTRA 2016 [ULTRAPAR 2016 Annual Report], Grupo, 2016, http://www.ultra.com.br/Ultra/relatorio/2016/pt/, 2016, [Online; accessed 17-November-2020].
[89] Relatório Anual GRUPO ULTRA 2015 [ULTRAPAR 2015 Annual Report] http://www.ultra.com.br/Ultra/relatorio/2015/pt/destaques-2015.html, 2015, [Online; accessed 17-November-2020].
[90] Valor Econômico, ULTRA define R$ 1,8 bilhão para investimento em 2016 [ULTRA sets R$ 1.8 billion for investment in 2016], https://valor.globo.com/empresas/noticia/2015/12/11/ultra-define-r-18-bilhao-para-investimento-em-2016.ghtml, 2015, [Online; accessed 17-November-2020].
[91] Valor Econômico, Santos contabiliza perdas com incêndio na ULTRACARGO [Santos accounts for fire losses at ULTRACARGO], https://valor.globo.com/empresas/noticia/2015/04/27/santos-contabiliza-perdas-com-incendio-na-ultracargo.ghtml, 2015, [Online; accessed 17-November-2020].
[92] Diário do Grande ABC, Incêndio em Santos prejudica exportações [Fire in Santos damages exports], https://www.dgabc.com.br/Noticia/1304207/incendio-em-santos-prejudica-exportacoes, 2015, [Online; accessed 17-November-2020].

[93] Valor Econômico, Proibição da descida de caminhões para Santos é afrouxada [Ban on truck descent to Santos is loosened], https://valor.globo.com/brasil/noticia/2015/04/09/proibicao-da-descida-de-caminhoes-para-santos-e-afrouxada.ghtml, 2015, [Online; accessed 17-November-2020].
[94] Economia Uol, Incêndio no Porto de Santos reduziu exportações agrícolas em 4,3%, diz Cepea [Fire in the Port of Santos reduced agricultural exports by 4.3%, says Cepea], https://economia.uol.com.br/noticias/efe/2015/05/21/incendio-no-porto-de-santos-reduziu-exportacoes-agricolas-em-43-diz-cepea.htm?cmpid=copiaecola, 2015, [Online; accessed 17-November-2020].
[95] Ministério Público do Estado de São Paulo, Termo de compromisso de ajustamento de conduta parcial [São Paulo District Attorney, Term of commitment for partial adjustment of conduct], May 2019, http://www.mpsp.mp.br/portal/pls/portal/!PORTAL.wwpob_page.show?_docname=2646111.PDF, [Online; accessed 27-October-2021].
[96] Globo G1, Com o petróleo em baixa, por que o preço da gasolina não cai no Brasil [The price of gasoline does not fall in Brazil], http://g1.globo.com/economia/noticia/2016/01/com-o-petroleo-em-baixa-por-que-o-preco-da-gasolina-nao-cai-no-brasil.html, 2016, [Online; accessed 16-March-2021].
[97] Ministério Público Federal, MPF, MP-SP e Tequimar assinam acordo para compensar parte dos danos causados pelo incêndio da ULTRACARGO [Federal Prosecution Office, District Attorney and Tequimar sign agreement to compensate part of the damages caused by the ULTRACARGO fire], http://www.mpf.mp.br/sp/sala-de-imprensa/noticias-sp/mpf-mp-sp-e-tequimar-assinam-acordo-para-compensar-parte-dos-danos-causados-pelo-incendio-da-ultracargo, 2019, [Online; accessed 16-March-2021].
[98] Jornal da Orla, Prefeitura de Santos aplica na ULTRACARGO maior multa da história do Município [Santos City Hall applies the largest fine in the history of the Municipality to ULTRACARGO], https://www.jornaldaorla.com.br/noticias/18217-prefeitura-de-santos-aplica-na-ultracargo-maior-multa-da-historia-do-municipio/, 2015, [Online; accessed 16-March-2021].
[99] CETESB, Ultracargo paga 16 milhões de multa por danos ambientais [Ultracargo pays 16 million fine for environmental damage], https://cetesb.sp.gov.br/blog/2016/03/18/ultracargo-paga-16-milhoes-de-multa-por-danos-ambientais/, 2016, [Online; accessed 16-March-2021].
[100] Valor Econômico, Justiça abre processo contra Tequimar [Justice opens suit against Tequimar], https://valor.globo.com/empresas/noticia/2018/02/22/justica-abre-processo-contra-tequimar.ghtml, 2018, [Online; accessed 17-November-2020].