An Investigation into the Best Practice for the Closure of Tailings Dams in Brazil

BACHELOR THESIS

Gaast, H.B. van der
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H.B. (Rik) van der Gaast

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Summary

The aim of this research is to investigate into the best practice of the closure of tailings dams in Brazil. The bulk of this investigation was done by a thorough literature review on the closure of Tailings Storage Facilities (TSF). In order to conduct this investigation three TFS rich location with different geological, hydrological and climate related characteristics are chosen (State of Para, State of Minas Gerais and State of Maranhão). Three cover methods which are analysed in this research are:

- a low permeability cover
- a water-shedding cover
- an alternative cover which makes use of a material called Trisoplast.

Before the thee alternatives are analysed in a Multi-Criteria Analysis (MCA) a stakeholder analysis is conducted. Six parties are included in this analysis: local residents, mining companies, government of Brazil, Greenpeace Brazil, International Council on Mining and Metals (ICMM) and the International Commission on Large Dams (ICOLD). Together with the findings of the literature review and a meeting with an expert from Antea Group it was decided to assess the following criteria: cost, efficiency and sustainability.

The three study areas have different characteristics which could have an impact on the performance of the cover alternatives. Therefore, a MCA is conducted for all three locations. The analysis in the State of Para resulted in an equal score between the water-shedding cover and the alternate cover. Followed closely by the low permeability alternative. In both remaining study areas, the alternate cover method is optimal solution. The main reason for this conclusion is the low volume of Trisoplast which is needed to achieve a sufficiently low permeability. Even though the material cost of Trisoplast is higher than clay (which is used as a sealing layer for the other two alternatives) per m^2. The Trisoplast layer only requires a thickness of 70 mm instead of the 425 mm and 500 mm for the low permeability cover and water-shedding cover respectively. This results in lower transport cost, which also contributes to sustainability in the mining industry.

Because of these results and the available literature, this study concludes that Trisoplast can be considered as a valuable alternative for the coverage of TSF. However, since the results are based on literature only, the performance values cannot be validated yet. Therefore, additional research and in-situ tests have to be conducted.

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1. Introduction

1.1. TAILINGS DAMS

Tailings dams or tailings storage facilities (TSF) as they are often referred to, are large basins which store tailings. Tailings are waste materials that result from large mining operations. The structures vary in size but the facilities can occupy an area of up to 250,000 m^2 (WISE Uranium Project, 2021), which is equivalent to 35 football pitches. In addition, there are about 18,000 tailings dams worldwide, form which only 3,500 are still in operation (Earthworks, 2021).

Unlike conventional water dams, the eventual height of a tailings dam is dynamic over its service life. This is necessary in order to keep the dam in operation and to prevent overtopping. When the hight of a tailings dam has to be increased, three methods can be applied. These methods can be seen in Figure 1. The most common method is the upstream method (a) This method is the cheapest alternative, but also has a low stability which results in a high risk of failing. Alternative (b) is the downstream method which, unlike the upstream method, remains it shape while being increased in volume. Downstream tailings dams are relatively the most expensive but also have a high stability. Finally alternative (c), which is the centreline method, is in the middle regarding both cost and stability. (London Mining Network, 2021)

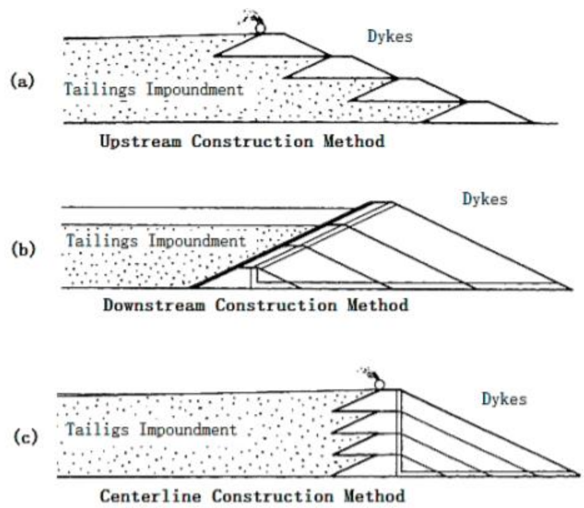

Figure 1: The three main tailings dam construction methods: (a) upstream, (b) downstream, (c) centreline (Vick, 1990)

Eventually when a TSF reaches the end of its service life, the facility is closed down. Depending on the characteristics of the tailings, the dam should be completely sealed off from the environment. Most often this is the case, since tailings are a mixture of amongst others: crushed rocks, fluids which were used during the processing of the metals, minerals and coal (D.Kossoff, et al., 2014) and are generally either toxic or radioactive (Mylona, et al., 2004).

1.2. PROBLEM CONTEXT

Tailings dams are large structures which store waste created by large scale mining operations. These mine tailings are most often a mix of rocks, water which is used to machine the rocks, heavy metals and chemicals. This basically makes tailings dams large storage facilities of toxic sludge. When the tailings dams are about to reach the end of their operation time, it has to be decided how the tailings dam should be closed down. Since little research has been conducted on this topic it is still unclear what the most suitable solution is. Brazil has a large mining industry and therefore a lot of TSF's. Antea Group is working together with her Brazilian division in order to investigate whether TSF closure can be improved in a general context.

1.3. RESEARCH AIM

The aim of this project is to carry out an investigation into the best practice of the closure of tailings dams in Brazil. Three alternatives are considered and therefore, a multi-criteria analysis is conducted in order to find the most suitable method for closure of tailings dams in Brazil. Most suitable method in this context is primarily defined as a more cost-efficient, sustainable and effective closure than the existing alternatives. This includes not only the physical cover, but also the transport and implementation. It was chosen to only include three alternatives because of the time frame of the project.

1.4. TRISOPLAST

It was chosen to look into three alternatives for the multi-criteria analysis. At least one of these alternatives should make use of the sealing material Trisoplast (Figure 2). Trisoplast is a mixture of special clay polymers and filler material. Because of this it has a sand like structure when implemented on location. The material becomes watertight when it absorbs water (Trisoplast Mineral Liners, 2021). More information about the working of Trisoplast and the cover which will be assessed can be found in Section 4.2.2.

Figure 2: Trisoplast being applied by a heavy roller (Trisoplast Mineral Liners, 2021)

1.5. STUDY AREA

In order to determine the best practice for tailings dam closure in Brazil a study area has to be determined. Since this analysis is for Brazil in general it was chosen to consider TSF hotspots in different parts of Brazil. These hotspots were found using the Global Tailings Portal (Investor Mining and Tailings Safety Initiative , 2020) and can be seen in Figure 3. Three locations with a high number of TSF are identified. These are located in (A) the State of Para, (B) the State of Minas Gerais and (C)the State of Maranhão (C).

This database was set up after the tragic event of the Brumadinho tailings dam collapse in January of 2019, with its aim being to issue mining and tailings safety. According to the database approximately 100 companies have submitted information about their TSF's. Important to mention is that the database is not fully complete since not all companies have responded (332 responses from 727 listed mining companies, as of Dec. 2019) and the database is still a Beta version.

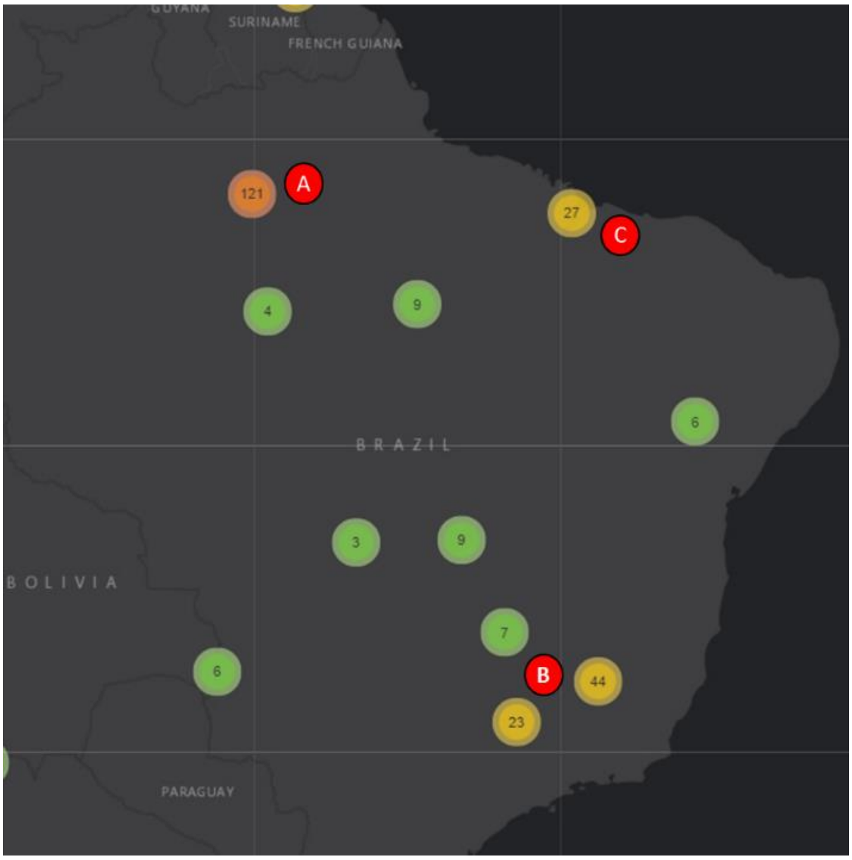

Figure 3: Locations and number of tailings dams which are incorporated in the TSF portal. Coloured circles with numbers represent the number of tailings dams in that vicinity (Investor Mining and Tailings Safety Initiative , 2020)

1.6. RESEARCH QUESTIONS

The following research question are set to achieve the research aim, which is: To investigate in the best practice of the closure of tailings dams in Brazil.

Which social factors play a role during the closure and abandonment phases of tailings dams in Brazil?

- *Which parties are affected by the closure of the tailings dams?*
- *What are the wishes and desires of the affected parties?*
- *How can the wishes and desires of the stakeholders be translated into criteria?*

Which three alternatives should be considered in the Multi-criteria analysis?

- *Which methods are currently used for the closure of tailings dams?*
- *Which factors play a role in choosing an appropriate closure method?*

What is the most suitable solution for the closure of tailings dams in Brazil?

- *Which criteria should be used to evaluate solutions for closing the tailings dams and how much should each criteria weigh relative to each other?*
- *Which of the three alternatives is the most suitable for the closure of tailings dams in Brazil?*

1.6. SCOPE OF THE REPORT

Chapter 1 has introduced the research by giving general context and stating the research aim and research questions. In order to answer the research questions, an intensive literature review has been done. The review can be found in chapter 2. The information which was found during this literature review will mainly be applied in chapter 4. This chapter consist of a stakeholder analysis and a multi-criteria analysis. However, before the results will be given, the methodological steps are described in chapter 3. An important thing to mention is that the literature research also has a few worked out results. Even though the reasoning behind these are explained in chapter 3. Finally, a conclusion is given.

2. Literature review

This chapter presents the literature review. The first section describes the closure of TSF and what a cover is. Secondly, the geological, hydrological and climate related characteristics of the States of Para, Minas Gerais and Maranhão are described. Finally, three covers are selected based on the characteristics of the three locations and are explained.

2.1. CLOSURE OF TAILINGS DAMS

The closure phase takes up a substantial part of the life cycle of a tailings dam. This is because the closure phase is a transitional period between the operational phase and the final state of becoming a landform (Figure 4). In order to make this transition successful, the dam and cover require after care and monitoring. When time progresses the intensity of care and monitoring decreases until the TSF is considered a landform.

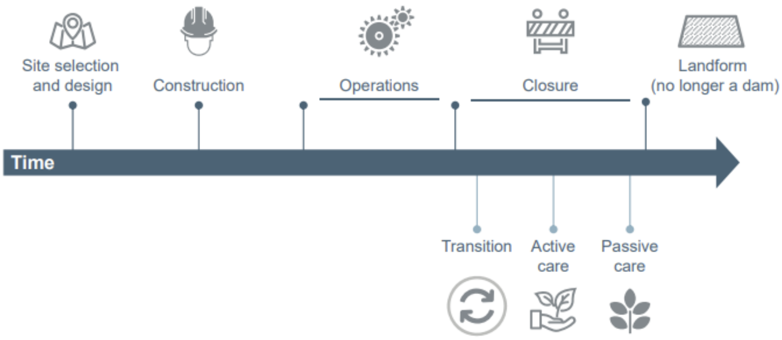

Figure 4: Life cycle of a tailings dam (BHP, 2019)

Before a TSF can be closed down a decommissioning plan has to be created. A decommissioning plan contain a detailed approach for the complete closure of the dam. This includes the preparation and the after care and monitoring. Along with these aspects, the plan also presents a closure design. These designs are different for each specific location since multiple factors can affect the closure design.

In 2012 the sub-committee of ICOLD, the Committee on Tailings Dams and Waste Lagoons have published a paper which mainly focussed on sustainable closure principles and design considerations. In order to evaluate sustainability, several factors and their impacts need to be considered. These can be seen in Table 1.

Table 1: Sustainability factors for tailings dam closure (Bjelkevik, 2011)

Objectives	**Description**
Physical stability	Weathering of materials , stress and strain effect, erosion, temperature effects, degradation of non-natural materials, hydraulics, long-term seismic effects, geo-hazards
Chemical stability	Transfer of chemicals into environment
Ecological stability	Climate, material properties, vegetation, animals and humans
Social stability in the area of influence	Future land use, possible benefit for society (post closure)

Covering a tailings dams is not limited to one sophisticated solution. The possible combinations are endless. However, not all covers function in the same way and thus cannot be applied as a general solution. Even though there are a many alternatives, there are three main categories. These categories and description are stated in Table 2.

Table 2: Cover types and corresponding description (Williams, 2021)

Cover type	Appropriate climate	Description
Water covers	Wet climate	A layer of water which acts as an oxygen barrier. There should be a sufficient amount of water supply for the water layer to keep a minimal depth
Water-shedding soil covers	Moist climate	Promote revegetation: erosion protection and limit percolation of rainfall
Store and release soil covers	Seasonally dry climate	Store water during wet season and releasing it though evapotranspiration in dry season

Other variable factors which are relevant in the choice of a closure design include: geography, environmental setting, hydrology, mineralogy, ore processing and variabilities withing the structures themselves (Lacy & Barnes, 2009). Since three alternatives are compared in general, not all variables can be considered. The primary reason is that several variables are site specific. Therefore, it is chosen that the focus will be on: geography, climate and hydrology. A list of minerals and appropriate closure methods are shown in Table 3. Dry covers will be analysed since they are an option for all mined minerals

Table 3: Mineral and possible closure methods (shortened table of (Mylona, et al., 2004))

Mineral	Closure and after care
Base metals	Wet or dewatering and dry cover
Bauxite	Dewater and dry cover
Coal	Dewater and dry cover
Phosphate	Dewater and dry cover
Precious metals	Wet or dewatering and dry cover
Uranium	Wet or dewatering and dry cover

2.2. STUDY AREA CHARACTERISTICS

2.2.1. Climate and hydrology

The three TSF location hotspots can be separated into two main climate zones, which are tropical at locations A and C and humid subtropical at location B (Figure 5). An additional division can be made at all three locations. Location A is located at the border of a tropical climate without a dry season (Af) and a Monsoon climate (Am). Location C covers a Monsoon climate (Am) and both a climate with a dry winter (Aw) and a dry summer (As). Finally the climate zones at location B include a tropical climate with a dry winter (Aw), a humid subtropical climate with a dry winter (Cwa & Cwb).

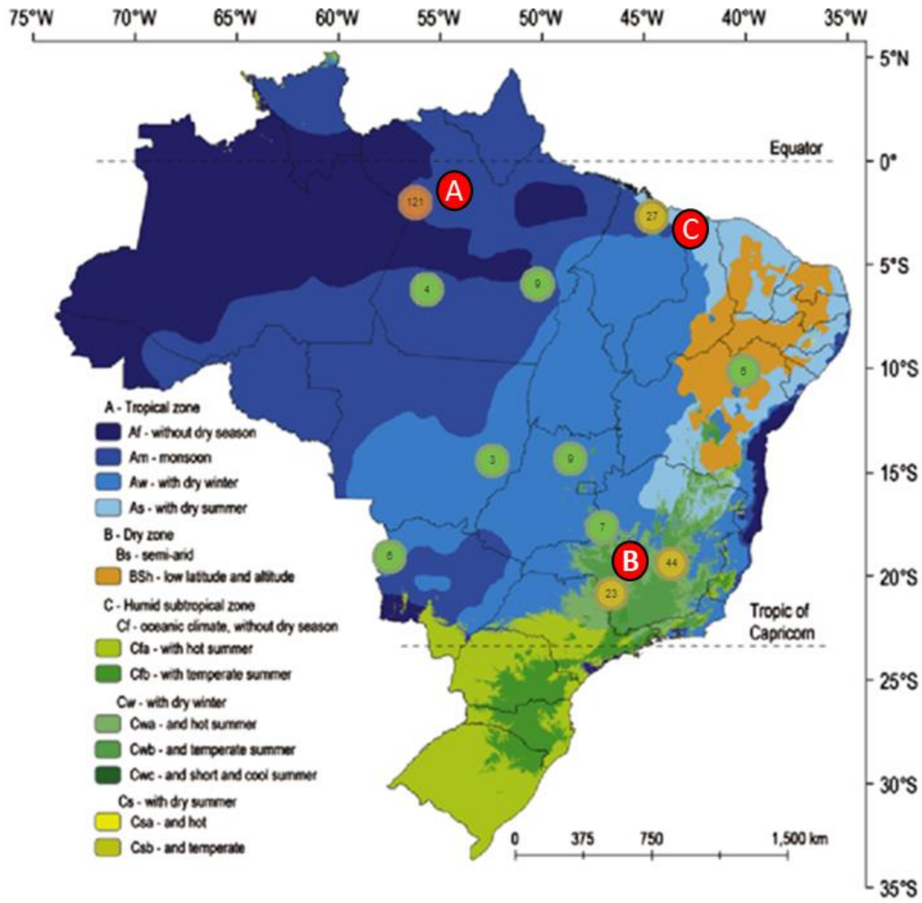

Figure 5: Climate zones and TSF locations in Brazil (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2013) and (Investor Mining and Tailings Safety Initiative , 2020)

The important difference between these climate zones is the hydrology. This is relevant since the precipitation and evapotranspiration determine which type of cover is feasible. For example: a water cover is not feasible in a dry climate zone with low precipitation and high evapotranspiration. When applying a water cover it is required to maintain a certain depth (Mylona, et al., 2004). Within a dry climate zone there is not enough natural supply of water to cancel out the high evapotranspiration. Therefore, the water level of the cover cannot be maintained which makes the application of the water cover not feasible.

In order to validate whether this is the case at the locations A, B and C, the annual precipitation and potential evapotranspiration are investigated. Values for the annual precipitation are found in literature (World Bank Group, 2021) and displayed in Table 4. The potential evapotranspiration is calculated for all three locations using the Thornthwaite equation (Eq.1).

Even though the estimated potential evapotranspiration is calculated per month, Table 4 displays the annual value (The calculations for the estimated potential evapotranspiration per month can be found in Appendix A.). This is necessary in order to calculate the potential evapotranspiration ratio, which gives an indication which type of cover to use. The cover type indication is displayed in Figure 6.

Table 4: Climate related values per location

Location	State	Climate zone	Annual precipitation [mm]	Estimated annual evapotranspiration [mm]	Potential evapotranspiration ratio
A	Para	Tropical	2131.45	1782.07	0.84
B	Minas Gerais	Tropical	1265.76	1587.26	1.25
C	Maranhão	Dry	1522.80	1748.57	1.15

It should be noted that the annual values can give a distorted picture because these values do not show the dry periods which occur at all three locations. The monthly evapotranspiration ratio increases to 2.52, 12.46 and 9.22 for the locations A, B and C respectively (Appendix A.4.). Additionally, the evapotranspiration is higher than the precipitation for at least six months at all three locations.

Figure 6 shows the appropriate cover methods for the three relevant location based on the potential evapotranspiration ratio and annual precipitation. The annual averages of the potential evapotranspiration ratios are near 1 for the three locations and therefore result in a thin spread between the humid and sub-humid climates. It can also be seen that the methods for the States of Maranhão and Minas Gerais are similar while the preferred method in the State of Para tends to lean towards a methods which should be able to deal with a higher annual precipitation.

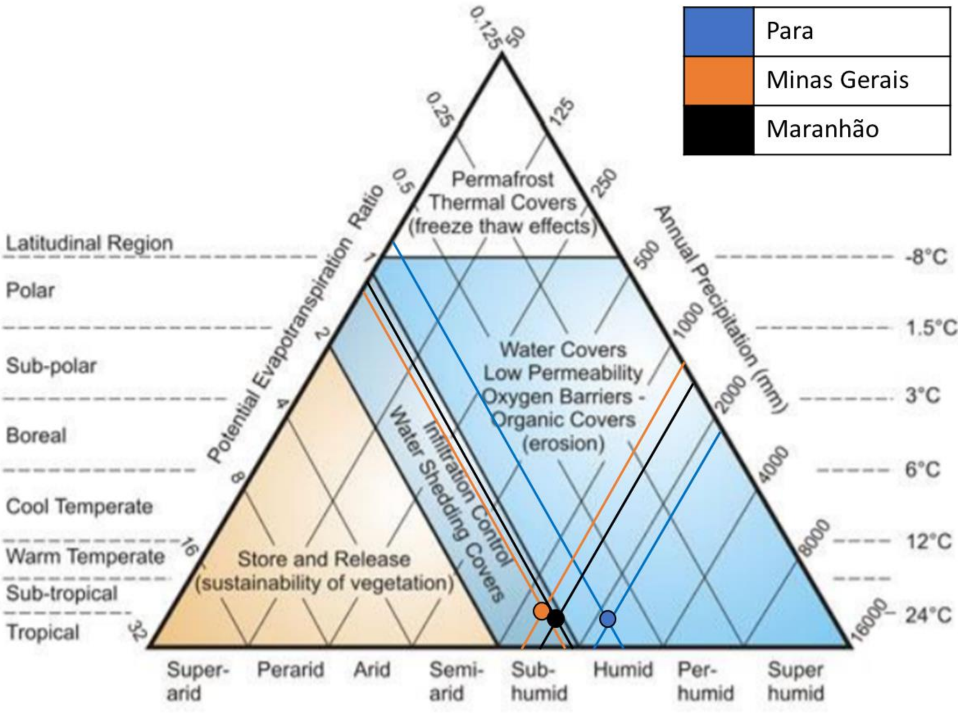

Figure 6: Choice of cover method with respect to climatic values (Williams, 2021)

Even though Figure 6 and Table 2 suggest that there is a hard division between the methods, there are commonalities within the cover layers. The infiltration control/water-shedding cover is a great example since this layer incorporates features from both the low permeability covers and the store and release covers. The water-shedding covers generally have some sort of low permeability layer which mitigates infiltration. As a top layer, the water-shedding cover commonly has a growth layer, which basically functions as a store and release layer (Ayres & O'Kane, 2013).

Figure 6 shows a thin spread of the preferred cover methods. Additionally, there is a close resemblance of certain layers within the different methods. Therefore, it was assumed that the considered alternatives can be implemented at all three locations.

2.2.2. Geography

State of Para

The TSF hotspot which is situated in the State of Para is located in the west of the state, near the border with the State of Amazonas. As can be seen in Figure 7, the complex is surrounded by forest with the closest city being Porto Trombetas. Additionally, the facility is located between the river of the Amazonas and the tributary Trombetas. According to the Tailings Storage Facility dashboard, the complete hotspot is centralised in one location (Investor Mining and Tailings Safety Initiative , 2020).

Figure 7: TSF complex in the State of Para

Even though the complex is located rather remote, the accessibility is relatively high. The main reason for this is that the city of Porto Trombetas has both a harbour and an airport. Accessibility is an important factor which has to be taken into account when designing a cover since a high accessibility can reduce the transport costs.

The soil types which can be found near the complex are split up in two sections. Directly near the two rivers, the main soil type are sediments related to current alluviums. Furthermore, more land-inwards, the dominant soil types are clay, sandy and gravel sediments (Souza, et al., 2018).

State of Minas Gerais

Unlike the TSF complex in the State of Para, the facilities in the state of Minas Gerais are more wide spread. With the main two hotspots being in the south west of the state near the border with Sao Paulo just south of the municipality of Poços de Caldas (A, Figure 8). The bulk of the remaining TSF's are located in the vicinity of the city of Belo Horizonte (B, Figure 8).

Figure 8: (A) TSF south of the city of Poços de Caldas and (B) TSF in the vicinity of the city of Belo Horizonte

Since these facilities are located in a more densely populated area they are easier to reach by road than the facilities in Para. However, because of the absence of large river systems, there might be difficulties bringing in non-local materials.

Due to the difference in location and climates, the soil types which can be found near the TSF's in Minas Gerais are rather different than the more fluvial related soil types in Para. Dominant soil types near the municipality of Poços de Caldas mostly consist of different types of latosols and cambisol. These soil types generally have a high permeability (Silva, Silva, Coelho, & Pinto, 2017). Belo Horizonte's soil types have a low infiltration capacity. The most dominant types are: Leptosols, Arenosols, Fluvisols and rock outcrops

State of Maranhão

This facility is located in the North of the state of Maranhão near the Atlantic ocean in an estuary of several rivers (Figure 9). Location wise, the TSF in Maranhão is similar to the complex in para. However, unlike the facility in Para, this facility is located in a more densely populated area. The city of São Luis is located to the north of the TSF and provides great accessibility because of the harbour and airport. Since this facility is located in an estuary, the main soil type is marine fluvial alluvium (Rocha, Silva, Marques, & Filho, 2015). This type includes loose clay, silt sand and gravel which is disposed by the rivers feeding into the estuary.

Figure 9: TSF south of São Luis

2.3. ALTERNATIVES

Since the three methods have similar characteristics it is important to make a clear distinction between them. These differences are based on the variations in Figure 10. The figure shows a base method which is just a single layer of material on top of the tailings, followed by five other methods which increase in complexity, performance and cost. When analysing Figure 6, two alternatives are variations of type iii: the water-shedding control and the low permeability cover. A Trisoplast based cover method will be considered a type iv cover since this type is defined as an alternate cover method.

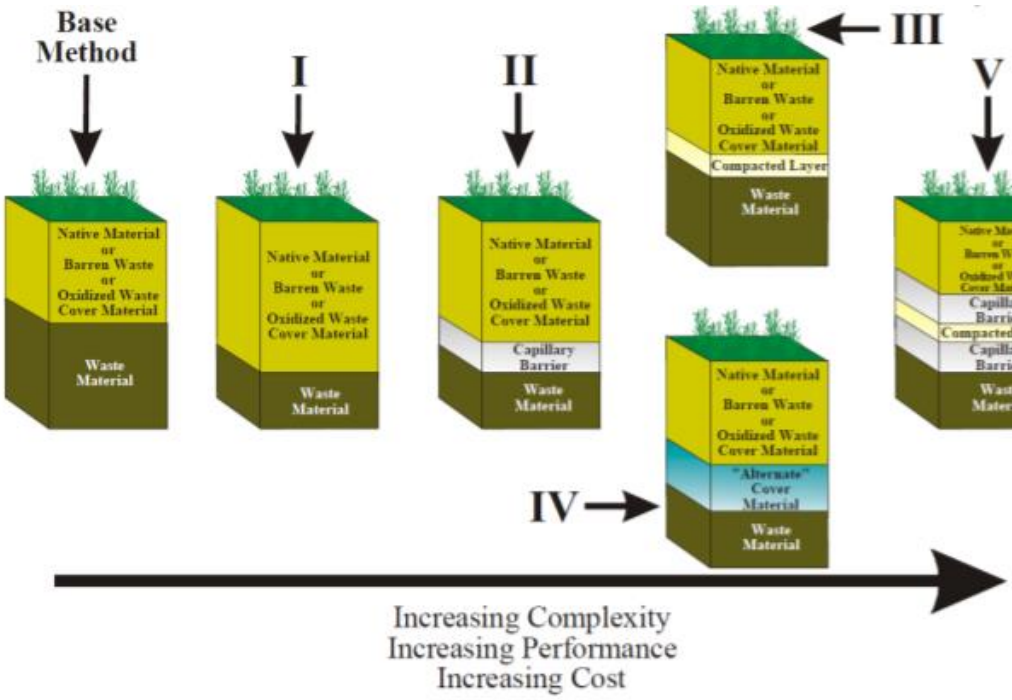

Figure 10: Variations on base method (Perotti, Gitirana, & Fredlund, 2019)

2.3.1. Low permeability cover

For the low permeability cover, two slightly different compacted clay covers are used in order to validate what a representative layer build up should be. The cover in Figure 11 was tested in Albany, GA in America. It was chosen to include this cover since the average climate characteristics of this location are similar to Minas Gerais and Maranhão. With an average temperature, precipitation and Potential evapotranspiration ratio of 19 °C, 1263 mm and 1.10 respectively. A compacted clay cover based form Brazil is displayed in Figure 12.

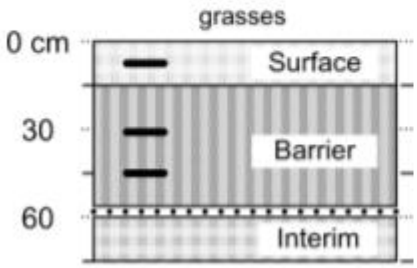

Figure 11: Profile of compacted clay cover from Albany, GA (Albright, et al., 2006)

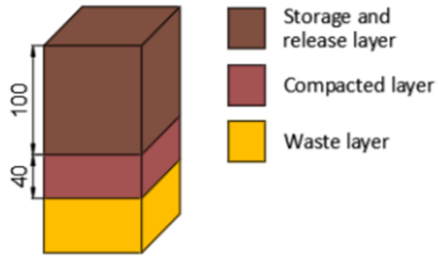

Figure 12: Profile of compacted clay cover from Brazil (Perotti, Gitirana, & Fredlund, 2019)

As can be seen in both Figure 11 and Figure 12, the thickness of the clay layers is similar in size (45 and 40 cm). The main difference is that the cover from Albany has a top layer of only 15 cm, this layer is 100 cm in the cover profile form Brazil. Since both covers are implemented in similar climatic conditions it is chosen to use the average thickness of the top layer in the analysis. The same applies to the thickness of the clay layer.

Table 5: Layer build-up of the low permeability cover

Layer type	**Material**	**Thickness [mm]**	**Hydraulic conductivity [m/s]**
Top layer	Bimodal soil	575	$7.8 * 10^{-6}$
Clay layer	Clay	425	$1.0 * 10^{-9}$
Support layer	Sand	150	$1.2 * 10^{-4}$

2.3.2. Trisoplast cover

Alternative two is a cover method which makes use of the material Trisoplast. Since this material has not been used before in the construction of a TSF cover, it is considered an alternate cover method. Trisoplast has been implemented in a number of different locations ranging from company terrains and petrol stations to waterways and ponds (Trisoplast Mineral Liners, 2019). In the Netherlands, Trisoplast has a market share of over 90% of isolation at landfill sites where it functions as either top or bottom sealing layer. The general build-up of a Trisoplast cover can be seen in Figure 13. All characteristics of this arrangement have been tested with the following layer build-up. (Smits, 2007)

Table 6: Layer build-up of the alternate cover

Layer type	**Material**	**Thickness [mm]**	**Hydraulic conductivity [m/s]**
Top layer	Bimodal soil	400<	$7.8 * 10^{-6}$
Drainage layer	Sand	300	$1.2 * 10^{-4}$
Trisoplast layer	Trisoplast	70	$7.57 * 10^{-11*}$
Support layer	Sand	300	$1.2 * 10^{-4}$

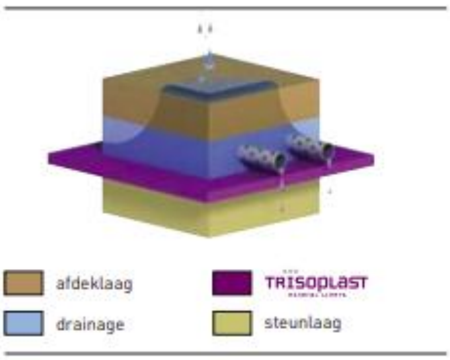

Figure 13: Trisoplast sealing cover

Trisoplast consists of three materials: clay mineral, a polymer and granular filler material. In this case natrium rich bentonite and river sand are used for the clay mineral and granular filler material respectively. The soil mixture has to be applied in dry form. When applied, the mixture becomes active when it absorbs water. When this happens, a chemical reaction takes place which creates a connection between the swelling clay minerals and the polymer. This results in a hydrogel which fills the pores in the filler material (Trisoplast Mineral Liners, 2021). The hydrogel causes the material to have a very low hydraulic conductivity but also high flexibility. A top-layer is needed in order to keep a sufficient amount of pressure on the Trisoplast layer since it swells when absorbing the water.

2.3.3. Water-shedding cover

The final type of cover is a water-shedding/infiltration control cover. Even though this cover type is the most common cover type together with a 'store and release' cover (Morrison, 2022), little detailed information could be found about this type. The cover design in Figure 14 appears in most of the literature. Therefore it was chosen to include this design in the MCDA. The purpose of a water-shedding cover is to limit the amount of water infiltration and thus maximise runoff. Generally this is achieved by having a clay layer topped by a 'thin' growth layer Figure 13. This growth layer should be thick enough to allow vegetation to grow. The promotion of runoff can have negative consequences for the growth layer because of surface erosion. This may influence the efficiency and service life over time.

Additionally, it is possible to introduce a capillary break in the cover. This layer is placed right on top of the tailings. Capillary breaks or barriers prevent the capillary barrier effect which means that water cannot flow upwards in these layers. When applied in TSF covers, capillary barriers are generally constructed at the bottom of the cover, thus preventing potential upward water flow form the contaminated tailings.

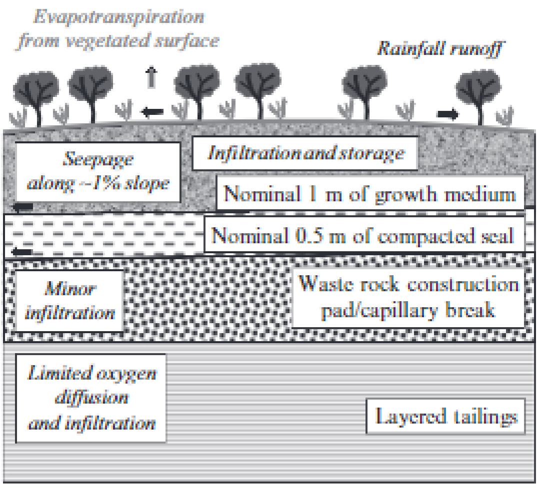

Figure 14: Water-shedding cover (Williams, 2015)

Since little detailed information about this cover could be found the build-up and measurements for the layers could not be verified, which was the case for the low permeability alternative. Therefore it was chosen to make use of the measurements which can be found in Figure 14. The capillary break is assumed to be 600 mm since nothing about this layer is specified in literature and the break appears to be thicker than the compacted sealing layer (Figure 14).

Table 7: Layer build-up of the water-shedding cover

Layer type	**Material**	**Thickness [mm]**	**Hydraulic conductivity [m/s]**
Top layer	Unimodel soil	1000	$1.6 * 10^{-7}$
Compacted layer	Clay	500	$1 * 10^{-9}$
Capillary break	Waste rocks	600	$1 * 10^{-2}$

2.4. PREVIOUS COMPARATIVE RESEARCH

Similar research has been conducted in the past. This section highlights two other comparative analysis and reports their findings. The major difference between this analysis and the two previously conducted ones is that this research includes an alternate cover type which has never been implemented in TSF closure. Additionally, only one of the researches has been conducted in Brazil.

Pabst, et al. (2018) compared different cover systems based on their hydro-geochemical performances located in Quebec (Canada). The analysis included laboratory testing, field measurements and simulation. Three different covers were part of the analysis: a mono layer cover (inert material), a bilayer cover (inert material on top of capillary barrier) and a three-layer cover (inert layer between two coarse layers). Instead of specific measurements the layers had a range, since each cover is simulated with multiple layer thicknesses. Since only the coupled hydrogeological and geochemical performance was considered, only the effectiveness of the covers was determined. This can be seen in the conclusion since the researchers do not include cost whatsoever. Hence, the Three-layer cover is deemed the best alternative even though the cost might also be higher than the other two alternatives.

The research of Perotti, et al. (2019) was conducted in Brazil and therefore more similar to this research. During this research four different cover systems were considered (Figure 15). All these covers included tropical soils which can be found locally. Similar to the previous research, a simulation was used to assess the hydrological performance of the covers. These simulations cover a period of one year and simulate water infiltration and runoff during different precipitation events. Again, this research only focusses on the performance of the covers. Therefore, the most complicated cover (S4) also has the highest performance. However, they do mention that this cover is more expensive than the other three.

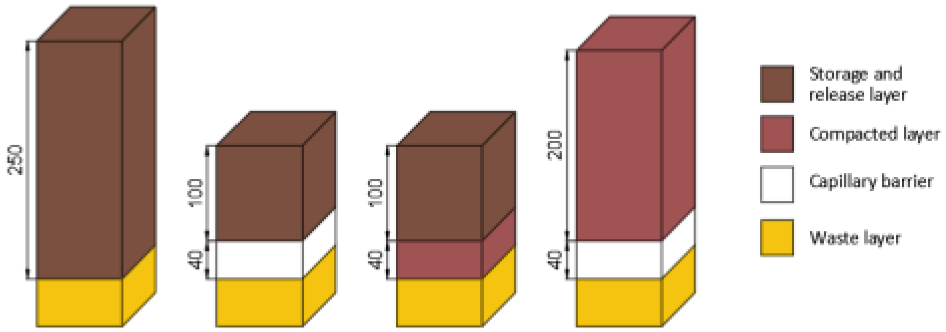

Figure 15: Cover system arragements considerd (fltr: S1, S2, S3, S4) (Perotti, Gitirana, & Fredlund, 2019)

2.5. CONCLUSION

As identified at the beginning of the literature review, there is no specific solution for a general TSF cover. The relevant characteristics which are different between the states of Para, Minas Gerais and Maranhão are climate, hydrology and geography related. Especially the climate and hydrology related characteristic were used to determine which alternatives are analysed. It is already established that a Trisoplast based cover will be analysed. Figure 6 suggested that a low permeability and a water-shedding cover should also be considered since these are applicable for the climates in the study areas.

As can be concluded from the previous two researches, simulations are needed in order to assess the performance of the covers correctly. However, it was determined that simulation modelling was outside the scope of the project.

3. Methodology

This chapter describes the approach of the project. The chapter starts off with the choice of cover type based on hydraulic characteristics of the three states. Secondly, the method of the stakeholder analysis is described. This chapter concludes with the explanation of the Multi-Criteria analysis (MCA).

3.1. HYDRAULIC CHARACTERISTICS

The first alternative was already know: a cover method which used the material Trisoplast. In order to identify which other alternatives should be considered, characteristics about the TSF locations are analysed. These include: climatical, hydrological and geological data. Precipitation and evaporation amounts will play an important role. Figure 16 shows a triangular plot which gives an indication what cover type to use for a certain Potential Evapotranspiration Ratio and Annual Precipitation. For this research the annual precipitation in Belem, Belo Horizonte and São Luiz were considered for hotspots A, B and C respectively.

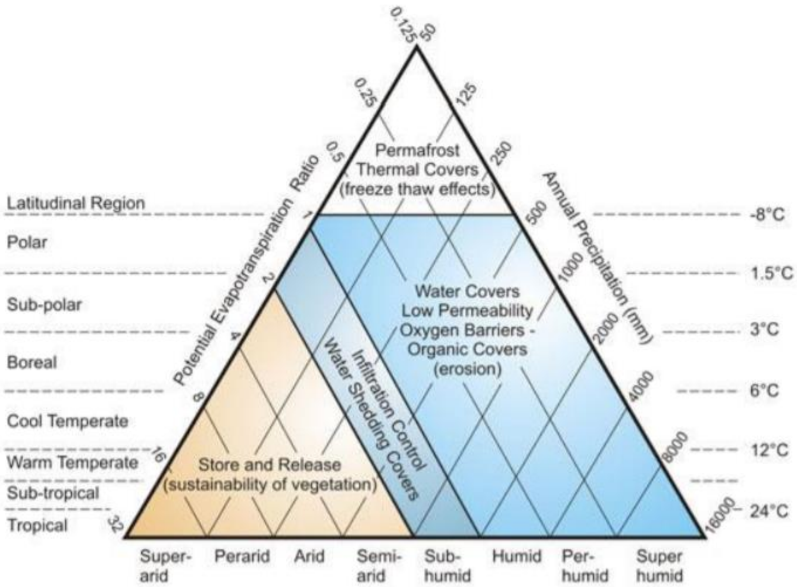

Figure 16: Choice of cover type related to climate (Williams, 2021)

The method which is used for the calculation of the potential evapotranspiration is the Thornthwaite equation (Eq.1). This equation makes an estimation of the monthly evapotranspiration for a standard month of 30 days and a length of day of 12 hours (Pereira & Pruitt, 2004).

$$ET_m = 16\left(10\frac{T}{I}\right)^a, 0°C \leq T \leq 26°C \quad \text{Eq.1}$$

$$I = \sum_{n=1}^{12} (0.2 * T_n)^{1.514}, T_n > 0°C \quad \text{Eq.2}$$

$$a = (6.75 * 10^{-7})I^3 - (7.71 * 10^{-5})I^2 + (1.7912 * 10^{-2})I + 0.49239 \quad \text{Eq.3}$$

$$ET_m = -415.85 + 32.24T - 0.43T^2, T > 26°C \quad \text{Eq.4}$$

Where:

- ET_m= Estimation of potential evapotranspiration [mm/month]
- T= Monthly average temperature [°C]
- I= Thermal index [°C]
- T_n= Local normal climatic temperature regime [°C]
- a = Thermal index [°C]

3.2. STAKEHOLDER ANALYSIS

In order to get a good understanding of which social factors need to be taken into account, it is important to know which parties are involved and how they are affected by the project. The steps which are taken in order to conduct the stakeholder analysis can be seen in Figure 17. The method has three main blocks: Context, Application of Stakeholder methods and Actions. During this research the final step has been slightly altered to translating the wishes and desires of the stakeholders into criteria which are used for the MCA. This is not a problem since this methods can be used for both participatory and non-participatory analysis (Reed, et al., 2009). Firstly, the context and system boundaries are determined. The application of the stakeholder analysis is split up in three parts which are described in the following sections.

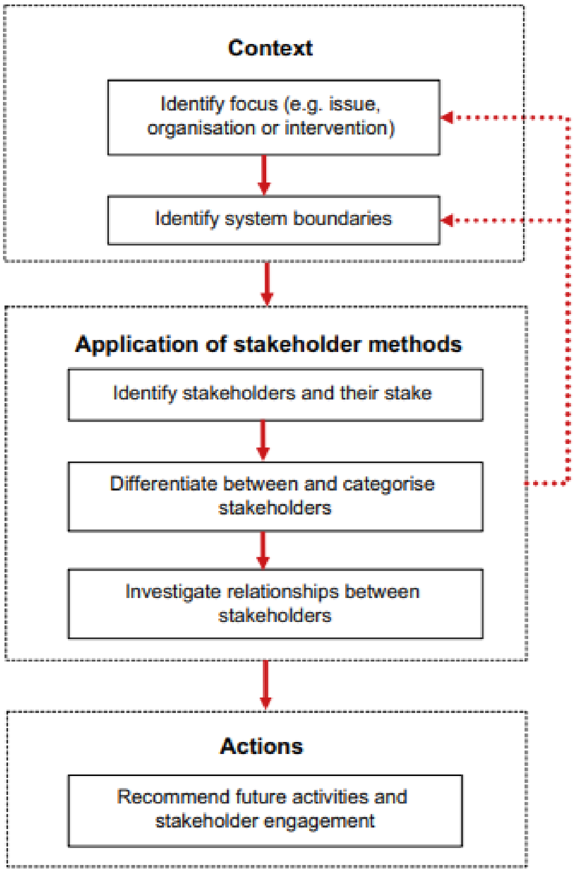

Figure 17: Schematization of Stakeholder analysis process (Reed, et al., 2009)

Stakeholders are first identified in the stakeholder inventory. For this research it was chosen to analyse six different stakeholders which were divided into three scales of operations: local, national and international. Even though the project is based in Brazil, international stakeholders are included, since international laws apply to the requirements of the TSF closure.

Now that the stakeholders are identified and described they are differentiated and categorised. The purpose of this step is to rank each stakeholder based on their interests and level of influence on the project. Due to time restrictions it was chosen to conduct this step using analytical categorisation. This means that the categorisation is top-down and thus will not directly include the stakeholders in the analysis. Nevertheless, a large variety of literature is consulted to gather a sufficient amount information.

In order to differentiate the stakeholders, it was chosen to make use of a power-interest grid. This grid creates an overview of all stakeholders and ranks them based on the previously identified influence and interest. Table 8 describes the four different quadrants of the power interest grid.

Table 8: Quadrant description of the power interest grid (Reed, et al., 2009)

Stakeholder type	Description
Key players	Most important stakeholders which have both high power and interest. These stakeholders should be actively involved in the different steps of the project.
Context setters	High power but low interest. They have a large influence on the project and should be monitored since it can have large negative impacts if they decide to abort the project.
Subjects	High interest but low power. These stakeholders do not tend to have an impact on the project when on their own. However, in order to achieve this, they can form alliances with larger stakeholders.
Crowd	Low interest and low power. Which means it is not necessary to include their wishes and desires since they do not care about the end result.

The final step of the application is to investigate in the relations between the stakeholders. These can be either conflicting, complementary or cooperative. The results of this step show which stakeholders share opinions. Based on all previous steps, the wishes and desires of the stakeholders are translated into criteria. These criteria are subsequently filtered and considered as input for the MCA, this will further be described in the following section.

3.3. MULTI-CRITERIA ANALYSIS

Inputs for the criteria are the stakeholder analysis which was conducted in the first research question and literature research. The selection process of the criteria was done by having a meeting with an expert of Antea Group. During this meeting the criteria from the stakeholder analysis were filtered and when necessary, combined to overarching criteria.

The remaining criteria are then ranked since not all criteria are equal in weight. Therefore, the method which will be used to conduct the multi-criteria analysis is the Analytical Hierarchy Process (AHP) method. The weights of the criteria will be set up using methodological triangulation. Figure 18 shows the three methods which are used to set up the weights. The function of methodological triangulation is to use multiple methods to validate a theory or answer (Guion, 2002). During this research the following methods are used to determine the weights of the criteria: Literature review, Expert interviews (Appendix B) will be conducted and finally case studies will be done. It was chosen to conduct a case study instead of field research since this is simply not possible. This case study is in the form of a stakeholder analysis.

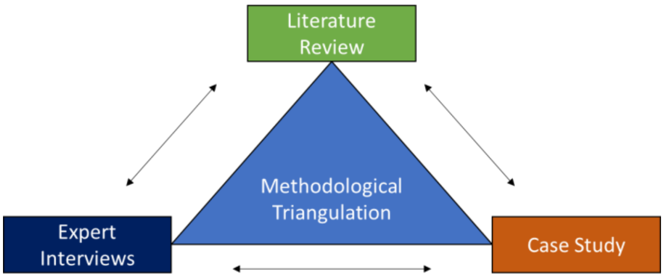

Figure 18: Methodological triangulation for the project

The AHP method makes use of a hierarchy tree which includes all the three building blocks: an objective/goal, criteria and the alternatives. Figure 19 shows an example of such a hierarchy tree.

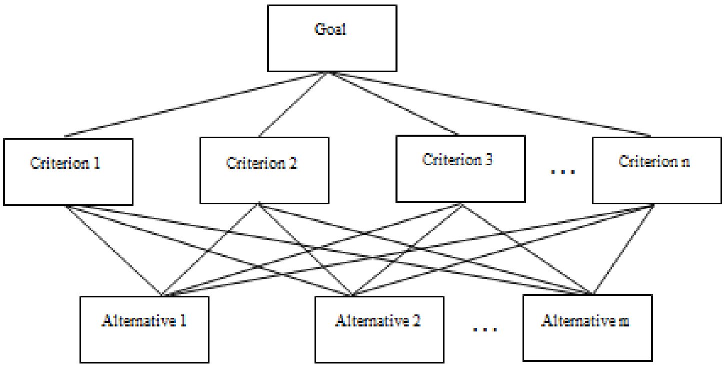

Figure 19: Example of a AHP hierarchy tree (Daghouri, Mansouri, & Qbadou, 2018)

Before the alternatives are ranked based on the criteria, the criteria are compared to receive a score relative to each other. The scale of how the criteria are ranked relative to each other is arbitrary (Bukhsh, 2019). However, to keep things not to complicated this analysis uses a 1-3 scale, where 1 means that the criteria are equally important and 3 means that one criteria is much more important than another.

When the priority factor has been calculated, the performances of the alternatives are evaluated for each criteria. This is done by literature research. The performances of the alternatives will be validated using the same methodological triangulation as the criteria. The units of the different performances do not have to be equal to one another since all columns will be normalised.

When performance scores are appointed to the criteria for each alternative, the scores are normalised. The final step of the MCA is to multiply the normalised version of the performance vector with the previously calculated priority vector of the criteria. When the normalised values of the alternatives are multiplied with the priority vector, the alternative with the lowest score is the most optimal solution.

The covers are assessed on their Infiltration and runoff performance. These phenomenon are related to each other as shown in Figure 20. Before runoff takes place, the soil has to reach a certain level of saturation. When this level of saturation is reached, the runoff is maximised since no additional precipitation can infiltrate the soil. Runoff only takes place on the surface layers, while infiltration occurs through the complete cover. Therefore, the performance value for the runoff will mainly focus on the hydraulic conductivity of the top layer. The performance value for the infiltration will is based on the hydraulic conductivity and durability of the sealing layers.

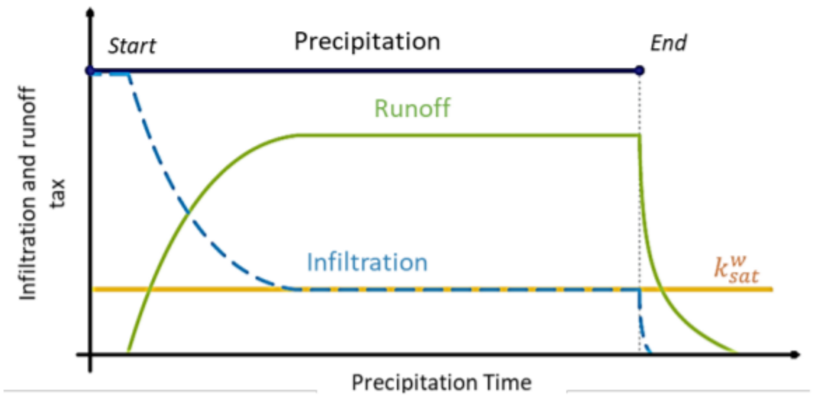

Figure 20: Mechanism of water infiltration in soil (Perotti, Gitirana, & Fredlund, 2019)

3.4. SUMMARY

This chapter presented the methods which are used to answer the research questions. During the literature research it became evident that the precipitation and evapotranspiration ratio influence which type of cover is most suitable. The Thornthwaite equations are used to calculate the potential evapotranspiration for the three study areas. Precipitation values are retrieved from online database and correspond with the precipitation in the largest nearby cities. In order to assess the covers types during the MCA, criteria are needed. These criteria are determined using several methods including a stakeholder analysis, an expert meeting and literature. When the relevant criteria are determined a MCA is conducted for the States of Para, Minas Gerais and Maranhão separately. The MCA is conducted using the AHP approach.

4. Results

This chapter includes the results of the research. The first sub-question will be answered in the form of a stakeholder analysis. Secondly, a multi-criteria analysis will be conducted for each of the three locations. (Para, Minas Gerais and Maranhão). A discussion will conclude this chapter. This discussion includes the assumptions that were made and general points of interest.

4.1. STAKEHOLDER ANALYSIS

The objective of this stakeholder analysis is to look into the different perspectives of the involved parties and translate these into. This analysis consists of three main steps (Reed, et al., 2009): first the stakeholders will be identified. Which includes an inventory of the involved parties and their level of power and interest. Secondly, when the stakes of the involved parties are known, they will be differentiated and categorised based on their stakes. The final step in the analysis is to analyse the relationships of the stakeholders. However, before the analysis will be conducted, the focus and boundaries will be explained.

Both affected and effecting groups are included in the focus of the analysis. Thus creating a large spectrum of different views on the closure of tailings dams. In order to keep the analysis effective but yet concise, the parties are only involved if they are directly affected by, or have a direct impact on the project. Additionally, to keep the boundaries clear it is chosen to divide the parties in three levels: local, national and international.

4.1.1. Stakeholder identification

Table 9 displays the inventory of selected stakeholders. This inventory is build up of three parts: the identification of the stakeholder, the scale of operation, and a description of who the stakeholder is and why they are included in the analysis. In order to get a well-balanced analysis, multiple stakeholders form each scale of operation are chosen.

Table 9: Stakeholder inventory

Stakeholders	Scale	Description
Local residents	Local	This group represents the people who live near tailings dams and thus are in immediate danger when a failure occurs. Since the agricultural sector is one of the major economic pillars in Brazil, nearby farmers are also part of this group (WeForest, 2019). Figure 21 shows the locations of the tailings dams in Brazil in combination with the population density. It can be seen that the population density is high near the TSF's in the States of Minas Gerais and Maranhão. The population density near the TSF's in the State of Para are low since this complex is not located in an urban area.
Mining companies	Local	Mining companies are most often the owners of the tailings dams which they utilise. These companies are obligated to make a rehabilitation plan for their tailings dams. Unfortunately, not all mining companies can be addressed since Brazil counts 662 registered tailings dams (Garcia, Ribeiro, Roque, Ochoa-Quintero, & Laurance, 2017). Therefore the following mining companies will be addressed: Alcoa, Vale, Anglo Gold Ashanti, ArcelorMittal. These companies were chosen based on the Global Tailings portal database (GRID-Arendal; Investor Mining and Tailings Safety Initiative, 2020)

Stakeholders	**Scale**	**Description**
Government of Brazil	National	The government of Brazil is included since the dams in question are on Brazilian soil. In addition: the ICOLD states that, apart from the international regulation about tailings dam closure, the closure should also comply with local laws and relevant regulations (Justo, et al., 2019). Within the Brazilian government, the national mining agency (ANM) is the regulatory organ for maters regarding tailings dams (Agência Nacional de Mineração, 2021). The ANM is also linked to the Ministry of Mines and Energy
Greenpeace Brazil	National	Environmental bodies such as Greenpeace is included because the failure of tailings dams have a major impact on the environment. Greenpeace is an activist organisation that aims to protect the environment (Greenpeace, 2021)
ICOLD	International	The International Commission on Large Dams provides bulletins about different kinds of dams which includes internationally respected regulations. These bulletins also include regulations for tailings dam management (ICOLD, 2021). ICOLD is active in more than 100 counties.
ICMM	International	The international council on mining and metals are dedicated to making the mining industry a: 'safe, fair and sustainable industry' (ICMM, 2021). The council is run by 28 mining and metal company CEO's and 35 other members.

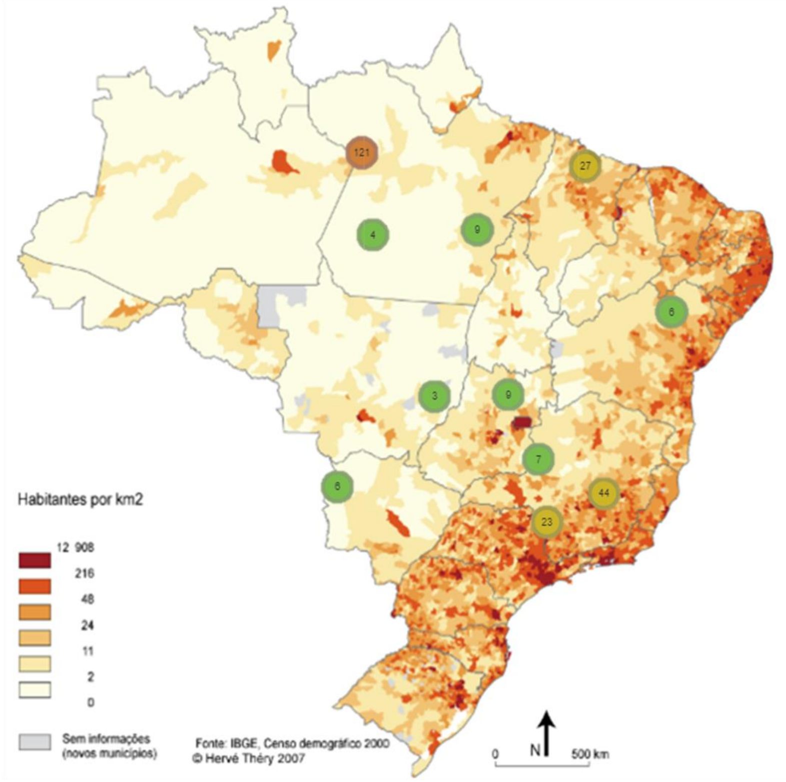

Figure 21: Locations of tailings dams in combination with population density of Brazil (GRID-Arendal; Investor Mining and Tailings Safety Initiative, 2020) (Instituto Brasileiro de Geografia e Estatística, 2010)

4.1.2. Differentiating and Categorisation

Power and interest

The stakeholders described in the previous section all have different levels of power and interest in the project. This implies that not all stakeholders have an equal say in the project. However, wishes and desires of all stakeholders are taken into account since this enhances transparency and equity of the decision making process in development projects (Reed, et al., 2009). Table 10 includes the level of power and the interests of the stakeholders regarding tailings dam management and closure.

Table 10: Power and interest of the stakeholders

Stakeholders	**Power**	**Interest**
Local residents	Not powerful: people cannot take much action as individuals. One of the reasons for the inequality between the locals and the large mining companies is the lack of transparency and accountability (Motta & Litvinoff, 2021)	Residents who live near tailings dams live in constant fear. Especially those who live downstream of upstream constructed tailings dams (Bloch, Reinhard, & Peçanha, 2019). A dam failure could result in contaminated rivers and farmland. Which hinders the life of the residents (Motta & Litvinoff, 2021).
Mining companies	Moderately powerful: These companies cannot decide to which regulations the cap should comply. However, they have do decide how their tailings dams should be closed down. Since the ICOLD promotes equality, it was determined that the mining companies are considered equal when looking at power and influence. However, the larger companies Alcoa and Vale might rank a little higher than Anglo Gold Ashanti and ArcelorMittal.	All four companies focus on the same values which most often take the following points into account: - Safety - Sustainability - Protect the environment - Add economic value However, not all companies focus on the same materials: - *Alcoa* (Alcoa, 2021)*:* Bauxite - *Vale* (Vale, 2021)*:* Iron ore, Nickel, Manganese and ferroalloy and copper - *Anglo Gold Ashanti* (AngloGold Ashanti, 2021)*:* Gold - *ArcelorMittal* (ArcelorMittal, 2021)*:* Iron ore
Government of Brazil	Powerful: its agencies and ministries are responsible for matters surrounding tailings dams.	The ANM is responsible for (Agência Nacional de Mineração, 2021): - Registration and classification, according to their risk. - Oversee safety management - Creating standards regarding safety - Ensure owners of the mines comply with regulations
Greenpeace Brazil	Moderately powerful: Greenpeace is a large organisation which can promote measures for a green future. However, the organisation is limited in their influence on the closure of tailings dams.	Greenpeace is mainly interested in safeguarding the Earths' ability to nurture life by means of the following points (Greenpeace, 2021): - Protect biodiversity - Prevent pollution(air, water, land)

Stakeholders	Power	Interest
		Their mission includes two additional points. However, these were not deemed relevant for this research.
ICOLD	Powerful: Since the ICOLD is active in a lot of countries and takes the lead in determining the standards and guidelines for tailings dam management (ICOLD, 2021).	ICOLD ensures that the construction of dams and the operation is (ICOLD, 2021): - Safe - Efficiently - Economically - Environmentally sustainable - Socially equitable
ICMM	Moderately powerful: The council is build up from 27 mining companies. However, they do not set up any regulations regarding tailings dam closure. Their primary task is to act as a catalyst for change. (ICMM, 2021)	ICMM wants the mining industry to be (ICMM, 2021): - Safe - Fair - Sustainable Improve the mining and metals industry by increasing the social and environmental performances. Promote to commit to the ICMM mining principles.

Categorisation

The power-interest grid (Figure 22) ranks the stakeholder based on the information from Table 10. As can be seen, there are three key players. The main reason for this is that because these parties define the rules and regulations about sustainable tailings dam closure and management. Mining companies are located at the boundary of the key players. However, they were categorised as subjects since they lack the regulatory power but still have high interest since there is a possibility that there is a more suitable solution for the closure of their tailings dams. Greenpeace Brazil has both lower interest and power than the mining companies. But is still located in the subject quadrant. Finally, the local residents are considered to be part of the crowd. They have interest in the project since they can be influenced by it. However, they lack the power to make any differences to the outcome.

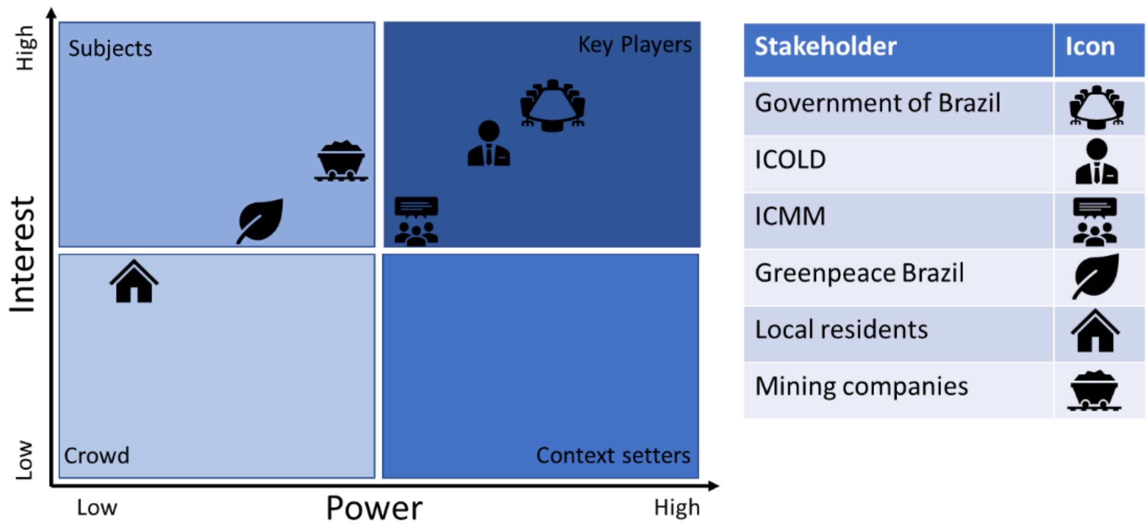

Figure 22: Power interest grid

4.1.3. Investigating Relationships

Finally, the relations between the stakeholders is investigated based on the information from the previous sections. Three key words are used to indicate whether the relation: conflicting, complementary, cooperative (Reed, et al., 2009). It is especially important that the key stakeholder have good relationships. As can be seen in Table 11, the key stakeholders (bold) only have complementary or cooperative relations with the other stakeholders. Note that only half of the table is filled in since the results are mirrored.

Table 11: Stakeholder relations, (Comp = Complementary)

	Local residents	Mining companies	Government of Brazil	Greenpeace Brazil	ICOLD	ICMM
Local residents						
Mining companies	Conflict					
Government of Brazil	Comp	Comp				
Greenpeace Brazil	Cooperative	Conflict	Comp			
ICOLD	Comp	Cooperative	Cooperative	Comp		
ICMM	Comp	Cooperative	Cooperative	Comp	Cooperative	

4.1.4. Criteria

All steps of the stakeholder analysis function as the input for the collection of criteria which will be used to analyse the alternative solution which will be discussed in a later chapter. The alternatives which are analysed in the MCA are already developed. Hence, the criteria will only focus on the performance of the alternatives rather than whether they comply with the standards and regulations. The criteria in Table 12 are a result of the wishes and desires from Table 10.

Table 12: Overview of stakeholder criteria

Stakeholder	**Type**	**Criteria**
Government of Brazil	Key player	Safety, environmentally and socioeconomically friendly,
ICOLD	Key player	Safety, efficiency, economically, sustainability, socially equitable
ICMM	Key player	Safety, sustainable, social and environmental performance (GlobalTailingsReview, 2020):Human rights, robustness
Mining companies	Subject	Safety, Sustainability, Protect the environment, Add economic value/Cost effectiveness, suitability, post closure developments
Greenpeace Brazil	Subject	Environmental
Local residents	Crowd	Safety, environmental

4.2. MULTI-CRITERIA ANALYSIS

The aim of this section is to create a preferred order for the alternatives which are described in Section 2.3. This decision is made based on relevant criteria which became evident during the literature review, case studies and an expert session(Appendix B). Performance levels of these criteria are evaluated in order to form the preference order of the alternatives. Since three different locations are considered in this research, three different MCA's are conducted. The reason for this is that the climate, hydrological and geographical related characteristics of Para, Minas Gerais and Maranhão are different form each other and thus cannot be compared in one MCA.

4.2.1. Criteria

Table 12, which contains criteria which were translated from the wishes and desires of the stakeholders, is the main input for the decision on which criteria to evaluate. The table includes several criteria which are either irrelevant or similar to one another. Therefore it was chosen to choose three main criteria for the MCDA: Cost, efficiency and sustainability. Since these criteria are rather broad, Sub-criteria are used. The (sub-)criteria can be seen in the Hierarchy tree in Figure 23. Elaborations on these decisions are found in Appendix B.

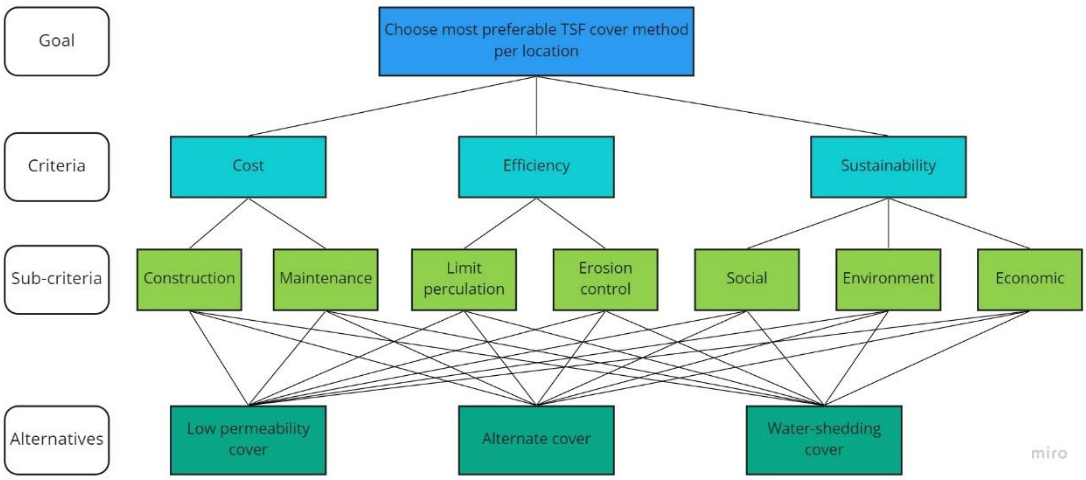

Figure 23: Hierarchy Tree

The weighing factor of the criteria are displayed in Table 13. These values were determined based on methodological triangulation which included the stakeholder analysis, literature research and a session with an expert form Antea Group. Elaboration on the calculations regarding the criteria are also found in Appendix B.

Table 13: Priority vector of the criteria

Criteria	Priority vector
Cost	0.46
Efficiency	0.32
Sustainability	0.22

4.2.2. Performance

Efficiency

Erosion control

The efficiency of the alternatives is analysed based on two criteria: infiltration and surface runoff. These two criteria are dependent on one another since both are mainly related to the characteristics of the surface layer. The hydraulic conductivity plays an important role here since this value represents the speed at which the rain water can infiltrate into the soil. Table 14 displays the k-values of the surface layers for each alternative. The k-values for the low permeability- and alternate cover are the same since they use the same material in the top layer.

Table 14 : Hydraulic conductivity of the surface layers of the alternatives

Cover alternative	Soil type	Thickness [mm]	Hydraulic conductivity [mm/h]*
Low permeability cover	Bimodal soil	1000	28
Alternate cover	Bimodal soil	400	28
Water shedding cover	Unimodal soil	1000	0.58

* (Perotti, Gitirana, & Fredlund, 2019)

The water shedding effect of alternative 3 can clearly be seen in the last column of Table 14 since the flow of rainwater in the top soil is restricted to 0.58 mm/h. This means that any additional rainwater will be runoff. Since only monthly and annual precipitation values could be found it is impossible to determine infiltration and runoff at specific moments of high precipitation.

What can be said however is that when the precipitation is less than the storage capacity of the surface layer, infiltration rates are higher. This can happen when the rainfall intensity is low but lasts over a long period of time. Unfortunately, only averaged precipitation data was found. These include daily averages and monthly averages which do not include information about separate rainfall events.

The cumulative monthly precipitation and evaporation can be seen in Figure 24. The resulting net precipitation (short dotted lines) equals the precipitation minus the potential evapotranspiration. Between June and October, all three locations experience a negative net precipitation. This would imply that no runoff is generated during this period when average rainfall and evaporation are considered. Where the cumulative precipitation of the States of Minas Gerais and Maranhão appear to be nearly constant during this period, the State of Para shows a slight increase in cumulative perception during these months. Therefore, it is concluded that the covers in the State of Para experience more erosion than in the other two states.

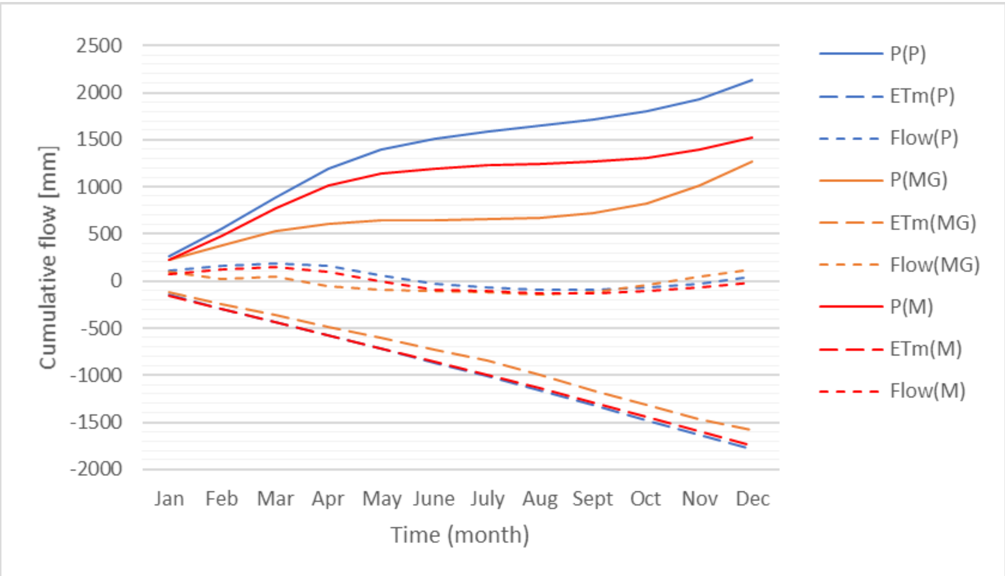

Figure 24: Cumulative flow for Para(P), Minas Gerais(MG) and Maranhão(M), (average over 1991-2020) (World Bank Group, 2021), (World Weather Online, 2021), (Meteoblue, 2021)

Infiltration

Table 15 lists the hydraulic conductivities of the sealing layers of the three alternatives. The most noticeable difference is the difference in thickness of the sealing layers in combination with the lower hydraulic conductivity of the Trisoplast layer. Here the thickness of the layer is a factor 6/7 smaller while the hydraulic conductivity a factor 10 smaller. Therefore, Trisoplast is les permeable than the clay based sealing layers while taking up a much smaller volume.

Table 15: Hydraulic conductivity for the sealing layers per alternative

Cover type	Sealing layer	Thickness [mm]	Hydraulic conductivity [m/s]*
Low permeability	Clay	425	$1.0 * 10^{-9}$
Alternate cover	Trisoplast	70	$7.57 * 10^{-11}$
Water-shedding cover	Clay	500	$1.0 * 10^{-9}$

*Clay (Shackelford, 2003) ,Trisoplast (Berg, 2016)

Additionally, since all three locations experience a dry season where the average monthly nett precipitation is negative (Figure 24), it is important to analyse the behaviour of the hydraulic conductivity when exposed to wet-dry cycles. Several tests have been conducted on this matter. Even though conducted on small scale samples ($2 * 10^{-2} m$), the clay samples showed crack forming after only 72 hours of desiccation. These crack then heal themselves when re-wetted, but remain a preferential flow path which increase the hydraulic conductivity of the clay (Julina & Thyagaraj, 2020). Trisoplast on the other hand has been tested for a period of five years where the dry cycles lasted at least four months or until desiccation occurred. In addition to Trisoplast, clay and bentonite liners were tested. The results of the experiment showed that Trisoplast is resistant to desiccation related crack forming and kept a low permeability throughout the whole experiment (Berg, 2016).

Cost

It is difficult to correctly estimate the cost of the three alternatives. A hindering factors which keeps returning is the lack of available detailed information regarding the cost. Therefore, the three alternatives are compared with one another and are ranked based on available literature and reasoning when no price indication were found.

Construction

The considered expenses are material cost, transport cost and implementation cost. For the material cost, only the price of the sealing layers is considered since the remaining materials: sand, gravel and top-soil are mainly mine overburden material and thus already available for the mining companies. Additionally, a general approach is used for TSF closure in this research, the material price indications are given per m^2. An overview of the cost can be seen in Table 16. For the clay, €13.95 ($16, conversion rate on 4 February 2022) per ton used (US Geological Survey, 2021) and a range of €10 to €14 was used for the Trisoplast layer (Antea Group, 2022).

Table 16: Cost indication per m^2 for the sealing layers

Cover alternative	Material	Thickness [mm]	Price [$€/m^2$]	Volume per m^2 [m^3]
Low permeability	Clay	425	9.48*	0.425
Alternate	Trisoplast	70	10 – 14	0.07
Water-shedding	Clay	500	11.16*	0.5

*calculated for the column of clay with a density of $\rho = 1600\ kg/m^3$ (Engineering Toolbox, 2022)

Even though the price per m^2 of Trisoplast is higher than the clay layers of the low permeability and water-shedding covers, the volume per m^2 is a factor 6 smaller. This is the main advantage of Trisoplast over other sealing material such as clay and other clay-bentonite mixtures. Since a sufficiently thick Trisoplast layer uses less material than its competitors it safes a lot on transport cost. This is dependent on the location of the TSF. Because if a large amount of clay is available nearby, the transport cost of the clay might eventually be lower.

Implementation costs include the remaining materials (top-soil, sand, waste rock) and heavy machinery since these are necessary in order to implement the layers. The precise number of machinery (heavy rollers, bulldozers, mobile cranes) is dependent on the size of the to be closed down TSF. Since this factor is unknown, the thickness of the alternatives is used to reason the implementation cost. The thickness of the layers can be seen in Table 17. From this table it can be concluded that the implementation cost of the low permeability cover and alternate cover are in the same magnitude since the total thickness of the covers is similar. The water-shedding cover on the other hand is nearly two times as thick as the other two alternatives. Therefore it can be concluded that the implementation costs will be higher.

Table 17: Total thickness of the covers

Cover alternative	Number of layers	Total thickness [mm]
Low permeability	3	1150
Alternate	4	1070
Water-shedding	3	2100

Maintenance

Maintenance contributes to long term dam safety. And since the cover of tailings dams is most often not a walk-away procedure, periodic monitoring has to be done. However, eventually the TSF can be labelled as rehabilitated and requires little ongoing maintenance (Australian Government, 2016). Monitoring should consider: the stability of the structure with respect to erosion, the low risk of uncontrolled release (if release occurs, make sure it has no large negative effects on the surroundings) and a successful self-sustaining plant growth (MCMPR, 2003).

Measuring erosion is complex, since this includes the measuring of local surface runoff (MEND, 2004). The accuracy of these measurements is low. What can be said however, is that the water-shedding cover has the highest amount of runoff since the hydraulic conductivity of the topsoil is low. However, since this soil is more compacted the result of the runoff is lower than the other alternatives. Additionally, Para has a higher annual precipitation rate than Maranhão and Minas Gerais. Thus it can be concluded that all the cover alternatives have a higher chance of erosion in the state of Para. Resulting in higher maintenance cost. Erosion is also dependant on slope angle and length. However, since this is based on the detailed design of the cover and thus dependant on a specific TSF, it is not considered in the analysis.

Percolation monitoring can be done with the use of Lysimeters (MEND, 2004). In order to save cost on the instalment of these components, they can be installed before the cover is completed. Alternatively, they can be placed after construction. However, this can result in disturbance of the soil and eventual vegetation. The effect of dry-wet cycles is already discussed above and concluded that the clay based sealing layers experience more negative effects form the dry periods. Therefore, requiring more aftercare.

Finally, the eventual vegetation needs to be maintained up until it becomes self-sustaining. These plants should not have roots that penetrate the sealing layer. Since the low permeability cover and the alternate cover have a similar distance form surface to sealing layer, similar plant types can be uses.

The top-layer of the water shedding cover is thicker and thus can provide an growing environment for vegetation with deeper roots. These vegetation types can also influence the amount of erosion since it can limit the amount and speed of the runoff water.

Sustainability

Sustainable development is getting more important in the mining industry, and since sustainability is a relevant criteria for several stakeholders, it is important to consider. The ICOLD has published a bulletin on sustainable design and post-closure performance of tailings dams (Bjelkevik, 2011)**.** Additionally, the Global Mining Initiative (GMI) was created which defined the concept of sustainable development in the mining industry. The general sustainability of the alternatives will be assessed based on the three pillars of sustainability which are displayed in Figure 25. Here, social sustainability relates directly to the local stakeholders since they can experience the impact of the covers the best. The environmental and economic sustainability are for the stakeholders in general.

Figure 25: Three pillars of sustainability (Purvis, Mao, & Robinson, 2019)

Social

Since all three covers are designed to meet the requirements failure is not considered. Therefore, the best result for the stakeholders which directly experience the presence of the cover is to don't suffer from the consequences of the whole closure process. This includes construction of the cover and post closure. The areas near the TSF's in Maranhão and Minas Gerais are more densely populated than the facility in Para. Therefore, less hinder is experienced in the State of Para. However, also less people can benefit from the cover when it is deemed a landmass. When the TSF eventually is rehabilitated, the area offers a lot of opportunities to promote well-being of the local residents. Since the goal of rehabilitation is the same for the three alternatives there is no clear winner.

Economic

Even though the Trisoplast based cover is more expensive to implement per m^2 it requires a lower amount of raw materials. Additionally, desiccation testing has concluded that Trisoplast has a higher life expectancy in comparison to other clay based sealing layers. A negative aspect however is that this kind of cover has never been implemented in Brazil. Therefore, the actual performance is difficult to determine. Which makes it a potential risky investment for the mining companies. The other two alternatives have been used in tailings covers before and several researches have been conducted proving their effectiveness.

Environmental

Environmental sustainability can be assessed based on the amount of re-used materials. In all three cases, the alternatives re-use mine overburden materials in their layer build-up. Since the sealing materials are not part of the mine overburden material they have to be transported. One of the differences between the three locations which could have an impact on sustainability is the transport of the raw materials. As mentioned previously, there is a major difference between the required volumes of the sealing material for each m^2 of cover. However, the amount of travelled kilometres is dependent on the origin of the sealing materials. Both the state of Para and Maranhão are located in riverine areas which have access to river clay. The state of Minas Gerais on the other hand has a drier climate and thus less access to clay. The rives in the state of Para and Maranhão also offer the possibility of transportation via water.

Even though the remaining material of the cover (sand, gravel, topsoil) should also be transported, it is important that at least the top-soil is of a native origin (Skousen, Zipper, McDonald, Hubbart, & Ziemkiewicz, 2019). This is important for the eventual re-vegetation of the cover.

4.2.3. Ranking

The performance levels for the alternatives have been described. Since the sub-criteria did not all have actual numbers which could be compared it was chosen to rank the alternatives on a scale of 1-3. Here 1 is the best and 3 is the worst in comparison with the rest. Equal scores can be appointed if there is no clear advantage for one alternative. Elaborations on the calculations of the final scores can be found in Appendix B. Expert session.

State of Para

Based on the performance levels of the three alternatives and the characteristics of the state of Para, it was decided that the water-shedding and the alternate cover score equally high (Table 18). Closely followed by the low permeability cover.

Table 18: Result MCA Para

Alternative	Cost	Efficiency	Sustainability	Final score	Ranking
Low permeability	2	2	2	0.38	2
Alternate	2	1	2	0.31	1
Water-shedding	2	1	2	0.31	1

The cost of the three alternatives was found to be equal. The main reasoning behind this was that the State of Para offers a lot of clay because of the river systems. Therefore it was assumed that the total transport cost would not be significantly high. Balancing out the low transport cost for Trisoplast. Efficiency wise, the water-shedding alternative scores the best since it mitigates infiltration due to the low hydraulic conductivity of the surface layer. The alternate alternative equals the score of the water-shedding because of the high desiccation resistance and low permeability of Trisoplast. No major differences could be found sustainability wise.

State of Minas Gerais

Based on the performance levels of the three alternatives and the characteristics of the state of Minas Gerais, it was decided that the alternate cover scores the highest (Table 19).

Table 19: Result MCA Minas Gerais

Alternative	Cost	Efficiency	Sustainability	Final score	Ranking
Low permeability	2	3	2	0.40	2
Alternate	1	1	1	0.17	1
Water-shedding	3	2	2	0.42	3

The main reasoning behind the result is the low amount of precipitation throughout the year. Which increases the risk of desiccation of the clay layers. Since the state of Minas Gerais does not have access to large river systems, clay is not a widely available material. Hence, the difference in transport cost becomes more prominent and as explained in Section 4.2.2. Trisoplast requires much less volume to create a high performance sealing layer. The latter also caused the alternate cover to be more sustainable.

State of Maranhão

Based on the performance levels of the three alternatives and the characteristics of the state of Maranhão, it was decided that the Alternate cover scores the highest (Table 20).

Table 20: Result MCA Maranhão

Alternative	Cost	Efficiency	Sustainability	Final score	Ranking
Low permeability	1	2	2	0.36	2
Alternate	1	1	1	0.24	1
Water-shedding	2	1	2	0.40	3

Cost wise, the water-shedding scores lower than the other alternatives. This is mainly due to the thickness of the cover which results in higher transport and implementation cost. The efficiency of the water-shedding cover is considered equal to the alternate cover and better than the low permeability cover. The reason for this is that covers of this type perform good in the climatical conditions of Maranhão (Figure 6). The alternate cover also scores higher from a sustainability perspective because of the economic and environmental aspects.

4.3. DISCUSSION

For the stakeholder analysis only six parties were considered, it was chosen to analyse two of each local, national and international. However, these could be split up into more or different groups.

The three locations which were considered (Para, Minas Gerais and Maranhão) in this research were determined by the Global Tailings Portal (GRID-Arendal; Investor Mining and Tailings Safety Initiative, 2020). However, this database is still incomplete. As of December 2019, 332 out of the 727 listed mining companies have responded to the survey. Hence, the locations of the study areas could be biased since not all companies have responded and thus have not been incorporated in the database.

All three alternatives were chosen and described based on literature. Even though there is a significant amount of literature about TSF, the amount of detailed information about cover designs is lacking. Especially when looking at Brazilian tailings dams. Therefore, the cover alternatives were determined by also looking at designs from other countries than Brazil. And if possible, verified by looking at countries with similar climate related characteristics. Since these all turned out to be general designs or designs for specific locations, the covers might not be optimised for Brazilian climates. As a result, the performance levels might be skewed because of this.

The Trisoplast cover is an innovative solution which has not been seen before in the mining industry in Brazil. Since Trisoplast has never been used before it is difficult to assess the potential economic benefit. The Trisoplast cover which is assessed in this analysis is a standard cover which has been implemented in the Netherlands and thus is in compliance with Dutch regulations. Extensive testing in Brazil can result in other measurements or a change in layer build-up which optimises the performance and economic benefit of the cover.

Most of the performance levels are determined based on literature, since no real experiments could be or have been conducted. Because of this, the alternatives are ranked from 1-3 instead of actual performance units (for example: expressed in €).

It was decided to limit the number of criteria which are assessed in the MCA to three. More criteria would have led to a more thorough analysis. However, since the alternatives were not optimised for the three locations the criteria were chosen to be as general as possible.

5. Conclusion

In this project, an investigation of the best practice for the closure of tailings dams in Brazil was done. The analysis featured three different cover methods which were determined by using hydrological data form the States of Para, Minas Gerais and Maranhão. These included:

- a low permeability cover
- an alternate cover
- a water-shedding.

Subsequent to the literature research a stakeholder analysis was conducted in order to come up with criteria which could be used for the multi-criteria analysis. Three main criteria were determined by combining information form the stakeholder analysis, the literature research and a meeting with an expert from Antea Group. The three criteria which were used to analyse the alternatives were: cost, efficiency and sustainability

Since the three locations had different geological, hydrological and climate related characteristics, a multi-criteria analysis was conducted for each of the three locations. The results of the analysis, which are summarised in Table 21 show that the alternate cover which makes use of the material Trisoplast was ranked first at two of the three locations (Minas Gerais and Maranhão) while it shared the top spot in the state of Para. Therefore, it can be concluded that, based on the available literature, the Trisoplast cover can be considered as a viable alternative when covering a TSF in Brazil.

Table 21: Results MCA

#	**Para**	**Minas Gerais**	**Maranhão**
1	Water-shedding	Alternate	Alternate
2	Alternate	Low permeability	Low permeability
3	Low permeability	Water-shedding	Water-shedding

Since this research was based on literature and not actual tests, the results might not be a reliable representation of a real world scenario. In order to validate whether a Trisoplast based alternate cover really is a viable solution for the closure of tailings dams in Brazil, it would be recommended to conduct real life test at the study locations. Since TSF cover a large surface area, the tests could be conducted on a smaller scale. Similar tests have been conducted in the Netherlands in order to analyse the change in hydraulic conductivity over longer periods of time.

Additionally, as mentioned in the discussion, more criteria could be assessed in order to make a more robust analysis. However, this would only benefit the research when all cover alternatives were optimised for the specific conditions at the study locations.

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Appendix

APPENDIX A. EVAPORATION CALCULATIONS

The potential evapotranspiration was calculated using the Thornthwaite equation. This equation estimates the potential evapotranspiration based on a month of 30 days and days of 12 hours. (Pereira & Pruitt, 2004). According to the equations, the potential evapotranspiration can be calculated using two equations (Eq.1 and Eq.4) which is dependent on whether the monthly average temperature exceeds 26 degrees Celsius or not.

$$ET_m = 16\left(10\frac{T}{I}\right)^a, 0°C \leq T \leq 26°C \quad \text{Eq.1}$$

$$I = \sum_{n=1}^{12}(0.2 * T_n)^{1.514}, T_n > 0°C \quad \text{Eq.2}$$

$$a = (6.75 * 10^{-7})I^3 - (7.71 * 10^{-5})I^2 + (1.7912 * 10^{-2})I + 0.49239 \quad \text{Eq.3}$$

$$ET_m = -415.85 + 32.24T - 0.43T^2, T > 26°C \quad \text{Eq.4}$$

Where:

- ET_m= Estimation of potential evapotranspiration [mm/month]
- T= Monthly average temperature [°C]
- I= Thermal index [°C]
- T_n= Local normal climatic temperature regime [°C]
- a = Thermal index [°C]

Appendix A.1. State of Para

Table 22: Monthly average local normal climatic temperature regime for the State of Para (World Weather Online, 2021), (World Bank Group, 2021)

T_n	Avg [°C]	Max [°C]	Min [°C]	$(0.2 * T_n)^{1.514}$ [°C]
Jan	26	29	23	12,13
Feb	25,5	28	23	11,78
Mar	25,5	28	23	11,78
Apr	26	28	24	12,13
May	25,5	28	23	11,78
June	26	29	23	12,13
July	25,5	29	22	11,78
Aug	26,5	31	22	12,49
Sept	27	32	22	12,85
Oct	28	33	23	13,58
Nov	28	33	23	13,58
Dec	27,5	32	23	13,21
I			**Sum**	149,24

Table 23: Monthly average temperature for the State of Para (World Weather Online, 2021)

T	Avg [°C]	Max [°C]	Min [°C]
Jan	27,5	31	24

T	Avg [°C]	Max [°C]	Min [°C]
Feb	27,5	31	24
Mar	27,5	31	24
Apr	27	30	24
May	27,5	31	24
June	27	31	23
July	27,5	32	23
Aug	28	33	23
Sept	29	34	24
Oct	29	34	24
Nov	29	34	24
Dec	28	32	24
Avg.	28		

Avg temp $T > 26°C$, thus potential evapotranspiration is calculated using Eq. 4

$$ET_m = -415.85 + 32.24T - 0.43T^2, T > 26°C$$

Table 24: Monthly potential evapotranspiration and precipitation for the State of Para (World Weather Online, 2021)

Month	ET_m [mm]	Precipitation [mm]
Jan	145,56	257,69
Feb	145,56	301,45
Mar	145,56	329,53
Apr	141,16	297,52
May	145,56	205,65
June	141,16	115,91
July	145,56	78,39
Aug	149,75	59,52
Sept	157,48	65,00
Oct	157,48	95,41
Nov	157,48	130,55
Dec	149,75	194,84
Sum	1782,07	2131,46

Evapotranspiration ratio = $\frac{ET_m}{\text{Precipitation}} = \frac{1782{,}07}{2131{,}46} = 0.84$

Appendix A.2. State of Minas Gerais

Table 25: Monthly average local normal climatic temperature regime for the State of Minas Gerais (World Bank Group, 2021), (World Weather Online, 2021)

T_n	Avg [°C]	Max [°C]	Min [°C]	$(0.2 * T_n)^{1.514}$ [°C]
Jan	25,5	28	23	11,78
Feb	25,5	28	23	11,78
Mar	25,5	28	23	11,78
Apr	25	28	22	11,44
May	25	28	22	11,44
June	25	29	21	11,44
July	25,5	30	21	11,78

T_n	Avg [°C]	Max [°C]	Min [°C]	$(0.2 * T_n)^{1.514}$ [°C]
Aug	27	32	22	12,85
Sept	28,5	33	24	13,94
Oct	28	32	24	13,58
Nov	26,5	30	23	12,49
Dec	26	29	23	12,13
I			**Sum**	146,43

Table 26: Monthly average temperature for the State of Minas Gerais (World Bank Group, 2021)

T	Avg [°C]	Max [°C]	Min [°C]
Jan	26	30	22
Feb	26	30	22
Mar	25,5	29	22
Apr	26	30	22
May	25,5	30	21
June	25,5	31	20
July	26	32	20
Aug	27,5	34	21
Sept	28	34	22
Oct	27,5	33	22
Nov	27	32	22
Dec	26	30	22
Avg.	26		

Avg temp $0°C \leq T \leq 26°C$, thus potential evapotranspiration is calculated using Eq. 1

$$ET_m = 16\left(10\frac{T}{I}\right)^a, 0°C \leq T \leq 26°C$$

Table 27: Monthly potential evapotranspiration and precipitation for the State of Minas Gerais (World Weather Online, 2021)

Month	ET_m [mm]	Precipitation [mm]
Jan	125,06	226,97
Feb	125,06	144,34
Mar	116,66	163,11
Apr	125,06	74,80
May	116,66	29,52
June	116,66	11,94
July	125,06	10,57
Aug	152,88	12,61
Sept	163,07	42,69
Oct	152,88	108,61
Nov	143,16	194,80
Dec	125,06	245,98
Sum	1587,27	1265,94

Evapotranspiration ratio = $\frac{ET_m}{\text{Precipitation}} = \frac{1587{,}27}{1265{,}94} = 1.25$

Appendix A.3. State of Maranhão

Table 28: Monthly average local normal climatic temperature regime for the State of Maranhão (World Bank Group, 2021), (World Weather Online, 2021)

T_n	Avg [°C]	Max [°C]	Min [°C]	$(0.2 * T_n)^{1.514}$ [°C]
Jan	27	30	24	12,85
Feb	26	29	23	12,13
Mar	25,5	28	23	11,78
Apr	25,5	28	23	11,78
May	26	29	23	12,13
June	26	30	22	12,13
July	26	30	22	12,13
Aug	27,5	32	23	13,21
Sept	28,5	34	23	13,94
Oct	29,5	35	24	14,69
Nov	29,5	35	24	14,69
Dec	28,5	33	24	13,94
I			**Sum**	155,44

Table 29: Monthly average temperature for the State of Maranhão (World Bank Group, 2021)

T	Avg [°C]	Max [°C]	Min [°C]
Jan	28,5	32	25
Feb	27	29	25
Mar	27	29	25
Apr	27	29	25
May	27	29	25
June	27	29	25
July	26,5	29	24
Aug	27,5	30	25
Sept	28	31	25
Oct	28,5	31	26
Nov	28,5	31	26
Dec	28	30	26
Avg.	27,54		

Avg $T > 26$°Cthus potential evapotranspiration is calculated using Eq. 4

$$ET_m = -415.85 + 32.24T - 0.43T^2, T > 26°\text{C}$$

Table 30: Monthly potential evapotranspiration and precipitation for the State of Maranhão (World Weather Online, 2021)

Month	ET_m [mm]	Precipitation [mm]
Jan	153,72	222,55
Feb	141,16	262,31
Mar	141,16	290,82

Month	ET_m [mm]	Precipitation [mm]
Apr	141,16	235,90
May	141,16	135,26
June	141,16	48,12
July	136,54	36,57
Aug	145,56	15,78
Sept	149,75	18,43
Oct	153,72	44,75
Nov	153,72	81,72
Dec	149,75	130,59
Sum	1748,57	1522,80

Evapotranspiration ratio = $\frac{ET_m}{\text{Precipitation}} = \frac{1748{,}57}{1522.8} = 1.15$

Appendix A.4. Monthly evapotranspiration ratio's

Table 31: Monthly evapotranspiration ratio's for all three locations

Month	State of Para	State of Minas Gerais	State of Maranhão
Jan	0,56	0,58	0,69
Feb	0,48	0,91	0,54
Mar	0,44	0,78	0,49
Apr	0,47	1,76	0,60
May	0,71	4,29	1,04
June	1,22	10,61	2,93
July	1,86	12,46	3,73
Aug	2,52	11,54	9,22
Sept	2,42	3,51	8,13
Oct	1,65	1,34	3,44
Nov	1,21	0,72	1,88
Dec	0,77	0,54	1,15

APPENDIX B. EXPERT SESSION

On Friday the 24th of December meeting was organised with Bouke van Meekeren. The purpose of this expert meeting was to identify relevant criteria for the CMA, as one input for the methodological triangulation (Figure 18). The setting of the session was more like a discussion than an interview. During this meeting his the following points were discussed:

- Which criteria came forward during the stakeholder analysis and literature
- Which criteria should be part of the MCA
- How should these criteria weight relative to each other.

Table 32 Displays the criteria which were identified during the stakeholder analysis. During the discussion, we came to the conclusion that several criteria are similar or could be labelled under one larger criteria. Environmentally friendly, sustainability, post closure development and social related criteria are therefore combined in the criteria: sustainability. Additionally, safety and robustness are combined to form the criteria efficiency. Even though cost-effectiveness is not part of the key stakeholder criteria it was decide upon to include it as a criteria for the MCA since the mining corporations have to implement the covers.

Table 32: Criteria resulting from stakeholder analysis sorted by type of stakeholder

Type of stakeholder	Criteria
Key player	- Safety - Environmentally friendly - Socioeconomically friendly - Efficiency - Sustainability - Socially equitable - Robustness
Subject	- Safety - Sustainability - Environmentally friendly - Add economic value/cost effective - Suitability - Post closure development
Crowd	- Safety - Environmentally friendly

However, these three criteria are still quite broad and thus sub-criteria are necessary to make a robust analysis. During the session Bouke van Meekeren and myself had a brainstorm session to determine sub-criteria. It was chosen not to consider too many criteria because of the limit time frame of the project and the fact that the three covers are analysed for three different locations. Shows the sub-criteria which were determined based as a result of the brainstorm session.

Table 33: Criteria and sub-criteria for MCA

Cost	Efficiency	Sustainability
Construction	Limit infiltration	Social
Maintenance	Erosion control	Economic
		Environmental

The sub-criteria were validated with additional literature review: for the cost criteria, multiple papers refer to the importance of construction and maintenance cost as a closure objective (Mylona, et al., 2004), (Bjelkevik, 2011), (Lacy H. , 2016). The efficiency related criteria: infiltration and erosion are more related to studies where on site testing or modelling has been conducted (Perotti, Gitirana, & Fredlund, 2019), (Ouchebri, Göksu, & Junqueira, 2021), (Mylona, et al., 2004). Finally, since sustainability is becoming much more relevant over the last years, the mining industry cannon lag behind. Hence, sustainability is relevant for TSF closure (Bjelkevik, 2011), (ICOLD, 2021), (ICMM, 2021).

Finally, the used MCA method (AHP) needs relative weighing factors for the criteria in order to rank them. According to Bouke van Meekeren the three criteria could be considered as near equal. Therefore he suggested to apply a relative weighing factor of 0.33 for all three alternatives. The reasoning behind this suggestion is based on the amount of assumptions which have to be made when determining the performance values of the covers. These assumptions cause the results to lack precision. Therefore, a more detailed division in weighing factors would not be relevant.

Even though this suggestion was made, it was chosen to slightly change the weighing factors. Elaborations can be found in the following Appendix C.

APPENDIX C. MCA CALCULATIONS

Appendix C.1.Criteria calculation

First the criteria are ranked with respect to each other. A 1-3 scale is used. Here 3 means that one criteria is much more important than another and 1 means they are equally important

Table 34: Criteria ranked with respect to each other

Standard	Cost	Efficiency	Sustainability
Cost	1	1,5	2
Efficiency	0,67	1	1,5
Sustainability	0,5	0,67	1
Sum	2,17	3,17	4,5

The matrix is normalised and the Priority Vector is calculated by taking the average value for each row.

Table 35: Normalised matrix and priority vector

Normalised	Cost	Efficiency	Sustainability	Priority Vector
Cost	0,46	0,47	0,44	0,46
Efficiency	0,31	0,32	0,33	0,32
Sustainability	0,23	0,21	0,22	0,22
Sum	1	1	1	1

In order to find out whether the rankings are consistent, a consistency ratio is computed.

Step 1: the priority vector is multiplied with its corresponding criteria rating in order to form the weighted sum.

Table 36: Result (weighted sum) of priority vector multiplied with Table 35

Cost	Efficiency	Sustainability	Weighted sum
0,46	0,48	0,44	1,38
0,31	0,32	0,33	0,96
0,23	0,21	0,22	0,66

Step 2: divide weighted sum to corresponding priority vector value

Step 3: $\lambda_{max} = average\ of\ results$ = 3,0015

Table 37: Weighted sum divided by priority vector

Weighted sum	Priority vector	Result
1,38	0,46	3,0021
0,96	0,32	3,0015
0,66	0,22	3,0010
	Avg.	3,0015

Step 4: Consistency index

$$CI = \frac{\lambda_{\max - n}}{n - 1} \qquad \text{Eq.5}$$

Where:

- CI = Consistency index

- λ_{Max} = average of Weighted sum/Priority vector
- n = number of criteria

$$CI = \frac{3.001542 - 3}{2} = 0.0008$$

Step 5: Consistency ratio

$$CR = \frac{CI}{RI} \qquad \text{Eq.6}$$

Where:

- CR = Consistency ratio
- CI = Consistency index
- RI = Random index

n	RI
2	0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.51

Figure 26: Random index (Saaty, 1980)

$$CR = \frac{0.0008}{0.58} = 0.001 \ \leq 0.10$$

Thus, making the ranking of the criteria consistent.

Appendix C.2. State of Para

Table 38: MCA scores for State of Para

Performance	Cost	Efficiency	Sustainability
Low permeability	2	1	2
Alternate	2	1	2
Water-shedding	2	2	2
Sum	6	4	6

Table 39: Normalised matrix of Table 38 and ranking for State of Para

Normalised	Cost	Efficiency	Sustainability	Priority vector	Ranking
Low permeability	0,33	0,25	0,33	0,46	0,31
Alternate	0,33	0,25	0,33	0,32	0,31
Water-shedding	0,33	0,5	0,33	0,22	0,39
Sum	1	1	1		

Appendix C.3. State of Minas Gerais

Table 40: MCA scores for State of Minas Gerais

Performance	Cost	Efficiency	Sustainability
Low permeability	2	3	2
Alternate	1	1	1
Water-shedding	3	2	2
Sum	6	6	5

Table 41: Normalised matrix of Table 40 and ranking of State of Minas Gerais

Normalised	Cost	Efficiency	Sustainability	Priority vector	Ranking
Low permeability	0,33	0,5	0,4	0,46	0,40
Alternate	0,17	0,17	0,2	0,32	0,17
Water-shedding	0,5	0,33	0,4	0,22	0,42
Sum	1	1	1		

Appendix C.4. State of Maranhão

Table 42: MCA scores for State of Maranhão

Performance	Cost	Efficiency	Sustainability
Low permeability	1	2	2
Alternate	1	1	1
Water-shedding	2	1	2
Sum	4	4	5

Table 43: Normalised matrix of Table 42 and ranking of State of Maranhão

Normalised	Cost	Efficiency	Sustainability	Priority vector	Ranking
Low permeability	0,25	0,5	0,4	0,46	0,36
Alternate	0,25	0,25	0,2	0,32	0,24
Water-shedding	0,5	0,25	0,4	0,22	0,40
Sum	1	1	1		