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Cost-Benefit Analysis of Historical Copper Slags and Tailings

- a case study from Boliden Rönnskär Smelter in Skelleftehamn

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Abstract

This thesis aims to investigate different treatment scenarios for the potential clean-up of Rönnskär's historical copper slags and tailing sands. Both materials are known to contain potential toxic elements that can put the environment and humans at risk. Between 1930 and 1966, Rönnskär smelter had been using these by-products from enrichment and pyrometallurgical processing as land-fillings for the extension of its industrial area, located on an Island nearby Skellefteå (Sweden). The examined scenarios, namely Rönnskär, Boliden Area and Aitik, are all equipped with suitable technology but differ in their treatment methods as well as location along with required transportation. A social cost-benefit analysis is used to determine the net-present values of each scenario, based on economic, social and environmental input factors. All results state Boliden Area as the most beneficial scenario regarding the treatment of Rönnkär's historical copper slags and tailings, showing only small deviations when purely focusing on environmental costs. Based on the remediation of 400 000t copper slags and tailings, this study's calculations show a net present value of -772 kr/t copper slag and -530 kr/t tailings for Boliden Area. However, a total clean-up of the existing 5.5 Mton copper slag and 1.8 Mton tailings is currently impossible which is why further research and investigation is needed.

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1. Introduction

Boliden is one of Sweden's biggest and most important mining companies, a market leader in the field of zinc and electronic scrap recycling as well as a known pioneer in terms of sustainable metal production (Boliden, 2017). The company has mining and metal smelting in Sweden, Norway, Finland and Ireland, including altogether 5500 employees, figure 1.

Figure 1: Boliden mines, smelters and marketing offices (Boliden, 2019).

Within this paper, all focus lies on the Boliden smelter Rönnskär in Skelleftehamn (red arrow) which is one of the world's most efficient copper smelters, primarily extracting copper along with gold, silver, lead and zinc. During the enrichment of ore and the smelting process unavoidable by-products known as tailings sand and copper slag are produced which are either used as building material or considered as waste by-product and disposed in one of the dumping areas. In the case of Rönnskär smelter, these materials were also used as land-fillings in order to create new industrial area from the shore area and the sea (WSP Samhällsbyggnad, 2007). This was a necessary expansion step due to the fact that Rönnskär smelter is built on an Island whose space was limited for economic development and manufactural growth. However, these historical slags and tailings consist of potentially toxic elements that are posing a risk to humans and the environment. Therefore, Rönnskär continuously investigates actions in order to meet legal criteria and possible remediative measures. The ground consists of historical copper slags and tailings that are overlain with the active industrial area, which gives an relatively unique setting with few, if any, previous projects that could be used as directory. Hence, this study focuses on investigating different treatment scenarios in order to provide directions for further research and a final decision.

1.1 Background and overview of copper

Copper, also known as the red metal, is one of todays most required and important metals. Its employment by man goes back thousands of years but its actual breakthrough came with the usage of electricity and the discovery of metallic conductivity. Since the middle of the 19th century, copper production and consumption rates increased tremendously while costs and prices declined due to technological development (Radetzki, 2009). Besides a booming market and a predicted rise in future demand, copper production comes along with copper slag and tailing sands. The latter accrues during the purification of copper from the copper ores. Once the valuable minerals are freed from its embedding rock matrix, the left over product is stored in piles, so-called tailings (Thomas et al., 2013). Copper slag is generated in the subsequent pyrometallurgical treatment and can be described as a liquid phase swimming above the molten metals as a combination of impurities from ores, fluxing agents as well as metal contents. It is produced during the process of smelting and converting where it is used to encapsulate impurities and added additives for the further purification of metals (Neubert et al., 2014). According to Gorai et al. (2003), estimates revealed that every tonne of processed copper generates about 2.2 tons of slag. Multiplying this with the worldwide production rates of copper resulted in a total slag production of approximately 24.6 million tons in 2003, followed up by a rising trend in numbers.

The recycling of these copper slags and tailings is one of the important challenges within todays copper industry and its success provides potential environmental and economic benefits for all related industries. It is well known that the disposal of copper slag and tailings, in e.g. so called land-filling areas, leads to a potential risk for air, water and soil contamination including negative impacts on humans, plants and animals. Various researchers indicated elevated levels of toxic elements nearby and even on further distannce from smelters or dumping sides in their studies (Lee and Corea, 2005; Pandey et al. 2007; Kundu et al., 2016). Besides the environmental side-effects, copper slag and tailings also bear potential economic benefits in the form of unclaimed metal values or marketable end-products which will be lost without recovery methods or further processing. The focus of recovery lies thereby mainly on valuable elements such as gold and silver as well as on the conversion of copper and iron into alloy products for different industries (Sarfo et al., 2017; Echeverry-Vargas et al., 2017). But even the non-metallic residues can be of economic interest as long as critical contamination levels of toxic components are not exceeded. In general, many researchers suggest the implementation of copper slag into the production process of building materials such as cement, fill, ballast, as well as roofing granules, glass or other products (Yang et al., 2010; Behnood et al., 2015).

Another issue addressed by the recycling of copper slag and tailings is the current and future problem of space availability mentioned by Reuter et al. (2004). He thereby states the complication of continuously increasing slag production and rapidly reducing land for disposal areas. Further concerns are named by Owusu et al. (2011) who points out the declining chance of finding new and exploitable copper mineral deposits due to the fact that most untapped resources are unfavourably located and therefore too expensive to mine.

Besides the constant increase in copper slag production, many problems accruing from this by-product have their origin in the past. Over the years, applied smelting procedures as well as new technologies with higher efficiencies, environmental standards and quality levels developed and replaced the old machinery. Therefore, slag compositions differ and hence former slags contain significantly higher amounts of toxic and valuable substances compared to today's slags. In addition, old land-fillings that had been considered and approved as suitable dumping piles for copper slag might not comply with today's standards and requirements for waste disposal. Another big driving force is the raising environmental awareness not only amongst scientists but also amongst the overall population, leading to more and stricter environmental claims and the enactment of new laws and regulations. Accordingly, this huge amount of potential waste along with new environmental legislations, high market competition and developing technologies are encouraging companies to gradually replace the typical dumping and disposal methods by recycling, reuse and recovery ideas, differing depending on the quality and characteristics of the converted slag (Van Riel, 2018).

1.2. Rönnskär project

Rönnskär smelter is located on the peninsula Rönnskär in Skelleftehamn and is partly built and enlarged by copper slag and tailings itself. Between 1930 and 2007, the actual industrial area expanded from its original 50ha to approximately 153ha with further expansion in progress (WSP Samhällsbyggnad, 2007).

Rönnskär 1930 (Allmän, 2017).

Rönnskär 2016 (Allmän, 2017).

Today, these land-fillings, consisting of historical copper slags and tailings, are posing a potential risk to humans, animals and the environment. Even though the general health risk is considered to be low, elements such as arsenic, lead, cadmium, copper or zinc have the potential to leach or accumulate into sediments or the sea. Further concerns have been published in the 'Miljö- och hälsoriskbedömning som en följd av utredningsvillkor U11' report by Boliden, stating a poor but clearly improving environmental status around Rönnskär, including the analysis of land- and water bodies [Appendix A]. Besides Rönnskär's own motivation to take on responsibility for their pollution, additional pressure is coming from the development of environmental laws and regulations. In this regard the European Union decided to follow the approach of a circular economy and Sweden agreed on a sophisticated management of minerals with special focus on increased resource efficiency. Further concerns regard the Swedish Environmental Protection Agency which has previously been involved with Rönnskär as well as actively initiating judicial proceedings against the mining industry [Appendix B]. In summary, Rönnskär's active approach on taking on responsibility, the already concerning environmental status as well as the rapid development of environmental laws and regulations are the driving factors for this thesis project.

It is well-known that there exist more than one way to recycle, reuse and recover valuable metals from dumped copper slag and tailings including different costs, benefits, end-products and wastes. However, no processing results can be copied and transferred between smelter factories due to their different base products and technical treatment procedures. Therefore, each copper slag production side has to investigate and conduct its own research and analysis in order to implement the most economic, environmentally and socially beneficial method for their smelter.

Therefore, this study is a unique examination aiming to support Rönnskär with the treatment of their historical copper slags and tailings, motivated by the present economic, social and legal changes regarding the environment and sustainability approaches. It is built on the previous investigation of Landström (1989) which is based on the original idea of Rönnskär to utilize all, or at least most, accruing material streams. Compared to Landström who purely focused on the economic benefits of residual products at Rönnskär, this project is examining the issue from an economic, environmental and social point of view. The decision process is supported by the conduction of a social cost-benefit analysis for each possible treatment scenario in order to guarantee the inclusion of all concerned parties. The resulting net present values are then counterweight and meant to be a starting point for future tests and investigations.

Structure of the study

The study is organized into 6 chapters. The introduction gives a general background of copper slag and tailings production as well as the actual problem and purpose of this paper.

The following literature review is focusing on two different areas: 1. Sustainability within mining and 2. The application of cost-benefit analysis on remediation projects. The third chapter is introducing the three main treatment scenarios for Rönnskär's historical copper slags and tailings, namely Rönnskär, Boliden Area and Aitik. Following this comes the methodology part which is presenting and describing the cost-benefit analysis as well as the concerning input data. After the methodology, the result chapter states the outcomes of the cost-benefit analysis for each analysed scenario plus an additional sensitivity analysis in order to ensure robustness of the analysis. The final chapter discusses the outcomes and limitations, ending in a short conclusion. Additional information regarding the project can be found in the appendix.

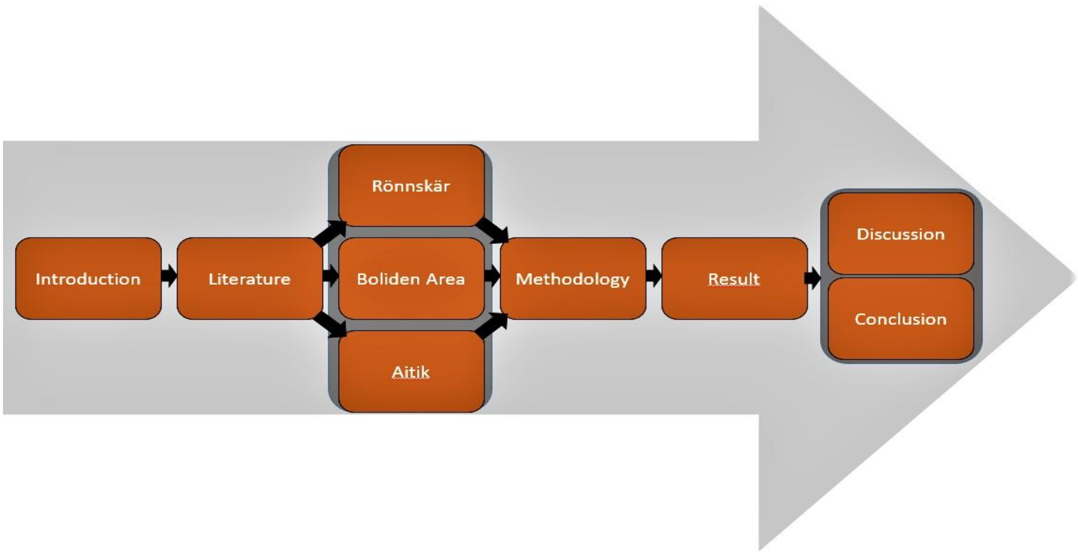

Figure 2: Graphical demonstration of the study.

2. Literature review

Within this literature review, the two impact areas, sustainable mining and cost-benefit analysis (CBA) performance on remediation work are investigated and summarized. Besides being directly linked to this research study, both areas give great motivation and support for the conduction of this project.

2.1 Sustainable mining – copper slag and tailings treatment

The mining sector and its activities are commonly seen as a threat to humans and the environment through mineral extraction, transportation, smelting, dewatering or other processes. Nevertheless, mining activities are indispensable and humans depend heavily on the extraction of these natural resources. When following literature, a trend towards a more sustainable mining sector can be recognized as different waste management approaches got introduced and tested (Hilson & Murck, 2000). The following paragraphs will give a short insight into the current status of sustainability practices within the mining industry.

In their paper about the environmental sustainability in the mining sector, Hilson and Murck (2014) described a successful adoption of environmental practices amongst small and medium sized companies in the Spanish region of Catalan. The study is based on the analysis of quality, environmental, occupational health and safety as well as corporate social responsibility management. Data was gathered through the conduction of a questionnaire, consisting of 41 items concerning environmental management systems and environmentally sustainable practices. The descriptive statistical analysis shows that most companies are committing to environmental approaches and sustainable practices. In general, most companies are legally forced to prepare restauration plans for the closing of their mines as well as an annual declaration of their waste. About 50% of the surveyed companies have adapted to energy sources consumption controls and mining source reduction whereas only 37% agree on environmental goal definition. The lowest percentage, only about 2%, received the cooperation with environmental non-governmental organizations. Despite the very positive results, Hilson and Murck also point out that an increase of stricter environmental regulations and an improved governmental promotion is needed to further enhance companies' engagement with the environment and sustainability practices.

One of the biggest topics regarding sustainability in the mining sector is the concept of zero-waste, meaning an elimination or at least minimization of waste generation. Most mining activities are generating huge amounts of slag which are commonly dumped in so called land-fillings. Sarfo et al. (2017) discusses the possibility to recover valuable metals from copper slag while producing an environmentally harmless slag that could potentially be used in the glass and ceramic industry. The application of thermodynamic processing with optimized reduction time, temperature and carbon content proves Sarfo's theory and presents a waste free pyrometallurgical processing technology. This paper clearly states the potential of metal recovery and properties of secondary slag processing.

A different process technology regarding the recycling of copper slag from smelters was investigated by Miganei et al. (2017). In this paper, a new way of residue-free processing was implemented, making it possible to fully recycle all contents accruing from copper slag by producing four marketable products: blasting agent, cement additive, metal salts solution and fertilizer. The method is based on the hydrometallurgic technology but differs in the application of the leaching substance. Miganei et al. successfully demonstrate the sustainability and economic beneficiary of this new process development. The production of the four end-products make sure no residue is left behind and by using HCL, the required acid for the leaching procedure can be cut by 50% and undesired dissolution of silicate matrix of copper slag can also be prevented. This paper therefore presents a technological idea with high potential for future application within the copper industry.

The application of flotation on calcium-ferrite-based slags has been examined by Bruckard et al. (2004) and states copper recovery rates between 80% and 87% for three tested slags. During the study, a series of laboratory batch flotation tests were performed as part of a wider Minerals' research project. The goal of the project was to develop a single-stage continuous copper making process. The authors conclude that improved recovery rates can be achieved when extending the grind time, fining the pre-flotation screen size as well as prolonging the actual float. This paper clearly demonstrates the recycling potential of copper slags through flotation technology.

The issue of sustainability and zero waste technologies in the mining sector is not only affecting industrialized countries but also developing countries such as India which is said to be a major copper market in the future. Agrawal and Sahu (2010) examined different pyrometallurgical and hydrometallurgical process technologies regarding the copper recovery from secondary products. Indian's motivation to investigate recycling and recovery technologies are coming from the worldwide increase in demand as well as from the implementation of strict environmental rules. The paper concludes that India has to commercialize new technologies for recycling and recovery in order to stay competitive, save costs and energy, push the development of value adding products and reduce the amount of waste and thereby reducing environmental pollution.

Lastly, Ranängen and Lindman (2017) give some valuable insights into the Nordic mining industry and their approach towards sustainability. The study is built on the missing knowledge regarding sustainable actions taken by the European mining industry in combination with the positive economic trend that this industry is currently experiencing. The result of this study reveals a sustainability criteria guideline but further suggest additional research on 'how' to implement these criteria within the Nordic mining industry.

2.2 CBA performance on remediation work

In recent years, environmental awareness and sustainability have started to play vital roles within economies, policies and societies. People are no longer accepting the indirect effects of pollution from companies on their own lives and the demands for stricter regulations, taxes and sanctions are getting louder (Anton & Shelton, 2011). In order to support the evaluation of such policy proposals, it is quite common to use cost-benefit analysis due to the possibility of incorporating social effects (OECD, 2018).

Besides the application of CBA, the so called Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) are also common tools regarding the evaluation of sustainability approaches. Hoogmartens et al. (2014) discusses these three assessment tools with the help of the following figure and states the different features in order to ensure the right application.

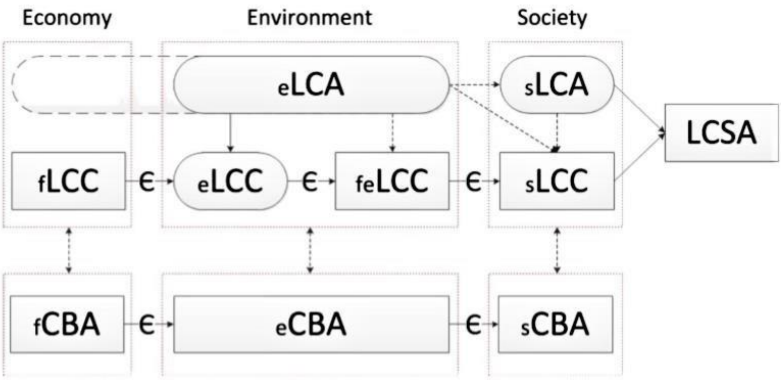

Figure 3: Interaction of CBA and LCA assessment tools. Full arrows indicate that information from one methodology is needed to perform another methodology. Dashed arrows indicate that although a methodology can provide useful input to another methodology. When '€' is included as a symbol, this indicates that a methodology is part of another methodology (Hoogmartens, 2014).

It shows the interaction of the different sustainability assessment tools whereby both, LCA and CBA, remain stand-alone methods. Focusing on CBA, it can be seen that a social CBA (sCBA) is built on the financial and environmental CBA and can therefore be considered as the most extensive approach within this regard. The difference between the two stand-alone methods, CBA and LCA, is mainly the fact that LCA focuses on products whereas CBA is more applicable to projects and policies. Furthermore, LCA is a comparative assessment tool and shouldn't be used for autonomous project evaluations. Hoogmartens concludes that all three methods are capable of performing a full sustainability assessment but one has to be careful in picking the most suitable tool.

The main problem that comes along with the performance of a social CBA within remediation projects is the monetization of benefits, stated by Lavee et al. (2012). Direct benefits are marketable benefits and can usually be monetized by e.g. an increase in land value whereas indirect benefits are not marketable and therefore difficult to include in a CBA. Lavee et al. also mentions that most studies can only theoretically assume or analyse the additional positive effects from cleaning contaminated sites which negatively affects the actual outcome and following remediation activities. The result is a too low number of remediation projects as well as the rising questions of the feasibility of these operations. According to this paper, some researchers are using the hedonic pricing method, describing changes in property values to monetize environmental attribute, in order to value indirect benefits. Unfortunately, this method is not applicable to all accruing benefits, such as risk reduction for future generations or the actual value of life. Lavee et al. successfully applies a CBA on contaminated industrial sites in Israel but emphasizes the difficulty of monetizing benefits as well as the prevailing uncertainties which were cared for by a sensitivity analysis.

Söderqvist et al. (2015) conducted a cost-benefit analysis on a former chemical industry area close to the city of Gothenburg. It was planned to transform this place into a residential area of metropolitan character which requires in-depth cleaning of the ground due to the hazardous health risks for children. The study investigated 4 different alternatives with the help of a CBA, taking uncertainty into explicit account. The results are shown in table 1 and clearly demonstrate the uncertainty and the non-existing knowledge regarding relevant influencing factors.

Main items	Sub-items	Alternative 1			Alternative 2			Alternative 3			Alternative 4		
		B/P	MLV	Unc	B/P	MLV	Unc	B/P	MLV	Unc	B/P	MLV	Unc
B1. Increased property values		DEV	48.81	M	DEV	48.81	M	DEV	48.81	M	DEV	48.81	M
B2. Improved health	B2a		NR			NR			NR			NR	
	B2b	EMP	0.0003	M	EMP	0.0003	M	EMP	0.0003	M	EMP	0.0003	M
	B2c	PUB	0.07	M	PUB	0.07	M	PUB	0.07	M	PUB	0.07	M
B3. Increased provision of ecosystem services	B3a	PUB	X		PUB	X		PUB	X		PUB	X	
	B3b	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
	B3c	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
B4. Other positive externalities than B2 and B3			NR			NR			NR			NR	
C1. Remediation costs	C1a		NR			NR			NR			NR	
	C1b		NR			NR			NR			NR	
	C1c	DEV	1.18	M	DEV	0.78	M	DEV	0.77	M	DEV	0.95	M
	C1d	DEV	38.90	M	DEV	25.87	M	DEV	25.52	M	DEV	31.40	M
	C1e	DEV	9.32	M	DEV	9.32	M	DEV	9.32	M	DEV	9.32	M
	C1f	DEV	4.56	M	DEV	2.41	L	DEV	1.70	L	DEV	1.65	M
C2. Impaired health due to the remedial action	C2a	DEV	0.84	M	DEV	0.84	M	DEV	0.84	M	DEV	0.84	M
	C2b	DEV	1.52	M	DEV	0.90	M	DEV	0.77	M	DEV	0.64	M
	C2c		NR			NR			NR			NR	
	C2d	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
C3. Decreased provision of ecosystem services due to remedial action	C3a	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
	C3b	PUB	0.56	M	PUB	0.35	M	PUB	0.33	M	PUB	0.31	M
	C3c	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
C4. Other negative externalities than C2 and C3			NR			NR			NR			NR	

Table 1: CBA base case remediation alternatives: P=player, B=Beneficiary, DEV=developer, EMP=Employees, PUB=public, including neighbour, MVL=most likely value of the present value, (X)=Non-monetized item judged to be somewhat important,, X=Non-monetized value judged to be very important, NR=Non-monetized item judged to be of no relevance or no importance, Unc=degree of uncertainty, L=low uncertainty, M=medium uncertainty, H=high uncertainty.

Especially the ‘increased provision of ecosystem services’ would be of great importance within these calculations but can’t get assigned any monetary value. It is also of interest that almost all stated values are of medium uncertainty, a result of the difficulties concerning monetization of costs and benefits. Concluding, the CBA can be used to weight the different alternatives and support the decision process but further evaluation methods for non-monetized items must be developed in order to be able to calculate the real costs and benefits of such remediation projects.

Similar to Söderkvist et al. (2015) is the case study from Volchko et al. (2017). The paper investigates the potential social profitability of metal recovery technology at Köpmannebro remediation site in Sweden. It therefore analysed 5 different alternatives using the conventional 'excavation and disposal' method but differed regarding pre-treatment as well as distance and means of transportation. Due to a lack of data, uncertainties were either handled by including them in the input variables or by using lognormal distributions. The calculations were based on 4 benefit and cost categories whereby the benefit 'increased provision of ecosystem services' couldn't get monetized. Volchko et al. (2017) states the problem of the monetization of benefits and internal project costs along with the suggestion of a case-by-case study to obtain the optimal price of copper from slag in order to make the metal recovery technology economically competitive.

Compared to Söderkvist et al. (2015) and Volchko et al. (2017), Huysegoms et al. (2018) added a Life Cycle Assessment (LCA) to the application of a CBA. His paper examined the contamination of a school ground by a former gas plant which is supposed to get remediated by excavation and off-site cleaning. The outcome states a social beneficiary when thinking long-term (100 years) but declares limitation on data in existing databases, specific for soil remediation, as well as on the quantification and monetization of impacting items.

2.3 Summarised findings

Sustainable mining

Sustainability and environmental approaches are clearly influencing mining activities all around the globe. Nevertheless, this environmental development within the mining sector is still not sufficiently implemented and most companies haven't introduced efficient technologies or guidelines yet. Furthermore, there exist a lack of literature on this topic within the Nordic countries, especially from real case studies supported by accurate data coming from operating companies.

CBA performance on remediation projects

All presented papers chose cost-benefit analysis but state limitations regarding the application of this method within the context of remediation work. This is mainly due to the difficulty of monetizing indirect benefits as well as accurate numbers on projects costs or metal extraction values.

Gap in literature

The literature review clearly shows a lack of research and literature on sustainable mining in the Nordics as well as the limited application of cost-benefit analysis within remediation projects. This thesis will therefore apply a cost-benefit analysis, based on reliable data from one of Sweden's biggest mining companies, Boliden Rönnskär, in order to examine different remediation scenarios for its historical copper slags and tailings. Compared to most studies, the contaminated material is not located in a land-filling nor an uninhabited area but rather coming from Rönnskär's industrial area which is partly built on these contaminated, historical ground fillings. Furthermore, these areas will continue to be used as industrial areas whereas most remediation projects are motivated by a change of usage purpose.

3. **Scenarios**

The following paragraphs examine the possible treatment methods for the historical copper slags and tailings at Rönnskär, Boliden Area and/or Aitik. All three scenarios are shortly described regarding their process technology and project feasibility. The major differences characterising each scenario are found in the applied technologies, pyrometallurgy at Rönnskär and flotation technology at Boliden Area and Aitik, as well as the location along with the existing transportation systems.

The decision on the three treatment scenarios investigated in this study is mainly based on logic. Rönnskär smelter initiated the treatment project and it is just natural to assume certain advantages of an internal solution. The two other scenarios, Boliden Area and Aitik, are mainly chosen due to three reasons. Firstly, both units, as does Rönnskär, belong to the Swedish mining company Boliden which enables access to important documents and data, necessary to conduct such a research project. Secondly, Boliden and Aitik are relatively closely located to Rönnskär and have an already established connection via road and rail, reducing the problems caused by required logistics. Thirdly, it was known that Boliden Area as well as Aitik consist of technology to theoretically process Rönnskär's historical copper slags and tailings.

3.1 Rönnskär scenario

The most obvious and simplest idea is a direct treatment at Rönnskär, one of the most complex industrial smelters, consisting of a sophisticated network of different machinery connected in a multiple number of ways in order to ensure minimal waste production and sustainability. Figure 7 shows a simplified version of Rönnkär's ongoing process routes but omits plenty of arrows that reintroduce and feed side products or residues back into the operation system.

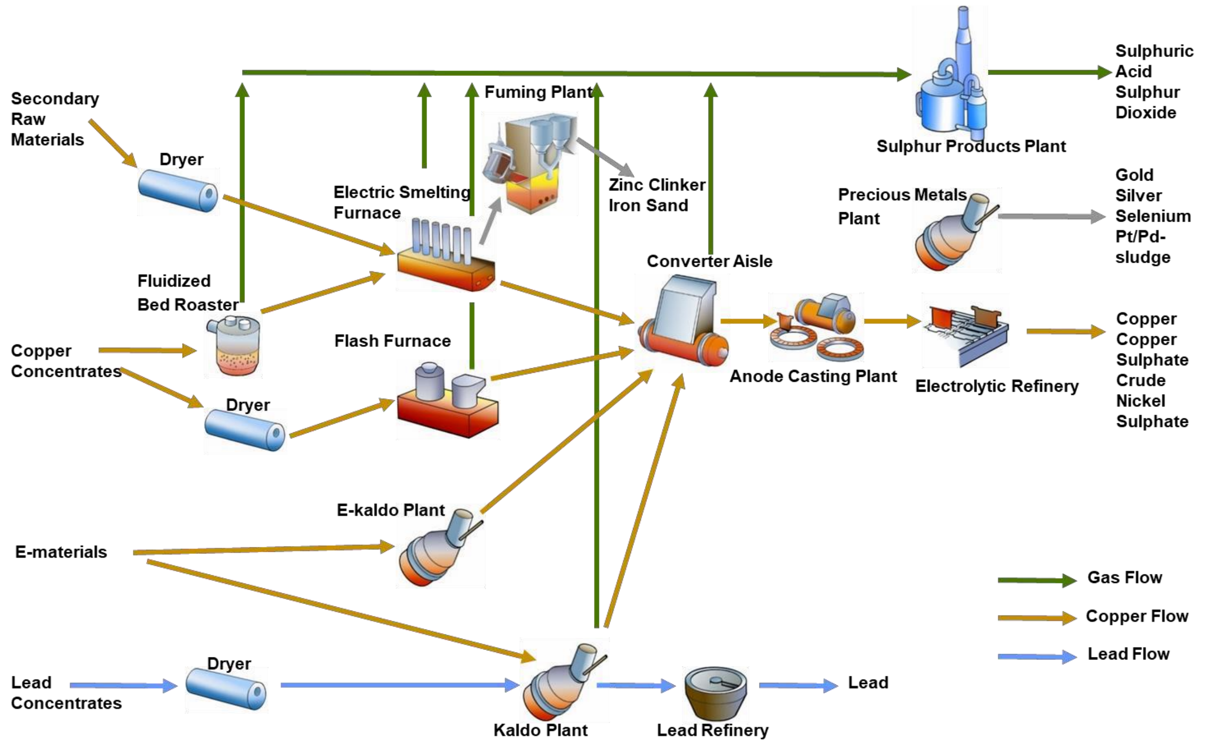

Figure 4: Rönnskär processes (simplified) (Allmän 2017).

Rönnskär smelter specialises in using pyrometallurgy on primary ores and secondary products such as electronic scrap and metal rich wastes. This technology is a melting method that applies high temperatures to extract and purify valuable metals.

This existing machinery would theoretically and practically be able to process both, copper slag and tailings. Both materials would get introduced into the treatment process through the dryer and further passing the Electric Smelting Furnace. Subsequently, materials consisting of zinc, such as copper slag, are usually sent to the Fuming Plant whereas the rest, e.g. tailings, continues their journey to the Converter Aisle or end up as non-dangerous side-product (not shown in the figure) which might get fed back into another process stage. The treated slag from the Fuming Plant gets granulated and then dewatered in order to get stored intermediately at Rönnskär. The resulting product is sold under the product name Boliden Järnsand and is used for construction purposes, soil insulations or as blasting agent (Boliden, 2009).

3.2 Boliden Area scenario

Boliden area is located in the mineral rich Skelleftea field in Västerbotten, nearby Rönnskär smelter. Besides several underground mines, the area also consists of a concentrator which could potentially be used to process Rönnskär's historical copper slags and tailings. This concentrator is a so called enrichment plant and ensures the separation of the majority of valuable metals from the residual material parts.
A flotation process is used to achieve the separation of valuable metals from the residual material. This technique is based on the different surface properties of valuable - and unwanted gangue minerals, carried out by the selective separation of hydrophilic from hydrophobic materials. This means that particles which dissolve in water or are capable of hydrogen bonding (hydrophilic) will be freed from particles repelling water (hydrophobic) (Wills and Napier-Munn, 2006). After separation, these metals are concentrated and prepared for further selling. Figure 8 represents an overview of the enrichment process for copper, lead, zinc, gold and tellurium at Boliden.

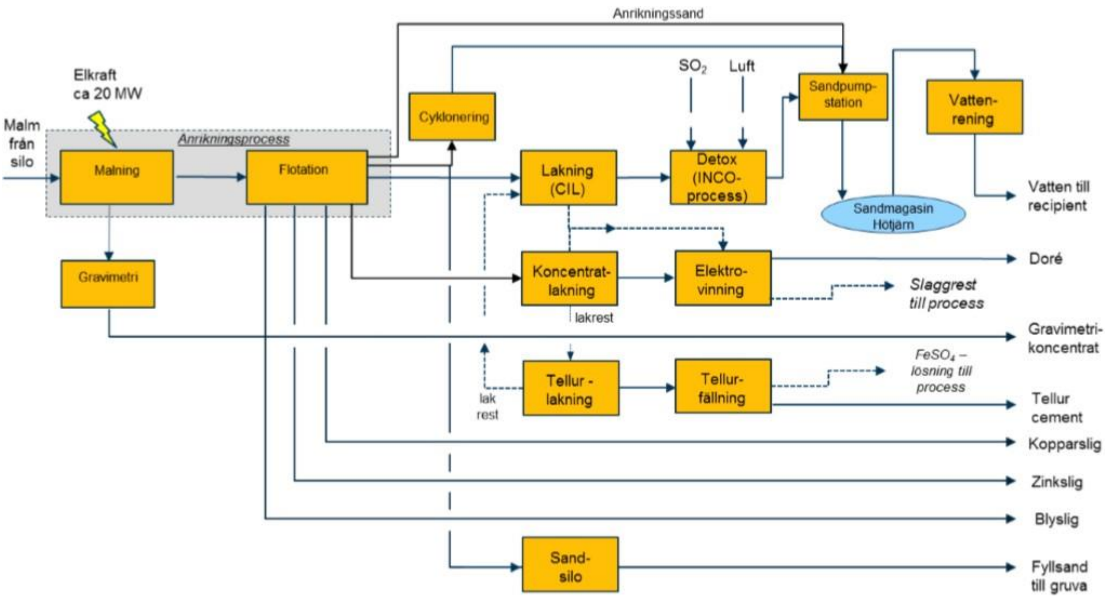

Figure 5: Enrichment process Boliden (Boliden, 2015).

Copper slag and tailing sands from Rönnskär would get transportet by trucks to Boliden and then injected into the enrichment process at the crushing step (malning), followed by the flotation process. After a successful extraction of precious metals, the left over material (tailings) get further pumped to the storage area Hötjärnsmagasinet. If the input material possesses sufficient amounts of gold, such as Rönnskär's tailings, it will undergo a leaching (lakning) process with subsequent cyanide destruction for the residual solution before being transferred to the Hötjärnsmagasinet. Hötjärnsmagasinet is located 3 km south from the enrichment plant and will cover, if fully filled up with tailings, an area of about 236 ha, accounting for 20 Mm^3 tailing sands (Boliden, 2015; Eriksson et al, 2015).

3.3 Aitik Scenario

The last scenario within the recycling approach is Aitik, Sweden's largest open-pit copper mine, located just south of Gällivare in northern Sweden. Similar to Boliden, Aitik uses an enrichment plant to extract and purify valuable metals from the processed ores, figure 6.

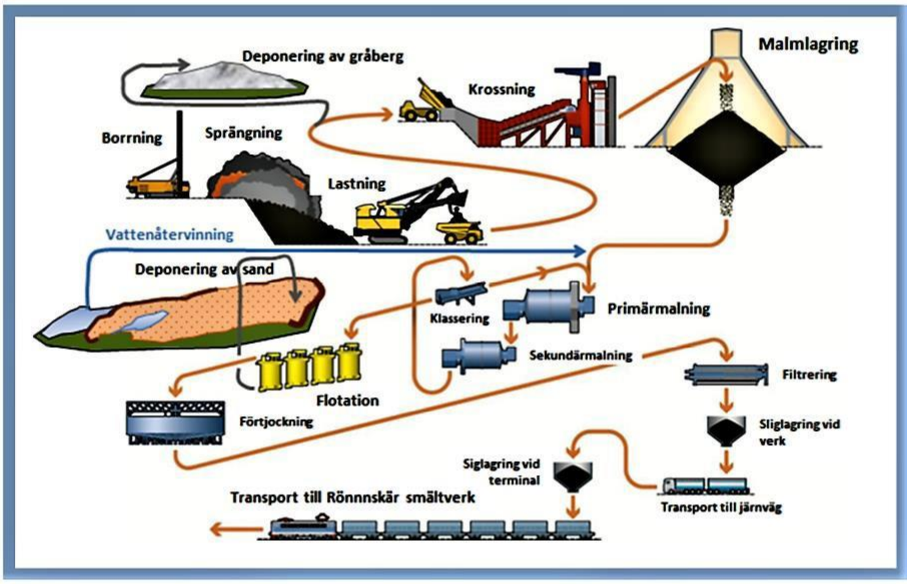

Figure 6: Aitik overview production processes (Johannson, 2012).

Aitik applies the same extraction method (flotation) as Boliden but with specific modifications regarding the processed ores and other input materials. One significant difference is the additional separation technic for tailing sand from the processing. The reason for this extensive approach is the risk for acid formation in the outside storage area 'sandmagasin'. This sandmagasin has a maximal input capacity of 750 Mton (2012) tailing sand and will cover, when filled up, an approximate area of 1400 ha (14 km^2) (Eriksson and Lindström, 2012). Aitik equipped its enrichment plant with a separation technology for low-sulphur sand and high-sulphur sand and thereby limiting the amount of potential acid forming tailings. The two different sand types will then be deposited in the sandmagasin (low-sulphur) and the HS-magasin (high-sulphur) (Johansson, 2012).

With the already existing logistics, copper slags and tailings could be transported by train from Rönnskär to Aitik. Once a day, a train is going to Rönnskär delivering around 400ktn concentrate annually. Its empty return freights could theoretically be used to move copper slag and tailings to Aitik. After an intermediate storage at the railway terminal, the material would be further sent to the grinding process (malning) before entering the flotation. (Johansson, 2012).

4. Methodology and data collection

4.1 Cost-benefit analysis

The cost-benefit method is a common, systematic tool to identify, value and compare costs and benefits of different investment projects. During recent years, it became more and more popular regarding the evaluation of environmental issues. This method is no longer limited to purely economic estimates but rather includes social and environmental factors. Nevertheless, the fundamental idea is still the same, stating that benefits are defined as an increase in human well-being whereas costs are defined as a decrease in that well-being. A project usually qualifies for further execution when its benefits outweigh its expected costs.

Regarding this study, a social cost-benefit analysis was chosen due to its rationality, enforcing the wider view by including the most significant economic -, social - as well as environmental costs and benefits. Following this approach, it is guaranteed that the beneficiaries are not limited to a single subset of people or companies. Furthermore, this method enables the examination and comparison of different alternatives with the same single goal, using the net benefit values as a decision tool. It also offers the opportunity to not choose at all, if for instance the net benefits of a project are too low or even negative. Lastly, a cost-benefit analysis is explicit rather than implicit, meaning that costs and benefits are directly stated in monetary values, resulting in fewer room for confusion and speculations (OECD, 2018).

Performing a cost-benefit analysis requires the collection of all costs (C) and benefits (B) over a certain period of time accruing from the project. The total monetized costs and benefits are then compared and used for the calculation of the net present value (NPV), formula. The NPV includes the discount rate (r) in order to make sure that the depreciation of the value of money over time is been taken into account. Generally, if the NPV of a project is positive, its execution seems to be socially beneficial (Huysegoms et al, 2018). However, if all NPVs are negative, the alternative with the lowest negative value will be the one causing the lowest social costs (Volchko et al., 2017).

$$NPV = \sum_{t=0}^{T} \frac{1}{(1+r)^{\wedge}t} (B_t - C_t)$$

Formula: Net present value (NPV), T = time, r = discount rate, t = time horizon of the project, B = benefit, C = cost.

Applying a cost-benefit analysis in the case of Rönnskär's treatment approach of previously dumped historical copper slags and tailings is therefore aiming to support the decision process and appraise the feasibility of possible treatment scenarios. It will be based on the economic costs and benefits accruing from the actual digging up and refilling process, the needed transportation/logistics, the operational costs (already including financial benefits from end-products), the costs for required permits and the benefits for human health. In addition, environmental costs are examined in form of greenhouse emissions through transportation and processing as well as from energy production required for the process machinery and negative effects on other ecosystems.

In addition, after performing the cost-benefit analysis, a sensitivity analysis has been conducted in order to gain insights into the existing uncertainties. Therefore, the cost-benefit outcomes will be systematically tested through the change of input values. This approach decreases uncertainty regarding determining input factors and thereby demonstrates the robustness of the CBA along with its resulting conclusions (Borgonovo & Plischke, 2016).

4.2 Cost-benefit analysis criticism

A cost-benefit analysis is a useful tool to easily and effectively evaluate costs and benefits of a proposed investment project. Nevertheless, it is important to properly consider its limitations and try to develop a clear understanding for an adequate use of this method. The most common problems to keep in mind are:

1. Identification of costs and benefits

An accurate cost-benefit analysis requires all costs and benefits which are typically identified by human nature. Therefore, it is not uncommon that errors, in terms of omitted costs and benefits, occur during the evaluation process. This is mostly due to the challenge of forecasting indirect causal connections, especially in regard to environmental issues and resource shortages (Plowman, 2011).

2. Quantification of costs and benefits

In order to be a reliable tool for economic evaluation, all costs and benefits included in a CBA have to be in monetary terms. This is easily done for the financial analysis but the social and environmental analysis often contain intangible values. The quantification of these intangibles is usually based on past experiences and expectations which often results in biased estimates. (Wegner & Pascual, 2011; Kwangseon, 2016; University of Technology Hamburg)

3. Net Present Value calculation

The calculation of the net present value is performed by a certain discount rate which equalizes all present and future costs/benefits. However, the idea of circumventing possible inflation impacts does not eliminate the fact that this discount rate is based on the comparison and weighting of present values to future values, which might not always reflect reality (Hansjürgens, 2004).

Assumption of perfect markets

A CBA prefers the scenario where supply and demand is in perfect balance, a so called perfect market. Unfortunately, there exist monopolies or governments that can easily and without predictions intervene into the market situation and cause changes affecting CBA estimations (University of Technology Hamburg).

4. Income distribution

The CBA determines economic efficiency in general but does not account for income distribution. This means that accruing costs and benefits are measured and taken into account regardless of who is actually paying and gaining from it (Kwangseon, 2016; Frank, 2000).

4.3 Data collection

All data, used within this study, regarding copper slag and tailings, comes from different investigations commissioned or conducted by Rönnskär itself. The total amount of material regarding this project comprises of 5 512 000 tons of copper slag and 1 827 580 tons of tailing sands.

4.3.1 Copper slag

The collection of reliable data on copper slag required the investigation of 3 different sources, summing up to one complete data set covering all necessary information on remained element contents, as seen in table 2. Firstly, the Landström report from 1989 contained important average sample results from the copper slag production between 1930 and 1966 [Appendix A]. It shows that during the first 19 years, copper slag was produced by a flaming furnace which then got replaced by an electric furnace in 1949. For each year, the type of production process, the amount of copper slag in kilo ton produced as well as the measured metal content for gold (Au), silver (Ag) and copper (Cu) in g/ton and % are stated. These yearly numbers originated from monthly proves which were based on daily samples added up and divided by the right amount of examinations. Furthermore, the calculation of mean values regarding Au, Ag and Cu clearly revealed that the furnace replacement mainly affected the gold extraction efficiency by almost doubling it and thereby significantly reducing the left-over gold contents in the copper slags. Inaccuracies during sampling and analysis can naturally occur but should be minimized due to the application of the so-called fireassay method, one of the most accurate methods to measure the content of gold and silver (Battaini et al., 2014). However, a meaningful result can only be achieved by a complete set of analysed elements which is why additional information was collected from the Mifo report and the selection of 7 drill-holes/sections samples from the historical copper slag area at Rönnskär. The Mifo report is an inventory and classification study of potentially polluted areas at Rönnskär smelter carried out by WSP Samhällsbyggnad in Umeå on behalf of Boliden Mineral AB and provides outcomes on the analysis of the historical copper slag in 1988 and 1998 [Appendix C]. The concluding data was finally added by the selection of 7 selected drill-holes/section which cover the broadest spectrum of analysed elements. The samples were taken in November 2018, each coming from machine excavated diggings which confirmed slag layers within a total depth range of 0.5 – 4.5m below ground [Appendix C]. In summary, the aggregation of all information resulted in a reliable data set were the different sources are filling each other’s data gaps and the comparison of repeated element results ensure data accuracy.

Regarding the preparation of the data, except for the Landström report (Au, Ag and Cu) where average values were a valid instrument to describe the normally distributed numbers, all other data was summarized by the calculation of the median. This was necessary due to generally skewed distributions that might have been caused by impurities during the sampling process. Subsequently, the averages of the element values from the three sources were taken and used for further calculation through Rönnskär's economic department, table 2.

Analyte		Ag-FA	As	Au-FA	Bi	Cd	Clx	Cu	Hg	Ni	PD	PT
Unit		g/t	%	g/t	%	%	%	%	g/t	%	g/t	g/t
Rönnskär	Median	10	0.11	0.4	<0.005	<0.002	<0.10	0.51	2.8	0.023	<0.1	<0.1
Mifo	Median		0.415			0.015		4.85	1	0.3		
Landström	Median	6		0.4				0.365				
total median		8	0.2625	0.4	<0.005	0.015	<0.1	0.51	1.9	0.1615	<0.1	<0.1
Analyte		Sb	Zn	Fe	O	Si	Ca	Al	Mg	S	Pb	Co
Unit		%	%	%	%	%	%	%	%	%	%	%
Rönnskär	Median	0.04	1.75	34.3	36.5	13.2	2.14	2.65	0.701	1.47	0.612	0.115
Mifo	Median		1.67								2	
Landström	Median											
total median		0.04	1.71	34.3	36.5	13.2	2.14	2.65	0.701	1.47	1.306	0.115

Table 2: Median calculations copper slag; reference number: 5 512 000 tons.

4.3.2 Tailing sand

The area filled up with historical tailings is located in the south of Rönnskär and has a range of about 24 hectares (ha), describing 16% of the entire industrial area. According to Boliden report, calculations to obtain the total area were carried out with MapInfo, a geographic information system (GIS) software, resulting in the total volume when multiplying with the average depth. Based on the volume and average density of the tailings the total minimum tonnage was determined. Samples of the tailings were taken in autumn 2016 with the help of handheld auger which gives undisturbed samples [Appendix D].

In total, 26 test points were chosen on an average depth of 4.6m, but only 17 were available to conduct the 71 samples. These samples were then sent further to Australian Laboratory Services (ALS) for the analysis with respect to 40 elements, as shown in table 3. The results of each element states its total calculated amount in tonnage as well as the average amount in part per million (PPM) and percentage (%) referring to the entire analysed tailings area. The minimum amount of calculated tonnages was 1.827.580. In synchronization with copper slag data, the medians for all analysed tailing sand elements were calculated to guarantee the elimination of influencing/manipulating outliers.

Analyte		Au	Ag	Al	As	Ba	Be	Bi	Ca	Cd	Ce	Co
Unit		PPM	PPM	%	PPM	PPM	PPM	PPM	%	PPM	PPM	PPM
Rönnskär	Average	0.88	5.04	7.96	2656.32	363.71	0.64	43.54	1.20	7.47	95.96	147.62
	Tonnage	1.61	9.21	1454153	4854.64	664.72	1.17	79.57	219048.5	13.64	175.37	269.78
	Median	0.77	3.09	8.2	2040	360	0.4	38.65	1	2.26	94.75	106

Analyte		Cr	Cs	Cu	Fe	Ga	Ge	Hf	In	K	La	Li
Unit		PPM	PPM	PPM	%	PPM	PPM	PPM	PPM	%	PPM	PPM
Rönnskär	Average	236.41	0.90	1219.18	6.80	30.05	0.31	4.58	1.24	2.29	44.24	17.20
	Tonnage	432.07	1.65	2228	1241997	54.91	0.56	8.37	2.265	417602	80.84	31.43
	Median	38	0.695	779.5	3.995	30.65	0.28	4.95	0.4485	2.34	43.6	17.5

Analyte		Mg	Mn	Mo	Na	Nb	Ni	P	Pb	Rb	Re	S
Unit		%	PPM	PPM	%	PPM	PPM	PPM	PPM	PPM	PPM	%
Rönnskär	Average	1.42	416.84	22.60	0.71	3.56	61.61	1308.43	622.95	46.24	0.00	2.32
	Tonnage	260064.6	761.81	41.30	130306.5	6.50	112.5998	2391.26	1138.491	84.50	0.008172	424024.7
	Median	1.01	289.5	3.315	0.72	3.45	37.15	1205	149.25	48.3	0.004	1.17

Analyte		Sb	Sc	Se	Sn	Sr	Ta		Si
Unit		PPM	PPM	PPM	PPM	PPM	PPM		Wt%
Rönnskär	Average	87.16	18.42	43.19	41.21	113.66	0.83		28.71
	Tonnage	159.28	33.66	78.93	75.32	207.66	1.52		
	Median	47.65	19.45	31.5	9.7	109.5	0.255		28.71

Table 3: Median calculations tailing sand; reference number. 1 827 580 tons; Si is based on a pooled analysis.

4.4 Economic and social costs & benefits

4.4.1 Excavation work

Before it is possible to process any material, it is necessary to conduct excavation work at Rönnskär. The accruing costs are consistent for all three examined treatment scenarios and are based on previous project costs and experiences from NCC (Swedish Construction Company). NCC is the contractor for the construction of the leaching plant at Rönnskär and has previously performed similar excavation work which can be used as reference value in this study. Generally, a "base case" is assumed, meaning that all calculations are kept as simple as possible and additional costs such as water piping or electricity lines are not included. Regarding NCC's calculation, 873 644 SEK were needed to dig up an area of 11 806m³ (=ca. 19 000 t when using general multiplication factor 1.6 to convert m³ into tons), put it on a lorry and move it 800m further on a pile. Assuming that some additional costs were avoided, it is reasonable to calculate with 1 000 000 SEK in total, resulting in digging up costs of about 53 kr/t in total. According to Rönnskär, similar costs accrue for refilling the mechanically excavated hole with iron sand which is normally be sold for 50kr/t including on site transportation and loading. Therefore, it is presumable that costs for excavation and refilling work can be estimated around 2 x 53kr/t = 106 kr/t for copper slag as well as tailings [Appendix E:1].

4.4.2 Transportation

Rönnskär

Processing the copper slags and tailings directly at Rönnskär doesn't require significant additional transportation costs. The material is already located at the industrial area and any costs from small transportation ways are included in the excavation/refilling approximations.

Boliden Area

Boliden Area and Rönnskär are connected via roads, meaning that the transportation possibilities are limited to trucks. Nevertheless, a working transportation system for slag transports to the concentrator is present, including a total of 11-12 trucks per day. Every year, approximately 100-200kton fines are transported via trucks from Boliden to Rönnskär and vice versa 250-400kton slag from Rönnskär to Boliden. The transport distance is about 60km and each truck has an approximate capacity of about 45tons of concentrate (Boliden, 2015). According to internal information from Boliden, an approximated 45 kr/t can be used, excluding loading and unloading of the material. Therefore, the actual accruing costs will be slightly higher depending on the circumstances [Appendix E:2].

Aitik

Between Rönnskär and Aitik exists an approximately 365km long railway connection with one train consisting of 47 waggons and 2 locks. Once a day, this train leaves Aitik and goes towards Rönnskär, delivering around 400ktn concentrate every year. In theory, the return freight of this train could be used to transport copper slags and tailings from Rönnskär to Aitik but further investments for additional loading, unloading and storage facilities are most likely needed in order to handle these amounts of material. In order to assume reasonable transportation costs, numbers regarding the already existing concentrate transport are taken as a base for further calculations. In this scenario, costs are calculated regarding material containing about 22% copper along with the loading/unloading costs at Aitik and Boliden (same costs assumed due to same company and same country) as well as the actual costs for the operating train. According to confidential material from Aitik, the capital and operating expenses for a total amount of 3 996 557t fines between 2019 and 2028 are about 339 275 278 SEK. Subsequently, the transportation of one ton material would cost about 85kr/t.

This number is excluding the additional loading/unloading costs at Rönnskär, which can be assumed to be around 20.5kr/t. Summing up, a scenario where copper slags and tailings would be transported from Rönnskär to Aitik, one ton of material transport would costs around 100.5 SEK [Appendix E:2].

4.4.4 Operation/processing

In order to monetize the potential scenario for copper slag and tailings within these complex industrial structures, rough calculations were performed by Rönnskär's economic department (Tobias Långström). These calculations also include the economic benefits arising from extracting valuable elements as well as additional handling costs (crushing, local handling) which might be required up front. The first step consists of the determination of valuable elements that might give economic benefits. This has been done with the help of a logical test, IF-test, followed by the calculation of the potential economic benefits of these elements when processed at Rönnskär. These calculations are then based on the total amount of valuable extractable material [Potential], the potential extraction levels [Utbyte] as well as on the element's long term prices (LT price), given by Boliden. All results are standardized to MSEK (million Swedish kroner). Subsequently, the accruing handling costs, that mainly consist of costs for sieving, as well as the resulting financial losses from treating copper slag or tailings instead of more valuable material are both subtracted from the original benefits.

Rönnskär

The possible treatment of tailings is technically feasible but would, according to Tobias Langström (Production Controller, Boliden Rönnskär), most likely result in a great financial loss for Rönnskär. All elements contained in the tailings are of such low amounts that Rönnskär's technological extraction methods wouldn't be able to generate any financial benefits. However, the tailings contain significant amounts of pyrite (source of acidification) and arsenic which are causing the environmental risk classification. Meaning, that a tailings treatment is necessary regarding the environmental status but financially not feasible at Rönnskär which is why other scenarios must be investigated for a potential tailing treatment.

The treatment of copper slag on the other hand would be more beneficial due to elevated zinc levels which could be extracted up to 85%. Rough calculations state a potential revenue of about 1.019 MSEK when processing copper slag. Subtracting the speculated handling costs, 551 MSEK, as well as the capacity costs from other raw materials, 16.536 MSEK, results in a cost of 16.068 MSEK. Applying this number on the total amount of treatable copper slag, 5 512 000tons, the processing of one ton copper slag would hence require 2915 SEK investment [Appendix E:3].

Boliden Area

Regarding tailing sands processing at Boliden Area, the only valuable element worth considering is gold (Au). Based on the total amount of tailing sands, 1 827 580tons, the remaining gold content of 0.77ppm, the potential extraction rate of 74% as well as the LT price of 289 357 SEK, a total benefit of 30 MSEK could be calculated. Subtracting the potential gain from processing other material, 493 MSEK, and the required handling costs, 183 MSEK, the calculated net-benefit will result in -376 MSEK. Applying this number on the total amount of tailings, the processing of one ton tailing sand would costs around 206 SEK [Appendix E:3].

In the case of copper slag, all economic benefits are, as mentioned in the Rönnskär scenario, based on its zinc content. Boliden concentrator has the potential to extract up to 5% of the remaining zinc leading to a total profit of 63 MSEK when considering a long term price of 18.000 SEK, a possible payment for 85% and total costs of 10 MSEK. Subtracting the financial losses from replacing more valuable raw material plus the general handling costs finally results in a net benefit of -3 631 MSEK. This means that per ton processed copper slag, Rönnskär would have to pay about 659 SEK processing costs [Appendix E:3].

Aitik

According to Nils-Johan Bolin (project leader at Boliden Mineral AB), half of the recovery rates from Boliden concentrator can be assumed when processing Rönnskär's copper slags and tailings at Aitik concentrator. This is due to the technological differences during the recovery processes when comparing these two concentrators.

In the case of tailings, these assumption lead to a gold extraction rate of 37%, resulting in a total economic benefit of 150 MSEK. Including accruing handling costs as well as the potential benefits when processing more valuable materials, the net benefits will be around -526 MSEK. However, when spreading the cost over the amount of tailings that has to get processed, each ton would only account for approximately -288 kr/t [Appendix E:3].

The extraction rate of copper from copper slag is extremely low and only reaching about 2.5%. Based on this, the total economic benefits sum up to 31 MSEK and when subtracting additional costs (concentration, other raw materials and handling costs) the net benefits are about -3 662 MSEK. Calculating the costs per ton results in -664 kr/t [Appendix E:3].

4.4.4 Environmental permit

Boliden AB and its sub companies are constrained to apply for environmental permits before performing operations outside the limits for current permits. These permits set rules and limitations regarding production processes, production volumes, emission rates, treatment methods, etc. Along with the permit process comes an additional Environmental Impact Assessment (EIA), including extensive environmental investigations as well as consultation with authorities and other stakeholders (Granberg, 2013). In the case of a positive outcome and application, the company will obtain a permit and can legally proceed with its operation whereby a negative outcome will keep the planned operation on hold until the project's application passes the investigation process thoroughly.

An environmental permit for processing Rönnskär's copper slags and tailings is only required for the scenarios at Boliden Area and Aitik. Similar to the calculations of excavation costs, the environmental permit costs are also based on a previously conducted project from Boliden which involved the application for one of these permits. The original scenario concerned the construction of an expanding industrial area with 42 000m² in the sea, which, when breaking it down, will give a hypothetical cost of 4 000 000 SEK for 750 000t of material. This would result in 4 000 000kr /750 000t = ca 5 SEK/t perhaps even lower in the end, depending on the final circumstances and project execution. Naturally, each permit application has its own specific circumstances meaning that a process regarding smaller tonnages could potentially end up in relatively high SEK/t costs.

4.4.5 Human health

Besides the economic benefits from extracting valuable metals such as zinc and gold from copper slags and tailings, human health is also playing a vital role within these operations. Generally, cleaning up those contaminated areas will reduce the risk of potential health issues accruing from low but long lasting impact on humans through for example water, air or direct soil contact. Söderqvist et al. (2015) examined a remediation project in Mölndal (south of Sweden, close to Gothenburg) where he monetized the reduction in non-acute health risks as well as other types of improved health which can be used as a reference point within this study. The non-acute health risks reduction was the result of a decrease in carcinogen elements DEHP and PAH-H in the remediation area and the latter comprises monetary values regarding anxiety of residents. Similar benefits can be seen in Rönnskär's project. The tailing sand contains significant amounts of arsenic which can cause gastroenteritis, neurological manifestations, vascular changes, diabetes and even cancer when absorbed in too high doses over a long time period (Abernathy et al., 2003).

The main problem is not that arsenic is in the tailings located at Rönnskär right now, it is the risk of leaching and transferring arsenic into the sediment or groundwater which might be used by future generations in softer ways than the current industrial activities. Copper slag on the other hand contains no carcinogen elements but is also considered as contaminating due to elements such as copper, zinc, lead, nickel or cobalt (Golder Associates AB, 2018). Söderqvist's study calculates a decrease in non-acute health risk of 0.0003 MSEK and a decrease in other health type risk of about 0.07 MSEK. However, these numbers must be adapted to Rönnskär's case and even then, it is important to remember that these numbers accrue from assumptions.

Assumption for reduction of non-acute health risk:
Rönnskär's tailings area is ca. 24ha / 3.5ha = 6.85 times bigger than the examined area in Mölndal which results in a greater risk reduction when cleaning reducing the risk of Rönnskär's contaminated tailings from arsenic and other toxic elements. However, Golder Associates AB states only a small leaching potential of tailings which is why the accruing risk of health impacts on humans has been considered to be very low. Combining these two facts, the reduced health risks from cleaning tailing sand is calculated with a multiplication factor of 4, due to the bigger area but a low leaching potential.

0.0003 MSEK x 4 = 1 200kr

Assumption for other types of improved health risks
Compared to Söderqvist's remediation project, Rönnskär's contaminated areas are significantly larger as well as located further away from residential areas. Additionally, there are less inhabitants living in Skellefteå than in Mölndal and most of them are aware of the possible risks accruing from a nearby copper smelter. The reduced health risks in Mölndal were calculated to be around 0.07 MSEK, based on a hedonic approach, including neighbour's anxiety regarding their likely increase in the market value of properties. Assuming a lower, further away located but enlightened population in Skellefteå, it is reasonable to expect a minimum of at least 0.05 MSEK.

4.5 Environmental costs & benefits

4.5.1 Transportation

If supposed to get processed at Boliden Area or Aitik, copper slags and tailings at Rönnskär must be moved with the help of transport vehicles. Rönnskär and Boliden are currently connected via a highway whereas Rönnskär and Aitik are linked via railway. Both transportation possibilities imply additional costs in form of greenhouse gas emissions. These emissions can be monetized as environmental costs and must be taken in consideration when examining an investment project holistically. This study therefore uses recommendations from the German Federal Environmental Agency, informing about estimations regarding the environmental costs within the energy and traffic sector (Burger, 2013).

Boliden Area

As previously examined, trucks with a loading capacity of 45ton are daily transporting concentrate and slags between Rönnskär and Boliden. These trucks are run by fuel and are causing damage to human health, animals and the nature as well as additional risk for normal traffic. According to the German Federal Environmental Agency, trucks with heavy loads (SNF) are producing 2.4 €-Cent/tkm (ton * kilometre) environmental damage. Multiplying this with the total amount of copper slags (5 512 000t) and tailings (1 827 580t) as well as the 60km long distance between both locations, results in a total environmental cost of 111 MSEK, about 15.15 kr/t transported material [Appendix E:4].

Aitik

Rönnskär and Aitik are connected by a 365km long railway, transporting mainly copper concentrate from Aitik to Rönnskär. Calculating the environmental costs for this cargo train highly depends on its type of energy source. Trains run by diesel can have up to 10 times higher environmental costs compared to trains run by electricity. Regarding the rail connection to Aitik, Boliden cooperates with Green cargo, Sweden's most experienced operator in rail logistics, using electric trains in order to reduce carbon emissions (my news desk, 2017). Based on these circumstances, one ton of material causes about 0.3€-cent environmental costs per kilometre transportation, summing up to an environmental cost of 11.5 kr/t [Appendix E:4].

4.5.2 Operating/Processing

Besides the economic costs of processing copper slags and tailings, these operations are also known for causing environmental emissions that have to be accounted for. The most common ones, monetized by the German Federal Environmental Agency, are CO2, PMx, NOx, SO2, NMVOC and NH3. However, within this study, it is impossible to get exact measurements on all of these elements. The focus is mainly put on CO2, PM10 (dust), SO2 and NOx emission levels due to the simple fact that these are the elements that got measured and reported by Rönnskär, Boliden Area and Aitik. Nevertheless, additional costs from non-measured elements should not be neglected and are considered in the discussion.

Rönnskär

Generally, it is very difficult to comment on the exact amount of emissions produced by the processing of certain materials at Rönnskär. The entire industrial area is a big complex of interacting machinery and each material is passing through at least more than one process step. In the case of copper slag, the electric smelting furnace as well as the zinc fuming plant are most likely the main causes of emissions whereby the latter is by far the greatest CO2 contributor.

Assuming that Rönnskär could hypothetically process 100 000t of copper slags per year it would take approximately 55 years to process all copper slag. According to the 'emissionsdeklaration' from the Miljörapport in 2018, Rönnskär's CO2 emissions from fossil burning were measured to be around 285 404 000kg per year. Regarding the fact that most of the CO2 emissions are emitted by the zinc fuming plant and that copper slag only accounts for a certain percentage of input material (0.1 Mton of total 0.85 Mton), this study is considering about 3% of the total CO2 emissions accruing from a 55 year long processing of copper slag (Miljörapport, 2018).

Additional emission levels are presented in the Miljörapport 2017, Table 4 (Hägglund et al. 2017).

Utsläpp till luft under	**2017**	**SO2**	**Stoft**	**Cu**	**Pb**	**Zn**	**Cd**	**As**	**Hg**	**NOx**	**Dioxin [g I-TEQ]**
Materialhantering	ton		2,6	0,22	0,07	0,05	0,001	0,022			
Kopparhytta	ton	499	3,7	0,41	0,19	0,50	0,008	0,070	0,005		
Flashugn	ton		1,2	0,33	0,01	0,01	0,0001	0,002	0,001		
Konverterhall/anodgjuteri	ton	2065	12,3	0,27	1,35	0,30	0,032	0,082		50	0,009 g
Ädelmetallverk	ton		0,1		0,01						
Blykaldoverk/blyraffinering	ton	147	2,3	0,01	1,12	0,12	0,002	0,007	0,002	15	0,001 g
Svavelproduktverk	ton	200							0,002	76	0,003 g
Slaggfuming/klinkerverk	ton	628	15,6	0,09	0,69	6,95	0,017	0,084	0,004	59	0,16 g
E-kaldoverk	ton	33	0,4	0,05	0,07	0,03	0,003	0,004	0,001	40	0,005 g
Energicentralen	ton									20	
Summa samtliga anläggningar	**ton**	**3571**	**38,2**	**1,4**	**3,5**	**7,96**	**0,063**	**0,27**	**0,01**	**259**	**0,18 g**
Begränsningsvärde	ton	4500	40	2	4	8	0,075	0,5	0,06	350	1 g

Table 4: Air emissions at Rönnskär in 2017, subdivided into process plants.

Due to the fact that the Kopparhyttan (place where material processing takes place at Rönnskär) not only consists of the Electric Smelting Furnace but also of the Fluidized Bed Roaster, which is not included in the processing of copper slags, this study will mainly focus on the emission rates of the Slaggfuming/klinkerverk (table 4, yellow marked). Combining this with the approximated production share of 10% (100 000t) results in environmental costs of about 103 kr/t. In total, when adding all 4 emission sources up, one ton of copper slag processing would cause about 233 kr/t of environmental costs [Appendix E:5].

Boliden Area and Aitik

Determining the emission levels of copper slag and tailings processing at Boliden Area and Aitik is linked to their extraction technology as well as the different characteristics of the input material. Furthermore, copper slags and tailings will be fed into the extraction process together with copper ores and other material, making it almost impossible to separate the according emission rates. Therefore, it is extremely difficult to calculate these emission rates from Boliden Teknisk Beskrivning – Bilaga A and Aitik's Miljökonsekvensbeskrivning which are both stating the total amount of emissions accruing from their production sides. In order to circumvent the possibility of accounting emissions from other input materials, this study will use general emission numbers regarding copper slag processing calculated by Yingshun and Jie (2009). Their paper examined the environmental impacts from copper slag recycling as well as copper ore processing. The following table 5 shows the different emission rates accruing from copper ore or slags during the four process stages: crushing, milling, flotation and dehydration.

Concentration process		Input					Output					
		Resource /kg	*Water /kg*	*Balls /kg*	*Reagents /kg*	*Energy /kwh*	*Product /kg*	*SO_2 /kg*	*CO_2 /kg*	*NOx /kg*	*Waste water /kg*	*Waste solid /kg*
Ore mining		34556.7	41468	–	–	662.45	1000	6.58	708.82	4.28	14589	59986
Crush -ing	slag	8935.5	0	0	0	28.59	8935.5	0.28	30.59	0.18	0	0
	ore	17489.6	0	0	0	38.48	17489.6	0.38	41.17	0.25	0	0
Mill -ing	slag	8935.5	17870	16.08	0	384.23	8935.5	3.82	411.13	2.48	17870	0
	ore	17489.6	52470	17.49	0	367.28	17489.6	3.65	392.99	2.37	52470	0
Flota -tion	Slag	62545.5	35740	0	3.57	49.15	1760	0.49	52.59	0.32	44675	16111
	ore	157409.6	87450	0	16.88	166.15	1760	1.65	177.78	1.07	122431	33218
Dehyd -ration	Slag	62545.5	0	0	0	27.7	1000	0.28	29.64	0.18	52392	9154
	ore	157409.6	0	0	0	54.22	1000	0.54	58.02	0.35	85802	69912

Table 5: Input and output rates of copper slag and ores during the four different process stages: crushing, milling, flotation and dehydration.

Regarding the process stages, it is important to notice that tailings are already in small fractions and therefore not in need of crushing before processing. The opposite applies for copper slags which have to get pre-crushed at Rönnskär before sending them to Boliden Area or Aitik. In order to determine the actual emission rates of Rönnskär's copper slags and tailings, it is necessary to calculate the emission rates per kg/ton input material based on the above table. The results state an approximate cost of 192.5 kr/t copper slag and 179.6 kr/t tailings [Appendix E:5].

4.5.3 Energy

A more indirect environmental effect is caused by the energy consumption of the different processing technologies. Rönnskär, Boliden Area and Aitik are all buying substantial amounts of electricity in order to keep their production running. However, even renewable energy sources are causing environmental damages.

Rönnskär

At Rönnskär, 65% of the required energy consumption regarding the copper processing line is needed for the electric melting plant. The Teknisk beskrivning Rönnskärs verskamhet (2009) states a total consumption of 220 000 MWh, resulting in about 144 000 MWh solely for the electric melting plant, table 6.

Komponent	Förbrukning (MWh/år)
Elektroder kopparhytta	143.995
Blåsmaskin	5.838
Ventilationsfläkt	4.260
Processgasfläkt	3.395
Kylfläktar	624
Kylvattenpumpar	491
Hydraulaggregat	273
Vakuumsug Cu-hytta	245
Elvärme	4
Förbränningsluftfläkt	2

Motsvarar 88% av avdelningens förbrukning.

Table 6: Summary of the components that are consuming electricity in the hyttan (electric smelting furnace and fluidized bed roaster) (Epsilon, 2007).

For the subsequent process in the zinc fuming furnace, coal is the main energy input product instead of electricity which is why all focus lies on the electric smelting furnace. The only process way for copper slag at Rönnskär is through the dryer with a maximum handling of 100 000t copper slag per year. Hypothetically, this would lead to a total process time of about 55 years regarding the 5 512 000t copper slag that have to be treated. The electric fuming plant has a yearly running time of ca. 7700h and copper slag would only account for approximately 10%

of the total processed material. Combining this information with the fact that most of Rönnskär's electricity is coming from water energy which is stated to have an environmental cost of 0.18cent/kWh, results in 2.72 kr/t environmental electricity cost for copper slag treatment [Appendix E:6].

Boliden Area

The total energy consumption for Boliden's enrichment plant composes of 78% electricity and 22% fossil fuels accruing from 95% gas consumption. For a maximal production capacity of about 2.5 Mton ore and slags, Boliden's enrichment plant requires approximately 135 GWh. Most of the energy is been used for milling (35%) and only 20.7 GWh (15.3%) for the actual flotation process (Boliden, 2015). When trying to calculate the environmental costs of energy consumption it is of great importance to identify the original energy sources. According to Energimyndigheten, Sweden's energy production consitsts of the following mix:

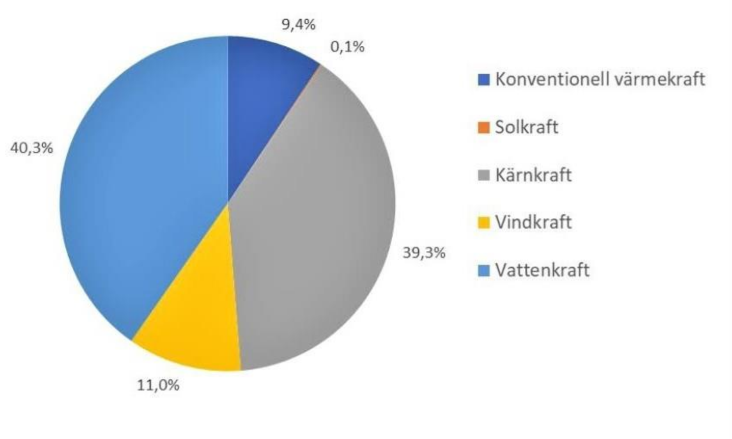

Figure 7: Sweden's energy production 2017.

As mentioned before, copper slags and tailings are only accounting for 17% of the total processed material at Boliden, meaning they are only responsible for about 17% of the total energy consumption per year (copper slag = 18.4 years, tailings = 6.01 years). Focusing on the energy consumption from the crushing (47.25 GWh) and the flotation process (20.7 GWh), in total 67.95 GWh, and assuming the same amount of hours (7700) processing than previously for the electric fuming plant at Rönnskär, a yearly environmental energy consumption cost of 13 MSEK is been calculated. Applying these numbers to the total amount of processed material sums up to a total environmental cost of 56 MSEK, corresponding to approximately 7.59 kr/t [Appendix E:6].

Aitik

To enable such an immense production capacity at Aitik (45 Mton) requires an equally immense amount of electricity. The yearly consumption rate is calculated to be around 1130.9 GWh whereby 68% is comprising electricity and 30% is coming from diesel. Most of the energy is needed for the actual mining process (breaking down rock) and the transportation of ores to the different production processes. Only 10% of the total energy is consumed by the flotation process whereas transportation and the pumping of tailings to the sandmagasin accounts for 38%. The following table gives an overview over the energy distribution at Aitik:

Process	%	GWh (45Mton capacity, based on 1130.9 GWh in total)
Crushing and grinding	46	520.2
Transportation and pumping	38	429.74
Flotation	10	113.09
Water pumping	3	33.927
Direct heating of premises and band resorts	2	22.62
Dewatering	0.5	5.65

Table 7: Energy distribution at Aitik in 2010 (Johannson, 2012).

Based on the fact that Rönnskär's copper slags and tailings don't need the same amount of crushing than the fresh ores coming from the mines, nor do they require special transports from the mines to the enrichment plant, it can be assumed that only about 10% of the energy for crushing as well as transportation are accounting for these slags and tailings. Therefore, calculations are based on the remaining 36% energy consumption (407.12 GWh), of which 90% are hypothetically based on electricity and only 10% on diesel due to the fact that diesel is mainly used for transportation processes. As in the previous Rönnskär and Boliden Scenario, 7700h of production time per year are assumed, leading to yearly environmental energy costs of about 43 MSEK. Hence, the total environmental energy costs then sum up to 67 MSEK, approximately 9.1 kr/t copper slag and tailings [Appendix E:6].

4.5.4 Other affected ecosystems

An additional indirect side effect also comes from the excavation work that has to be conducted at Rönnskär in order to process the dumped copper slags and tailings. During this work, it is quite common to produce emissions (CO2, dust, etc.) which can easily be transferred to nearby ecosystems and negatively affect their services and life-forms. Söderqvist et al. (2015) investigated this exact environmental impact regarding the Hexion site, a former chemical industry area close to the Swedish city Gothenborg, in his study, performing a CBA for possible remediation scenarios. His calculations were based on data that could be converted into equivalent CO2 emissions and monetized through default costs stated by the Swedish Transport Administration (2012). The results varied concerning the different scenario set-ups whereby alternative 4 seems to be closest to the approaches of this study's investigation. Söderqvist et al. assumes 310 000 SEK costs for the damage of other ecosystems, including environmental damage from transportation (usually the biggest impact factor). Excluding these transport emission costs, due to the fact that they have already been considered before, it is reasonable to expect a maximal damage amount of 100 000 SEK. Regarding the size of the remediation site, Hexion covers a total area of 3.5ha whereas already the tailings at Rönnskär comprise about 20ha (based on minimal tonnage). Determining the area of dumped copper slags is more complicated and requires the conversion of tons to ha. Assuming a maximal copper slag depth of 4.5m, the calculated ha size would be around 76.6ha. Subsequently, the assumed 100 000 SEK regarding Hexion's 3.5 ha large area can be used to calculate the impact of a one hectare big remediation operation. The result can then be applied to the concerned areas at Rönnskär, tailings (20ha) and copper slag (76.6ha) [Appendix E:7].

4.6 Theory vs. Reality

The investigation of the three potential treatment sites, Rönnskär, Boliden Area and Aitik, showed us the feasibility of processing copper slags and tailings in each of the scenarios. However, theory usually differs from reality and the same applies for this project.

Copper slag

Historical copper slags at Rönnskär were used as land-fillings and are therefore part of the Rönnskär's industrial area today. Its investigation revealed that these slags are not an easily located contiguous area but rather small fillings that are spread over the entire industrial area. In addition, these land-fillings are now covered with infrastructure such as road, factories and office buildings. Both arguments result in the conclusion that the theoretical scenario of a simple excavation, transportation and processing might be far away from reality. Furthermore, the 5 512 000t copper slags are tremendous amounts of material which represent important parts of Rönnskär industrial area. Therefore, it is impossible to dig up and clean all of it without destroying the smelter area itself. A more realistic approach would be the treatment of smaller amounts of concentrate over a relatively long time period. Projects such as the new crusher at Rönnskär demonstrated the possible excavation of approximately 20 000t a year. Accordingly, it is reasonable to assume a yearly processing rate of 20 000t copper slag over a time period of 20 years, summing up to 400 00t in total (~7.26% of total amount).

Tailings

The scenario of treating tailing sand is, compared to copper slag, more easy and likely to happen. The tailings are all located in the south of Rönnskär and accounting for a total area of 24ha. However, they are also partly covered by infrastructure objects which complicates the idea of a contemporaneous and comprehensive treatment. Instead of an immediate project aiming for the entire tailings volume or at least the first one or two metres surface area, it would be more realistic to assume smaller but deeper excavation and processing work. Based on this idea, it is reasonable to aim for a treatment of about 400 000t tailings (~21.89% of the total amount) over a period of 10 years.

Cost benefit-analysis

The cost-benefit analysis is performed on the general hypothetical scenarios, based on the total amount of copper slag and tailings, as well as on the presented more realistic scenarios accounting for 400 000t copper slag and tailings respectively.

5. Results

The following result section presents the outcomes of the hypothetical and the more realistic cost-benefit analysis. Both analysis state all included economic and environmental costs and benefits along with the resulting net present values regarding the three treatment scenarios, Rönnskär, Boliden Area and Aitik.

Additionally, when calculating and analysing the net present values, it is of great importance to take the given time frames into consideration. Therefore, this study decided to follow Weitzman (2001) approximate recommended discount rates of 4% if the project time stays between 1 to 5 years, 3% if the project lasts between 6 to 25 years and 2% if the project time exceeds 25 years but is shorter than 75 years. Regarding the hypothetical scenario (total amount of material), processing copper slag at Rönnskär is discounted with 2%, processing tailings at Aitik is discounted with 4% and all other scenarios are calculated with a 3% discount rate. Less variety is presented in the realistic approaches, due to the copper slag and tailings time frames laying within the time period that is accounting for a 3% discount rate. A similar discount rate of about 3.5% is also recommended by the Swedish Transport Administration (Trafikverket, 2014).

5.1 Hypothetical cost-benefit analysis

The first paragraphs state the monetized input factors as well as the resulting net present values from the CBA of the hypothetical scenario (5 512 000t copper slag and 1 827 580t tailings). The second paragraph focuses on the more realistic approach, based on a yearly extraction of 20 000t copper slags over a time period of 20 years and the removal of 400 000t tailings within a 10 year time frame. Following this scenario, a detailed presentation of the input factors is not needed due to the fact that the only changing factor is the total amount of processed material, keeping all relationships and per ton calculations in place while solely changing the total economic and environmental costs.

5.1.1 Input factors

		Rönnskär	Boliden Area	Aitik
Economic/social cost/benefit	in [SEK]			
Digging up and refilling	copper slag	584272000	584272000	584272000
	tailings	193723480	193723480	193723480
Transportation	copper slag	0	248040000	553956000
	tailings	0	82241100	183671790
Operation/processing	copper slag	16067800000	3631000000	3662000000
	tailings	0	376000000	526000000
Permits	copper slag	0	27560000	27560000
	tailings	0	9137900	9137900
Human health	Reduced non-acute	-1200	-1200	-1200
	other types	-50000	-50000	-50000
Environmental cost/benefit	in [SEK]			
Transportation	copper slag	0	83507329	63500365
	tailings	0	27688010	21054425
Processing	copper slag	1284300000	1061202730	1061202730
	tailings	0	328277435	328277435
Energy production	copper slag	14998595	42002762	64411222
	tailings	0	13719381	2137074
other affected ecosystems	copper slag	2188571	2188571	2188571
	tailings	685714	685714	685714

Table 8: Costs and benefits of the hypothetical scenario, determined by the input factors; cost are presented in positive values and benefits in negative values.

Table 8 states the economic and environmental costs and benefits calculated from the three different treatment scenarios based on the total possible amount of copper slag (5 512 000t) and tailings (1 827 580t). In general, all costs concerning a potential processing of tailings at Rönnskär are not shown due to inefficiency and non-feasibility of the existing machinery.

Digging up and refilling (excavation)

All three scenarios are calculated with the same excavation costs due to no accruing difference regarding that very first step of the planned remediation. The stated 584 MSEK for copper slag and 194 MSEK and can increase and decrease according to the corresponding amount of material.

Transportation

The stated transportation costs for copper slags are 306 MSEK higher for Aitik's train connection than for Boliden's truck transportation. This can be seen as relatively low regarding the fact that Aitik is 6 times further away located from Rönnskär than Boliden. The same applies for tailings, resulting in approximately 101 MSEK higher transportation costs when choosing the Aitik scenario. In general, transportation by train is economical and environmentally more efficient but the distance is playing a vital role between these two scenarios, meaning that despite the lower per ton and km costs of trains, the longer distance is causing the exceeding costs compared to Boliden's truck connection. This is also shown in table 9, stating per/ton transportation costs of 45 kr for trucks and 100.5kr for trains. Calculating the kr/ton per kilometre results in 0.75kr for trucks and 0.28kr for trains, clearly showing the merit of trains.

Economic cost	in [SEK]	Rönnskär	Boliden Area	Aitik
Transportation	copper slag	0	248040000	553956000
	tailings	0	82241100	183671790
	per ton	0	45	100.5

Table 9: Economic costs for transportation - hypothetical scenario.

When comparing the operation/processing costs amongst the scenarios in table 10, it is quite obvious that treating copper slags at Rönnskär would cause significantly higher costs than a potential processing at Boliden Area or Aitik. Boliden Area has the lowest cost of about 206 kr/t copper slag, followed by Aitik with ca. 288 kr/t whereas Rönnskär requires almost 14 times higher expenses than Boliden Area and 10 times higher than Aitik. Tailings on the other hand can be processed for almost the same amounts at Boliden Area or Aitik, 659 kr/t and 664 kr/t accordingly. This cost distribution is most likely caused by the different technologies used in the three scenario. Rönnskär applies pyrometallurgy whereas Boliden and Aitik are both using flotation, which explains the similar accruing operating/processing costs. Even if Rönnskär states the highest extraction rates of about 85%, the losses by replacing more valuable material are exceeding the gains by far. In comparison, Boliden Area and Aitik show very similar and low operating costs, even though their extraction rates only reach about 5%. This clearly demonstrates that the historical copper slags and tailings replace less valuable material at Boliden and Aitik than at Rönnskär.

Economic cost	in [SEK]	Rönnskär	Boliden Area	Aitik
Operation / processing	copper slag	16067800000	3631000000	3662000000
	tailings	0	376000000	526000000
	copper slag per ton	2915	206	288
	tailings per ton	0	659	664

Table 10: Economic costs for operation/processing - hypothetical scenario.

Permits

The accruing permit costs of 28 MSEK for historical copper slags and 9 MSEK for historical tailings are only applying for Boliden and Aitik due to the fact that Rönnskär already possesses permits to process these materials at their smelter location. The costs are the same due to the same project requirements and conditions. These costs are relatively little compared to for instance transportation or operating costs.

Human health

Human health is the only social positive benefit included in the cost-benefit analysis. The reduced non-acute health benefits are about 1200 SEK per scenario whereas the other types of health benefits account for approximately 50 000SEK. Both these values are extremely low compared to all the accruing costs and are exactly the same throughout all scenarios due to the same positive health outcomes regardless the treatment method. Therefore, changes regarding that input factor would affect all scenarios in the same way but won't cause any significant change in the outcome and conclusion of this study.

Environmental transportation

The environmental transportation costs are presented in table 11, showing no costs for Rönnskär, about 111 MSEK for Boliden Area and 86 MSEK for Aitik, including copper slag and tailings costs. This result confirms the above statement regarding trains being the more efficient and environmentally friendly transportation vehicle. Sending one ton of material from Rönnskär to Aitik is stated to be 4kr cheaper, 11.5kr/t in total, than sending it from Rönnskär to Boliden, 15.15 kr/t, which is only 60km away from Rönnskär.

Environmental processing

Compared to Boliden and Aitik that are both using flotation technology for metal extraction, Rönnskär applies pyrometallurgy which might be the reason for the presented results in table 11. Boliden and Aitik are causing around 1 061 MSEK environmental costs when processing the historical copper slags whereas Rönnskär would be responsible for more than 1 284 MSEK. The difference is more clear when analysing the per ton copper slag environmental costs which are 233kr at Rönnskär and 192.5kr at Boliden and Aitik. Environmental costs from tailings sum up to 179.6 kr/t which is slightly cheaper than copper slags. This cost difference is most likely due to the missing crushing process for tailings. Copper slags are usually found in big blocks and must be crushed before further processing whereas tailings are present in form of sands and therefore already suitable for processing. Generally, the environmental processing costs are the biggest share within all environmental costs.

Energy production

In terms of environmental costs accruing from energy production used to keep the machineries running, Aitik is causing the highest costs with about 64 MSEK, followed by Boliden with 42 MSEK and lastly Rönnskär with only 15 MSEK, regarding copper slags. The environmental cost difference between Aitik and Boliden is only about 1.5 kr/t whereas Rönnskär is clearly lower, with ca. 2.72 kr/t. The same costs apply for processing tailings. The reason for these results is clearly of technological nature and slightly influenced by the complexity of measuring the exact required amount of energy.

Environmental cost in [SEK]		Rönnskär	Boliden Area	Aitik
Transportation	copper slag	0	83507329	63500365
	tailings	0	27688010	21054425
	copper slag per ton	0	15.15	11.5
	tailings per ton	0	15.15	11.5
Processing	copper slag	1284300000	1061202730	1061202730
	tailings	0	328277435	328277435
	copper slag per ton	233	192.5	192.5
	tailings per ton	0	179.6	179.6
Energy production	copper slag	14998595	42002762	64411222
	tailings	0	13719381	2137074
	copper slag per ton	2.72	7.59	9.1
	tailings per ton	0	7.59	9.1

Table 11: Environmental cost – hypothetical scenario.

5.1.2 Net present values

All values in [SEK]		Rönnskär	Boliden Area	Aitik
total cost	copper slag	17953509166	5679723392	6019040888
	tailings		702458671	1264636618
NPV	copper slag	-10829130784	-4367307905	-4884057236
	tailings		-940326583	-1135079821
	total	-10829130784	-5307634488	-6019137057
per ton total cost	copper slag	3257.17	1030.43	1091.99
	tailings		384.37	691.97
NPV	copper slag	-1964.65	-792.33	-886.08
	tailings		-514.52	-621.08
total economic/social	copper slag	16652022000	4490822000	4827738000
	tailings	0	661051280	912481970
NPV	copper slag	-10044102417	-3458887302	-3922839767
	tailings		-605931896	-821533835
	total	-10044102417	-4064819198	-4744373603
per ton economic/social	copper slag	3021.05	814.74	875.86
	tailings		361.71	499.28
NPV	copper slag	-1822.22	-627.52	-711.69
	tailings		-331.55	-449.52
total environmental	copper slag	1301487166	1188901392	1191302888
	tailings		370370540	352154648
NPV	copper slag	-785028367.4	-908420603	-961217468
	tailings		-334394687	-313545985
	total	-785028367.4	-1242815290	-1274763454
per ton environmental	copper slag	236.12	215.69	216.13
	tailings		202.66	192.69
NPV	copper slag	-142.42	-164.81	-174.39
	tailings		-182.97	-171.56

Table 12: Net present values of the hypothetical copper slag and tailing scenarios in [SEK], cheapest treatment solutions are marked in yellow (highest NPV).

The lowest total net present value for both, copper slags and tailings, would be achieved by a hypothetical Boliden Area scenario, table 12. When processing all given material at Boliden, 5 512 000t of copper slag and 1 827 580t tailings, Rönnskär would have to pay a total amount of 5 308 MSEK, including economic and environmental costs. This would be around 711 MSEK cheaper than the Aitik scenario and 5 522 MSEK cheaper than Rönnskär when purely focusing on copper slag treatment. The same result is shown by the analysis of the total cost per ton of material, about 792 kr/t for copper slag and 515 kr/t for tailings. Aitik's costs measure 886 kr/t for copper slag and 621 kr/t for tailings whereby Rönnskär requires 1 965 kr/t copper slag. However, small differences such as the copper price between Boliden and Aitik can easily sum up to great amounts when applied to even greater concentrate numbers.

The same results are given when solely calculating the economic/social costs. In this connection, Boliden dominates with 628 kr/t copper slag and 332 kr/t tailings compared to Aitik with 712 kr/t copper slag and 450 kr /t tailings as well as Rönnskär with about 1822 kr/t. These per ton differences sum up to a total cost reduction of 680 MSEK when choosing Boliden over Aitik. Having a pure focus on copper slag, Rönnskär is causing 6 585 MSEK higher costs compared to Boliden whereas Aitik is only responsible for 464 MSEK more costs. Regarding tailings, a treatment process at Boliden would save up to 216 MSEK compared to Aitik.

Varying results are also presented through the pure analysis of environmental costs. Within this group, Rönnskär smelter takes the lead regarding the cheapest solution for copper slag treatment which is logical due to the missing greenhouse gas emissions from transportation and the lower required energy consumption of its pyrometallurgical process technology. From an environmental perspective, a treatment of copper slags at Rönnskär would cause 22kr/t less costs compared to Boliden and 32 kr/t less costs compared to Aitik. In the case of tailings, Aitik seems to be the more environmentally friendly solution, offering a tonnage cost of 172 SEK whereas Boliden Area is 11kr/t more expensive, causing a total of 21 MSEK higher environmental costs.

Concluding, the overall lowest treatment costs for historical copper slags and tailings from Rönnskär would be given by the Boliden Area scenario. However, a pure focus on environmental costs shows a shift in pattern and states Rönnskär as most efficient in terms of copper slag processing and Aitik as preferred regarding tailings.

5.2 Realistic cost-benefit analysis

5.2.1 Input factors

Table 13 presents the total costs determined by each input factor based on 400 000t of copper slags and 400 00t of tailings. The cost corresponds to 7.26% of the calculated 5 512 000t copper slag scenario and 21.89% of the calculated tailings scenario above.

		Rönnskär	Boliden Area	Aitik
Economic/social costs/benefiin [SEK]				
Digging up and refilling	copper slag	42400000	42400000	42400000
	tailings	42400000	42400000	42400000
Transportation	copper slag	0	18000000	40200000
	tailings	0	18000000	40200000
Operation/processing	copper slag	1166023222	263497823	265747460
	tailings	0	82294619	115124919
Permits	copper slag	0	2000000	2000000
	tailings	0	2000000	2000000
Human health	Reduced non-acute	-262.68	-262.68	-262.68
	other types	-3630	-3630	-3630
Environmental costs/benefitsin [SEK]				
Transportation	copper slag	0	6062632	4610126
	tailings	0	6060905	4608814
Processing	copper slag	93240180	77043318	77043318
	tailings	0	71859931	71859931
Energy production	copper slag	1088898	3049401	4676255
	tailings	0	3003173	467805
other affected ecosystems	copper slag	158890	158890	158890
	tailings	125086	125086	125086

Table 13: Costs and benefits of the realistic scenario, determined by the input factors; cost are presented in positive values and benefits in negative values.

5.2.2 Net present values

All values in [SEK]		Rönnskär	Boliden Area	Aitik
total cost	copper slag	1302907560	412208434	436832420
	tailings	0	153754804	276782662
NPV	copper slag	-969196023	-308628329	-326945467
	tailllings	0	-194557333	-238097904
	total	-969196023	-503185662	-565043371
per ton total cost	copper slag	236.38	74.78	79.25
	tailings	0	84.13	151.45
NPV	copper slag	-2422.990059	-771.57	-817.36
	tailings	0	-529.60	-744.06
total economic/social cost	copper slag	1208419592	325894193	350343830
	tailings	0	144690726	199721027
NPV	copper slag	-898908905	-244421433	-262608876
	tailings	0	-125420812	-172362766
	total	-898908905	-369842245	-434971642
per ton economic/social cost	copper slag	3021.05	814.74	875.86
	tailings	0	452.16	624.13
NPV	copper slag	-2247.27	-611.05	-656.52
	tailings	0	-313.55	-538.63
total environmental cost	copper slag	94487968	86314241	86488590
	tailings	0	81049094	77061635
NPV	copper slag	-70287119	-64206896	-64336591
	tailings	0	-69136521	-65735138
	total	-70287119	-133343417	-130071729
per ton environmental cost	copper slag	236.22	215.79	216.22
	tailings	0	253.28	240.82
NPV	copper slag	-175.72	-160.52	-160.84
	tailings	0	-216.05	-205.42

Table 14: Net present values of the realistic copper slag and tailing scenarios in [SEK], cheapest treatment solutions are marked in yellow (highest NPV).

The analysis of the net present values in table 14 regarding the realistic scenario shows that the cheapest treatment alternative is provided by Boliden Area. Processing both, copper slags and tailings, at Boliden concentrator would sum up to a net present value of -503 MSEK, more than 62 MSEK lower in cost than Aitik. The highest total costs for copper slag treatment accrue when choosing Rönnskär scenario, with approximately -969 MSEK.

Focusing on the economic/social part of the CBA, the results show the same patterns as in the hypothetical scenario. The cheapest way for historical copper slags and tailings from Rönnskär would be a potential processing at Boliden. The treatment of one ton of copper slag at Boliden would require about 611 SEK, which is 46 SEK cheaper than Aitik with 657 kr/t and 1 636 kr/t cheaper than Rönnskär with about 2247 kr/t copper slag. A potential processing of 400 000t tailings would cost around 314 kr/t, which is 225 kr/t cheaper than Aitik, saving a total of 47 MSEK.

Regarding the environmental cost, Boliden and Aitik show almost similar per ton copper slag cost of 160.52 kr/t and 160.84 kr/t respectively. However, when applying these numbers to the total amount of 400 00t copper slag, the potential Aitik scenario would be about 129 695 SEK more expensive for the environment. Compared to Aitik and Boliden Area, Rönnskär smelter clearly exceeds the given costs of about 160 kr/t by more than 15 kr/t, resulting in total costs of about 70 MSEK for copper slag treatment. Regarding tailings, Aitik states per ton tailing costs of around 205 SEK whereas Boliden Area requires almost 11SEK more per ton, 216 SEK. Summing these numbers up, a potential treatment of tailings at Aitik would save Rönnskär more than 3 MSEK.

5.3 Conclusion

Both scenarios, the hypothetical and the realistic one, state Boliden as the most beneficial treatment option for historical copper slags and tailings compared to Rönnskär and Aitik. However, when focusing solely on environmental factors, Rönnskär and Aitik seem to be the better choice for the hypothetical scenario whereas in the realistic scenario Boliden is replacing Rönnskär with respect to the lowest environmental costs for copper slags. Regarding input shares, the most influencing factors for the economic/social costs are the operating processing costs as well as additional transportation costs for Boliden and Aitik. In terms of environmental costs, the biggest share is dominated by the greenhouse gas emissions accruing from operating/ processing at the three locations.

5.4 Sensitivity analysis

The following sensitivity analysis is needed in order to investigate uncertainty amongst the most determining input factors. Its goal is to eliminate any doubts about the chosen cost-benefit method and its input values as well as make sure that the applied assumptions do not distort the final conclusions. This is done by the alteration of the discount rate, the environmental cost for

CO2 emission and the extraction rates of the different concentrators. Besides the discount rate, which was chosen due to its significant impact on the net present values, the choice of the two other factors was partly based on the distribution of the total costs regarding copper slag and tailings treatment as well as on the potential of change causing their uncertainty.

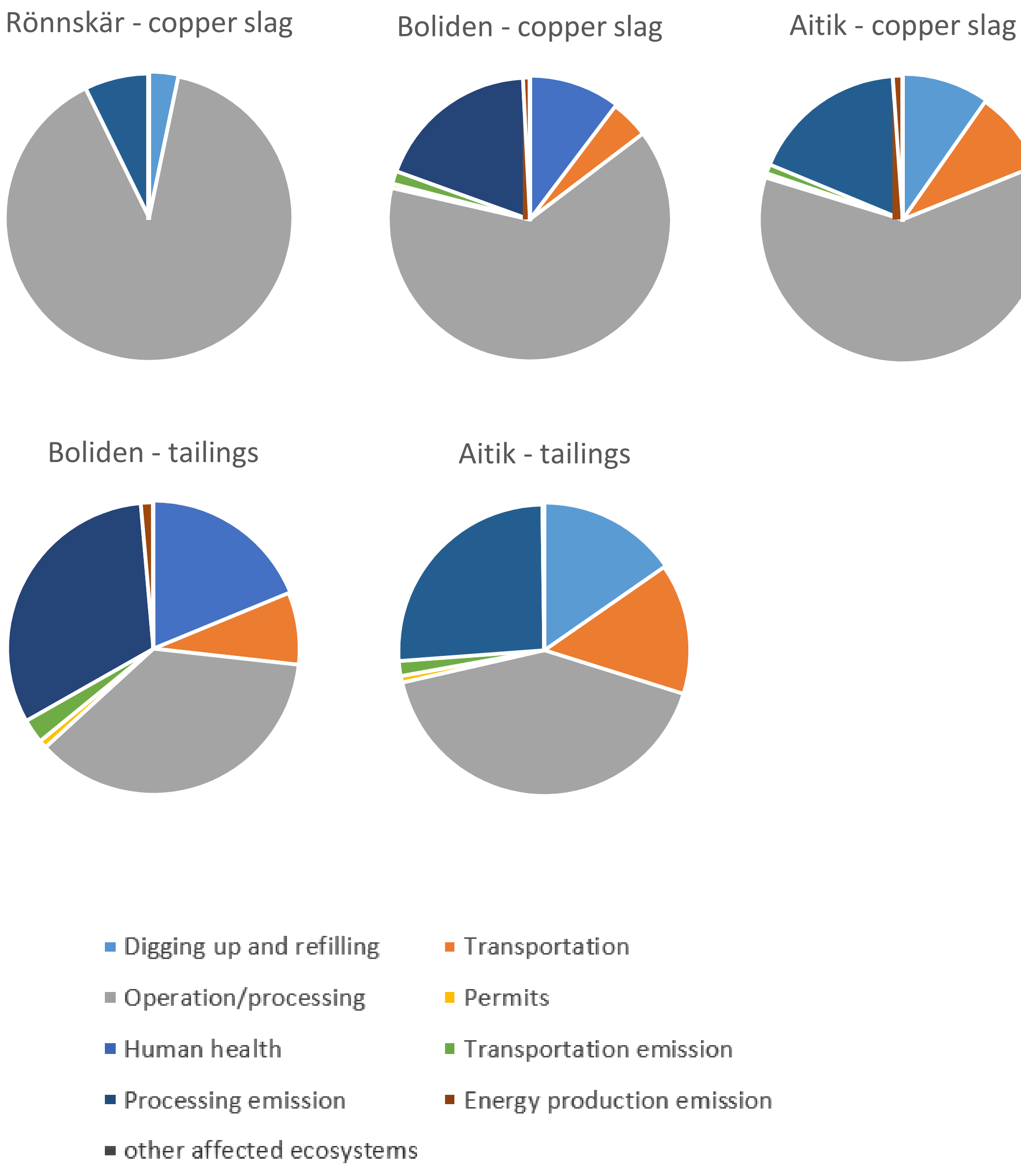

Figure 8: Input factor distribution for each scenario and material.

The charts in figure 8 present the cost distribution for all input factors, divided into copper slag (up) and tailings (down), showing clearly the domination of operation/processing costs and environmental processing costs. All numbers that are used in the following relate to the realistic scenario with a processing rate of 400 000t respectively. If the presented net present values, resulting from varying input factors, are still providing similar outcomes, the conducted cost-benefit analysis can be assumed to be robust.

5.4.1 Discount rate

Since the discount rate is, on one hand, a significant determinant of the net present value and, on the other hand, a constantly discussed value within literature, it is advisable to test for it at different levels (Ludwig et al., 2005; Barro, 2014; Howarth, 1996). Therefore, this study examined the effects of a change in discount rate on the net present values, including all economic and environmental factors, regarding all three scenarios. Besides the applied 3% discount rate, all calculations were conducted with a 1% discount rate and a 5% discount rate, shown in table 15.

		Rönnskär	Boliden Area	Aitik
Discount rate		Net Present Value in [MSEK]		
1%	copper slag	-1176	-374	-396
	tailings	0	-216	-264
3%	copper slag	-969	-309	-327
	tailings	0	-195	-238
5%	copper slag	-812	-259	-274
	tailings	0	-176	-216

Table 15: Net present value calculations based on 1%, 3% and 5% discount rates for Rönnskär, Boliden Area and Aitik realistic scenario.

The calculations in table 15 clearly show a relationship between an increasing discount rate and declining net present values. This means that a higher discount rate will cause lower costs for Rönnskär if an investment would happen. In addition, figure 9 demonstrates the significant impact of time. The realistic copper slag scenarios are based on a 20 year time frame whereas the two tailings scenarios are based on a 10 year time frame. The longer the time frame, the lower the value of the future cash flows and the steeper the slopes in the graph. Compared to the copper scenarios, the tailing scenarios seem relatively flat, almost straight. However, all net present values are still negative.

Figure 9: Net present values for realistic copper and tailings scenarios based on 1%, 3% and 5% discount rates.

5.4.2 Price CO2 emission

A significant impact factor on the environmental costs caused by the released emissions from a potential processing of the copper slag or tailings is the price for CO2 emissions. Unfortunately, there exist no consistent exact price for the environmental damages that CO2 emissions are responsible for and an even bigger problem is the pricing of future CO2 emissions. Just taking a look at the price development of CO2 emissions over the past 10 years, presented by Markets Insider (2019), demonstrates quite vital pricing activities with a strong upward trend since mid/end of 2017, figure 10.

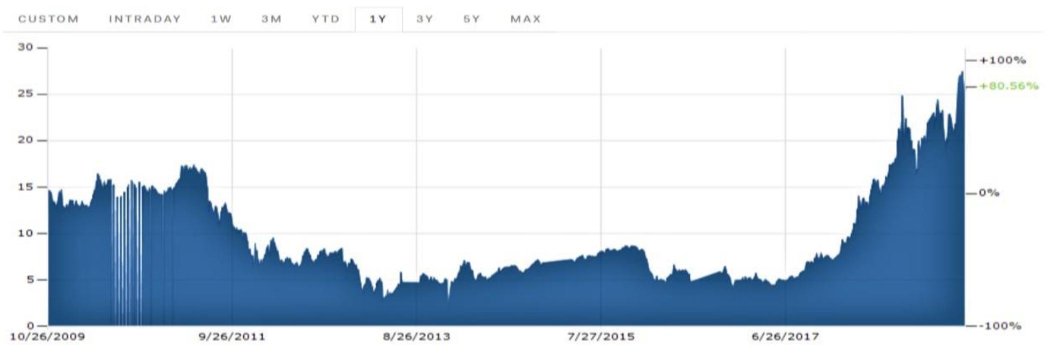

Figure 10: CO2 European emission allowance price chart between 2009 and 2019 (Markets Insider, 2019).

Within this study, all calculations regarding the cost-benefit analysis were based on the CO2 emission price of 145€/t which was recommended by the German Federal Environmental Agency. This price represents a medium-term pollution over an approximate time period of 15 to 20 years. Sweden introduced its carbon tax in 1991 with a starting rate of 250 kr/t and a present rate of 1 180 kr/t in 2019 (Government Offices of Sweden, 2019). In general, short-term and long-term emissions are priced lower and higher, respectively. Therefore, the reliability of CO2 prices as input factors were tested, using 80€, 110€ as well as 170€.

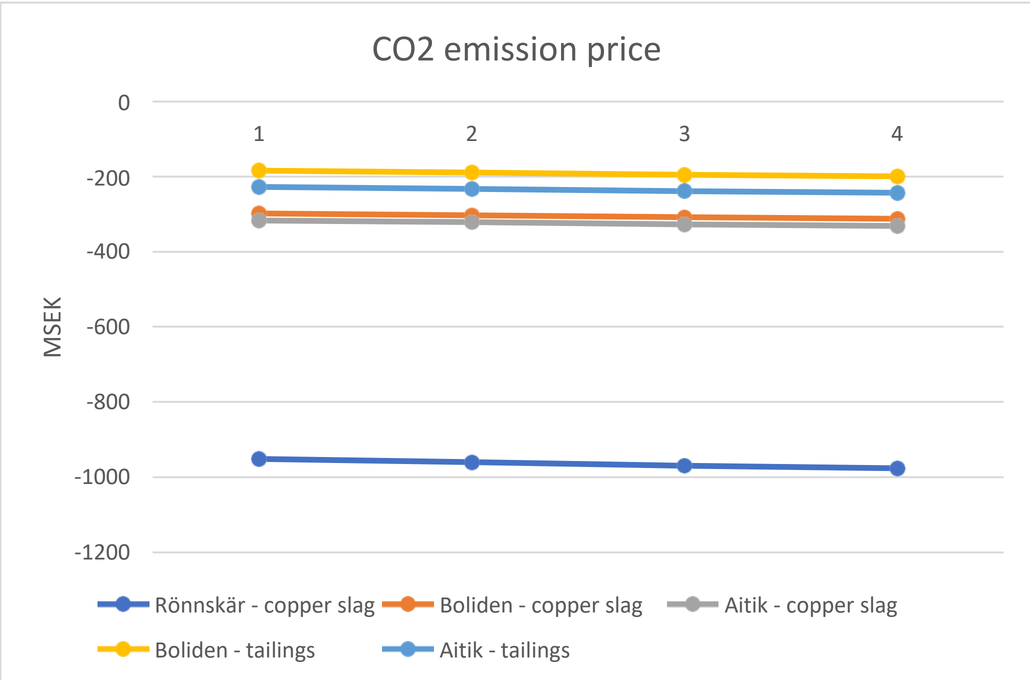

Figure 11: Net present values for copper slag and tailings treatment calculated on the basis different CO2 pricing.

Supported by the visualization in figure 11, it can be concluded that none of the remediation scenarios would be significantly impact by the change of CO2 emission prices.

5.4.3 Extraction rates

The extraction rates of valuable metals from copper slag and tailings vary greatly amongst the three investigated scenarios, Rönnskär, Boliden Area and Aitik. In general, the higher the extraction rates, the more financial benefits for the company and the lower the project costs. However, there exist a financial turning point, describing the moment when extraction costs overcome the potential benefits from these valuable metals. Therefore, companies are usually not aiming for 100% extraction rate but rather for the most economically efficient rates.

However, the extraction rate can be increased by improved technology, but it depends on the accruing cost-benefit margin whether it is worth doing it.

Regarding copper slag, the accruing benefits are coming from the extraction of zinc whereas tailings are contributing with gold contents. Aitik is known to operate with approximately half of the stated extraction rate of Boliden concentrator, which reaches 5% for zinc from copper slags and 74% for gold from tailings. In comparison, Rönnskär is capable of extracting up to 85% of the total zinc from historical slags. In order to examine the impact of extraction rates on the cost-benefit analysis of this study, the most relevant NPVs got calculated based on different extraction rates shown in table 16 and table 17.

	Rönnskär	Boliden	Aitik
Extraction rates	NPV copper slag in [MSEK]		
5%		-309	-325
25%		-295	-312
50%		-278	-295
85%	-969	-255	-271
95%	-963	-248	-265
100%	-960	-245	-261

Table 16: Net present values of copper slag based on varying extraction rates.

	Boliden	Aitik
Extractions rates	NPV tailings in [MSEK]	
74%	-195	-210
85%	-186	-202
95%	-178	-194
100%	-175	-190

Table 17: Net present values of tailings based on varying extraction rates.

When analysing the tables, it is obvious that an increasing extraction rate results in higher net present values for each project regardless which material to process. However, increased extraction rate don’t cause any significant change in the general outcome of the net present values and the based conclusions. Therefore, it is questionable whether it would be financially worth improving the present extraction rate.

6. Discussion and conclusion

This last chapter provides a summary of the most important steps and results from the previous chapters. Furthermore, it will discuss limitations and alternative treatment methods, followed by a conclusion.

6.1 Summary

This study investigated three different treatment scenarios for Rönnskär’s historical copper slags and tailings which were used as land-fillings in the past for the expansion of their own industrial area. The motivation for this project is the result of the economic, social and legal changes regarding the environment and sustainable approaches. The three examined scenarios differ regarding their process technologies as well as their location and applied logistics. In order to evaluate the different treatment scenarios, a social-cost-benefit analysis was conducted, including the most determining economic and environmental input factors. After careful consideration of the total amount of treatable material, 5 512 000t copper slag and 1 827 580t tailings, it emerged to be an impossible underpinning to excavate and process all of it without destroying Rönnskär’s industrial area. Therefore it was decided to perform two different cost-benefit analysis, a hypothetical one and a more realistic one. The hypothetical analysis covered the impossible scenario of all existing copper slags and tailings whereby the realistic scenario focused on smaller amounts, 400 000t of each concentrate, based on previous construction experience and process capacities at Rönnskär, Boliden Area and Aitik. The results of both CBAs showed the lowest total accruing costs for Boliden Area, followed by Aitik concentrator and last of all Rönnskär.

6.2 Discussion

Based on the actual results of this study, the cost-benefit scheme would classify none of the investigated scenarios as socially beneficial. All calculated net present values are negative which usually implies the exclusion of the concerning investment idea. However, this result doesn’t come unexpected. In the case of this study, the CBA is used to compare the different scenarios in order to indicate the right direction for further research. This is a common approach regarding soil remediation projects due to the difficulty of generating enough benefits to offset the accruing costs. If the negativism of the net present value would be the decisive factor within soil remediation projects, the amount of such activities would significantly decrease.

Generally, the accruing costs, stated as NPVs, seem incredibly high. This can easily give a wrong impression if not considering the size of the project and its total amount of copper slags and tailings. The consultants of the U11 project presented realistic estimates of about 1 500 SEK per ton of contaminated soil (based on investigations of contaminated ground close by storage areas at Rönnskär) which covers the most accruing costs such as digging, planning, handling and more. This expert opinion clearly shows the financial reality of soil remediation projects.

In addition, internal information from Boliden states that NPV calculations are usually performed with higher interest rates than used in this study. Instead of a recommended discount rate of 3%, the treatment of copper slags and tailings will most likely be calculated with a 10% rate in reality. This significant change would result in less negative NPVs, meaning significantly lower costs for the treatment of these materials. Nevertheless, all three examined scenarios would be equally affected and thereby still state Boliden as the most beneficial treatment scenario. The adjustment of the discount rate is based on the facts that mining is considered to be a high-risk industry and that the project itself requires very large investments.

6.2.1 Internal limitations

There is no doubt about the uncertainty amongst most of the chosen input factors for this research project. Generally, they can be divided into three different groups, one group comprising of all input factors that affect all three scenarios in the same way (non-determining factors), one group comprising of all input factors that can change the potential results of the entire project (determining factors) and one group stating all missing input factors which could not get monetized and are therefore not included (missing factors).

Non - determining factors

The first group consist of the costs/benefits for excavation, environmental permits, human health and other affected ecosystems. All of these factors might vary in reality but have one thing in common: All three scenarios will be affected in the exact same way. Therefore and within the scope of this project, it is not necessary to discuss non-determining factors any further.

Determining factors

The second and more important group consist of the determining input factors such as transportation costs. Both cost assumptions, for trucks and train, are very close to reality but indirect effects are unpredictable and therefore difficult to include. A good example is shown by the recent release of the local news, stating a new transportation route for trucks between Rönnskär and Boliden. This change is caused by the closing of an important connection road in Skellefteå, forcing the mining company to reorganize their truck route (Lundholm, 2019). Such a change on short-term notice can cause great costs in the long-term through e.g. addition fuel costs, transportation time, labour, greenhouse gas emissions or increased traffic risk. Similar problems can also apply to the train connection between Aitik and Rönnskär.

Another uncertain cost factor is the actual processing of these materials. Calculations regarding this matter are coming from Rönnskär's economic department (Tobias Långström) that tried to give as accurate numbers as possible. Nevertheless, a concentrator is a complex construct with a variety of processes, making it extremely complicated to exactly determine all accruing costs and benefits.

The same complex issue applies to the greenhouse gas emission from processing and its required energy supply. Calculations regarding the latter are all based on energy reports from the different scenarios but assumptions were needed and results might vary. Accruing greenhouse gas emission are, in the case of Rönnskär, also based on internal reports whereas the other two scenarios have to rely on a general flotation case from China. On one hand, these numbers are supposed to be closer to reality than speculations based on vague internal reports but on the other hand, there might be significant differences in operation procedures, measurement technics or environmental protection goals regarding China and Sweden.

Missing factors

The inclusion of cost and benefit items within this study was limited to time, data base access and existing science. Therefore, the three input areas, economy, society and environment were unable to be equally included in the cost-benefit analysis. Regarding the economic values, factors such as labour, additional construction or transportation are not completely covered in the presented values meaning that the actual economic costs might be higher than stated. In terms of environmental factors, it was tried to cover the most important and significant environmental determinants but missing minor input factors such as emissions from excavation, potential pollution of water bodies or the actual value of clean soil on an industrial area. The social input section is the one that has the fewest input data and support due to the difficulty of monetizing these effects. It was tried to capture these values by incorporating reduced non-acute health effects and other types of health improvement but the stated values are far too low and further supporting monetized information on e.g. labour, safety or job creation are clearly missing.

Concluding impact on the project

However, the actual influence of the determining input factors is limited due to the conducted sensitivity test as well as the percentile shares regarding the total amount of costs. The sensitivity analysis states the robustness of the CBA, meaning that uncertainties amongst cost-benefit from processing and emission levels are removed. All other determining input factors have only few uncertainties or too small of a share to change the actual outcome of the project. Regarding missing input factors, it would definitely be beneficial having more extensive data but it is quite unlikely that it would seriously change the outcome of this project. Most of the missing items would either affect all three scenarios in the same way or be of too low impact to actual cause significant changes. In summary, despite great uncertainties and missing input factors, the results of this study are reliable and robust and therefore providing a useful base for further research and the decision process concerning such an investment.

6.2.2 External limitations

Besides the internal limitations within the execution of this study, there exist more significant external barriers that can put a hold on such remediation projects. One considerable problem is the existing capacity of the different concentrators. Boliden Area and Aitik are fully scheduled within the next couple of years and Rönnskär is also running on full capacity right now. Processing Rönnskär's historical copper slags and tailings would therefore mean creating capacities by replacing more valuable input materials. Such an approach is not impossible but requires detailed planning and more precise calculations.

Furthermore, the investigation showed that the hypothetical scenario (all copper slags and tailings) is out of the scope and that a more realistic scenario has to be aimed for. The presented realistic scenario with a treatment rate of 400 000t for each material was therefore examined and confirmed as theoretically feasible. Nevertheless, such a scenario implies that only part of the problem would be eliminated, leaving more than half of the contaminated soil behind. However, one has to be aware of the fact that the presented scenarios are based on the current situation, providing only current possibilities based on current knowledge and development. Naturally, there exist a variety of treatment alternatives and future possibilities that are providing potential methods of resolution.

6.2.3 Alternative treatment methods

There exist plenty of alternatives which might be worth considering but were unfortunately outside the scope of this thesis project. Future leading technologies such as bio-hydrometallurgy and phytoremediation are promising approaches as well as other concentrators with different logistics. However, the idea of covering the tailings by an impermeable layer of special material which prevents any toxic element from leaking would be a very cost-effective and environmentally friendly method. By doing so, any negative environmental effects mentioned in the cost-benefit analysed of the three main scenarios would be avoided. In addition, it is very likely to enable a full coverage of the entire tailings area which is definitely preferred to only partly remediating the potentially leaking material. In summary, all alternative treatment methods have their advantages and disadvantages and further research is needed to build a better understanding of each method and its project specific feasibility [Appendix F].

6.3 Conclusion

The main goal of this project was to investigate various remediation scenarios for Rönnskär's historical copper slags and tailings. The analysis and examination of the three main scenarios, Rönnskär, Boliden Area and Aitik, resulted in Boliden Area being found as the most favourable location for a potential processing of these materials. Although, all calculated net present values have been negative, these results are not a criterion for exclusion of the entire investment project. The conducted cost-benefit analysis was mainly used as a comparing assessment tool in order to weight the different offered scenarios and indicate the possible right direction for further research.

Summing up, this project gives great insights in the possibilities and responsibilities of Rönnskär smelter in Sweden, and thereby also into sustainable mining in the Nordics. It further addresses the weak environmental regulations concerning soil remediation projects in Sweden and Europe, especially the lack of concrete guidelines. In order to pro-actively work towards a more sustainable mining industry, more cooperation between mining companies and environmental institutions would be advantageous as well as more comprehensive support and guidelines regarding sustainable approaches within mining.

Further research is also required in the monetization of indirect social and environmental effects. Most limitations concerning this study emerged from the lack of monetized input factors which directly affected the outcome of the net present values. Fortunately, most of these missing items would have had similar effects on all three examined scenarios and thereby no significant impact on the overall outcome of the performed cost-benefit analysis and its conclusions.

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Appendix A: Rönnskär history and environmental status

Rönnskär history

To secure the future of Boliden and the leading role of Rönnskär as one of Europe's most efficient copper smelters, it is crucial to think sustainable and in the long-run by developing a profitable and environmental friendly recycling procedure for their historical dumped by-products, copper slag and tailing sand. As mentioned before, Rönnskär smelter is located on the Island Rönnskär in Skelleftehamn and is partly build and enlarged by copper slag and tailings itself. The Island was first chosen due to its advantageous environment designated by an adequate distance to congested urban areas, agricultural and forestry industrial operations as well as favourable meteorological and marine conditions (Koncessionsansökan, 1985). The expansion of the Island started right after 1930 when copper slag, first produced by a furnace and from 1949 by an electric furnace, was used to fill up the surrounding areas and create new space for further extensions and machineries.

By 2007, an investigation revealed that Rönnskär Island has been growing from its original 50ha in 1928 to approximately 153ha with further expansion in progress (WSP Samhällsbyggnad, 2007). Most of these new land parts were built from copper slag or other by-products, still containing a considerable amount of attractive metals such as gold, silver, zinc, copper or lead.

Besides these economic interesting metal contents, landfilling areas are also posing a potential risk to the environment and society close to Rönnskär. In his book "Mine wastes", Bernd Lottermoser (2003) states the environmental instability of previously assumed inert copper slag due to the exposure to bio-hydro-climatic conditions and the possible mobilization of hazardous metals. Further motivation comes from Rönnskär's commissioned environmental and health risk assessment as a result of the U11 investigation, concluding that additional risk reduction is necessary and has to be introduced in order to comply with the overall environmental and production goals (Boliden Rönnskär, 2018).

Environmental status

The analysis of the water bodies surrounding Rönnskär demonstrate an overall poor situation regarding its environmental status. In figure 12, Skelleftehamnsfjärden [2] reports a bad ecological status as well as only a moderate chemical status, based on the investigated bottom fauna and the amount of environmental toxins. Similar results are found in Skelleftebukten [4], stating moderate ecological levels and poor chemical status. The two water bodies in the south of Rönnskär, Sörfjärden [1] and Simpan [3], have both moderate ecological status but the chemical status of Simpan is considered as bad compared to its neighbour part Sörfjärden.

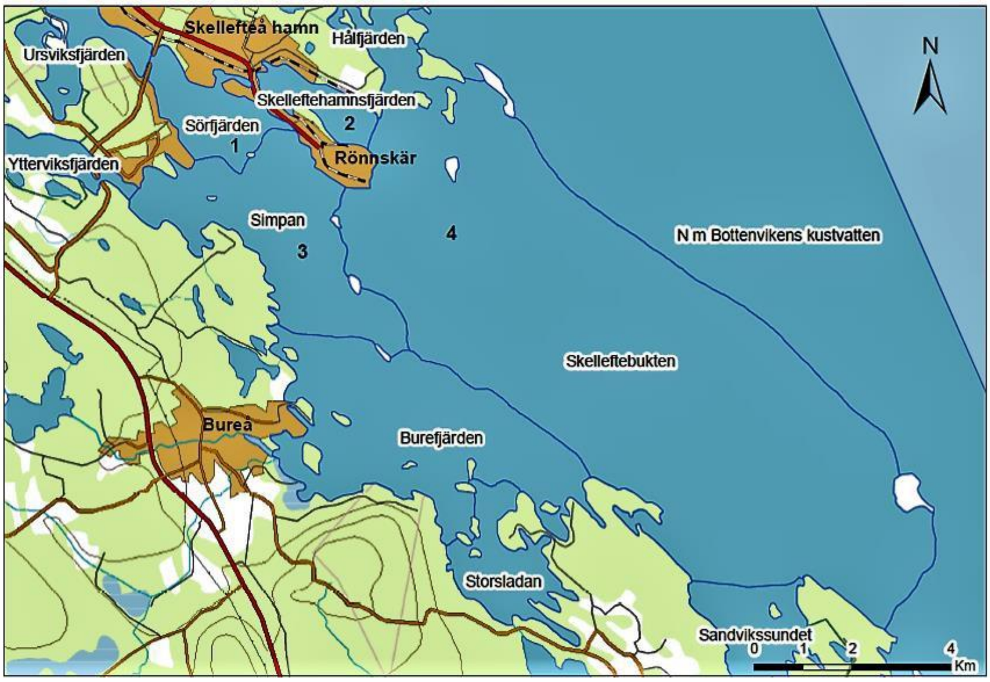


Figure 12: Waterbodies around Rönnskär. 1: Sörfjärden, 2: Skelleftehamnsfjärden, 3: Simpan, 4: Skelleftebukten.

Further analysis has been conducted through the installation of in total 30 groundwater pipes spread over Rönnskär Island. The samples were analysed for elements and organic compounds (chlorinated pesticides, PCBs, aliphatic and aromatics, etc.) as well as physico-chemical parameters such as pH, conductivity and temperature. According to the Geological Survey of Sweden (SGU), the groundwater at Rönnskär is affected by a non-natural source of pollution causing the levels of the majority of elements to be greatly increased (Boliden Rönnskär, 2018).

Supplementary studies were carried out on 32 locations in the water areas around Rönnskär, figure 13. Hereby, sediment samples were analysed for metals and organic compounds (PCB, PAH, etc.) as well as compared to risk values based on the environmental quality standards

(EQS). The measurements identified elevated levels of most substances, mainly arsenic, cadmium, copper, lead, zinc and mercury. These levels first started decreasing at greater distance from Rönnskär Island (Boliden Rönnskär, 2018).

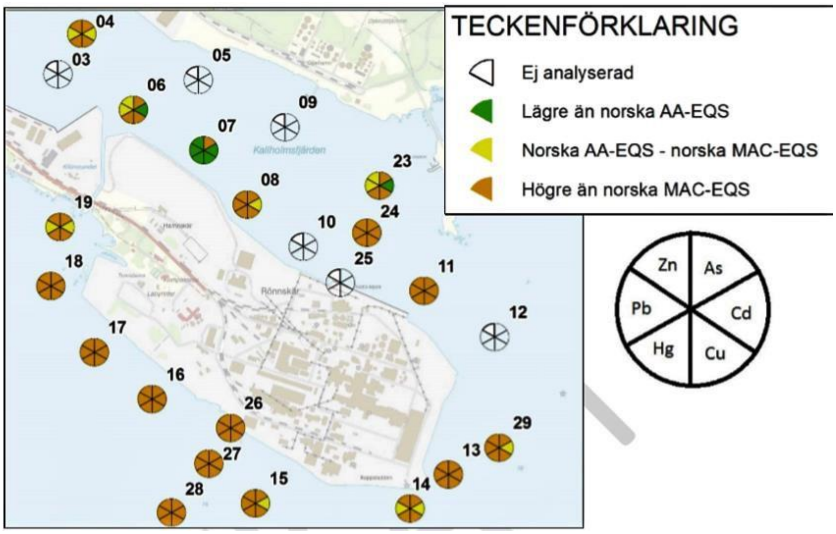


Figure 13: Metal contents in the sediment around Rönnskär compared to the Norwegian Environmental Directorate's Class II and III. Yellow marked: exceeding Class II, orange marked: exceeding Class III, green marked: lower than Class II/III, no colour: unspecified.

The investigation of surface water on 5 locations around Rönnskär Island also revealed exceeding arsenic, zinc and copper levels regarding the environmental quality standards (EQS) in all samples including the reference point. In general, despite the pollution of the water bodies, a large proportion of dissolved pollutants also means a more easy access and uptake from plants and animals (Boliden Rönnskär, 2018).

A summary of all elements exceeding environmental standards found in groundwater, soil, sediment and surface water samples around Rönnskär is presented in the following table.

Ground water	Soil	Sediment	Surface water
Arsenic	Arsenic	Arsenic	Arsenic
Cadmium	Barium	Cadmium	Cadmium
Copper	Cadmium	Copper	Copper
Chrome	Cobalt	Mercury	Nickel
Mercury	Chrome	Nickel	Lead
Nickel	Copper	Lead	Zinc
Lead	Mercury	Zinc	
Zinc	Nickel	PCB	
	Lead	PAH-L	
	Zinc	PAH-M	
		PAH-H	
		TBBP-A	
		Dioxins	

Table 18: Groundwater measurements at Rönnskär are based on SGU's (geological Survey of Sweden) guidelines; Soil measurements are based on the Swedish Environmental Protection Agency's general guidelines for sensitive land use; sediment samples were measured on the Norwegian Environmental Directorate's class boundaries; Surface water results are based on the environmental quality standards (EQS), contained in the Swedish Environmental Code.

Despite the poor environmental status around Rönnskär Island, the Golder report is also shedding light into the spreading risk of different materials located at Rönnskär by assessing groundwater flows and controlled emissions from sewage pipes. Results state only low leachability levels for copper slag and tailings. Copper slag samples are thereby comparable with the relatively low leaching characteristics of iron sand and even the analysed high levels of lead were not able to be traced back to possible leaching conditions. Similar results apply for samples taken from tailings. The latest leaching tests from 2017 revealed low leaching levels for almost all substances. Compared to previous studies, neither copper nor do the easily soluble elements cadmium and nickel appear to be a major problem anymore (Boliden Rönnskär, 2018).

Nevertheless, earlier studies revealed varying arsenic and copper contents which probably depended on the original composition of the tailing sands. Another important factor is the possible oxidization of tailings. Unoxidized tailings are more likely to leach large amount of copper, cadmium, nickel and zinc causing hazardous waste considerations. Especially zinc is partially exhibiting high acceptance levels these days. Furthermore, a possible drop in pH could mobilize cadmium and nickel leading to increased spreading and higher environmental risks of these elements (Boliden Rönnskär, 2018).

Additionally, the ABA (acid-base accounting) test confirmed that all areas that had been filled up with copper slag or tailing sand contain potentially acid-forming materials. Therefore, it is assumed that weathering can cause leaching till down to the groundwater face which lies below the copper slag and tailing fillings. Other concerns are related to the future and the ongoing climate change. Higher temperatures and increased precipitation levels can cause increased infiltration into copper slag and tailings areas, resulting in increased dispersion into the groundwater. Also, the yearly elevation of the Island of about 8mm will shift the ground water surface further down resulting in the oxidization of previously sealed land masses. This change, depending on further circumstances, might have additional unexpected effects regarding the leaching capacity of copper slag and tailing areas at Rönnskär smelter (Boliden Rönnskär, 2018).

However, it must be mentioned that these leaching tests were conducted by crushing all material to <4mm before investigating. Tailings sands is by nature finer than that but old copper slag can easily be much coarser than 4mm. Therefore, the conducted tests on slag might most likely overestimate the actual leaching capability of copper slag, which is already known to be low.

Copper slags and tailings

Copper slag and tailings at Rönnskär belong to the group of non-ferrous by-products which have a potentially stronger negative impact on the environment compared to ferrous-slags (Piatak et al., 2014). They accrue from the pyrometallurgical processing of mineral ores and have been used as building and landfilling material for the expansion of Rönnskär Island between 1930 and 1964, figure 14.

1. 1930-1949: copper slag from flaming furnace (varmtippad slagg or kallkupor)
2. 1949-1964: copper slag from electric furnace (varmtippad slagg or kallkupor)
3. 1934-1954: tailing sand (anrikningssand)

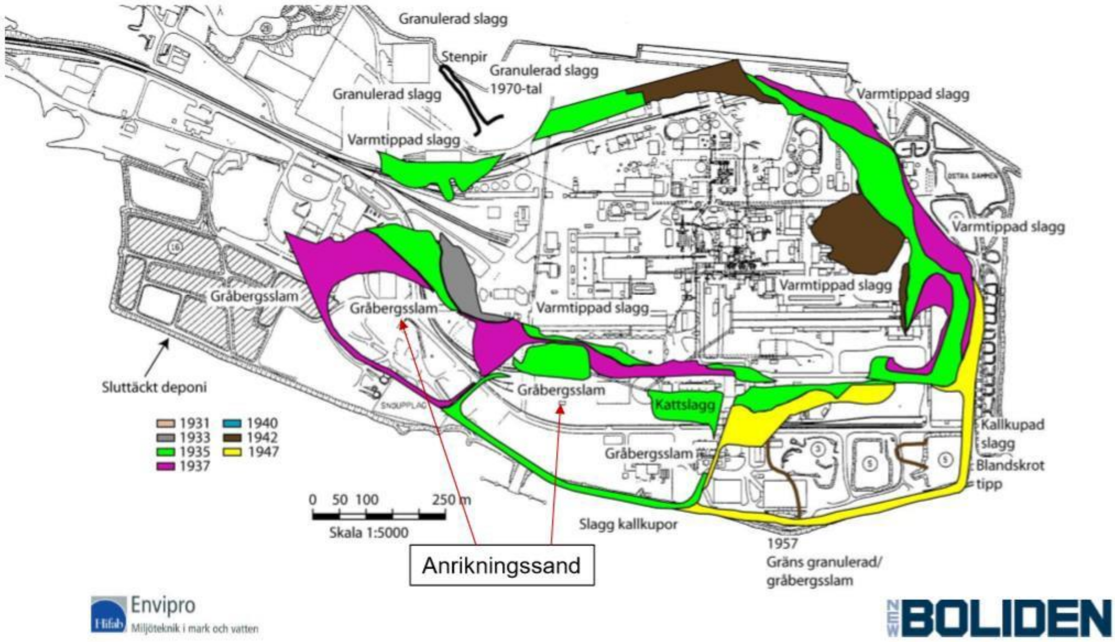
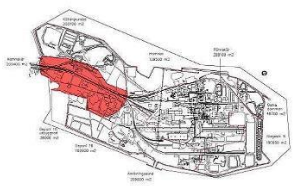


Figure 14: Rönnskär industrial area (2015) (Rönnskär industriområde, 2015).

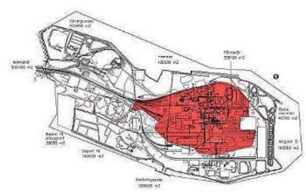
In general, copper slag, used as filling material, gets dumped while being extremely hot and quickly solidifies into big segments. This process results in low permeability for any kind of precipitation as well as difficulties for the formation of groundwater. Therefore, copper slag is assumed to have a relatively low risk of leaching or dispersion even though it might contain dangerous amounts of pollutants. On the contrary, tailing sand has high permeability and hydraulic conductivity (1-2*10^-5) enabling water to easily access and percolate. Containing high levels of toxic pollutants, areas build from tailings which are not covered up with dense material pose a great risk to environmental pollution due to the resulting high leaching potential (WSP Samhällsbyggnad. 2007)

At Rönnskär smelter, the analysed copper slags and tailings contain various elements that can be separated in two groups: economically important and environmentally important. Of economic interest are the elements gold (Au), silver (Ag), zinc (Zn), copper (Cu) and lead (Pb) (Boliden, 2017). Highest priority is usually given to the element gold due to its immense economic value. Regarding the environment, heavy metals such as arsenic (As), cadmium (Cd), copper (Cu), cobalt (Co), mercury (Hg), nickel (Ni), lead (Pb), zinc (Zn) as well as chrome (Cr) are playing a vital role (Golder Associates AB, 2018). When mobilised, most of these elements are known to cause negative impacts on human health, plants or animals. Additional focus will be put on the recovery of silicon (Si) which is commonly used as slag former and causes carbon monoxide as well as silicosis, a lung disease (The Environmental Literacy Council).

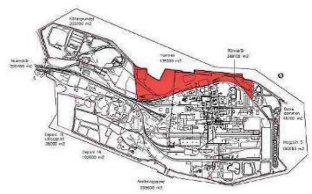
In 2007, Boliden released a report stating the contamination levels and risks potential for Rönnskär. Thereby, Rönnskär got divided into 8 subareas, focusing on the leaching potential of land-fillings and waste deposits. The concerned areas were Hamnskär, Rönnskär, Hamnen, Anrikningssand and Område vid Magasin 5 whereby each was assigned to a contamination risk level, 1=very high risk, 2=high risk and 3=moderate risk.



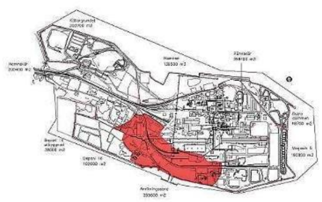
Hamnskär (3)



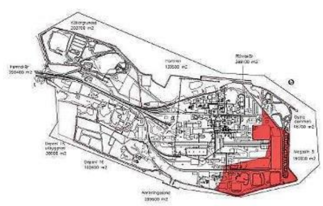
Rönnskär (2)



Hamnen (2)



Anrikningssand (1)



Område vid Magasin 5 (1)

Very high risk	1
High risk	2
Moderate risk	3

Risk levels

Figure 15: Risk areas at Rönnskär.

When examining Rönnskär’s industrial area, the lowest risk class of contamination and dispersion (3) was measured in Hamnskär, the connecting land part between Hamnskär and Rönnskär Island. The analysis showed high levels of arsenic, lead, cadmium, copper and zinc. However, most of the area consists of natural material with only small parts of land-fillings and thereby reducing and minimizing the risk of environmental pollution. The subareas Rönnskär and Hamnen got classified into risk class 2 – high risk. Both areas were filled up by copper slag and iron sand which lowers the risk for dispersion and leaching. Nevertheless, both areas are considered as highly polluted regarding arsenic, lead, cadmium, copper and zinc. The highest risk class were reached by Område vid Magasin 5 and Anrikningssand (tailings) due to the tailings characteristics regarding weathering and the local conditions. Both locations consist of tailing fillings, whereby Område vid Magasin 5 is only partly filled with tailings. None is good enough covered to prevent the formation of groundwater and thereby the risk of leaching. Besides the common elements arsenic, lead, cadmium, copper and zinc, the analysis of tailings further identified moderate amounts of cobalt and vanadium as well as chrome, mercury and nickel (WSP Samhällsbyggnad, 2007).

Appendix B: Mining laws and regulations

Sweden's mining industry has experienced a remarkable boom over the last two decades and does currently count as Europe's leading producer of ores and minerals (SGU, Geological survey of Sweden). Along with this industrial development comes its impact on society from an economic, environmental and social point of view. Social responsibility has long been underestimated by Swedish mining authorities until, in recent years, stakeholders and governments started supporting ecological movements and implementing sustainability strategies (Kapelus, 2002). Due to Sweden's entry into the European Union in 1995, its mining industry is tied to European as well as Swedish laws and regulations.

The European Union aims to develop into a circular economy where "the value of the products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised" (European Commission, 2015). Accordingly, the EU Commission adopted the BAT decisions (2016) in order to establish the best-available techniques (BAT) for the non-ferrous metals industries. Its reference documents (BREFs) provide descriptions covering respective operating conditions and emission rates of industrial mining processes, using Rönnskär smelter as example plant. This green movement had its kick-off in 1984, when companies started adopting the Council Directive 80/360/ECC which was designed to prevent and reduce air pollution from industrial plants. Since then, new environmental laws have been constantly introduced and a steady improvement of environmental performance can be measured (European Commission, 2016; European Commission, 2017).

In Sweden, the principal environmental laws regulating the mining industry are covered by the Environmental Code and the closely tied Minerals Act. Both are applicable to all exploitation and exploration on land whereby the actual mining operations, including recycling processes, are managed by the Environmental Code and granted by the Land and Environmental Court (Dyer and Pehrson, 2018). Furthermore, in June 2017, Sweden decided on a new climate policy framework, the most important throughout history, following the objectives of the Paris Agreement (Ministry of the Environment and Energy, 2017). Already in 2013, five strategic objectives for the management of minerals had been identified by the Swedish government with the aim to provide the basis for a sustainable usage and a maintained and strengthened position within the EU (Swedish Ministry of Enterprise, Energy and Communications, 2013). The results should help to build up a so called "smart industry" sector, which is a newly established concept by the Swedish government in order to strengthen companies' capacity for change and competiveness. One of its focus areas concerns sustainable production and within the mining industry, claiming increased resource efficiency, environmental considerations and a more sustainable production (Ministry of Enterprise and Innovation, 2016).

However, additional pressure is coming from Naturvårdsverket, the Swedish Environmental Protection Agency, whose work ensures the fulfilment of the generation's goal for environmental work and environmental quality objectives in Sweden. The recent past shows that the Swedish Environmental Protection Agency has been actively involved with the mining business in Sweden as well as pro-actively initiating judicial proceedings such as the appeal against Rönnskär's issue of energy efficiency in 2018 or the annulment of the approval of financial security in 2016 (Naturvårdsverket, 2018; Naturvårdsverket, 2016).

Appendix C: Data collection copper slag

Landström (1989) – Restprodukter. Vad gör vi med dem?

Copper slag production between 1930 and 1966 at Rönnskär smelter

SLAGGPRODUKTION

År	Typ	kton	Au	Ag	Cu	Anm.
			Halt g/t el. %			
1930	Flamugn	24	0,5			Startår
1931	"	60	0,8	9	0,31	
1932	"	167	1,5	9	0,3	
1933	"	244	1,3	7	0,24	
1934	"	226	1,4	7	0,27	
1935	"	247	0,9	6	0,25	
1936	"	218	0,9	7	0,34	
1937	"	195	0,9	6	0,28	
1938	"	201	0,8	5,5	0,25	
1939	"	174	0,9	6	0,27	
1940	"	192	1,0	7	0,33	
1941	"	197	0,8	6	0,35	
1942	"	193	0,5	6	0,37	
1943	" /Elugn	168/29	0,35/0,8	4 / 1	0,37/0,64	Nuv. Pb-hytta
1944	" "	145/20	0,4 /0,8	4 /14	0,40/0,70	
1945	" "	118/20	0,2 /0,5	3,5/ 6	0,40/0,80	
1946	" "	79/11	0,4 /0,4	4 / 9	0,50/0,86	
1947	"	132	0,2	4,5	0,50	
1948	"	128	0,3	3	0,50	
1949	"	55	0,2	3	0,50	
	Summa:	3 243	0,75			
1949	Elugn	69	0,6	5	0,44	Nuv. Cu-hytta
1950	"	142	0,3	3	0,40	
1951	"	128	0,2	2	0,34	
1952	"	107	0,3	4	0,31	
1953	"	142	0,3	3	0,34	
1954	"	170	0,4	4	0,34	
1955	"	151	0,3	5	0,33	
1956	"	158	0,3	6	0,35	
1957	"	186	0,3	5	0,38	
1958	"	163	0,3	6	0,36	
1959	"	171	0,3	6,5	0,40	
1960	"	159	0,4	7	0,37	
1961	"	150	0,3	6	0,43	
1962	"	173	0,3	7	0,40	
1963	"	200	0,4	6	0,41	
1964	"	44	0,5	8	0,60	Fumingstart 1)
1965	"	56	0,4	14	0,69	
1966	"	28	0,5	10	0,66	
	Totalsumma:	5 512				

7 selected drill-holes from the industrial area at Rönnskär (2018)

NEW BOLIDEN Analysintyg **Pris:** 19 383 kr

RCP-000798 **Provdatum:** 2018-11-29

Boliden Mineral AB

Kostnadsställe: 7204 Verena exjobb

Insändare Pasi Peltola

Föremål: Markprov (från borrhål på industriområdet)

Labnr	Märkning	Ag-FA g/t	As % FAAS	Au-FA g/t	Bi % FAAS	Cd % FAAS	Clx % JONSEL	Cu % FAAS	Hg g/t AFS
122848	*** 15GV08U 1-2 /	9	0.030	0.4	<0.005	<0.002	<0.10	0.51	0.4
122849	*** 15GV08U 4-5 /	6	0.57	0.2	<0.005	0.003	<0.10	0.36	7.4
122850	*** 15GV09U 2,5-3,5 /	11	2.34	0.5	0.005	<0.002	<0.10	0.60	4.3
122851	*** 15GV09U 3,5-4,5 /	11	0.92	0.4	<0.005	<0.002	<0.10	0.58	2.8
122852	*** 15GV10U 0,5-1,5 /	10	0.084	1.0	<0.005	<0.002	<0.10	0.54	1.0
122853	*** 15GV20U 0,5-2 /	7	0.11	0.4	<0.005	0.002	<0.10	0.42	< 0.1
122854	*** 15GV22U 2-3 /	10	0.070	2.0	<0.005	<0.002	<0.10	0.29	< 0.1

Labnr	Märkning	Ni % FAAS	Omnian - XRF	PD g/t ICP	PT g/t ICP	Sb % FAAS	Zn % FAAS
122848	*** 15GV08U 1-2 /	0.010	Resultatfil	<1.0	<1.0	0.018	2.05
122849	*** 15GV08U 4-5 /	0.024	Resultatfil	<1.0	<1.0	0.044	4.01
122850	*** 15GV09U 2,5-3,5 /	1.07	Resultatfil	<1.0	<1.0	0.044	0.59
122851	*** 15GV09U 3,5-4,5 /	1.01	Resultatfil	<1.0	<1.0	0.026	0.67
122852	*** 15GV10U 0,5-1,5 /	0.009	Resultatfil	<1.0	<1.0	0.040	1.75
122853	*** 15GV20U 0,5-2 /	0.022	Resultatfil	<1.0	<1.0	0.055	4.15
122854	*** 15GV22U 2-3 /	<0.005	Resultatfil	<1.0	<1.0	0.027	1.05

WSP Samhällsbyggnad (2007) MIFO fas 1 – Inventering av potentiellt förorenade områden enligt NV rapport 4918

Tabell 8. Resultat från analyser av varmtippad slagg utförda 1988 och 1998. Resultaten redovisas i mg/kg TS med en antagen TS-halt på 100 %.

Prov nr.	Sb	As	Pb	Cd	Cu	Hg	Ni	Zn
1988:1	400	700	3000	-	6100	-	400	19800
1988:2	600	600	1000	-	3600	-	200	13800
1998:1	-	230	2100	20	3500	1	-	17200
1998:2	-	180	2300	10	3100	<1	-	16200

Appendix D: Data collection tailings

Boliden Report Technology (2017) – Investigation of technical, economic and environmental conditions to reprocess Rönnkärs old deposit for flotation tailings

Analyte		Au	Ag	Al	As	Ba	Be	Bi	Ca	Cd	Ce	Co	Cr	Cs
Unit		PPM	PPM	%	PPM	PPM	PPM	PPM	%	PPM	PPM	PPM	PPM	PPM
Rönnskär	Average	0.879857	5.041714	7.956714	2656.323	363.7143	0.641714	43.54029	1.198571	7.465714	95.95786	147.6171	236.4143	0.902
	Tonnage	1.608009	9.214136	1454153	4854.643	664.717	1.172784	79.57336	219048.5	13.64419	175.3707	269.7821	432.066	1.648477
Analyte		Cu	Fe	Ga	Ge	Hf	In	K	La	Li	Mg	Mn	Mo	Na
Unit		PPM	%	PPM	PPM	PPM	PPM	%	PPM	PPM	%	PPM	PPM	%
Rönnskär	Average	1219.18	6.795857	30.04643	0.306857	4.578571	1.239129	2.285	44.23571	17.19571	1.423	416.8429	22.59557	0.713
	Tonnage	2228.149	1241997	54.91225	0.560806	8.367706	2.264607	417602	80.84431	31.42654	260064.6	761.8137	41.29521	130306.5
Analyte		Nb	Ni	P	Pb	Rb	Re	S	Sb	Sc	Se	Sn	Sr	Ta
Unit		PPM	PPM	PPM	PPM	PPM	PPM	%	PPM	PPM	PPM	PPM	PPM	PPM
Rönnskär	Average	3.555714	61.61143	1308.429	622.95	46.23714	0.004471	2.320143	87.15571	18.41714	43.18571	41.21286	113.6243	0.831286
	Tonnage	6.498352	112.5998	2391.258	1138.491	84.50208	0.008172	424024.7	159.284	33.6588	78.92535	75.31979	207.6575	1.519241
Analyte		Te	Th	Ti	Tl	U	V	W	Y	Zn	Zr			
Unit		PPM	PPM	%	PPM	PPM	PPM	PPM	PPM	PPM	PPM			
Rönnskär	Average	11.82843	6.563143	0.210471	8.516286	4.09	109.9857	8.828571	15.07571	1920.914	161.17			
	Tonnage	21.6174	11.99467	38465.34	15.56419	7.474802	201.0077	16.13492	27.55207	3510.625	294.5511			

Australian Laboratory Services

Table 1 MLA Calculated Assay (%)

Element	Prov1 70305 - Wt%	Prov2 70306 - Wt%	Prov3 70307 - Wt%
Al	8.28	4.88	6.01
As	0.17	0.41	0.06
B	0.02	0.02	0.00
Ba	0.00	0.01	0.02
C	0.08	1.45	0.48
Ca	0.99	3.28	2.41
Ce	0.01	0.00	0.00
Cr	0.00	0.01	0.00
Cu	0.11	0.11	0.11
F	0.02	0.00	0.00
Fe	6.74	13.29	11.58
Gd	0.00	0.00	0.00
H	0.34	0.26	0.27
K	2.40	1.40	1.61
La	0.01	0.00	0.00
Mg	1.59	3.18	2.25
Mn	0.04	0.10	0.07
Na	0.67	0.53	0.92
Nd	0.01	0.00	0.00
O	45.73	38.91	40.03
P	0.12	0.02	0.02
Pb	0.13	0.13	0.16
Pr	0.00	0.00	0.00
S	3.07	10.34	9.87
Se	0.00	0.00	0.00
Si	28.71	20.82	23.42
Sm	0.00	0.00	0.00
Sn	0.01	0.01	0.00
Th	0.00	0.00	0.00
Ti	0.60	0.21	0.27
V	0.00	0.00	0.00
Zn	0.13	0.60	0.40
Zr	0.00	0.01	0.03
Total	100.00	100.00	100.00

Appendix E: Methodology - calculations

Economic/social cost & benefit

1. **Excavation work**

Digging up	1 000 000kr / 19 000t = 53 kr/t
Digging up and refilling with cost free iron sand	53 kr/t x 2 = 106 kr/t
Excavation cost copper slag	106 kr/t x 5 512 000t = 584 272 000kr
Excavation cost tailing sand	106 kr/t x 1 827 580t = 193 723 480kr

2. **Transportation / logistics**

Boliden Area

Number of trucks needed for copper slag transportation	5 512 000t / 45t = 122 489
Number of trucks needed for tailing sand transportation	1 827 580t / 45t = 40 613

Transportation cost copper slag	45kr x 5 512 000t = 248 040 000kr
Transportation cost tailing sand	45kr x 1 827 580t = 82 241 100kr
Total transportation cost	248 040 000kr + 82 241 100kr = 330 281 100kr

Aitik

Transportation cost copper slag	5 512 000t x 100.5kr = 553 956 000kr
Transportation cost tailing sand	1 827 580t x 100.5kr= 183 671 790kr

3. **Operation / processing**

Rönnskär

Copper slag	5.512.000 tons		
Utbyte			0.85
Potential			80116.92
LT price			18000
Payable			0.82
TC			163.0952
MSEK			1019.431
Oth raw materials MSEK			16536
Handling Rö			551.2
Net			-16067.8
cost per ton			-2915.05

Table []: Copper slag calculations for processing at Rönnskär

Boliden Area

tailings:	1.827.580 tons	copper slag	5.512.000
Utbyte	74%	Utbyte	5%
Potential	1037	Potential	4713
LT price	289357	LT price	18000
		Payable	1
		TC	10
MSEK	300	MSEK	63
Concentration	493	Concentration	1488
		Oth raw materials MSEK	1654
Handling Rö	183	Handling Rö	551
Net	-376	**Net**	-3631
per ton	-206	per ton	-659

Table []: Tailings and copper slag calculations for concentrator at Boliden

Aitik

Tailings			Copper slag		
Utbyte		0.37	Utbyte		0.025
Potential		519	Potential		2356
LT price		289357	LT price		18000
			Payable		0.85
			TC		5
MSEK		150	MSEK		31
Concentration		493	Concentration		1488
			Oth raw materials M		1654
Handling		183	Handling		551
Net		-526	Net		-3662
per ton [sek]		-288	per ton [SEK]		-664

Table []: Tailings and copper slag calculations for concentrator at Aitik

Environmental cost & benefit

4. Transportation

Boliden Area – truck transportation

	[€]	[SEK] (exchange rate 24.04.2019) 1€ = 10.5209 SEK
Copper slag	5 512 000*60km*2.4cent = 793728000cent ~ 7 937 280€	83 507 329kr
Tailings	1 827 580*60km*2.4cent = 263171520 ~ 2 631 715€	27 688 010kr
Total	7 937 280€ + 2 631 715€ = 10 568 995€	111 195 340kr
Per ton	10 568 995€ / (5 512 000t + 1 827 580t) = 1.44 €/t	111 195 340 / (5 512 000t + 1 827 580t) = 15.15 kr/t

Aitik – train transportation

	[€]	[SEK] (exchange rate 21.04.2019) 1€ = 10.5209 SEK
Copper slag	0.3cent x 5 512 000 x 365km = 603564000cent ~ 6 035 640 €	63 500 365kr
Tailings	0.3cent x 1 827 580 x 365km = 200 120 010cent ~ 2 001 200€	21 054 425kr
Total	6 035 640€ + 2 001 200€ = 8 036 840€	84 554 790kr
Per ton	8 036 840€ / (5 512 000t + 1 827 580t) = 1.094 €/t	84 554 790kr / (5 512 000 + 1 827 580) = 11.5 kr/t

5. Processing

Rönnskär

	[€]	[SEK] (exchange rate 21.04.2019) 1€ = 10.5209 SEK
Total CO_2 emission (copper slag)	0.03 x (55 x 285 404 000kg) = 470 916 600kg = 470 916.6t	
Total cost	470916.6t x 145€ = 68 282 907€	718 397 636kr
Cost per ton	68 282 907€ / 5 512 000t = 12.4 €/t	718 397 636kr / 5 512 000t = 130 kr/t

	Total amount in 55 years	[€]	[SEK] (exchange rate 21.04.2019) 1€ = 10.5209 SEK
Dust	15.6t x 0.1 x 55 = 85.8t	85.8t x 39 700€ = 3 406 260€	35 836 921kr
SO_2	628t x 0.1 x 55 = 3454t	3454t x 13 200€ = 45 592 800€	479 677 290kr
NO_x	59t x 0.1 x 55 = 324.5t	324.5t x 15 400€ =	52 576 094kr

		4 997 300€	
Total		3 406 260€ + 45 592 800€ + 4 997 300€ = 53 996 360€	568 090 304kr
Per ton		53 996 360€ / 5 512 000t = 9.79€	568 090 304kr / 5 512 000t = 103 kr/t

Dust, SO2 and NOx emissions accruing from processing 5 512 000t copper slag at Rönnskär's zinc fuming plant

Per ton cost CO2	130 kr/t
Per ton cost dust, SO2, Nox	103 kr/t
Total cost per ton	130 kr/t + 103 kr/t = 233kr/t
Total cost	233 kr/t x 5 512 000t = 1 284 296 000kr = 1284.3 MSEK

Boliden Area and Aitik

	CO2	NOx	SO2
Crushing per 1 kg input	30.59kg / 8935.5kg = 3,42kg/t	0.18kg / 8935.5kg = 0.020kg/t	0.28kg / 8935.5kg= 0.0313kg/t
Milling per 1 kg input	411.13kg/ 8935.5kg = 46kg/t	2.48kg / 8935.5kg = 0.278 kg/t	3.82kg / 8935.5kg = 0.428 kg/t
Flotation per 1 kg input	52.59kg / 62 545.5kg = 00.841 kg/t	0.32kg / 62 545.5kg = 0.00512 kg/t	0.49kg / 62 545.5kg = 0.0078 kg/t
Dehydration per 1 kg input	29.64kg / 62 545.5kg = 0.474 kg/t	0.18kg / 62 545.5kg = 0.00288 kg/t	0.28kg / 62545.5kg = 0.00448 kg/t
Total (with crushing) = copper slag	50.735 kg/t	0.306 kg/t	0.472 kg/t
Total (without crushing) = tailings	47.315 kg/t	0.286 kg/t	0.44 kg/t

	Copper slag (5 512 000t)	Tailings (1 827 580t)
CO2 (145€/t)	5 512 000t x (50.735kg/t / 1000) x 145€ = 40 549 441.4€	1 827 580t x (47.315 kg/t /1000) x 145€ = 12 538 432.42€
NOx (15 400€/t)	5 512 000t x (0.306kg/t /1000) x 15 400€ = 25 974 748.8€	1 827 580t x (0.286 kg/t /1000) x 15 400€ = 8 049 393.35€
SO2 (13 200€/t)	5 512 000t x (0.472 kg/t / 1000) x 13 200€ = 34 341 964.8€	1 827 580t x (0.44 kg/t / 1000) x 13 200€ = 10 614 584.64€
Total [€]	100 866 155€	31 202 410€
Total [SEK] (exchange rate 21.04.2019) 1€ = 10.5209 SEK	1 061 202 730kr	328 277 435kr
Cost per ton [SEK]	1 061 202 730kr / 5 512 000t = 192.5 kr/t	328 277 435kr / 1 827 580t = 179.6 kr/t

6. Energy production

Rönnskär

Total electricity per year	144 000MWh
Total electricity needed for copper slag	0.1 x 144 000MWh x 55 = 792 000MWh
Total environmental costs electricity for copper slag processing [€]	792 000 000 kWh x 0.18cent = 1 425 600€
Total environmental costs electricity for copper slag processing [SEK]] (exchange rate 21.04.2019) 1€ = 10.5209 SEK	14 998 595 SEK = 15 MSEK
Total environmental costs electricity for copper slag processing per ton [SEK]	2.72 kr/t

Boliden Area

Electricity source	GWh based on 53 GWh (78% of total) and Sweden's energy production	€-cent / kWh	Total costs €	[SEK] (exchange rate 21.04.2019) 1€ = 10.5209 SEK
Water energy	21.36	0.18	38 448	404 508
Wind energy	5.83	0.26	15 158	159 476
Nuclear energy	20.67	-	-	-
Conventional	4.98	9.8	488 040	5 134 620
Solar energy	0.053	1.18	625.4	6 580
Total			542 271	5 705 179
Fossil Fuel	GWh based on 14.95 GWh (22% of total)			
Gas	14.95	4.91	734 045	7 817 502
Electricity + fossil fuel			**1 276 316**	13 427 993

Environmental costs of energy consumption at Boliden in one year based on the environmental costs for energy production in Germany 2010 (Umweltbundesamt).

Yearly energy consumption environmental cost	13 427 993 SEK
Copper slag	0.17 x 13 427 993 x 18.4 = 42 002 762 SEK
Tailings (lower, due to no crushing, only milling)	0.17 x 13 427 993 x 6.01 = 13 719 381 SEK
Total	42 002 762 SEK + 13 719 381 SEK = 55 722 142 SEK
Per ton	55 722 142 SEK / (5 512 000t + 1 827 580t) = 7.59 kr/t

Aitik

Electricity source	GWh based on 366.41 GWh (90% of in total 407.12 GWh)	€-cent / kWh	Total costs [€/h]	[SEK/h] (exchange rate 21.04.2019) 1€ = 10.5209 SEK

Water energy	147.66	0.18	265 788	2 796 329
Wind energy	40.31	0.26	104 806	1 102 654
Nuclear energy	143.99	-	-	-
Conventional	34.44	9.8	406 392	4 275 610
Solar energy	0.366	1.18	4 319	45 440
Total			**781 305**	8 220 032
Fossil Fuel	GWh based on 40.71 GWh (10% of in total 407.12 GWh)			
Diesel	40.71	8.06	3 281 226	34 521 451
Electricity + fossil fuel, total			**4 062 531**	42 741 482

Yearly energy consumption	42 741 482 SEK
Environmental cost copper slag	0.15 x 42 741 482 SEK = 64 411 222 SEK
Environmental cost tailings	0.05 x 42 741 482 SEK = 2 137 074 SEK
Total environmental cost	64 411 222 SEK + 2 137 074 SEK = 66 548 296 SEK
Cost per ton	66 548 296 SEK / (5 512 000t + 1 827 580t) = 9.1 kr/t

7. Other affected ecosystems

Conversion factor	$1m^3 = 1.6t$
$1m^2$ copper slag with a depth of 4.5m	1.6t x 4.5m = 7.2t per m^2
Total approximate area covered by copper slag	5 512 000t / 7.2t per m^2 = 765 555.6m^2 (76.6 ha)

Costs per ha	100 000kr / 3.5ha = 28 571.43kr
Cost copper slag area	76.6ha x 28571.43kr = 2 188 571kr
Cost tailing sand	24ha x 2188571.54kr = 685 714kr

Appendix F: Alternative treatment scenarios

Besides the three main scenarios Rönnskär, Boliden Area and Aitik, there exist further options which are worth considering and looking into. On one hand, there are alternatives regarding the present time such as dumping all the material at a specialised dumping site or covering it up at Rönnskär in order to prevent any material from leaking. On the other hand, there are new options opening up when thinking in future terms regarding technological development and life-time cycles of mines. For several years now, scientists are focusing on more environmentally friendly remediation technologies such as bio-hydrometallurgy (making use of microbes) or phytoremediation (making use of various types of plants). Besides these technological developments, each mine has an end of lifetime and companies are bounded by law to perform remediation work, meaning they have to close up the underground mines by refilling and reconstruction of natural habitats.

Present alternatives

The following paragraphs describe a possible dumping, cover up and slag formation scenario which are all align with today's technological development and given time frame. Questionable is the beneficiary of these scenarios but first indications are given as potential starting point for further investigation.

<u>Dumping scenario Umeå</u>

Dumping Rönnskär's copper slags and tailings is one option that should be considered, even if it is quite unlikely to happen in reality. Dåva Deponi is a waste disposal area located in Umeå, south of Skellefteå and is specialized in both, dangerous and non-dangerous waste. According to Boliden Rönnskär (2018), copper slag can be categorized as non-dangerous waste whereas tailings belong to the group of dangerous waste. The different categorization is motivated by the material's leachability. The minimum requirements for every waste deposited at Dåva Deponi is a full characterisation of the material, including a detailed description of the waste's composition, its leaching behaviour in the short and long term as well as other characteristics of waste and additional tests. In the case of dangerous waste such as tailings, tailored leaching tests and ANC (acid neutralization capacity) have to be conducted before leaving the material at the deposit area. So far, no taxes would be applicable for Rönnskär's copper slags and tailings but the environment and corresponding risks are of constant present amongst politicians and the public which is why additional fees could be implemented in the future. If copper slags and tailing sands would be taxable, Dåva Deponi would charge additional 500 kr/ton waste. In general, the deponi's costs are:

Classification	volume	Costs [kr/t]
Dangerous	<50 tons	720
	>50 tons	500
Non-dangerous	< 50 tons	420
	> 50 tons	300-350

Table 19: Dåva Deponi costs for dangerous and non-dangerous waste depending on its volume size.

In order to get a rough approximations on the total costs, it is necessary to include accruing costs from excavation work, transportation as well as the required material characterization. Excavation and transportation costs are based on the results from the three main scenarios, assuming material transportation via trucks with an average costs of 90 kr/ton x 2 = 180kr/ton due to a distance of 130km instead of 60km (Boliden scenario) whereas the material characterization of each project is estimated to be around 10 000 SEK.

According to rough calculations it would cost about 611 kr/t copper slag and 786 kr/t tailings, however, these are only approximate calculations which might actually be higher in reality. Furthermore, Dåva Deponi has to comply with its licence from Umeå district court, a processing permit (including receiving, treating, storing, recycling and disposing) limited to an average of 250 000t of waste over two years with a maximum of

A, 150.000 tons are allowed to be deposited including only 75.000 tons of hazardous waste

B, 150.000 tons of contaminated waste can be treated

C, 10.000 tons of hazardous waste that can be stored and collected (DAC_Miljötillstånd, 2018). On grounds of this permit, transporting and dumping Rönnskär's copper slags and tailings at Dåva Deponi will most likely take several years and require great amounts of money (Dåva Deponi, 2019).

<u>Cover – up scenario</u>

A possible cover – up scenario is a site-specific operation which isolates the contaminated material from the surrounding environment. This method would only be applicable for Rönnskär's tailings due to their risk of oxidation. In that case, a coverage would minimize the oxygen transport within the tailings and thereby prevent the dangerous sulphide oxidation. In comparison, Rönnskär's copper slag leaching capacity is too low to actually benefit from such a method application.

Useful insights and data are coming from Boliden's Gillervattnet reclamation project, a former tailings pond which was undergoing reclamation work between 2013 and 2017. The goal was to transform this sulphur-rich tailings area into a wetland habitat for wildlife (Boliden, 2019). The used coverage consisted of a 0.3m high-compaction waterproof moraine (k <1*10-9 m/s), a 1.5 to 2m protective layer and a 0.2m plant growth layer with vegetation on top. This coverage is expected to limit the oxygen transport to <1 mole O_2/m^2/year. However, finding enough suitable moraine for the dense layer is not always guaranteed which is why bentonite can either be mixed into the sealing layer or put as a mat under the sealing layer.

The accruing costs of such an operation are highly dependent on the general circumstances such as location, moraine accessibility, contaminated material, etc. According to Nils Eriksson (Boliden) it can be expected to pay about 200 kr/m^2 for a pure moraine cover, 250kr/m^2 if you put a bentonite mat underneath and about 300 kr/m^2 if you decide to mix bentonite in the sealing layer.

Applying these numbers on Rönnskär's tailings, assuming an approximate area of about 20 ha and the construction of a bentonite mat under the sealing layer, results in 200 000m^2 x 250kr/m^2 = 50 MSEK. This corresponds to ca. 27.4kr per ton tailings and 250kr per m^2 tailings.

Slag formation

The production and extraction of lead is done by the Kaldo Plant which processes mainly lead concentrates and electric waste consisting of certain amounts of lead. At Rönnskär, about 3 600t iron sand is yearly used as a slag generator in order to obtain separable slag during certain operations. Instead of iron sand, it might be possible to feed the Kaldo Plant with historical copper slags, dug up from the industrial area (Boliden, 2009). However, when using copper slags as slag former, its characteristics have to accord with the operational conditions as well as the performance of iron sand.

In comparison with iron sand, copper slag contains approximately the same amount of Si and Fe but reasonably more Pb and other elements such as Cd and Zn which are usually extracted during the fuming process. According to Per Kautto (Boliden) one of the main problems would be an increased Zn content, which Rönnskär is even currently been struggling with, as well as the necessity of intensive slag tests. Feeding the plant with something un-known can lead to significant damages of the machinery and material.

Regarding iron sand, the advantage accrues from its consistent quality over time whereas the usage of copper slag would reduce the amount of problematic/contaminated soil fillings at Rönnskär. In addition, saved iron sand can be used as new fillings for the dug up wholes accruing from copper slag excavation. Simply said, the exchange of copper slag for iron sand would constitutes a more environmentally-friendly long-term solution for Rönnskär's dumped copper slags.

Future alternatives and research

This section covers thoughts and ideas which are not feasible yet but are worth considering in the future. Technological development and time are driving forces of change, meaning that there might exits other more suitable solutions for Rönnskär's copper slags and tailings than the ones given today. Therefore, this paper will shortly discuss two future leading technologies, bio-hydrometallurgy and phytoremediation, which have shown promising results regarding remediation work but are still not fully developed. Additionally, the incorporation of copper slags and tailing in reclamation work of mines is been investigated due to the fact that some Swedish mines are close to the depletion of their reserves.

<u>Bio-hydrometallurgy</u>

Bio-hydrometallurgy is considered as one of the future leading technologies regarding metal extraction and can be described as the conjunction of biotechnology and metallurgy. The interactions between microbial metabolism and minerals were crucial for the development of an integrated/hybrid bio-chemical process which enables the extraction of valuable metals from copper slag or other secondary products (Ilyas et al, 2017). According to Erüst et al. (2013), bio-hydrometallurgical treatment of copper encompasses mainly the process of bioleaching, the conversion of insoluble metal sulphides into soluble metal sulphates. The ability of microorganism to successfully recover valuable metals from different primary and secondary sources has been proven and discussed by several researchers in the past. Kaksonen et al. (2014) examined the process and recovery of gold from different sources by microorganism, Erüst et al. (2013) focused on the recovery of metals from spent batteries and catalysts whereas Lee and Pandey (2012) compared the different methods within the field of bio-hydrometallurgy for the extraction of metals from different industrial wages.

Pros/cons

Bio-hydrometallurgy is one of the most promising and revolutionary technologies in the field of metal recovery from secondary resources due to its economic and environmental advantages compared to traditional hydrometallurgical or pyrometallurgical processes (Erüst et al. 2013). This green alternative is considered to have lower energy consumption, lower capital investment, lower operational selectivity from lean ores, the technical feasibility for large scale applications as well as no need for addition of toxic chemicals or hazardous sludge (Lin et al. 2015; Sethurajan et al. 2018; Erüst et al. 2013). In addition, Lin et al. (2015) argues that using a bio-hydrometallurgical route for secondary metal resources has the potential side-effect of developing an increased metal tolerance by radiation, chemical mutagenesis as well as biological technology for higher achievements on the industrial scale. Although, bio-hydrometallurgy plays an important role in the current and future field of metal extraction, this method is also stroke by limitations. Ilyas et al. (2017) concludes that long-term commitments of time, money, management and facilities required by resource holders are mandatory in order to successfully apply this method whereby risk and commercial exploitation are not allowed to be underestimated. Therefore, most conducted research deduces that bio-hydrometallurgical treatment is highly relevant for the future extraction of metals from secondary resources, nevertheless, additional studies, theoretical and technological improvement as well as further improvisation and innovation has to be done before a comprehensive implementation of that method can take place (Ilyas et al. 2017; Sethurajan et al. 2018).

Phytoremediation (plants)

Phytoremediation, also known as “green and clean” technology, describes the cleaning of contaminated soils, sediments, surface water and groundwater with the help of plants (phyto=plant, remediation=amelioration of contaminated soil). This method comprises of 6 different approaches, namely phytoextraction, phytostabilization, phytodegradation, phytovolatilization, rhizodegradation and rhizofilteration whereby only the two first options are commonly used for the remediation of contaminated soils. The idea behind this method evolved from the plants’ capacity to absorb heavy metals from polluted mediums (phytoextraction) as well as the ability to facilitate the immobilization or degradation of heavy metals (phytostabilization) (Jakovljević et al., 2016). However, the success of this process depends not only on the plant but on multifarious interactions and relationships between plants, soil, microbes and heavy metals (Laghlimi et al., 2015).

Pros/cons

Phytoremediation, in comparison to conventional cleaning methods, is known to be a sustainable, cost-effective, environmentally beneficial and aesthetically advantageous approach (Bauddh et al., 2017). It's environmental and economic benefits can be found in all project stages starting with a general trust and acceptance of the public and followed by low investment-, operation- and maintenance costs. The sun is used as major energy source and the growing process of the plants is more of a passive than an active work environment for humans. In addition, the presence of plants can stabilize soils, enhance microbiological activities and decrease the amount of water which could facilitate the leaching of toxic substances. The disadvantages are determined by the required space and the long growing times of plants. The cleaning process might also be limited by the depth of the soil and relevant heavy metals could enter the groundwater as well as the food chain via animals. Furthermore, if phytoextraction is performed, plants can be harmed through high concentrations of contaminants and therefore pose problems to their disposal technique (Jakovljević et al., 2016). In terms of bioenergy production, phytoremediation contributes to a reduction in greenhouse gases and prevent the usage of land and water which is needed for food production. The crop generated bioenergy is cheaper, safer and more sustainable than fossil fuels (Bauddh et al., 2017).

Reclamation work

Each mine has a limit of life time due its natural reserves being exhausted one day. If a mine is no longer profitable it loses its general purpose and gets shut down. However, during a mine's lifetime, significant damage occurred above ground as well as underground which has to be taken care of. Therefore, most mining operations have arranged reclamation plans already before starting operating in order to assure the restoration of the previously used land. The same applies for Boliden who have some 30 active, closed down and soon to be closed down mining areas. These necessary reclamation works require, besides intense planning and long time periods (up to 10 years) for implementation, huge amounts of soil/material to fill up the mined underground parts (Boliden, 2019). The basic idea regarding Rönnskär's historical copper slags and tailings would be a direct incorporation as filling material within the reclamation work. On one hand, these environmentally problematic materials would disappear from their current locations and thereby eliminate the risk for any environmental or social damages. On the other hand, other more clean materials which would have been used as filling material will be saved and can serve different purposes in need of these particular materials and their characteristics.

Despite this stated win-win situation, using copper slags and tailings as filling material would most likely also result in fewer economic as well as environmental costs. Cost regarding excavation, transportation or the indirect effect on other ecosystems through operations would naturally occur but all costs accruing from processing, including most environmental costs coming from emissions, would basically disappear. In addition, costs for buying filling material on the reclamation projects balance sheet would disappear and probably benefit Boliden.