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TOWARDS CIRCULAR ECONOMY IN THE MINING INDUSTRY:

Implications of Institutions on the Drivers and Barriers for Tailings Valorization

Faculty of Management and Business
Master’s Thesis
May 2019

ABSTRACT

Kinnunen Päivi: Towards Circular Economy in the Mining Industry: Implications of Institutions on the Drivers and Barriers for Tailings Valorization
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May 2019

The main objective of this thesis is to advance knowledge of circular economy business potential in the mining industry. Mining and metal companies have been almost totally lacking from the circular economy conversation. In the light of this gap, there is a clear need to understand the business potential for circular economy also in the mining and metals sector. The development of circular economy model for the mining industry has clear potential to solve the challenges related to the shortage of mineral resources, waste of resources and environmental pollution with subsequent economic profits.

Metals are needed for modern applications to increase our standard of living e.g. in renewable energy production and high-tech products. Sustainable development goals of the United Nations for global economic development and environmental sustainability result in the wide utilization of various minerals for green technologies. In addition to economic and societal benefits, mining has produced significant amounts of mining and quarrying waste called tailings. Tailings have the potential to be transformed from hazardous waste to potentially valuable secondary metal sources. The valorization of mining waste could add to the raw materials supply, and subsequently reduce the environmental impact. Circular economy concepts can help to create value from mining waste.

Institutions emerging via regulative, normative and cognitive processes have a huge effect on the behavior of corporations. Circular economy itself has been considered as an institution. Institutional theory suggests that uncertainty and innovation characterize a new field. Organizations tend to mimic the successful organizations to overcome the uncertainty. When the field is mature, almost all organizations in the field follow the same kinds of rules and structures.

The utilization of circular economy concepts needs advancements in filling the knowledge gaps of business opportunities, drivers and barriers. The drivers, needs and barriers for tailings valorization in the mining industry were identified in the workshop and theme interviews in this study. The results pointed out, that there is clear potential for the tailings valorization in the long-term, even though this potential has remained underexplored. The identified opportunities and drivers were categorized under circular economy mindset, and technological, environmental, institutional and economic drivers. The needs were new value chains, technology development, a decrease in the amount of waste, stability, taxation and predictability of regulation. Challenges and bottlenecks were categorized under new value chains, technological, environmental, institutional, economic and knowledge bottlenecks.

Identification of drivers and barriers could accelerate the transformation towards circular economy in the mining industry. By understanding the circular economy business potential for tailings valorization in the mining sector, the study provides support for designing and implementing circular business in the mining sector. Even though there are several institutional initiatives to move the mining industry from linear to circular economy, also barriers to such transformation exist. There is clear business potential for metals recovery from mining waste in the future, but the identified barriers need to be addressed both by companies and by institutional stakeholders to speed up the transformation.

This thesis is based on the article "Towards circular economy in mining: Opportunities and bottlenecks for tailings valorization" by Kinnunen and Kaksonen (2019) published in the Journal of Cleaner Production and reprinted with permission from Elsevier in Appendix 3 in this thesis.

Keywords: Circular economy, institutional theory, mining industry, waste valorization, tailings

The funding of the Academy of Finland [EcoTail, Valorization of Tailings for Circular Economy, Decision no. 306079] is highly acknowledged.

TIIVISTELMÄ

Kinnunen Päivi: Kohti kiertotaloutta kaivosteollisuudessa: Instituutioiden vaikutukset rikastushiekkojen hyödyntämisen ajureihin ja esteisiin
Pro gradu
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Toukokuu 2019

Tämän tutkimuksen tavoitteena on edistää ymmärrystä kiertotalouden liiketoimintamahdollisuuksista kaivosteollisuudessa. Kaivos- ja metallurginen teollisuus ovat puuttuneet lähes kokonaan kiertotalouskeskustelusta, mikä on johtanut tarpeeseen ymmärtää kiertotalouden liiketoimintamahdollisuuksia myös näillä teollisuudenaloilla. Kiertotalouden mallin kehittäminen kaivosteollisuudelle voisi ratkaista metallien saatavuuden, resurssien hukkaamisen ja ympäristön pilaantumisen haasteita ja tuottaa samalla taloudellista hyötyä yrityksille.

Metalleja tarvitaan modernissa yhteiskunnassa esimerkiksi uusiutuvan energian tuotannossa sekä korkean teknologian tuotteissa. Yhdistyneiden Kansakuntien kansainväliseen talouskehitykseen ja ympäristöön liittyvät kestävän kehityksen tavoitteet tarvitsevat toteutuakseen erilaisten metallien hyödyntämistä vihreissä teknologioissa. Taloudellisten ja yhteiskunnallisten hyötyjen lisäksi kaivosteollisuuden toiminta on johtanut kaivosjätteen eli rikastushiekan muodostumiseen. Rikastushiekka on mahdollista muuttaa vaarallisesta jätteestä metallien raaka-aineeksi. Rikastushiekkaa hyödyntämällä olisi mahdollista lisätä raaka-aineiden tarjontaa ja samalla pienentää ympäristövaikutuksia. Siten kiertotalouden toimintamallit auttavat luomaan arvoa kaivosjätteestä.

Instituutioilla on merkittävä vaikutus yritysten toimintaan lainsäädännöllisten, normatiivisten ja kognitiivisten prosessien kautta. Kiertotaloutta itsessään voidaan pitää instituutiona. Institutionaalisen teorian mukaan epävarmuus ja innovointi luonnehtivat uutta toimintakenttää. Organisaatiot pyrkivät voittamaan toimintaympäristönsä epävarmuuden jäljittelemällä menestyviä organisaatioita. Kun toimintakenttä on kypsä, lähes kaikki alan organisaatiot noudattavat samanlaisia sääntöjä ja rakenteita.

On tärkeää saada lisää tietoa liiketoimintapotentiaalista sekä ajureista ja esteistä kiertotalouteen siirryttäessä. Tässä tutkimuksessa kaivosteollisuuden ajurit, tarpeet ja esteet rikastushiekkojen hyödyntämiselle selvitettiin työpajatyöskentelyllä ja teemahaastatteluilla. Tulokset osoittivat, että pitkällä aikavälillä rikastushiekkojen hyödyntämisessä on liiketoimintamahdollisuuksia, vaikka liiketoimintapotentiaali on tähän mennessä jäänyt hyödyntämättä. Kiertotalousajattelu, teknologinen kehitys, instituutiot, taloudelliset mahdollisuudet ja ympäristönäkökulmat tunnistettiin kaivosteollisuuden ajureiksi. Tarpeisiin lukeutuivat uudet arvoketjut, teknologian kehitys, jätteen määrän vähentäminen ja stabiilisuus, sekä verotus ja lainsäädännön ennustettavuus. Haasteina pidettiin arvoketjujen puuttumista, tiedon vähyyttä sekä teknologisia, institutionaalisia, taloudellisia ja ympäristöön liittyviä pullonkauloja.

Ajureiden ja esteiden tunnistaminen voi nopeuttaa kaivosteollisuuden muutosta kohti kiertotaloutta. Tämä tutkimus edistää ymmärrystä kiertotalouden liiketoimintapotentiaalista rikastushiekkojen hyödyntämisessä. Siten se tukee kiertotalouden suunnittelua ja käyttöönottoa kaivosteollisuudessa. Vaikka useat instituutiot kannustavat siirtymiseen lineaarisesta taloudesta kiertotalouteen, muutokselle on olemassa myös esteitä. Metallien talteenotto kaivosjätteistä arvioitiin tutkimuksessa tulevaisuuden liiketoimintamahdollisuudeksi, mutta yritysten ja instituutioiden pitää huomioida tunnistetut esteet muutoksen nopeuttamiseksi.

Avainsanat: kiertotalous, institutionaalinen teoria, kaivosteollisuus, jätteiden hyödyntäminen, rikastushiekka

Kiitän Suomen Akatemian rahoitusta EcoTail -projektille [Metallien talteenotto rikastushiekoista kaivosteollisuuden kiertotaloudessa, päätösnumero 306079].

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TERMINOLOGY

Barrier	A factor, which limits the adoption of circular economy concept.
Circular Economy	“A circular economy describes an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.” (Kirchherr et al., 2017a, 224–225)
Circular Economy Package	Circular Economy Package was adopted by the European Commission in 2015. The aim is to move Europe’s economy towards a more sustainable direction and to generate new and sustainable competitive advantages for Europe. (European Commission, 2015a; 2017.)
Critical Raw Material	A material is considered as a Critical Raw Material, when it is of high economic importance and has a high supply risk (European Commission, 2014b).
Driver	A factor enabling and encouraging the transition to circular economy (de Jesus & Mendonça, 2018, 77).
Institutional theory	Institutional theory argues, that the social context, norms and expectations influence the behaviour of companies (Meyer & Rowan, 1977; Dale, 2002; Scott, 2008).
Tailings	Mine tailings is the term used for the remaining fine-grained rock and processing fluids, when the valuable minerals have been extracted from the mined ore (Edraki et al., 2014).

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1 INTRODUCTION

1.1 Background

The main objective of this study is to advance knowledge of circular economy business potential in the mining industry, whose business can be significantly impacted by this transition. The current economy has been locked-in in the linear "take-make-dispose" production and consumption mode established in the beginning of industrialization (Sitra, 2015; Ellen MacArthur Foundation, 2013, 2015). Based on estimates, we are over-utilizing resources 50% faster than their replacement takes place (Esposito et al., 2017). However, disruptive trends exist bringing the economy towards a circular one (Sitra, 2015; Ellen MacArthur Foundation, 2013, 2015a). Circular economy is a new economic model, with a huge economic potential and zero waste creation in focus. Circular economy aims to keep products and materials in use as long as reasonable and to preserve the value of materials. (Ellen MacArthur Foundation, 2015a; Antikainen & Valkokari, 2016, 6; Ritzén & Sandström, 2017.)

Institutional incentives, such as regulations and business standards, can make the collaboration in circular economy easier and therefore have a huge effect on the transition towards circular economy. These rules enable the inter-firm collaboration in more complex and specific circular economy systems compared to the conventional linear system. (Fischer & Pascucci, 2017.) Several European-wide (European Commission, 2011, 2015a, 2017) and Finnish national institutions (Sitra, 2015, 2016) have emphasized the need for the transition to the circular economy model. European Commission adopted the Circular Economy Package in 2015. It includes legislative proposals on waste and aims to reduce landfilling and increase material recycling and reuse. The aim is to move Europe's economy towards a more sustainable direction, which at the same time can create novel sustainable competitive advantages for Europe. (European Commission, 2015a; 2017.) In Finland, the target is to make Finland a global leader in circular economy by 2025 (Sitra, 2016).

Mining has been an essential part of the economy for centuries (e.g. Agricola, 1556). Sustainable development goals of the United Nations and the implementation of the Paris Agreement result in wide employment of various minerals for environmentally sustainable technologies (Ali et al., 2017). Metals are needed for modern applications to increase our standard of living e.g. in renewable energy production and high-tech products. Mining has created significant economic and societal benefits to the society, but subsequently the operations have resulted also in the environmental challenges, such as remarkable amounts of processing waste specified as tailings. (Bellenfant et al., 2013; Edraki et al., 2014.) Tailings are a considerable challenge in mining because of the potential to generate acid rock drainage (ARD), which pollutes the water and soil, if discharged (Bellenfant et al., 2013; Simate & Ndlovu, 2014; Bascetin et al., 2016). Therefore, tailings are a significant long-term environmental liability to the mining industry (Wang et al. 2014, 128).

Circular economy in the mining and metal industry has the potential to create new business potential, significantly increase the value for the society and decrease the creation of waste (Bellenfant et al., 2013; Johnson, 2014; van Zyl et al., 2016). Tailings have the potential to be transformed from hazardous waste to potentially valuable secondary metal sources (Bellenfant et al., 2013; Johnson, 2014; van Zyl et al., 2016; Solomons, 2017). One tailings area can contain metals with the economic value up to several hundreds of millions of euros (e.g. Metals X Ltd, 2017). The European Union (2016) has emphasized, that the valorization of mining waste can add to the raw materials supply, and subsequently reduce the environmental impact. First, the treatment and storage needs of mining waste would be reduced with subsequent positive effects on the environment. Second, the need for primary extraction would decrease. (European Union, 2016, 84.)

Ellen MacArthur Foundation (2015b) suggested that sector-by-sector analysis could provide valuable insights and address various opportunities and challenges around the circular economy transition. Despite the fact that the current quarrying and extractive waste challenge can be an opportunity for metals and minerals recovery with a remarkable economic value, only very little has been made to make the circular economy concept operational in the mining industry (Lèbre et al., 2017). The adoption of circular economy concepts necessitates new knowledge to fill in the gaps of business opportunities, drivers and barriers (European Commission, 2014a; de Jesus & Mendonça, 2018), which are in the focus of this thesis.

1.2 Research motivation

Current systems in the mining waste management are premised on the linear economy concept ("take-make-waste") (Lèbre et al., 2017). The development of the circular economy concept for the mining sector could solve the challenges of increased demand and shortage of mineral resources, waste of natural resources, and environmental pollution with subsequent economic profits (Lottermoser, 2011; Zhao et al., 2012; Bellenfant et al., 2013; Johnson, 2014; van Zyl et al., 2016; Balanay & Halog, 2016). However, the conversation about circular economy has been dominated by the consumer goods companies (e.g. Singh & Ordonez, 2016). Mining and metal companies have been almost totally lacking from this conversation (Lèbre et al., 2017) both from scientific and practical aspects. In the light of this gap, there is a clear need to understand the business potential for circular economy also in the mining and metals sector. The extractive waste problem could be turned into the opportunity to recover metals with a remarkable economic value.

In the transition to circular economy, the organizations need to arrange their business relations and collaboration mechanisms in the institutional systems, which are still based on the linear economy principles (Fischer & Pascucci, 2017). The effects of institutions are widely overlooked in the current circular economy literature. If the circular economy in mining has been lacking from the scientific literature and practice so far, this is even more so for the institutional aspects of circular economy. This thesis contributes to this gap by combining circular economy and institutional aspects, and explains how these aspects could be taken into account especially in the mining sector.

Circular economy concepts could help to create value from mining waste (European Union, 2016, 84; Sitra, 2016). However, as emphasized by the European Commission (2014a), the utilization of circular economy concepts needs knowledge of business opportunities, drivers and barriers. Tailings are one of the most promising waste-based metal sources. This research work is to develop knowledge of possibilities to valorize mining waste as one of the largest global waste streams (Wang et al., 2014). The identification of drivers and barriers could speed up the transformation towards circular economy in the mining industry. By understanding the circular economy business potential for tailings valorization, the study provides support to both companies and institutional stakeholders for designing and implementing circular business in the mining sector.

1.3 Research questions

The main research question of this study is:

- How can mining industry transform towards circular economy in tailings valorization?

The main question is further divided into three secondary questions to provide understanding to answer the main question:

  - What are the drivers for tailings valorization?
  - What are the company needs in tailings valorization?
  - What are the barriers and key challenges in tailings valorization?

The observations will help the industry and society to find priorities and elements in the way towards circular economy in mining.

1.4 Research scope

The research focuses on waste valorization in the mining sector with the theoretical framework grounded in circular economy and institutional theory (Figure 1). Mining industry produces different kinds of waste materials including tailings, waste rocks, mine waters and drainage sludges (Lottermoser, 2011). The technologies and legislative framework are different for solid waste and mine waters (Directive 2006/21/EC; Punkkinen et al. 2016). Therefore, the opportunities, drivers and bottlenecks are expected to differ between the solid and liquid waste streams. This work focuses on solid mine waste and especially on tailings, considered as the most promising waste-based metal sources. In addition, the study deals with industrial mining in the European context and not with small-scale artisanal mining in the developing countries.

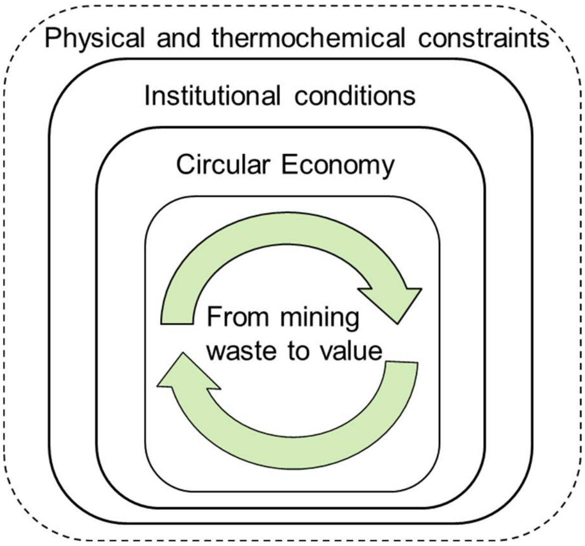


Figure 1. Scope and framework of the study.

The circular economy concept was chosen as framework, since the circular economy focuses on turning the waste into valuables with subsequent business potential (Ellen MacArthur Foundation, 2013; Antikainen & Valkokari, 2016, 6; Sauvé et al., 2016; Ritzén & Sandström, 2017; Esposito et al., 2017, 10). Mining industry is considered to be in the transition towards the circular economy, but this important industrial sector has been almost totally lacking from the circular economy discussion (Lèbre et al., 2017). The previous circular economy discussion has been mainly around the post-consumer waste (e.g. Singh & Ordonez, 2016).

Since the transformation of the mining industry towards the circular economy is a socio-technical transition, it involves the effects of institutions. External factors such as policies, different stakeholders etc. have significant influence on the business potential and transition. Current institutional systems are aligned with the linear economy model of operations, but they might transform into the circular model. (Ellen MacArthur Foundation, 2015b; Esposito et al., 2017, 13; Moreau et al., 2017; Govindan & Hasanagic, 2018.) Fischer and Pascucci (2017) successfully utilized the circular economy framework in combination with institutional analysis, when studying the circular economy transformation of the textile industry. Therefore, the concepts of circular economy and institutional theory were selected as the theoretical framework in this study related to the mining industry.

The limits for the circular economy of metals are determined also by nature's laws, such as physical and thermodynamic constraints (UNEP, 2013; Salminen & Olaussen, 2018). This means that the technology development for metals recovery from tailings and other secondary materials has certain limits e.g. due to the energy requirements. The limits of thermodynamic constraints need to be understood in the circular technology development and when doing policy decisions, but thermodynamics is not in the focus of this study.

This is the first study using the circular economy and institutional theory frameworks for understanding the possibilities of tailings valorization. This thesis aims to fill in the knowledge gaps of business opportunities, drivers, needs and barriers for mining waste valorization. The understanding of opportunities, drivers and barriers is critical in designing means to support the mining industry in the transition towards circular economy.

1.5 Thesis outline

Section 1 gives an introduction to the circular economy potential in the mining industry. Motivation, research questions and research scope are presented. Sections 2 and 3 are the theoretical background of the research including the description of circular economy and its institutional dimensions. Section 4 presents mining industry as the empirical context of this research. Section 5 describes methodological considerations including data gathering and analysis. In the section 6, the results from the workshop and theme interviews are shown. Section 7 discusses the main findings of drivers and barriers further, also in relation to the previous literature. Section 8 is the concluding section, where the scientific and practical implications of findings and the limitations are discussed. Section 9 focuses on future perspectives based on the results.

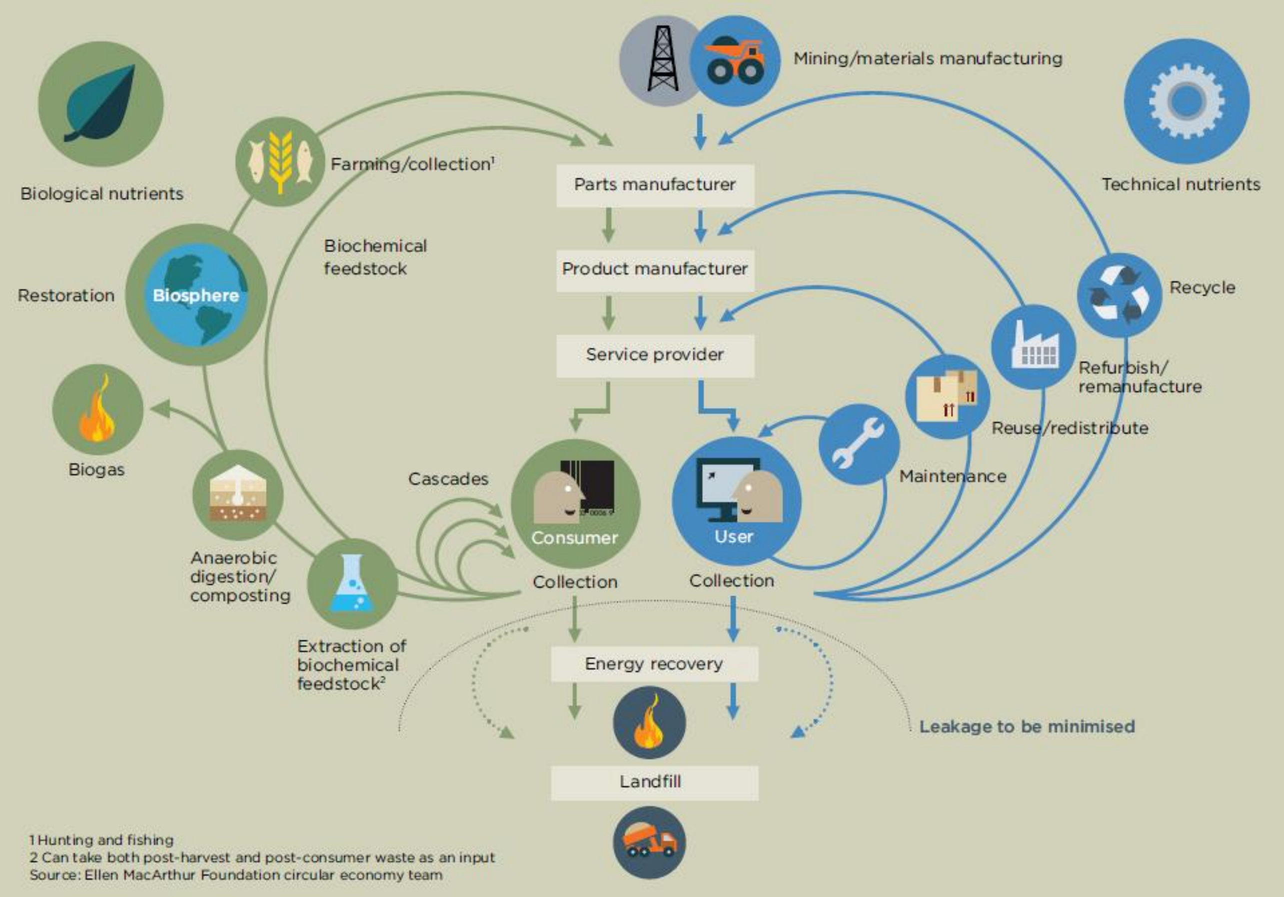
A scientific article was prepared based on the results of this study to the Journal of Cleaner Production (Kinnunen & Kaksonen. 2019. Towards circular economy in mining: Opportunities and bottlenecks for tailings valorization. Appendix 3 in this thesis). I organized the workshop, conducted the interviews, interpreted the results and wrote the article as the first author. Anna Kaksonen contributed by writing technology descriptions and background information of tailings amounts, and by editing the article. The text in this thesis was completely written by me. The results of the organized workshop are in Appendix 1 and the interview questions in Appendix 2.

2 TOWARDS CIRCULAR ECONOMY

2.1 Circular economy concept

Circular economy is a new economic model with a huge economic potential in zero waste creation (Ellen MacArthur Foundation, 2013). The aim is to decouple prosperity and resource utilization. Circular economy aims to keep products and materials in the long-term use and to preserve their value by closing the loop of materials. (Antikainen & Valkokari, 2016, 6; Sauvé et al., 2016; Ritzén & Sandström, 2017.) Circular economy maximizes what is already in use throughout the product's life cycle (Esposito et al., 2017, 10). Circular economy is premised on sustainable use of resources creating value from existing materials, but it is clearly more than just recycling of materials. For example, design of products for reuse and recycling, replacement of non-renewables with renewables, replacement of products with service and sharing of goods and service instead of owing are ways towards circular economy. (Sitra, 2015; Ellen MacArthur Foundation, 2015a.) Often too little attention is paid to saving the resources, as they constitute a minor percentage of total costs. However, the resource savings would affect directly to the bottom line. (Lovins et al., 1999.) Murray et al. (2017) emphasize the restorative characteristics of circular economy meaning that not only pollution is reduced, but also the previous damage can be repaired by designing better systems.

The term circular economy has a linguistic as well as a descriptive meaning. When considering the linguistic context, circular economy is an antonym of linear economy. The term linear economy has been widely used by the scholars writing about circular economy and related concepts to emphasize the difference between linear and circular economy. The descriptive meaning of circular relates to the concept of the cycle including the biogeochemical cycles and recycling. (Murray et al., 2017, 371.) The regularly used outline of circular economy made by the Ellen MacArthur Foundation (2013, 24) is shown in Figure 2. Circles on the left side present non-toxic restorative biological nutrient loops back into the biosphere. Circles on the right side present technical nutrient side, where also improvements in quality are possible. Both technological and biological materials and products cycle in the economic system. There is a drive to have a shift from technical nutrients to biological ones. (Ellen MacArthur Foundation, 2013.) Human activities can alter the biogeochemical cycles. The change of rate in the cycles is crucial concerning the slowing or managing flux. (Murray et al., 2017.) The inner circles present larger savings in material, energy, labour, capital and externalities costs. More consecutive cycles and more time within the cycle mean value creation potential. Products and materials can also cascade across various product categories and applications. Non-toxic inputs would result in purer material streams for easier reuse and recycling. (Ellen MacArthur Foundation, 2013.) Various strategies for circularity including useful application of materials, extended lifetime of products, and smarter product use and manufacture are shown in Table 1 (Kirchherr et al., 2017a, 224; Potting et al., 2017, 5).



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input
Source: Ellen MacArthur Foundation circular economy team

Figure 2. Outline of circular economy dividing biological and technical material cycles (Ellen MacArthur Foundation, 2013, 24). Copyright © Ellen MacArthur Foundation 2013, www.ellenmacarthurfoundation.org.

Table 1. Strategies for circularity in the production chain. Circularity decreases from top to bottom. (adapted after Kirchherr et al., 2017, 224a; Potting et al., 2017, 5).

Smart product use and manufacture	Refuse	Redundant product by abandoning its function or using a radically different product
	Rethink	More intensive product use
	Reduce	More efficient product manufacture or use with less natural resources and materials
Extended lifespan	Reuse	Reuse of discarded product fulfilling the original function by another consumer
	Repair	Repair and maintenance of product for the original function
	Refurbish	Restore and update of an old product
	Remanufacture	Parts used in a new product having the same function
	Repurpose	Product or parts used in a new product having a different function
Useful application of materials	Recycle	Materials processed to obtain the same or lower quality
	Recover	Incineration of material and energy recovery

Circular economy is not a totally new idea and it has its background in several concepts (Table 2). Various meanings and schools of thought around circular economy have the cyclical closed-loop system in common. The origin of the term has been under debate. The idea behind the circular economy was presented already in 1848, when the idea about the chemical factory producing no waste was introduced. (Murray et al., 2017.) The idea of industrial metabolism, in which physical processes are used in the conversion of raw materials, energy and labour into products and wastes, was introduced by Ayres (1994). Industrial ecology overlaps significantly with the concept of circular ecology (Murray et al., 2017). Lovins et al. (1999) described natural capitalism, which integrates ecological goals with economic goals. Closed-loop processes could decrease companies' materials requirements significantly (Lovins et al., 1999). The terms "closed loop" and "circular economy" are often used in parallel (Bocken et al., 2016, 309). Bocken et al. (2016) expanded the previous work in literature for the categories of linear and circular approaches in the attempt to reduce the resource use. They introduced the concepts of slowing resource loops meaning the extension of product's utilization period, closing resource loops meaning recycling and circular flow of resources, and narrowing resource flows meaning resource efficiency, where less resources are utilized per product (Bocken et al., 2016).

Table 2. Selected schools of thought and concepts of circular economy as collected by Homrich et al. (2018, 527) and de Jesus et al. (2018, 3003) from literature.

School of thought	**Definition**
Cradle-to-cradle	"Products designed to regenerate the ecosystem as biological nutrients or to regenerate industries […] in a 100% closed material loop."
Industrial ecology	"Cyclical resource-use patterns observed in biological ecosystems are used as a model for designing mature industrial ecosystems."
Biomimicry	"Designers are inspired directly by organisms, biological processes and ecosystems."
Regenerative design	"This means replacing the current linear system of transfer flows with cyclical flows at sources, consumption centers and sinks."
Natural capitalism	"An approach that protects the biosphere and improves profits and competitiveness. Some changes in how to run the business, based on advanced techniques to make resources more productive, can yield amazing benefits for both current and future generations."
Industrial symbiosis	"Industrial symbiosis is amerger of two or more different industries, where each industry tries to find optimal access to material components and material elements."
Closed-loop economy	"(…) highlighted the potential of a closed-loop economy impact on competitiveness, job creation, resource savings and waste prevention".
Zero Waste	"Zero waste is a unifying concept for a range of measures aimed at eliminating waste and challenging old ways of thinking."
Functional Service Economy	"The Functional Service Economy is a set of innovative business models that integrate products and services (…) to create health and jobs with considerably less resource consumption".

The circular economy concept has also been criticised, because it does not adequately engage with the unsustainable growth of materials demand and with the natural limits to resources (Florin et al., 2015, 5). The needed systemic shift has not been highlighted, and the concept has been often depicted mainly as reduce, reuse and recycle activities (Kirchherr et al., 2017a). The ideal level has been praised, but the actual enactment has been rather limited (Gregson et al., 2015; Ritzén & Sandström, 2017; Kirchherr et al., 2018). Murray et al. (2017) criticised the lack of the social dimension from circular economy conceptual framework, since the sustainability includes the economic, environmental and social aspects. They also noted that circular economy may have unintended consequences and sometimes over-simplistic goals. For example, the green fuels considered environmentally acceptable have led to clearing of forests in some geographical areas. (Murray et al., 2017.) The circular economy concept was shown to be still in an exploratory phase by Homrich et al. (2018), who in addition to Kirchherr et al. (2017a) showed a lack of consensus of even the circular economy definition. A comprehensive list of various definitions for circular economy used in the literature can be found in the extensive reviews of Homrich et al. (2018) and de Jesus et al. (2018, 3004). Kirchherr et al. (2017a) even suggested a potential collapse of the circular economy concept, if the definition continues to vary in the peer-reviewed as well as in the non-peer-reviewed articles. In this study, circular economy is defined after Kirchherr et al. (2017a, 224–225) as following:

> *"A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations."*

2.2 Business potential of circular economy

It has been estimated, that circular economy has the potential to generate cost savings on materials at US$ 1 trillion by 2025 (Esposito et al., 2017, 11). The value of annual renewable resources recovery in developed countries is $250 billion (Zhao et al., 2012). European Commission (2015b) has estimated circular economy to result in savings of €600 billion for EU business, creation of 580 000 jobs and in considerably reduced carbon emissions by 2030 in the EU. Based on the conservative estimates, the circular economy could have a value creation potential of €1.5–2.5 billion in Finland only by 2030 (Sitra, 2015).

2.3 Circular business models

Technologies and ideas are commercialized through business models (Chesbrough, 2010). Technology innovation and business model can be combined in different ways; a new business model for developed technologies, existing business model employs new technologies, and new business models are triggered by new technologies or vice versa (Boons & Lüdeke-Freund, 2013, 14). The same technology results in different economic outcomes, if it is brought to the market via a different business model (Chesbrough, 2010). The circular economy necessitates a change at various levels in companies including strategies, business models and processes (VTT, 2016). The creation of sustainable innovations can be more effective, when linked to the concept of business model (Boons et al., 2013). Florin et al. (2015) noted some common success factors and capacities for the implementation of circular economies. The development of new business models (for example sharing economy and utilization of waste streams as process inputs) was determined as an important success factor (Florin et al., 2015, 9).

The generic business model concept consists of value proposition, key activities, key partners, key resources, cost structure, revenue streams, customer relationships, customer segments and channels (Osterwalder et al., 2010, 18–19). Both sustainable and circular business models are related literature streams considered as a subcategory of business models. In sustainable business model innovation, the ideas of sustainable business and business model innovation have been combined. Sustainable business models extend the triple bottom line (economic, environmental, societal) approach by considering the society and the environment as key stakeholders. (Bocken et al., 2014.) Boons and Lüdeke-Freund (2013) reviewed the literature on business models and categorized the sustainable business model in technological, organizational and social innovation. These categories were further developed by Bocken et al. (2014). They defined the sustainable business models to create positive or reduce negative impact on the environment or society by the changes in creating, delivering and capturing value or changing the value propositions. The developed eight sustainable business model archetypes are (Bocken et al., 2014):

“1. Maximise material and energy efficiency
2. Create value from ‘waste’
3. Substitute with renewables and natural processes
4. Deliver functionality, rather than ownership
5. Adopt a stewardship role
6. Encourage sufficiency
7. Re-purpose the business for society/environment
8. Develop scale-up solutions.”

Antikainen and Valkokari (2016, 10) further suggested a novel framework for sustainable circular business model innovation including business ecosystem level and sustainability impact level parameters in addition to conventional business level parameters. Business ecosystem level includes the identification of trends and drivers, and stakeholder involvement. Sustainability impact contains sustainability requirements and benefits. All these aspects together contribute to the sustainability and circularity evaluations of business models. (Antikainen & Valkokari, 2016, 10.) The model proposed by Antikainen and Valkokari (2016) has highlighted the effect of drivers in the business ecosystem level, which is in the focus of this study. Even though the novel business models have been considered as a core of circular economy, there is a lack of discussion about circular economy business models (Kirchherr et al., 2017a).

3 INSTITUTIONAL DIMENSIONS OF CIRCULAR ECONOMY

The transition towards circular economy is multi-dimensional and complex with the need to take several aspects into account (Ritzén & Sandström, 2017). Current institutional systems are aligned with linear economy, which may create challenges in the circular economy transition (Fischer & Pascucci, 2017). According to Moreau et al. (2017), the circular economy concept should address social and institutional dimensions, which are lacking from the current circular economy discussions. Institutionalism is the dominant theory for the studies of macro-organizational phenomena (Suddaby, 2010). Institutional theory argues that the social context, norms and expectations influence the behaviour of companies (Meyer & Rowan, 1977; Dale, 2002; Scott, 2008). Institutionalists consider how different institutions emerge, change and vanish (Czarniawska, 2008). The institutional conditions set the rules, which need to be taken into account in the differentiation between profitable and non-profitable actions (Moreau et al., 2017). There are several heterogeneous views on institutions from “the basic rules of the game” to particular governing structures and to the certain behaviour in particular contexts (Nelson, 2006). According to Czarniawska (2008, 770), institutional theory is not a theory, but rather a framework to think about social life.

The principal dimensions of institutions are regulative, normative and cultural-cognitive (Scott, 2008, 2014). In the institutional theory, the institutions are considered as collectively held beliefs, rules, values and mores. Institutions have regulative, normative and cognitive elements, which can be formally written or unwritten codes of conduct. Regulative processes are for example rule setting, monitoring or sanctioning. Normative rules tell how things should be done. The appropriate behaviour, means, goals and values are described by the norms. The cognitive element of institution focuses on symbols, when shaping the meaning attributed to objects and activities. (Dale, 2002.) Organizations collectively interpret the attachment of meanings and the infusion of value (Suddaby, 2010). According to Czarniawska (2008, 776), institutionalists ought to find more interest also in technology. Technical norms can relate to human action (e.g. turning the cap of a bottle clockwise), machine behaviour (e.g. 220V voltage in Europe) or natural environment (e.g. SO_2 air pollution limits) (Czarniawska, 2008, 775).

Campbell (2006) argued that institutional conditions have a substantial effect on responsible behaviour of corporations. Stål and Corvellec (2018) considered circular economy itself as an institution, since it emerges via regulative, normative and cognitive processes. The outcomes are rules, norms and beliefs, which result in similarities in practice and structure, when companies align themselves with institutional processes (Figure 3) (Stål & Corvellec, 2018). The institutional terrain is dynamic and can change over time (Campbell, 2006) by the demand-induced change (changing demographic, technologies and environmental conditions) or supply-induced change (Tao, 2016). Individual organizations as well as systems of organizations have an important role in the social life in their environments (for a review, see Scott, 2004). Circular economy can operate at the micro-level focusing on product level changes, companies and consumers; at the meso-level with regional stakeholders e.g. in eco-industrial parks, and at the macro-level focusing on global, national and overall industry topics (Kirchherr et al., 2017a; de Jesus et al., 2018).

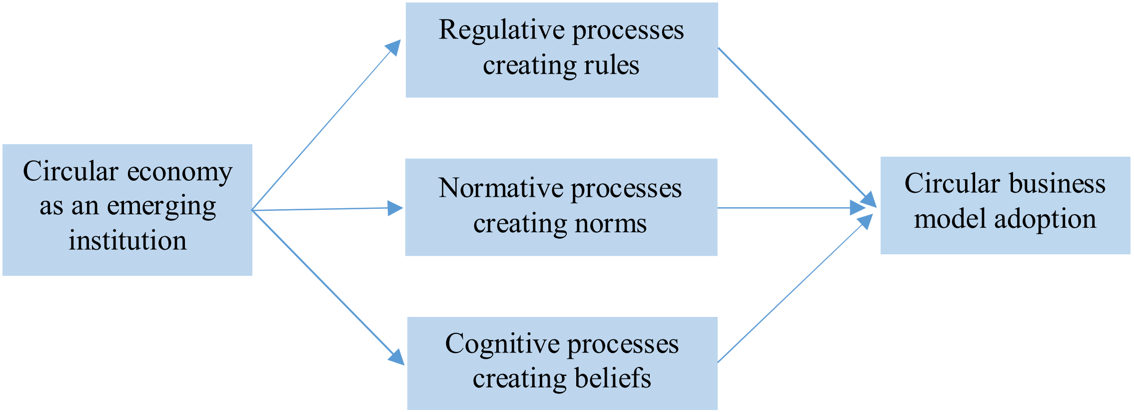


Figure 3. An institutional perspective of circular economy adoption (modified after Stål & Corvellec, 2018, 632)

According to Esposito et al. (2017, 13), regulations favouring the traditional linear economy business should be addressed by policymakers and legislators. Ellen MacArthur Foundation (2015b) proposed a toolkit for policymakers, since they can have a significant effect on the transformation to circular economy. Policymakers can focus on regulatory failures and fixing the market. They can also set targets, change public procurement policy, create collaboration platforms and technically or financially support business. (Ellen MacArthur Foundation, 2015b.) Institutional conditions can create win-win strategies reaching both improved competitive position at the same time with better environmental performance (Nikolaou & Evangelinos, 2010). An increase in the waste disposal costs, environmental concerns and regulations, as well as potential economic income from by-products and waste utilization have often been drivers for the reconsideration of the strategies in the companies (Lombardi et al., 2012, 2).

Sometimes existing policies and environmental regulations may hinder the possibility for the transformation to circular economy (van Beers et al., 2007, 70; Gregson et al., 2015). For example, global recycling networks can be considered as illegal trade and politics favour the recycling in a specific economic area (Gregson et al., 2015). Uncertainties in the legislative framework have haltered the practical implementation of industrial symbiosis (van Beers et al., 2007, 70).

In addition to the fact that institutions influence companies, companies also proactively influence the institutional demands for circularity towards their own interests (Stål & Corvellec, 2018). Entrepreneurship can be considered to catalyse the institutional evolution (Tao, 2016). In the literature, the entrepreneurs have been considered to create, destruct and maintain institutions (Weik, 2011). Dorado (2005) identified the will to change, the process of change and the locale of change as crucial factors in the institutional change. Institutional change requires in complex fields collaboration from various actors, which have a variety of interests and perspectives, resulting in complex social processes (Wijen & Ansari, 2006). Companies can use the legitimising strategies at the industry level, and undertake certain activities with other industry participants (Deegan & Blomquist, 2006, 347).

Institutional theory suggests that uncertainty and innovation characterize a new field. Organizations tend to mimic the successful organizations to overcome the uncertainty. Regulations and stakeholder demands further increase the conformance. Then, the professionals inside and outside of organization develop common ways to do things as normative approaches to the field. When the field is mature, almost all organizations in the field follow the same kinds of rules and structures, and the differences start to disappear. (de Villiers et al., 2014.)

The main research question of this study is how mining industry can transform towards circular economy and valorize waste. In the transition to circular economy, the organizations need to arrange their business relations and collaboration mechanisms in the institutional systems, which are still based on the linear economy principles (Fischer & Pascucci, 2017). The institutional effects, including the circular economy itself as one of the institutions, have thus a significant effect on the transformation and change in the mining industry.

4 MINING INDUSTRY

Mining industry was selected as the empirical context of this research. The importance of metals and mining industry, the status of circular economy in the mining sector, and the influence of institutions on the mining industry are elaborated in the next sub-chapters.

4.1 Metals requirements of a modern society

Metals are essential in the applications of a modern society. Finite mineral resources and fossil fuels have provided economic growth and prosperity (UNEP, 2013; Sauvé et al., 2016; European Union, 2016). Reaching the sustainable development goals of the United Nations and the implementation of the Paris Agreement require wide utilization of various minerals for modern green technologies (Ali et al., 2017). Low-carbon technologies needed in renewable energy systems and high-tech applications such as hybrid cars are some of the future drivers. European Union (2016, 14) has estimated the annual demand of certain metals for renewable energy technologies to significantly grow from 2012 to 2030. For example, the projected demand increases in the wind energy applications for neodymium and dysprosium are over 2000% and 600%, respectively (European Union, 2016, 24). The overall global raw materials demand is expected to even double between the years 2010 and 2030 (UNEP, 2013; European Union, 2016). At the same time, the ore grades have decreased in terms of both quality and concentration during the last decades (Giurco et al., 2014; Esposito et al., 2017). Easy-to-mine deposits have already been utilised in the past and future mining is as result more expensive and challenging (Esposito et al., 2017).

There is increasing focus on the recycling of metals from secondary end-of-life products. However, the demand of metals in the economy is higher than recycling and reuse can satisfy (European Union, 2016, 8). Metal’s lifetime in products may be rather long. This creates a lag between the metals input to the market and their availability for recycling. In addition, there are metal losses throughout the product’s lifecycle. (Florin et al., 2015, 5.) Even in the circular economy, primary raw materials from mining activities continue to play an important role (European Commission, 2015a).

4.2 Mining and metallurgical side streams and wastes

Extractive waste is formed in mining and minerals processing, and it belongs to the largest waste streams in the EU and Finland (Lèbre et al., 2017; Sitra, 2015; Official Statistics of Finland, 2015). Mine tailings is the term used for the remaining fine-grained rock and processing fluids, when the valuable minerals have been extracted from the mined ore. For example, 95–99% of crushed ore can be deposited in tailings in copper mining. (Edraki et al., 2014.) More than 1.2 billion tonnes of deposited tailings waste exists in the European Union (BRGM, 2001, 30) and billions of tonnes worldwide (Wang et al., 2014). The amount of tailings grows every year via new metals production. In Finland, the amount of mining and quarrying waste increased to close to 70 million tonnes in year 2013, which corresponds to almost 70 % of the total amount of annually generated waste. Finland belongs to the top five countries in the European Union in the amount of waste production from mining and quarrying. (Official Statistics of Finland, 2015.) Mining waste could be used as a raw material resource as one of the possible solutions to the restricted metal supplies (Nuss & Blengini, 2018).

The major environmental risks caused by the mining waste are potential pollution, such as acidity formation and heavy metals release into the environment, and stability of the tailings dam (Bellenfant et al., 2013; Simate & Ndlovu, 2014; Bascetin et al., 2016). In the history, tailings dam accidents have taken place for example in Spain and Romania (BRGM, 2001, 5). The majority of the mine waste still needs to be stored in disposal areas. Mine wastes contain potentially valuable mineral and energy resources, if new processing technologies are developed or market demands result in improved commodity prices (Lottermoser, 2011).

There are increased efforts to reuse and recycle mine wastes to turn one of the largest waste streams in the EU into valuable materials. Remining is extraction of energy or mineral from previously mined areas. Reuse involves the utilization of mine waste in the original form without reprocessing for another purpose. Recycling uses reprocessing of the entire mine waste. In reprocessing the waste, the material is used as feed to produce a valuable product. In treatment, the waste’s toxicity or volume is decreased. (Lottermoser, 2011.)

There are several characteristics, which differentiate industrial residues such as tailings from consumer goods waste (Table 3). Clear ownership of the material, good knowledge of the quality and quantity, and high volumes for large-scale business are some of the clear advantages, when thinking of industrial residue valorization business potential (UNEP, 2013; Florin et al., 2015).

Table 3. The differences between industrial residues and consumer goods (Florin et al., 2015, 15; UNEP, 2013).

Industrial residues	Consumer goods
-Clear ownership with a single owner -Quality and quantity typically well characterized -High volumes (economies of scale)	-Ownership widely distributed -Complex materials -Metals often as minor components -Lack of infrastructure/systems for collection -Collection logistics is a challenge -Dissipative effects -Recycling attitude and knowledge

4.3 Institutional influence in the mining industry

United Nations have adopted 17 Sustainable Development Goals for the years 2015-2030 for global economic development, social inclusion and environmental sustainability. Mining industry has the potential to contribute to all these goals either in a positive or negative way. Country-level dialogues have been designed between the UN and governments for moving the SDGs forward in the mining sector. Mine tailings mining can minimize the amount of waste and thus contribute especially to the SDG11 “Sustainable Cities and Communities” and to the SDG12 “Responsible Consumption and Production” (World Economic Forum, 2016).

Regulative, normative and cognitive aspects have a significant effect on the behaviour of organizations (Dale, 2002; Scott, 2008). The main external factor having influence on mining companies is the institutional context of the country of their headquarters. On contrary to many pre-assumptions, large mining companies prefer global standard setting and even stricter policies over regulatory uncertainties. (Dashwood, 2014.) Mining industry has faced a lot of stakeholder demands (Deegan & Blomquist, 2006; Prno & Slocombe, 2012). Local communities are nowadays especially important governance actors in the mining sector influencing decision making and political processes (Prno & Slocombe, 2012). Prno and Slocombe (2012) considered Social Licence to Operate as an institution, in which certain rules and decision making procedures are negotiated with local communities during the mine lifetime. Institutions have been studied in the mining sector on the corporate social responsibility topic and especially on the activities in the developing countries (e.g. Gifford et al., 2010). Mining companies have taken actively part in forming voluntary initiatives to meet their responsibilities. Voluntary reporting is an important mechanism for mining companies to improve the environmental and social performance, and also the industry’s reputation. The role of institutional influences on mining industry’s voluntary and self-regulatory initiatives has been significant. Voluntary measures can be considered as a response to external pressures. (Dashwood, 2014.) Nikolaou and Evangelinos (2010) explained the adoption of similar environmental management practices in the mines in Greece and globally as a mimetic strategy by the institutional theory. Table 4 shows the maturations of mining industry sustainability disclosure. First, the mining companies follow the examples of large and profitable mining companies. Then, after the changes in legislation, the companies respond to the new legislation. Finally, the professionals in the field have created shared norms and way of thinking. (de Villiers et al. 2014.)

Table 4. The maturations of mining industry sustainability disclosure (modified after de Villiers et al. 2014, 54).

	Mimetic isomorphism	**Coercive isomorphism**	**Normative isomorphism**
Description	Early stage uncertainty about the appropriate response to the pressures	Pressures formalise around new regulations and stakeholder demands	Maturity evolves through professionalization; similar training and social interaction
Applied to mining company sustainability disclosure	Companies follow the example of large and profitable mining companies	Mining companies response to legislation and corporate governance guidelines	Managers and consultants in mining industry have developed shared norms

Several European-wide and Finnish national institutions have emphasized the need for the transition to the circular economy model. A resource-efficient Europe belongs to the seven flagship initiatives of the Europe 2020 strategy with the aim to deliver growth. A resource-efficient and low-carbon economy is believed to boost European economic performance, create opportunities for economic growth and competitiveness, secure the supply of resources, and limit the environmental impacts. (European Commission, 2011, 3.) The circular economy package was adopted by the European Commission in 2015 including legislative proposals on waste with the aim to reduce landfilling and to increase materials recycling and reuse. The aim is to move Europe's economy towards a more sustainable direction, which at the same time can generate novel sustainable competitive advantages for Europe. (European Commission, 2015a; 2017.) In Finland, circular economy was selected as a spearhead project of Prime Minister Sipilä's government programme, which shows the development of circular economy to a major theme in Finland (Sitra, 2015). The target is to make Finland a global leader in circular economy by 2025 (Sitra, 2016). In addition, for example the largest nation China has adopted circular economy as the main framework for economic and environmental development (Murray et al., 2017) with a broader perspective than in the EU (McDowall et al., 2017).

Some metals are produced in a limited number of countries and export restrictions have increased during the last years presenting a supply risk (European Union, 2016, 29–33). Securing the supply of raw materials is crucial for the competitiveness of EU industries. The EU has adopted the Raw Materials Initiative in 2008 to ensure a secure supply of raw materials. Further, the European Innovation Partnership on Raw Materials launched in 2012 is emphasising the supply and use of raw materials as a strategic challenge. (European Union, 2016, 3.) In addition to the EU, access to crucial non-energy raw materials has raised concerns e.g. in the US and Japan, as for example some rare earth elements (REEs) needed in high-tech applications are produced almost only in China. The list of Critical Raw Materials (CRMs) at the EU level is updated at least every three years. A material is considered as a Critical Raw Material, when it is of high economic importance and has a high supply risk. (European Commission, 2014b.)

European Institute of Innovation & Technology, Knowledge and Innovation Community Raw Materials (EIT KIC Raw Materials) has 115 partners, which cover 80% of the raw material sector in Europe. The raw material sector's business partners represent over 700 000 jobs and over 200 billion euros turnover in Europe. EIT Raw Materials Lighthouse Programme 1 called "Extracting value out of residue stocks" drives raw material business to utilize residue stocks as raw material sources. (EIT Raw Materials, 2018.) The European Union (2016) has emphasized, that the valorization of mining waste can add to the raw materials supply, and subsequently reduce the environmental impact. First, the treatment and storage needs of mining waste would be reduced with subsequent positive effects on the environment. Second, the need for primary extraction would decrease. (European Union, 2016, 84.) Recycling and reuse of stockpiled tailings have been included also in the action proposals of Finland's mineral strategy (GTK, 2010). Finland is the net exporter of metals and minerals (GTK, 2010, 11) and many metal containing products are thus consumed abroad. Therefore, in the circular economy, Finland could have more focus on side streams and mine waste. Sitra (2016) has proposed methods, how circular economy could be created in Finland. Related to the mining sector, the proposition is to minimize environmental impacts and utilize side streams (Sitra, 2016).

The German government is considering various indicators to assess the raw material usage and productivity. When data quality is high enough, Total Material Consumption will be taken into use. Total Material Consumption covers also unused extracted resources such as mining spoils. (Ellen MacArthur Foundation, 2015b, 43.)

4.4 Status of circular economy in the mining industry

Ellen MacArthur Foundation (2015b) suggested that sector-by-sector analysis could provide valuable insights and address various opportunities and challenges around the circular economy transition. Only a few efforts have been made to get the circular economy concept operational in the mining industry (Lèbre et al., 2017). If we look at the widely cited circular economy model in Figure 2 developed by the Ellen MacArthur Foundation (2013), the mining industry is separate and excluded from the restorative loops. If the mining sector is considered apart from the circular economy concept, it would result in lost opportunities for materials recovery. The expansion of current circular economy system boundaries would reduce the need to open new mines exploiting untouched ore deposits. Reprocessing of mine waste is often considered as primary extraction, not recycling. (Lèbre et al., 2017.)

Lèbre et al. (2017) state that mines can obtain significant environmental and economic benefits, when applying the circular economy principles. According to Zhao et al. (2012), circular economy principle should follow the "Reduce, Reuse, Recycle" principle, which is often central in the circular economy concept (Murray et al., 2017). "Reduce" can be the efficient exploitation of resources, enhanced recovery rate improving the total recovery of resources and reducing pollutants such as tailings, gangue and wastewater. "Reuse" can be recycling of mine wastewater and changing tailings and mineral waste into valuables. Valuable metals can be recovered and the mineral matrix be utilized in producing new substances such as building materials. "Recycle" means reusing the resources again from secondary materials. (Zhao et al., 2012.) Circular economy in mining can be implemented at the company, mine area, mineral value chain and system levels (Zhao et al., 2012; Balanay & Halog, 2016). Mine waste utilization can occur both at micro- and meso-levels (Balanay & Halog, 2016). In the company level, the waste can be returned to the production process or be used as raw material after suitable treatment. For example, the tailings can be utilized in mine backfilling. In industrial symbiosis, the waste, energy and by-products can be utilized by other industries. In the social wide circulation mode, mining circulation system and other sub-cycles combine. The closed mines can be used for example as scenic spot or science education spot. (Zhao et al., 2012.)

Efficiency improvements can be obtained in the preparation of ores and in the mining waste reprocessing (Giurco et al., 2014). Based on the estimations, around 75 tailings re-mining projects are globally in operation for the recovery of gold, copper and diamonds (van Zyl et al., 2016). In commercial scale, e.g. mine tailings of the Washoe mine that were previously uneconomical to process, have been used as a source for REEs, Au, Pt and Pd with extract efficiency expectations of 60–70% (Raptor Technology, 2011).

Several areas have been identified important in the way to circular economy in mining. There is a need for technical solutions to reuse the current waste materials. Environmental liability and legacy issues need to be taken into consideration, when reusing mine waste. The reuse can result in lower environmental risks at the mine site. Enterprise development and more innovative business models for valorizing mine waste are also needed. (Golev et al., 2016.) Even though there are benefits in the transition towards circular economy in mining industry, there can be also several barriers to this transformation.

5 METHODOLOGICAL CONSIDERATIONS

5.1 Positioning of the study

This chapter discusses the methodological choices and the research setting of the study. The iterative research process is described in Figure 4.

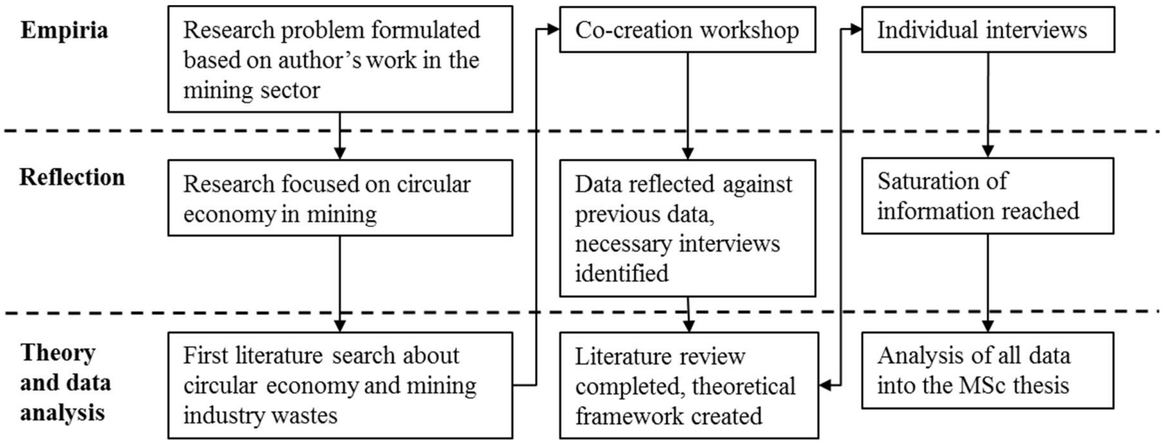


Figure 4. Research process of the study. The work was conducted in an iterative way.

The research philosophy of this study is based on interpretivism. Positivists believe in one single objective reality, while interpretivists see the reality as relative with the need to understand the research phenomenon from its specific context (Eriksson & Kovalainen, 2008, 18–19). The reality in this research is considered subjective, since I have been working a long time in the mining industry and thus I cannot be assumed totally objective and neutral. I used existing networks in addition to new contacts in getting in contact with the information sources. Also the knowledge created during the study is based on subjective knowledge and experience from the interviewees and workshop participants.

Qualitative research is linked to interpretation, insights and understanding, whereas quantitative research is concerned with explaining, statistical analysis and testing of hypothesis (Eriksson & Kovalainen, 2008, 4; Taylor et al., 2015, 8). Since the aim of this study was to better understand the opportunities, needs and barriers of tailings valorization in the mining industry, qualitative methodology was considered as the most appropriate for understanding the phenomenon. The research method of this study is thus qualitative data collection through a workshop and semi-structured theme interviews. Inductive content analysis, where data generated is the basis for the formation of categories (Elo & Kyngäs, 2008), was used for the analysis of obtained data.

The work started with a preliminary literature review before the organization of the workshop. The knowledge created in the workshop was analysed and interpreted against the created theoretical framework in an iterative way. Theoretical framework included circular economy in the beginning, and institutional aspects were added after the effect of institutional elements was clear. Further, the theme interviews were done to get more detailed information about the topics. The interview questions were done based on the created theorerical framework and workshop results. The iterative way of working was seen as the best way to collect and reflect information and to direct the research of this study. Data collection and analysis are explained in more detail in the following chapters.

5.2 Data collection with a workshop and interviews

Data was collected through a workshop and semi-structured interviews referred to as theme interviews. Workshops have been used as a tool for knowledge creation (Geissdoerfer et al., 2016). Innovation is a valuable potential outcome of the interactions (Frow et al., 2015). Workshop method has been previously utilized e.g. by Bard and Ntemiris (2017) and Scott (2016), and it was considered as an appropriate tool to create a broad view to the tailings valorization topic also in this study. The aim of the workshop was to create the initial framework and main concepts for the in-depth interviews. The workshop was held in the ideation and concept development phase to offer a diversity of opinions to the topic before the more in-depth theme interviews.

I organized and facilitated the workshop. Invitations were sent by e-mail to a wide group of recipients including managers in the mining companies, technology companies and recycling companies, and relevant raw material experts in research organizations and academia (in total 114 e-mail addresses), and the recipients were also free to circulate the invitation to any stakeholders and partners they thought that could be interested. Finally, in total ten participants including five representatives from mining and soil industry (e.g. R&D manager, chief metallurgist and CEO) and five raw materials related academic experts, participated the workshop. This enabled adding practical and also theoretical knowledge into the research. The workshop focused in three themes for new business for side and waste streams in mining and metallurgical industries in the order of: 1) drivers/opportunities, 2) needs and 3) challenges and bottlenecks. The workshop lasted for approximately four hours with one-hour lunch break. The participants discussed the themes very actively. They had post-it notes and pens and the possibility to add their ideas in the post-it notes to the wall (Appendix 1). Most of the post-it notes were written by me as a wrap-up summary of the on-going discussion. The participants had the possibility to comment the post-it notes and add their own notes, if they considered, that some ideas would be missing or misinterpreted.

Since this study aims at understanding more deeply the phenomenon of circular economy for mining waste valorization, semi-structured theme interviews were considered as an excellent data collection method in addition to the workshop. A theme interview focuses on a defined topic at a certain time period. The research question is known in advance and the researcher would like to know all about a specific issue. (Evers & Boer, 2012, 62.) In a semi-structured theme interview, the themes are pre-prepared, but the wording and order of questions can be changed in each interview (Eriksson & Kovalainen, 2008). The individual interviews were done to complement the research by providing more in-depth understanding of the research phenomenon. Themes were selected based on the theoretical framework, research questions and results from the workshop. More data was collected on the basis of what was already learned. The questions for the interviews were arranged in a semi-structured way. The interview template was planned before the start of the interviews and was as shown in Appendix 2. The interviews focused on drivers, needs and bottlenecks for tailings valorization. The themes were covered with all informants, but the order of the questions varied in a flexible way.

In total seven interviewees were selected for the study based on their expertise in the scope of the study and/or recommendation by the contacted company. The interviewees were mining industry representatives, technology providers for the mining industry and representatives of institutions related to the mining industry (Table 5). Technology developers have a wide understanding of their customers' needs and they are able to look at the situation from a wider perspective than from one mine's point of view. The theme interviews were done either face-to-face (1) or via skype for business (6). All interviews were recorded, except the face-to-face interview, where the interviewee did not approve recording and written notes were done instead. With two informants, the interview was done as a group interview by the request of the interviewees. The duration of interviews varied between 27 and 63 minutes. Since Finnish was the mother tongue of all interviewees, it was considered more natural to conduct the interviews in Finnish. The recordings were transcribed into text and then translated into English. After seven theme interviews, the data saturation was reached, which was shown by similar perspectives to the topic.

Table 5. Background information of the interviewees of the study. n.a. = not available

Interviewee	Title	Working time in the mining industry (years)	Duration of the interview (min)
I1	Director	41	27
I2	Development engineer	n.a.	53
I3	Research director	10	29
I4	Development manager	9	63
I5	Superintendent	20	63
I6	Technology director	27	42
I7	R&D Manager	10	30

5.3 Data analysis

Qualitative content analysis was used for the analysis of empirical data, since the target of the study was to create knowledge and interpret the obtained data in a flexible way. Elo and Kyngäs (2008) emphasize the flexibility of content analysis, as there are several ways to conduct content analysis with the ability to deal with large volumes of textual data. According to Alhojailan (2012), content analysis is a systematic element to data analysis and especially appropriate for studies seeking to discover using interpretations. In the content analysis, the collected data is organized and meaning is drawn from the data for realistic conclusions (Bengtsson, 2016).

Inductive content analysis was considered more suitable than deductive content analysis for this study, since the topic was rather new and underexplored. Since the content was analyzed by the inductive content analysis, the generated data was used as the basis for the formation of categories (Elo & Kyngäs, 2008). The process included open coding, creation of categories and abstraction as described in Elo & Kyngäs (2008). During open coding, notes were added to the text, when reading it. Then, the categories were created based on systematically and objectively classified data. This study followed the conventional content analysis, where the codes were defined at the same time with data analysis from existing data (Hsieh & Shannon, 2005). First, the workshop results were divided into different categories under the opportunities, needs and bottlenecks. Second, the results from the interviews were categorized under the previously identified categories. When necessary, new categories were created, when analysing the interviews. Most of the categories were identified both for the workshop and interview results, but some categories were recognizable only either in the workshop or in the interviews. Finally, all results from the workshop and interviews were combined, and summarised. The identified driver, need and barrier categories in the mining industry were further analysed in relation to the existing literature.

6 RESULTS

The results of the workshop and interviews on circular economy in mining, and identified drivers, needs and challenges of tailings valorization are presented in the following sub-sections. All main results have been published as a shorter version in a scientific article in the Journal of Cleaner Production (journal's Impact Factor 5.651, Appendix 3, Kinnunen & Kaksonen, 2019). This thesis has extended the results and described direct citations from the interviews, which were not included to the scientific article.

6.1 Current status of circular economy and tailings valorization in mining

All interviewees considered mining as an essential part of circular economy especially, as metals are the indestructible components, which can be recycled again and again as a basis for circular economy. Metals do not disappear anywhere, when they are considered at the atomic level. However, there is always some waste and losses during the production and recycling processes. The whole circular economy related to metals starts from the mines.

> *If we start from the primary side, there is no circular economy, if there is no primary production as a feed. We should see the primary production as a part of the larger circular economy. Another issue is to recover all fractions and to decrease the amount of waste rock based on possibilities, such as selective quarrying or whatever. We can utilize all different waste rocks and their characterization, fractioning and planning of alternative usages. And then of course reuse the tailings. (I1)*

The interviewees pointed out, that mining industry utilizes a significant variety of chemicals, which can be recirculated. These chemicals would have the potential to be used in internal processes in the mine or in the industrial symbiosis outside the mine site. There can be a link for example to the fertilizer industry, agriculture and chemicals industry. Mining industry utilizes a wide variety of chemicals and there are clear possibilities for linkages with other industries.

> *It is already in the determination of a side stream, if we utilize it and who really utilizes it. Circular economy means that literally materials circulate either inside the processes or between processes. It does not mean that we take the material and do something with it and then it never returns back, but ends up as some kind of waste. It can be the internal circle of a*

> *process, where for example chemical is recirculating and residuals are returned to the previous process step. Or it can be the circulation of a side stream, which benefits the process somewhere, or then we combine the processes of the same or different industries in a way, that the side stream of one process is raw material for another process. (I4)*

The interviewees also noted, that the mining industry is currently often lacking from the circular economy discussion. The linkage of circular economy to mining is not as clear as in many other industrial branches and would need more communication.

> *…when we talk about circular economy and other things, the discussion has focused quite much on municipal wastewater treatment plants and food industry, where the circles of nutrients are clearer. In the metals and mining industry, the circular economy is not completely clear. Therefore, some communication could be done. (I2)*

When considering the utilization of tailings, the mining companies have not really recovered metals and minerals from tailings so far even in the global context. Based on the interviews, even the evaluations of the recovery potential are lacking, since they would need long-term planning from the companies.

> *It has not necessarily been evaluated which side streams and elements would be usable in addition to the ways that they are used now. It is typical to focus on the operational side: we have a problem, let's do something. Then the long-term planning. There is not necessarily enough resources in the operations. (I2)*

The amounts of tailings are significant. So far, tailings have been in use as materials in backfilling and in the construction applications. Currently, the biggest part of the tailings is disposed of. If the use of tailings in the production of geopolymers would be possible, they could be used in covering the waste piles on mining sites. Geopolymers could substitute a part of the concrete. The on-site use would reduce the need of transportation of construction materials to the mining sites and subsequently bring clear added economical value. In addition, applications in more value-added products have been suggested for the already finely milled material, such as the use of tailings as material in 3D -printing.

6.2 Opportunities and drivers

The opportunities and drivers identified in the workshop are listed in Table 6 (original data in Appendix 1). The results can be categorized under the circular economy mind set, technological, environmental, economic and institutional drivers.

Table 6. Drivers and opportunities identified in the workshop and categorized into groups.

Drivers/opportunities	
Workshop results	***Categorization***
✓ From waste to raw material ✓ Storage of potential materials for future ✓ Waste waters may contain significant amounts of metals ✓ Willingness to collaborate; circular economy as a target	Circular economy mind set
✓ Available commercial technologies ✓ Processes developed for certain valuables, not the whole material ✓ New analytical methods reveal new sources ✓ Pre-treatment; logistics to another place	Technological drivers
✓ Removal of environmental hazard ✓ Cleaning of environment	Environmental drivers
✓ Involvement of the society ✓ International networks and EU collaboration	Institutional drivers
✓ Low grade ores ✓ Waste area investments; a few euros per tonne ✓ Possibility to pay a part of the final waste treatment costs with business from side streams ✓ New business in storage ✓ Possibility for geoenergy (other business) ✓ Industrial symbiosis e.g. municipal waste utilization ✓ Unidentified business e.g. phlogopite, REEs in gypsum ✓ New business: aquaculture, wine cellars, holiday resort, electricity ✓ Pyhäsalmi: energy utilization ✓ Recycling of phosphorus ✓ In Finland, Kylylahti and Kevitsa most valuable ones	Economic drivers

Circular economy and the transformation from waste to raw material were seen as drivers for the mining industry to utilize tailings as a source of raw materials. Cleaning of the environment and subsequent removal of the environmental hazard were considered important. As the primary ores become lower grade, the mining industry has to recover metals from more challenging ores than before. In comparison, the tailings can turn to be a technically and economically competitive option as a raw material source for the mining industry. The current technologies have focused only on certain elements, and not on the whole material. However, new commercial technologies have been developed for the low-grade ores and wastes. When analytical methods get better, new metal sources can be detected and found.

Institutions, including the society, international networks and EU collaboration, were considered to drive the mining industry towards circular economy. In addition, financial drivers were recognized. Waste area investments are a few euros per tonne of waste material, which could be avoided, if the waste would be utilized. The business from side streams could contribute to the final waste treatment costs. New non-conventional business opportunities could arise even outside of the recovery of metals for example in the fields of energy, aquaculture, wine cellars and holiday resorts. The utilization of closed mines have a wider spectrum of new business possibilities than only the recovery of metals, which is the core business of the mining industry. Industrial symbiosis was mentioned as one possibility to valorize e.g. municipal waste in the mining industry.

Raw materials scarcity, common attitudes, disposal costs, development of better technologies, higher price levels and more demanding permitting for virgin materials were mentioned in the interviews as drivers to recover metals from tailings. Common attitudes were mentioned as drivers, but their effect is rather slowly.

Even though there have not been many attempts to recover metals from the tailings yet, the workshop participants and interviewees believed, that there is clear potential to recover value from tailings in the future. The recovery of metals from lower grade materials has become more reasonable. Former technologies were not as efficient as nowadays and they have left high amounts of residual metals into the tailings. In the previous decades, the metals either did not have any use or then the concentrations or price levels were not suitable for valorization. When the needs and technologies of societies have changed, the components in side streams and tailings have become valuable and economically feasible. Certain elements previously not needed in the society may have nowadays demand. The demand and prices have increased for some metals even significantly, meaning that the recovery from lower grade material streams is going to become reasonable. Materials, which were previously considered as waste, have transformed into possible raw material sources.

Regulation around the mining waste was expected to be tighter in the future creating thus more opportunities for the valorization. Side stream processing was considered potentially less expensive than opening a completely new mining project. On the other hand, the investment costs for the recovery process are high and on the other hand, there are profits from the recovery of additional metals. For some components and cases, the recovery of metals will likely look reasonable. The efforts would affect positively also the imago and the social license to operate of the mining companies.

> *The way of thinking, how we process and which side streams are produced and how they are used, is definitively going to change. (I2)*

> *If the amount of waste can be radically decreased, the whole industrial branch will get an amelioration in imago. [...] It needs to be actively remembered, that such potential exists. (I5)*

The interviewees also highlighted long-term perspective and the effect of the mine lifetime. Mining companies with longer lifetimes consider their side streams and minor elements more actively compared to the mines with shorter lifetimes. When the operation time is only up to ten years, the companies tend to focus on the main metal and on proven conventional technologies. In the long-term mining activities, the usability of materials is evaluated in a wider manner. Some interviewees also mentioned the possibility to store the tailings in a suitable manner for the future use, even though the valorization would not be possible today.

> *Mining industry is slow to move, but it is also willing to make the activities more efficient and to bring the profit also from other than only the main product, and be also environmentally friendly. [...] The technology provider and the company take into account the timeframe, if some minor elements could be recovered. The current financial situation drives to invest on only those process solutions, which clearly bring returns, and which are well known. It makes the industry conservative. The other thing you can see is the lifetime of the mine. If we talk about a lifetime below ten years, the investments are made accordingly. To put it ugly, they are just quick wins. In such short lifetime mines, it is possible to make a simple process. They do not look at what happens after 10 years, when the main metal has been mined and recovered. [...] when lifetime is over 20 years onward, then the long-term thinking is more likely. (I2)*

Most of the interviewees considered the timeframe for tailings valorization rather 10 years than 5 years, since the project durations are so long. However, one of the interviewees mentioned that the possible timeframe for valorizing tailings can be shorter compared to opening a new mine, when the amounts and concentrations of metals in tailings are well known. The pre-feasibility and feasibility studies take a lot of time for getting a new mine opened. The recovery of virgin raw materials is getting more difficult, which means that the permitting is more challenging and it will take more time. When the side streams are valorized in the already operating mining sites, it is easier to predict the time to the start of the production.

> *If we start with the green field project, the process takes a lot of time. First to make the survey at a sufficient accuracy and then to make even the ore estimates. If we anyway have this kind of already treated material in a restricted area, where you already know what it is and the amounts, it is so much easier, if there is something to be valorized. (I4)*

6.3 Needs

The needs identified in the workshop are listed in Table 7 (original data in Appendix 1). The results from the workshop can be categorized under two categories: new value chains and technological needs. Despite the fact that the technological development was considered as a driver for mine waste valorization and technologies have been already developed for lower grade ores, there is also a clear need to develop the technologies further and to tailor them for side streams for metals recovery and whole mineral matrix utilization. The technology development for the side stream valorization was considered as core business of no one.

Table 7. Needs identified in the workshop and categorized into groups.

Needs	
Workshop results	***Categorization***
✓ Need of one large company as driver ✓ Closing mine; new company needed for waste processing ✓ Callio park: new company ✓ Not core business of anyone ✓ Large companies are willing to donate waste material, but volumes need to be big enough ✓ "Stock exchange" for certain side streams	New value chains, partnerships
✓ Technology development ✓ Tailoring technology for low grade ores ✓ Missing: Technology for mineral utilization e.g. barite ✓ Missing: New technologies for side streams; not core business of anyone	Technological needs

Based on the workshop and interviews, the mining industry is lacking existing value chains for the side stream valorization. Waste valorization is not core business of existing industrial players. At least one main large company would be necessary to include also other stakeholders to the value chain. Several interviewees emphasized, that the companies' strategies, culture and ownership determine the willingness to outsource activities or to do the work by themselves. Many mining companies would rather give the side stream to be treated by another partner company compared to processing the streams themselves. Sharing of the investment costs was suggested between the actors in the value chain. New companies already having the adequate capital for the creation of this kind of service business do not exist. Companies, which would have the capacity, have not started to utilize tailings due to the economic situation. Especially SMEs with entrepreneurship seem to be missing from the value chains. SMEs were considered more innovative than the conventional large mining companies. Every actor in the value chain should get benefits from the collaboration. One interviewee considered the role of technology providers as the most crucial already in the planning phase, when the decisions related to the production are made. Since the mining companies tend to focus on the main metals of the ore, which is their core business and expertise, the role of technology providers could be the active consideration of the recovery possibilities of also minor elements already in the planning of the operations.

> *Some companies define that they focus only on key operations. It depends on the ownership. There are geographical areas, where even the operations are outsourced, even the main*

> *processes. […] There exist also operating companies, which want to do everything by themselves. It depends on the company culture, area and ownership. If the company is based on investors, they may have more outsourcing. (I2)*
>
> *Maybe these small innovative companies could have the initiative, if you feed them with enough information, needs and challenging problems. The efforts then benefit everyone. Therefore, in these kinds of programs there should be a balance, that they would involve both big and small companies. […] You just need to remember the existence of SMEs and their potential to produce new information via basic research and innovative doings. (I6)*

Large mining companies would be willing to donate their waste material for the valorization, but the volumes to be treated need to be high enough. Sometimes it is unclear, which materials could be utilized by other companies. Therefore, a "stock exchange" -type of instrument was proposed to make the knowledge transfer of available materials more efficient. The lifecycle of the mine needs to be taken into account. When the mine site is closing or has already closed down, a new company would need to be established for the waste processing purposes.

The uptake of new technologies is slow in the mining industry due to the investment intensive nature. The tendency is to use proven conventional technologies, since the investments are extensive and can not be easily replaced. Technology readiness levels of novel technologies were considered too low in order to get the technologies scaled-up into the real practice. There exists a technology gap, since the scale-up of developed technologies to real practice takes several years. The long timeframe has slowed down the enthusiasm of companies to start surveys and projects.

Some interviewees had also concerns about the lack of research in the companies and universities. Big companies are not doing basic research anymore and it seems that even the universities are reducing the amount of basic research. Certain specific technological needs were identified with currently no available technologies, equipment or even research. For example, the concentrator technologies function at the level of hundred micrometers, but the industry would need technologies for about ten micrometers.

> *When a mining company invests in this kind of recovery, the technology for the investment needs to be tested and function. Therefore, the uptake of new technologies is not very simple*

> *and easy. As long as we use conventional technologies, we also need to deal with the problems related to them. (I3)*

Other needs mentioned in the interviews related to reducing the amount of waste and related risks, waste stability, taxation and predictability of regulations. Waste disposal costs typically go down at the same time with the waste mass reduction. The stability of the waste decreases the environmental risks related to the waste disposal. Water is stored in the tailings ponds. The tailings' quality and quantity thus also determine the quality of water in the mining site. The needs for economically reasonable solutions were emphasized. Taxation was considered as one of the needs to give an advantage to the circular product in the competition with non-circular products. Taxation has a remarkable effect on the profitability of operations. In addition, legislation and bureaucracy were considered challenging for the materials having a waste status.

> *...it should be understood in the early stage, that the natural sand and non-circular materials should carry a tax, which would give an advantage in the competition to the circular product in the beginning. We have seen it during the last 30 years, that when the conductor's stick swings in the taxation to some direction, it makes some parts of this business non-profitable and some parts profitable. (I6)*

6.4 Challenges and bottlenecks

The challenges and bottlenecks identified in the workshop are listed in Table 8 (original data in Appendix 1). The results can be categorized under categories of new value chains, knowledge gaps, technological, environmental, institutional and economic bottlenecks. The bottlenecks for technologies and new value chains were similar as already identified under the needs.

Table 8. Challenges and bottlenecks identified in the workshop and categorized into groups.

Challenges and bottlenecks	
Workshop results	***Categorization***
✓ Non-core business ✓ Old mines optimize the recovery of certain metals ✓ New mines take into account also the residue ✓ Quality requirements of the whole chain ✓ Need to manage the whole value chain ✓ Importance of volume ✓ Not all parts available for the value chain	New value chains, partnerships
✓ Impurities in circular materials ✓ Characterization important; not enough knowledge ✓ Technology needed for waste rock refinery ✓ Heterogeneous material in old waste dumps ✓ Secondary materials heterogeneity	Technological bottlenecks
✓ Risks in opening old heaps	Environmental bottlenecks
✓ Legislation e.g. arsenic; environmental requirements ✓ Process as in establishing a new mine ✓ "Contaminated land" stigma ✓ Environmental permits ✓ REACH; difficult to register new flotation chemicals	Institutional bottlenecks
✓ Knowledge on mineralogy, metal concentration and market price ✓ Virgin material often cheaper than secondary ✓ Material price ✓ Costs versus quality ✓ Pyrite, sulphur in excess; low markets ✓ Investment costs ✓ Building new process factory more expensive ✓ Financing for start-up companies ✓ Price of logistics	Economic bottlenecks
✓ Knowledge on mineralogy, metal concentration and market price	Knowledge gaps

Effect of mine lifecycle

The lifecycle of the mine affects how the mining industry handles side streams. New mines consider also residues, whereas old mines have focused on the optimization of the recovery of certain metals only. The valorization potential needs to be assessed before the mine site closure. When the old tailings ponds have already been landscaped, they are not reopened anymore. Some old mining sites have been transformed to other business, such as travel destinations, and are not anymore available for the raw materials supply.

> *When we close down the old tailings areas, it would be tragic to cover them first with taxpayers money and then to notice five years later, that there is a significant raw materials potential. [...] it might be that when the tailings have been reprocessed, the after-treatment could be easier and cheaper also from the environmental point-of-view. (I5)*

Environmental bottlenecks

Environmental risks were considered as bottlenecks in the tailings valorization in the workshop. There are environmental risks in keeping the tailings in the existing disposal areas. On the other hand, there exist environmental risks also in reopening the old tailings heaps.

Technological bottlenecks

Technology development for the mining side streams was considered as a bottleneck in the workshop and in the interviews. It was emphasized, that the secondary materials are heterogeneous and contain often impurities, which should be addressed in the technology development. Some interviewees identified specific challenges, which clearly are lacking technological solutions. The interviewees considered the technology gap for upscaling the technologies from the research and development stage to the actual utilization in the operations too wide. Tailings structures have been designed for the end disposal, and even getting the material physically from the tailings pond for further utilization creates challenges. It is easier to add tailings valorization to the existing process, because the mass transfer is more straightforward. With dry tailings, it is possible to get the material with a shovel.

Technology development in other industrial branches, such as in the energy sector, affects also the metal needs for their applications. Sometimes the predictability of technological advancements is low, and the future metals requirements are not well known. For example, lithium needs have increased significantly in the recent years, and the demand is expected to further increase. In previous years, these metals were not necessarily even considered in the recovery stage.

> *The development is so fast nowadays. Now we have a lot of lithium, cobalt and base metals. If some radical advancements happen in the energy storage, which is not at all excluded as the researchers are inventing, it can change the whole field completely. (I5)*

Value chain bottlenecks

As was already pointed out in the identification of needs, the value chains for tailings valorization are lacking. The proper management and maintaining the quality of the whole value chain are prerequisites of successful side stream utilization. The lifecycle of the mine affects how the mining industry handles the side stream. New mines have more focus also on residues, whereas the old mines tend to concentrate on optimizing the recovery of certain metals. The business could be profitable for SMEs even though the big mining companies would consider the business too small or not belonging to their core business. If it would be possible to outsource the business to some smaller players, such as SMEs, a financial incentive would exist.

> *If you consider a big mining company, it is not necessarily their core business. If you have a copper mine, and you find some small amounts of rare earth elements, it is not in their scope and in their core competence. They do not have the interest to change the big production process into the direction, where the new material would be circulated. This should be seen as a raw materials potential, which could get new business and there would be a new operator. It would need a collaboration mechanism, in which also the mining company would benefit from the other operator. (I5)*

The knowledge and expertise are scattered, which emphasizes the importance of networking and excellent industrial collaboration. The involved stakeholders need to be able to calculate the profit, value and usability of the developed solutions. Only one person or one company does not have all this necessary knowledge. Therefore, networking and making the service together, were suggested by the interviewees. However, suitable collaboration mechanisms would need to be developed, in which all partners would get benefits from the collaboration. Different development and collaboration programs should involve both large and smaller companies.

In addition, the lack of adequate human resources, such as knowledgeable engineers, was considered as a bottleneck. The utilization of a minor metal component is not the first and the most urgent issue, when at the same time the mining companies can focus on topics that are closer to the current operational activities.

Institutional bottlenecks

Permitting and regulations have clear effects on the selection of solutions for tailings. Institutional bottlenecks were related to legislation, environmental permits, REACH, processes and the views of the society. Regulations create necessity and determine how tailings can be disposed of. Authorities require an environmental permit, when tailings valorization is planned and started. The permitting process is rather extensive like in establishing a new mine. Due to the REACH requirements, it takes a lot of effort to register a new flotation chemical. Mine tailings areas were also considered to have a certain kind of "contaminated land" stigma, which could have an effect on the opinion of the society, when reprocessing the tailings areas. Ownership of the material and liabilities need to be clear. Some interviewees considered regulation as a positive issue, since it forces the progress to take place. It was highlighted that the regulations need to be predictable and fair, so that the regulations in various geographical areas would not vary too much and attract investments only to certain areas.

> *Different environmental permits likely restrict and the issues related to the ownership. Who owns the material and whether also the liabilities are transferred together with the ownership. These likely restrict the business. (I1)*

One interviewee compared the permitting of a virgin green field mine and tailings area inside an industrial area. When the operations take place inside an already existing industrial area, the permitting is easier than outside of the currently existing industrial areas.

> *The permitting is from the starting point lighter, if you already have it inside an industrial area. (I5)*

Economic bottlenecks

There exist also several market and economic bottlenecks in tailings valorization based on the workshop and interviews. Typically, virgin materials are cheaper in comparison to secondary materials. The low concentrations and amounts of the materials are the main challenges. Economically, the concentrations and masses of recoverable elements are often too low. In addition, the environmental investments are generally considered as costs in the companies. The lifetime of an infrastructure investment is decades. Therefore, the foresight is crucial to understand the long-term needs and trends. The possibility to get incomes from the valorization to even partly cover the processing costs would create more interest. The search for money and profit was considered as the biggest force in the interviews.

Material price affects directly the profitability of the secondary materials valorization. There is excess of some minerals and elements in the market, resulting in lower demand for these products. If the materials are located in remote areas, the logistics costs might be dominant. If something could be done to the logistics costs, it would change the situation significantly. It is a rule of thumb, that the transport of rock material over 100 km is unreasonable. Investment costs for the building of the processing plants are high and the profitable operation requires adequate size. There is not enough financing for start-up companies, which would be needed in the new value chains. To get the investments economically feasible takes time.

> *We do not necessarily have right kinds of financing models. A small company can get funding for research and piloting, but then the negotiation, who pays the upscaling, research, operation and build-up. Those players, who have the capital to invest in this kind of plant with the concept of own-and-operate and sell the service, are only a few. What I know of those few, the companies do not necessarily go to use especially new technologies, since the profit is so uncertain. Service companies do not have the experience to be able to price it as profitable business. (I2)*

> *In any case, this kind of operation requires plants and different kinds of competences, and therefore the profitability requires certain size. (I4)*

The benefits may however be wider than the value of the recovered metal, as was stated by another interviewee:

> *There is the double benefit, that the after-treatment might be cheaper, when the material is valorized. You can get the challenging particles away from there. (I5)*

Knowledge gaps

Knowledge gap of the tailings content was considered as one of the major bottlenecks in the interviews. If we do not know, what exists inside the tailings ponds, it is impossible to start valorizing them. Therefore, the knowledge of the existing and currently produced streams is crucial.

> *Our bottleneck is that we do not know, what is there. If we would know it better, it would increase the research about utilization. (I5)*

The analytics expenses were previously much higher than nowadays. The elements used in the novel technologies had no value in the past, and therefore they have not been ever analysed. In the previous decades, the analytics has been challenging and the accuracy of the results was considerably lower. The companies have a better understanding of their own disposal areas than what is publicly available. One interviewee also highlighted that the knowledge of the tailings materials can be higher than that of the virgin ores based only on some drillings in the area.

6.5 Summary of empirical results

The main findings of the workshop and interview results related to drivers/opportunities, needs and challenges/bottlenecks in tailings valorization have been summarized in Table 9.

Table 9. Summary of drivers and opportunities, needs, and challenges and bottlenecks related to tailings valorization identified in the workshop and theme interviews, and categorized into groups (Kinnunen & Kaksonen, 2019).

WORKSHOP	INTERVIEWS	CATEGORY
Drivers/opportunities		
From waste to raw material/ Storage of potential materials for future/ Waste waters may contain significant amounts of metals/ Willingness to collaborate; circular economy as target	Primary production needs to be seen as a part of the large circular economy/ Effect of the mine lifetime for long-term thinking/ Storing for the future	Circular economy mind set
Available commercial technologies/ Processes developed for certain valuables, not the whole material/ New analytical methods reveal new sources/ Pre-treatment and logistics to another place	New technologies enable the metal recovery from lower concentrations than before/ New technological use for certain metals/ New applications for tailings e.g. 3D printing and geopolymers	Technological drivers
Removal of environmental hazard/ Cleaning of environment		Environmental drivers
Involvement of the society/ International networks and EU collaboration	Recovery of metals from tailings in a restricted area can start faster than in Greenfield projects	Institutional drivers
Low grade ores/ Waste area investments a few euros per tonne/ Possibility to pay a part of final waste treatment costs with business from side streams/ Industrial symbiosis/ New business outside of mining	Demand and prices for certain elements have increased/ New needs turn certain components valuable	Economic drivers
Needs		
Need of one large company as driver/ Closing mine; new company needed for waste processing/ Not core business of anyone/ Large companies are willing to donate waste material, but volumes need to be big enough/ "Stock exchange" for certain side streams	Current value chains for tailings valorization incomplete/ Especially commercializing companies (SMEs) are missing/ Capital for new companies/ Various company strategies related to own core business and outsourcing/ Wider thinking and role of technology providers crucial already in the planning phase	New value chains, partnerships
Technology development/ Tailoring technology for low grade ores and side streams/ Technology for mineral utilization/	Increase of technology readiness levels/ Faster renewal of technologies/ Basic research	Technological needs
	Decrease of the amount of waste/ Isolation of harmful components/	Environmental needs

	Increase of the waste stability/ Management of storage needs/ Better final disposal	
	Logical and predictable regulation/ Legislation should favor the utilization of side streams/ Taxation to give an advantage to the circular product in the competition	Institutional needs
Challenges and bottlenecks		
	The valorization potential should be taken into account before closing the mine site/ Mining companies focus more on operational activities than on the recovery of minor components	Circular economy mindset
Non-core business/ Quality requirements and need to manage the whole chain/ Importance of volume/ Lacking parts in the value chain	Profit, value and usability calculations requires knowledge of several people and companies/ Networking and new value chains including SMEs/ Possibility to outsource the tailings valorization business/ Business too limited for large mining companies and not their core business or competence/ Collaboration mechanism needed	New value chains, partnerships
Impurities in circular materials/ Characterization important; not enough knowledge/ Technology needed for waste rock refinery/ Secondary materials heterogeneity	Technology gap for upscaling/ Pushing new technologies forward proceeds with small steps with good justifications	Technological bottlenecks
Risks in opening old heaps		Environmental bottlenecks
Legislation and environmental permits/ Process as in establishing a new mine/ "Contaminated land" stigma	Permitting process relatively extensive with clear effects on the selection of solutions/ Regulation determines, how tailings can be disposed/ Environmental permits and the issues related to the ownership likely restrict the valorization/ Linkage of ownership and liabilities/ More predictable and fair regulations/ Global market with different regulation in different areas	Institutional bottlenecks
Knowledge on mineralogy, metal concentration and market price/ Virgin material often cheaper than secondary/ Low material price and market/ Costs versus quality/ Investment costs/ Financing for start-up companies/ Logistics costs	Concentrations and masses of recoverable elements are not economically high enough/ High investment costs for the processing plants/ To get the investments economically feasible takes time/ Lacking capital/ Aftercare cheaper after valorization/ Logistics costs often dominant in remote areas	Economic bottlenecks
Knowledge on mineralogy, metal concentration and market price	Knowledge gap of the tailings content	Knowledge gaps

7 DISCUSSION

The adoption of circular economy concepts necessitates new knowledge to fill in the gaps of business opportunities, drivers and barriers (European Commission, 2014a; de Jesus & Mendonça, 2018). To my knowledge, this is the first study, where the opportunities, needs and barriers for tailings valorization in the mining industry have been identified. In the previous literature related to tailings valorization, the focus has been on the technology development. However, also other aspects identified in this study have a significant effect on the waste valorization possibilities. Mining industry has been widely lacking from the previous circular economy literature. This thesis contributes with new knowledge, which topics would need to be addressed, when mining industry makes the transformation towards circular industry.

The workshop and interviews pointed out, that there is a significant number of opportunities, needs and barriers in the mining industry, when the mine waste valorization is considered (Figure 5). Even though the valorization potential of tailings has been underexplored, clear potential for the future was recognized. The identified opportunities and drivers were categorized under circular economy mind set, and technological, environmental, institutional and economic drivers. The needs were new value chains, technology development, a decrease in the amount of waste, stability, taxation and predictability of regulation. Challenges and bottlenecks were categorized under new value chains, technological, environmental, institutional, economic and knowledge bottlenecks. The identified drivers and barriers were similar as reported in the literature (Ritzén & Sandstöm, 2017), but also some specifics typical to the mining industry were included. Even though in most studies in the literature technological barriers were blamed for the limited progress in the implementation of circular economy (de Jesus & Mendonça, 2018), in some studies cultural barriers were considered as main barriers (Kirchherr et al., 2018). Often the previous studies have given a helicopter view on the circular economy implementation in a general context and stated the possibility for sectorial differences (Kirchherr et al. 2018). Therefore, there is a need for more enhanced sectorial understanding of the circular economy potential in addition to the general view. This study has enhanced the understanding in the mining sector.

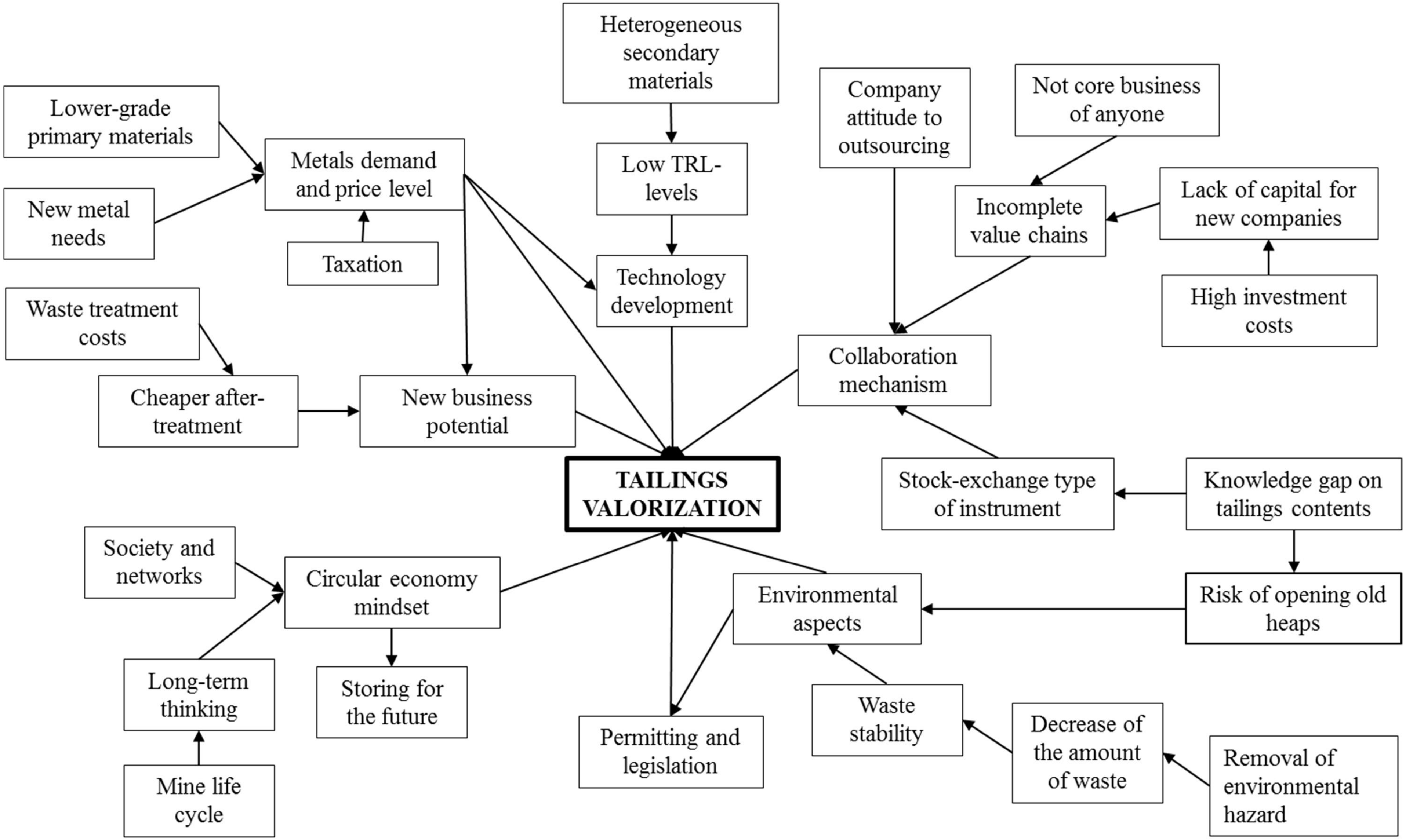


Figure 5. Identified aspects and their interconnections of tailings valorization potential in this study.

According to de Jesus and Mendonça (2018), typically a mixture of factors, not one single factor alone, either facilitate or hinder the circular economy adoption. Technology development was categorized under both drivers and barriers in this study, which clearly shows that the same factor can be at the same time an opportunity and a barrier. Often more than only one driver or barrier has an important role (de Jesus & Mendonça, 2018). The categories of opportunities, needs and barriers can have interactions, which was pointed out by e.g. Kirchherr et al. (2018), and de Jesus and Mendonça (2018). As an example, market limitations can hinder the implementation of ready technologies (de Jesus & Mendonça, 2018). This interactional phenomenon between identified categories was detected also in this study (Figure 5 and Figure 1 in Kinnunen & Kaksonen, 2019, in Appendix 3).

The most important identified factors as drivers, needs and/or barriers in the tailings valorization are discussed more in detail in the following sub-sections with the focus on implications on institutional effects.

7.1 Institutions

Bradley (2007) argued that instead of the resource scarcity, the focus should be on institutional arrangements, which influence the production of minerals. They can include for example the property rights, price flexibility and taxation levels (Bradley, 2007). There are several heterogeneous views on institutions from "the basic rules of the game" to particular governing structures and to the certain behaviour in particular contexts (Nelson, 2006). Identification and comparison of institutional drivers and barriers of circular economy in various areas could accelerate the transformation towards circular economy (Ranta et al., 2018). Globally, the particular driving forces towards circular economy have been identified as social, regulatory or institutional factors meaning for example institutional framing, social awareness, R&D support and legal set-ups (de Jesus & Mendonça, 2018). Often the social and regulatory factors are included under the institutional factor, and not distinguished separately. In the research of Ranta et al. (2018), the institutional environment in all selected areas, i.e. China, the US and Europe, supported recycling as the primary action in the circular economy. Institutional support for other types of circular economy were missing. In addition to general institutional drivers and barriers in circular economy, also regional differencies exist (Ranta et al., 2018).

In this study, various institutional factors were mentioned both as drivers as well as as bottlenecks, which is in accordance with the previous research. Institutions, i.e. the influence of the society, international networks, EU collaboration and regulations, were considered as drivers for the mining industry in the transition towards circular economy in the workshop and interviews. Similar drivers were found in the study of Lombardi et al. (2012, 2), where waste disposal costs, concerns over environment and stricter environmental regulations, and potential profits from waste and by-product utilization were recognized as drivers to reconsider company strategies.

In the interviews, taxation was mentioned as one of the needs to give an advantage to the circular product in competition with non-circular products. Interventions by governments favouring circular products via e.g. sustainable taxation decisions have been proposed also by Stahel (2013) and Kirchherr et al. (2018). In addition, virgin material prices can be artificially too low via governmental interventions, as some resources, such as energy, are provided at subsidized rates (Kirchherr et al. 2017b).

The institutional bottlenecks of this study included the views of the society, legislation/regulation, permitting, and processes in establishing an operation for the metal recovery from waste materials. Regulative and economic instruments have been found especially relevant, when considering the transformation of waste materials, such as gypsum, into useful materials (Jiménez-Rivero & Garcia-Navarro, 2017). According to van Beers et al. (2007, 70), the practical implementation of industrial symbiosis has been sometimes restrained by legislative uncertainties. On contrary to many pre-assumptions, large mining companies prefer global standard setting and even stricter policies over regulatory uncertainties (Dashwood, 2014). Bechtel et al. (2013) considered the complexity and discrepancies of regulations to have the potential to create barriers during the transformation to circular economy. One of the aims of the Circular Economy Package of the European Union is to “remove regulatory barriers for the circular economy” (European Union, 2017), which emphasizes the importance of regulations. However, based on the results of Ranta et al. (2018), the regulative pillar in institutional effects is not sufficient for the success of circular economy despite of its importance. Regulative processes can be supported or hindered by the normative and cultural-cognitive conditions (Ranta et al. 2018). Removing certain regulatory barriers does not necessarily result in the circular economy adaptation, if other barriers still exist, which highlights a holistic assessment of the situation (van Barnefeld et al., 2016). In addition, a “contaminated land” stigma was mentioned in the workshop with the possibility to affect the opinion of the society, when considering the reprocessing of tailings areas. Sauvé et al. (2016) have mentioned that sometimes there is unwillingness to use waste as a raw material source. Ownership of the material and liabilities related to secondary materials need to be clear.

7.2 Circular economy mind set

Stål and Corvellec (2018) considered circular economy as a specific institution, since it emerges via regulative, normative and cognitive processes. Mind set belongs to the cognitive processes, which formulate the beliefs and the way of thinking in a specific field. Circular economy thinking and mind set are crucial, since a reluctance to adopt circular economy thinking can be considered as a barrier for the circular economy transformation (Bechtel et al., 2013). Kirchherr et al. (2017b; 2018) found the lacking awareness or willingness to implement circular economy as the most pressing barrier in the transformation to circular economy. The workshop and interviews showed that the mining industry is aware of the circular economy thinking. The mining industry representatives considered circular economy in a positive way and they were willing to transform the sector towards circular economy. Many interviewees were familiar with the circular economy concept and had ideas how the mining industry could use the concept. Despite the exclusion of primary metals production from some of the cited circular economy descriptions, primary metal production was regarded as a part of larger circular economy concept in the interviews. However, the interviewees considered the circular economy in the mining sector unclear. A clearer role of mining in the circular economy framework would bring the transformation towards circular economy forward, and make better communication of its potential within the mining sector possible.

Based on the interviews, the utilization of tailings in the mining industry is only in its infancy. In addition, clear business potential for the future was emphasized. Since the transformation to the tailings utilization was expected to take a rather long time, there was emphasis on long-term thinking and storing tailings in an appropriate form for the future. The lifetime expectancy of the mining operation was considered to affect the attitudes of tailings treatment with longer-term operations making more efforts for tailings valorization. Wider thinking was highlighted especially in the planning and development phase, for the consideration of the metals and minerals recovery in a broader context. As an important remark, the valorization potential should be taken into account before finally covering the tailings in the closure phase. Even though the lacking awareness of circular economy can act as a strong barrier, the high interest in circular economy does not automatically mean its implementation (Kirchherr et al., 2018). The transformation from linear to circular economy can be challenging especially for the established companies (Antikainen & Valkokari, 2016, 6).

7.3 Knowledge gaps

Based on the workshop and interviews, knowledge gaps on mineralogy, metal and impurity concentrations in tailings, and on the market prices, are the challenges for tailings valorisation. This is in accordance with the findings of Nuss and Blengini (2018, 574), who noted that information on potential stocks, such as mine waste, is not broadly available. The challenge related to the knowledge gap was also defined by the European Innovation Partnership on Raw Materials in the Strategic Implementation Plan. When the data on raw materials exists in the EU, it is scattered and stored in various formats. The data is difficult to find and compare. (European Innovation Partnership on Raw Materials, 2013b, 42.)

The knowledge gap on the contents makes the valorization of tailings challenging. However, the analytical methods have become better and cheaper than in the previous decades, increasing the knowledge about tailings. In previous years, certain metals were not of interest and therefore they may have been left unanalysed. In the workshop, "Stock exchange" –types of instruments were suggested for the facilitation of knowledge transfer on available resources. Instruments for certain secondary resources have been developed e.g. the Advisory System for Processing, Innovation & Resource Exchange (ASPIRE) online market place (CSIRO, 2018) and the Urban Mine platform (www.urbanmineplatform.eu), but they have not been specifically targeted for the tailings or for the mining industry. Institutions can help in collecting the data from various sources, and in establishing suitable market places and instruments for secondary materials.

7.4 Economic factors

Finding suitable business cases for the implementation of circular economy may be challenging for companies (Bechtel et al., 2013). Various economics and market related drivers and bottlenecks in tailings valorization were recognized in this study. Logistics costs were mentioned by several interviewees as a bottleneck, since the mining areas are generally located in remote areas. Lower grade primary ore deposits can turn mining wastes into a competitive alternative as a raw material source, when total amounts and concentrations of recoverable elements are high enough for economic feasibility. Metal concentrations in waste piles may exceed the concentrations in currently operating mines. For example, the historic tailings piles in Snow Lake contain in average 9.7 grams of gold per tonne (BacTech, 2018) in comparison to the Laiva mine primary ore with approximately 1.2 grams gold per tonne (Firesteel Resources Inc., 2017). As an additional advantage, tailings have already been mined and crushed. This can decrease the treatment costs in comparison to primary materials, since mining and processing can result in 40–60% of the total costs (Cox et al., 2011; Zhao et al., 2012; Patent US2012/0114538 A1). Therefore, it could be economically profitable to use resources, which have already been mined and still contain considerable amounts of metals. Metal prices have a direct effect on the economics and profitability of secondary materials valorization. According to Bradley (2007), metal price is a scarcity value, which tends to be artificially too low or high due to overexploiting or underexploiting of minerals in various geographical areas.

The after-treatment of the tailings area might be cheaper after the metals recovery bringing further economic benefits. Also Lombardi et al. (2012, 2) considered the increased waste disposal costs and potential profits from by-product generation from waste as drivers for companies to reconsider their strategies. Tailings disposal operational costs vary typically between 0.5 and 1.5 US$/tonne (Center for Mathematical Modeling, 2018) and can go up to 7.39 US$/tonne depending on the technology used (Bascetin et al., 2016).

Investment costs for building up the processing plants are rather high, as stated by some interviewees. Therefore, there can be lack of capital for operations for mine tailings valorization. Also in a wider circular economy context, the lack of capital has been considered as a potential challenge (Roos, 2014). The lack of capital was shown to be a crucial element in the adoption of energy efficiency by SMEs in the study of Trianni and Cagno (2012). However, in some plants the infrastructure would already be in place in the area. The extension of a mine life has advantages such as existing infrastructure and investments, avoidance of uncertainties with opening a new mine, and delayed costs associated with the mine closure (West, 2011, 166). According to e.g. Somincor (Oliveira, 2016), solutions to recover value from their mine waste would reduce the amount to be managed, which would increase the lifetime of current facilities. The need for further tailings expansion would be eliminated (Oliveira, 2016). The investment needs and economic costs and benefits vary case-by-case, which emphasizes the need to consider the tailings valorization potential individually site-by-site.

When considering the effects of institutions on the economic factors, the institutional conditions differentiate profitable and non-profitable activities (Moreau et al., 2017). The econometric evidence has indicated that institutions applying contracts and protecting intellectual property rights increase economic development (Gagliardi, 2008). Moreau et al. (2017) argued that circular economy approach normally neglects biophysical, institutional and social aspects. Institutions are the actors distributing the costs among various economic agents. Institutions can determine the competitive conditions in circular economy with e.g. investment programs, fiscal policies and taxes (Moreau et al., 2017).

7.5 Technology development

Velis and Vrancken (2015) highlighted the need for more effective reprocessing technologies for closing the material loops in addition to advancing new business models. Technology development was considered both as a driver and as a barrier in the workshop and interviews. Newly developed commercial technologies for the low-grade ores and wastes make the utilization of previously non-attractive resources possible. Despite this fact, the technologies need to be developed and tailored further for side streams. Current technologies have focused only on certain materials, and not for the whole residue. The whole mineral matrix value would need to be considered in the technology development. In the technology development work for secondary materials, material heterogeneity and contents of impurities should be addressed. When analytical methods get better, new metal sources can be detected and found.

Inefficient and economical recycling technologies were potential challenges identified by Roos (2014, 260) in the transition from linear to circular economy. Technological barriers have been identified as a barrier to adopt the circular economy concept also in the studies of Bechtel et al. (2013) and de Jesus and Mendonça (2018). In addition to the appropriate technologies, this barrier includes technology gaps in bringing the technologies from invention to production stage, and lack of personnel with suitable specialized skills (de Jesus & Mendonça, 2018, 81). Technology gap for upscaling of technologies from research and development stage to the actual utilization in the operations, was considered too wide also in the interviews of this study.

The current recycling of raw materials from mining waste is low, as there are often economic or technological constraints (European Union, 2016, 84). Even though there would not be economically viable technological solutions at present, the mining waste management can focus on disposing the waste in a way that makes the utilization of waste possible in the future or sterilize the waste for any future purpose (Lèbre et al., 2017, 3). The future possibilities are thus determined by the decisions of today.

Nelson (2006) argued that the economic growth is intertwined with technologies and technological change, which further are intertwined with institutions and institutional change. Technologies are able to proceed in the conditions set up by certain institutions, while other institutions support the new technologies. When considering the classical economy, the resources are considered as fixed and finite in material terms. However, when considering the institutional perspective, the resources are not fixed, since they are determined by human knowledge resulting from technology and science. The stones were resources in the stone age, but when people started to develop tools made of metals, stones ceased to be resources. In the institutional approach, humans create resources. (De Gregori, 1987.) For example, according to West (2011), the metal grade decline in mining has resulted from new innovations turning the previously worthless waste into valuable ores. There have been major improvements in metallurgical technologies, development towards large-scale and cheap extraction technologies, and economic value when extending the lifetime of older mines instead of establishing new ones (West, 2011, 165). Knowledge and skills are thus needed in technology creation, which can create new resources (De Gregori, 1987).

According to Czarniawska (2008, 776), institutionalists ought to find more interest in technology. Technical norms can relate to human action (e.g. turning the cap of a bottle clockwise), machine behaviour (e.g. 220V voltage in Europe) or natural environment (e.g. SO2 air pollution limits) (Czarniawska, 2008, 775). In the recent years, the regulations in mining have got more stringent e.g. related to the sulphate removal limits into the natural environment (Kinnunen et al., 2017). Ali et al. (2017) have suggested institutional interventions, such as R&D efforts for technology development and investment support, as an action in turning the raw materials production more sustainable.

In addition to institutional effects on technology development, nature’s laws need special attention. As pointed out by Salminen and Olaussen (2018) and UNEP (2013), there are also physical and thermodynamic constraints, which determine the limits for circular economy of metals. Technology development for metals recovery from tailings and other secondary materials has thus certain limits.

7.6 Environment

In this study, the removal of environmental hazard, a decrease in the amount of waste and increase of waste stability were considered important, when utilizing mining side streams. The reopening of old mine tailings sites was considered on one side as a positive factor for the environment, but on the other hand the opening of old heaps can create also environmental risks.

Mining companies tend to favour politically stable countries as their operating area, but these normally have also the strictest environmental regulations. Environmental permits are based normally on case-by-case assessments, which can be affected by regulators’ competence and interpretations of rules and legislation. Even though the stringency of regulations is sometimes under criticism, more often the lack of predictable and timely decision-making is the perceived challenge. Institutions can address this challenge by giving more resources to authorities, establishing interactions between authorities and mining companies and forming standard procedures for assessments and legal interpretations. (Söderholm et al., 2015.) Interventions for environmental improvement may be e.g. voluntary standards, compulsory regulations, financial penalties and support, self-directed education, audits and reviews, and business advice (Parker et al., 2009).

The role of institutional influences on mining industry's voluntary and self-regulatory initiatives to improve the environmental and social performance has been significant (Dashwood, 2014). According to the institutional theory, when the professional field is mature, the companies act in a similar way. When looking at the environmental information between the larger and small mining companies, de Villiers et al. (2014) noticed that all companies were acting in a similar way and giving similar environmental information. In addition, Nikolaou and Evangelinos (2010) explained the adoption of similar environmental management practices in Greek and international mines as a mimetic strategy by the institutional theory.

7.7 Value chains

The lack of appropriate value chains can be an obstacle in the transition from linear model to the circular one (Sauvé et al., 2016). Companies are dependent on other organizations to adopt the circular economy concept (Bechtel et al., 2013). Based on the workshop results and interviews, the mining industry is lacking existing complete value chains for the side stream valorization. Especially SMEs seem to be missing from the value chains. European Commission has adopted The Green Action Plan for SMEs, where the purpose is "enabling SMEs to turn environmental challenges into business opportunities" (Rizos et al. 2015). Based on the study of Rizos et al. (2015), access to finance is a key issue for SMEs, when they try to develop products within a circular economy. This fact emphasizes the interrelatedness of various barriers, since financing and SME involvement in value chains are heavily interrelated.

The key role of technology providers to consider the recovery of minor elements already in the planning phase was mentioned in one interview. Companies' strategies, culture and ownership determine the willingness to outsource the activities and to engage in the partnerships. Most global mining companies focus solely on the main metals recovery from primary resources. However, mining companies might widen their participation along the value chain to integrate also into refining and recycling. An example of the wider participation in the value chain is the Swedish mining and smelting company Boliden, which has operations both in materials extraction and in recycling (Florin et al. 2015). When engaging into a wider part of the value chain, companies can get synergy in materials sourcing and resource recovery, and obtain a more stable business model.

Companies have the potential to participate in partnerships with other companies. Institutions help to increase cooperation and reduce opportunism (Gagliardi, 2008). Even though the partnerships have typically been grounded on the reuse and recycling of mining wastes, in addition other resources have the potential to be shared (Balanay & Halog, 2016). Industrial symbiosis integrating the waste streams of the mining industry has been described by Salmi (2007). In the industrial symbiosis, materials, water and energy are exchanged by company clusters. However, these possibilities for collaboration are generally overlooked. The external institutions, such as Kwinana Industry Council in Australia, connecting different network actors can further strengthen the relationships between companies and get stronger. (Chertow & Ehrenfeld, 2012.) In the Australian minerals industry, regional synergy opportunities were identified in water and energy efficiency and exchanges, and in industrial by-product reuse (van Beers et al., 2007, 70).

7.8 Summary of the effects of institutions on the identified drivers and barriers

This research contributes to the waste valorization in the mining industry and thus to the transformation towards circular economy. When the transformation is expected to progress, the barriers need to be overcome. Table 10 summarizes how the institutions can address the identified drivers, needs and bottlenecks for tailings valorization.

Table 10. Suggestions and implications how institutions already support and can address the identified drivers, needs and bottlenecks for the valorization of mining tailings.

Circular economy mind set	✓ Existing willingness to implement circular economy in the mining industry ✓ EU's and Finland's circular economy strategies support tailings valorization ✓ Recycled materials considered valuable from the beginning ✓ Wider thinking especially in the planning and closure phases in mining to consider the whole material ✓ The positive influence of the society, international networks and EU collaboration on mind set ✓ Removing the "contaminated land" stigma
Legislation	✓ Environmental permits and regulations determine what companies do ✓ Removing uncertainties in the legislative framework is necessary ✓ Ownership of the material and liabilities needs to be clear
Economics	✓ Taxation, subsidies, investment programs and fiscal policies could give an advantage on circular products ✓ Utilization of existing infrastructure and the increase of the lifetime of current facilities in tailings storage affect positively the economics
Technology	✓ R&D support can develop technologies and bring them to higher Technology Readiness Levels ✓ Education of students in circular economy aspects
Knowledge gap on content	✓ Gathering scattered raw material data (mineralogy, metal and impurity concentrations) into databases ✓ Establishment of a material stock exchange platform
Environment	✓ Environmental permits and regulation need to be predictable and decided timely ✓ Voluntary and self-regulatory initiatives of companies ✓ Benchmarking to most advanced companies in the mining sector
Value chains	✓ Mechanism to increase cooperation between companies and reduce opportunism ✓ Support for SMEs to complement the currently existing value chains

7.9 Research trustworthiness

According to Eriksson and Kovalainen (2008, 305), reliability is related to consistency and repeatability of research. Validity relates to accurately presenting the phenomenon and backing the research by sufficient evidence. However, reliability and validity can be substituted by trustworthiness consisting of credibility, transferability, dependability and confirmability in qualitative research. Dependability includes a logical and well documented research project (Eriksson & Kovalainen, 2008). I have offered information to the reader about the thinking and logics of my research process. Workshop results and direct quotations were included to the results to enable the reader to follow the rationale behind the interpretation of results. Transferability means the similarity in other research contexts with the connection of the work done and previous results (Eriksson &

Kovalainen, 2008). I have made a detailed literature review to find out similarities and differences between this research and previous studies in circular economy and also in mining, when possible. Credibility considers whether the data is sufficient for the claims and if the link between categories and observations is strong enough (Eriksson & Kovalainen, 2008). This research has received data from multiple sources; the workshop, interviews and literature. I have a long history in the mining industry and I am thus familiar with the topic. I consider the data to be sufficient to justify the claims that have been made. Conformability considers the links between findings and interpretations easily understandable to other people (Eriksson & Kovalainen, 2008). I have collected information and presented findings in a way that allows the reader to follow these links. Therefore, I consider the trustworthiness to be on a good level.

This study has also several limitations. The study focused only on tailings valorization, and it does not consider other aspects of circular economy in mining. Only a limited number of interviews was possible. Even though the saturation point was reached in the interviews and similar topics were raised by the informants, additional interviews could have brought some further aspects to the topic. The interviewees represented Finnish mining industry. Other stakeholders in Finland or mining industry representatives from other countries could have had different viewpoints. In addition to general institutional drivers and barriers in circular economy, there are also regional differencies (Ranta et al., 2018). This study has thus regional limitation. The anonymity of interviewees was kept throughout the study and it is not possible to track the informants to specific quotes and opinions.

The disadvantages of content analysis, which was used as the data analysis method, relate to ambiguous or too extensive research questions and potential for excessive interpretation (Elo & Kyngäs, 2008). There is also the possibility to fail in the proper identification of key categories (Hsieh & Shannon, 2005). The categories were not mutually exclusive in this study. More than only one driver or barrier was important. Typically, there is a large variety of factors to facilitate or hinder the circular economy adoption. The content analysis is rather a summary of research than a report of all details of messages (Neuendorf, 2017, 23).

There might be potential bias due to my involvement in the mining industry. I have tried to analyse the obtained data as objectively as possible, but my previous experiences from the mining industry may have affected the interpretation of the results.

Most of the organizations that were interviewed, have not necessarily adopted the circular economy concept in practice so far. Therefore, the answers of the interviewees can represent rather perceptions than the actual experience.

8 CONCLUSIONS

This study has contributed to the scientific and practical knowledge of the influence of various factors on circular economy approach in the mining industry. The utilization of circular economy concepts needs advancements in filling the knowledge gaps of business opportunities, drivers and barriers (European Commission, 2014a; de Jesus & Mendonça, 2018), which were in the focus of this study for mine tailings valorization. By understanding the circular economy business potential for tailings valorization, the study provides support for designing and implementing circular business in the mining sector. The drivers, needs and barriers in tailings valorization in the mining industry were identified in this study. Based on a better understanding of these factors, the ways to transform mining industry towards circular economy in tailings valorization were characterized. Even though there are several institutional initiatives to move from linear to circular economy, there exist also barriers to such transformation. The transformation from linear economy to the circular one does not come in place, if the challenges and barriers are not addressed and possible solutions demonstrated to lower the identified barriers.

The mine tailings valorization is still at its infancy. However, the situation is expected to change in the coming years. The current knowledge of the tailings contents and amounts is limited. This knowledge needs to be collected so that the mining industry would better understand the possibilities for tailings valorization. A critical requirement is the ability to find suitable business cases. These cases may be affected by the market demand and metal price evolution, savings in the disposal costs, and waste related liabilities. Access to finance is crucial especially for SMEs. Due to the technology development, some lower-grade materials can be turned into raw material sources, which take into account minor metals and the whole mineral matrix in addition to the targeted major metals. The residual mineral matrix can find application in geopolymers in the mine sites and construction industry or in new technologies, such as 3D printing. The lacking or incomplete value chains for tailings valorization can hinder the transformation towards circular economy, but on the other hand also offer business opportunities for new companies. Institutional influence, including for example taxation, might change the profitability of the business and accelerate the circular economy transformation.

This study contributes to the knowledge, how mining industry's transition to circular economy could be improved. Various stakeholders in the mining industry have now a better view, what can be taken into account, when considering the valorization of mining waste. In addition, the identified opportunities, barriers and bottlenecks can act as valuable references, when considering other waste streams.

Companies also pro-actively influence the institutional demands for circularity towards their own interests (Stål & Corvellec, 2018). Organizations, such as mining companies, can use the legitimising strategies at an industry level, and undertake certain activities with other industry participants (Deegan & Blomquist, 2006, 347). The transition into the circular economy model could help to overcome the fact, that the public in general in the EU has little trust that mining companies would behave in a responsible way (European Union, 2016, 8).

Current institutional systems are based on linear economic models, but they might transform into the circular model. This study can provide information to policymakers on how to help the mining industry into the circular economy transition. Policymakers need to understand the challenges related to the transformation, so that they can develop supporting policy frameworks. According to Esposito et al. (2017, 13), regulations favouring the traditional linear economy business should be addressed. Regulative and economic instruments were found especially relevant when considering to transform waste materials into useful materials (Jiménez-Rivero & Garcia-Navarro, 2017). Policymakers can focus on regulatory failures and fixing the market. They can also set targets, change public procurement policy, create collaboration platforms and technically or financially support business. (Ellen MacArthur Foundation, 2015b.) Institutional theory suggests that uncertainty and innovation characterize a new field. When the field is mature, almost all organization in the field follow the same kinds of rules and structures and the differences start to disappear (de Villiers et al., 2014).

The results enable a more detailed understanding of possibilities, needs, and bottlenecks for waste valorization in the mining industry. The identified mixture of various factors either facilitate or hinder the circular economy adoption. By understanding the circular economy business potential for tailings valorization, the study provides support to both companies and institutional stakeholders for designing and implementing circular business in the mining sector with highest priorities. There exists evident business potential for metals recovery from the mining waste in the future. Addressing the identified barriers both by companies and by institutional stakeholders can speed up the transformation towards circular economy.

9 FUTURE PERSPECTIVES

Typically, the business opportunities around mining tailings have not been evaluated by the mining companies. This emphasizes the need for active communication and increase of knowledge of the circular economy possibilities. Tailings valorization has the potential to become economically and technically more feasible. However, there is not enough information about tailings contents. Databases to collect the amount and content data of existing tailings are needed. When we get new knowledge of the tailings contents, also more research on the tailings utilization possibilities and development of technologies with higher technology readiness levels are expected. The value chains for tailings valorization were found currently incomplete. The establishment of SMEs and adequate financing to them have the potential to create the required actors to the value chains. Institutions can remove the identified barriers related to permitting, legislation and attitudes, and provide support for knowledge transfer, technology development, and business and ecosystem creation.

In the institutional approach, humans create resources. Even though the technologies would not be economically viable at present, tailings can be stored in a way that makes the valorization possible in the future. The future possibilities for tailings valorization are determined by the decisions of today.

REFERENCES

Literature

Agricola G. 1556. De Re Metallica.

Alhojailan M.I. 2012. Thematic analysis: A critical review of its process and evaluation. West East Journal of Social Sciences. December 2012, 1 (1): 39–47.

Ali S.H., Giurco D., Arndt N., Nickless E., Brown G., Demetriades A., Durrheim R., Enriquez M.A., Kinnaird J., Littleboy A., Meinert L.D., Oberhänsli R., Salem J., Schodde R., Schneider G., Vidal O. and Yakovleva N. 2017. Mineral supply for sustainable development requires resource governance. Nature 543: 367–372.

Antikainen M. and Valkokari K. 2016. A framework for sustainable circular business model innovation. Technology Innovation Management Review 6 (7): 5–12.

Ayres, R. U. 1994. Industrial metabolism; theory and policy, in B. R. Allenby and D. J. Richards (eds), The Greening of Industrial Ecosystems, National Academy Press, Washington, DC, 23–37.

Balanay R and Halog A. 2016. Charting policy directions for mining's sustainability with circular economy. Recycling 1: 219–231.

van Barnefeld J., van der Veen G., Enenkel K. Mooren C., Talman-Gross L., Eckartz K., Ostertag K., Duque-Ciceri N., Fischer T., Gama M., Scheidt L., Wilts H., Schäfer L. and Fischer S. 2016. Regulatory barriers for the circular economy. Lessons from ten case studies. Final report, 13 July 2016. 169 pp.

Bascetin A., Tuylu S., Adiguzel D. and Ozdemir O. 2016. New technologies on mine process tailing disposal. Journal of Geological Resource and Engineering 2: 63–72.

Bechtel N., Bojko R. and Völkel R. 2013. Be in the loop: Circular economy & strategic sustainable development. Master Thesis, Blekinge Institute of Technology, Karlskrona, Sweden.

van Beers D., Corder G., Bossilkov A. and van Berkel R. 2007. Industrial Symbiosis in the Australian Minerals Industry. The Cases of Kwinana and Gladstone. Journal of Industrial Ecology 11 (1): 55–72.

Bellenfant G., Guezennec A.G., Bodénan F., D'Hugues P. and Cassard D. 2013. Re-processing of mining waste: Combining environmental management and metal recovery? Mine Closure 2013, Sep 2013, Cornwall, United Kingdom. pp. 571–582.

Bengtsson M. 2016. How to plan and perform a qualitative study using content analysis. NursingPlus Open 2: 8–14.

Bocken N.M.P., Short S.W., Rana P. and Evans S. 2014. A literature and practice review to develop sustainable business model archetypes. Journal of Cleaner Production 65: 42–56.

Bocken N.M.P., de Pauw I., Bakker C. and van der Grinten B. 2016. Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering 33 (5): 308–320.

Boons F. and Lüdeke-Freund F. 2013. Business models for sustainable innovation: state-of- the-art and steps towards a research agenda. Journal of Cleaner Production 45: 9–19.

Boons F., Montalvo C., Quist J. and Wagner M. 2013. Sustainable innovation, business models and economic performance: an overview. Journal of Cleaner Production 45: 1–8.

Bradley R.L.Jr. 2007. Resourceship: An Austrian theory of mineral resources. The Review of Austrian Economics 20: 63–90.

BRGM. 2001. Management of mining, quarrying and ore-processing waste in the European Union, 79 p.

Campbell J.L. 2006. Institutional analysis and the paradox of corporate social responsibility. The American Behavioral Scientist 49 (7): 925–938.

Chertow M. and Ehrenfeld J. 2012. Organizing self-organizing systems. Toward a theory of industrial symbiosis. Journal of Industrial Ecology 16(1): 13–27.

Chesbrough H. 2010. Business model innovation: Opportunities and barriers. Long Range Planning 43(2/3): 354–363.

Czarniawska B. 2008. How to misuse institutions and get away with it: Some reflections on institutional theory(ies). In Greenwood R. Oliver C., Suddaby R. and Sahlin K. (Eds.). The SAGE Handbook of Organizational Institutionalism.

Dashwood H.S. 2014. Sustainable development and industry self-regulation: Developments in the global mining sector. Business & Society 53(4): 551–582.

Dale B. 2002. An institutionalist approach to local restructuring. The case of four Norwegian mining towns. European Urban and Regional Studies 9(1): 5–20.

De Gregori, T. R. 1987. Resources are not; they become: An institutional theory. Journal of Economic Issues 21(3): 1241–1263.

Deegan C. and Blomquist C. 2006. Stakeholder influence on corporate reporting: An exploration of the interaction between WWF-Australia and the Australian minerals industry. Accounting, Organizations and Society 31: 343–372.

Directive 2006/21/EC of the European Parliament and of the Council on the management of waste from the extractive industries.

Dorado S. 2005. Institutional entrepreneurship, partaking, and convening. Organization Studies 26(3): 385–414.

Edraki M., Baumgartl T., Manlapig E., Bradshaw D., Franks D.M. and Moran C.J. 2014. Designing mine tailings for better environmental, social and economic outcomes: a review of alternative approaches. Journal of Cleaner Production 84: 411–420.

Ellen MacArthur Foundation. 2013. Towards the circular economy. Economic and business rationale for an accelerated transition.

Ellen MacArthur Foundation. 2015a. Towards a circular economy: business rationale for an accelerated transition. November 2015. 19 p.

Ellen MacArthur Foundation. 2015b. Delivering the circular economy. A toolkit for policymakers.

Elo D. and Kyngäs H. 2008. The qualitative content analysis process. Journal of Advanced Nursing 62 (1): 107–115.

European Commission. 2011. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A resource-efficient Europe - Flagship initiative under the Europe 2020 Strategy. Brussels, 26.1.2011, COM(2011) 21 final.

European Commission. 2014a. Scoping study to identify potential circular economy actions, priority sectors, material flows and value chains. August 2014.

European Commission. 2014b. Report on critical raw materials for the EU. Report of the ad hoc working group ondefining critical raw materials. May 2014. Ref. Ares(2015)1819503 - 29/04/2015. 41 p.

European Commission. 2015a. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the loop - An EU action plan for the Circular Economy. Brussels, 2.12.2015, COM(2015) 614 final.

European Commission. 2015b. Circular economy. Closing the loop. An ambitious EU circular economy package.

European Commission. 2017. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the implementation of the Circular Economy Action Plan. Brussels, 26.1.2017, COM(2017) 33 final.

European Innovation Partnership on Raw Materials. 2013a. Strategic implementation plan for the European Innovation Partnership on Raw Materials. Part I. Final version - 18/09/2013.

European Innovation Partnership on Raw Materials. 2013b. Strategic implementation plan for the European Innovation Partnership on Raw Materials. Part II. Priority areas, action areas and actions. Final version - 18/09/2013.

European Union. 2016. European Innovation Partnership on Raw Materials. Raw materials scoreboard. Publications Office of the European Union, Luxembourg.

European Union. 2017. Commission staff working document. The EU Environmental Implementation Review. Country Report - The Netherlands. Accompanying the document Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. The EU Environmental Implementation Review: Common Challenges and how to combine efforts to deliver better results. Brussels, 3.2.2017. SWD(2017) 52 final.

Eriksson P. and Kovalainen A. 2008. Qualitative methods in business research: A practical guide to social research. 2nd edition. SAGE Publications Ltd, London. 363 pp.

Esposito M., Tse T. and Soufani K. 2017. Is the circular economy a new fast-expanding market? Thunderbird International Business Review 59 (1) January/February 2017: 9–14.

Evers J. and Boer F. 2012. Qualitative Interview: Art and Skill, Eleven International Publishing. ProQuest Ebook Central.

Fischer A. and Pascucci S. 2017. Institutional incentives in circular economy transition: The case of material use in the Dutch textile industry. Journal of Cleaner Production 155: 17–32.

Florin N., Madden B., Sharpe S., Benn S., Agarwal R., Perey R. and Giurco D. 2015. Shifting Business Models for a Circular Economy: Metals Management for Multi-Product-Use Cycles, UTS, Sydney.

Frow P., Nenonen S., Payne A. and Storbacka K. 2015. Managing co-creation design: A strategic approach to innovation. British Journal of Management 26: 463–483.

Gagliardi F. 2008. Institutions and economic change: A critical survey of the new institutional approaches and empirical evidence. The Journal of Socio-Economics 37: 416–443.

Geissdoerfer M., Bocken N.M.P. and Hultink E.J. 2016. Design thinking to enhance the sustainable business modelling process - A workshop based on a value mapping process. Journal of Cleaner Production 135: 1218–1232.

Gifford B., Kestler A. and Anand S. 2010. Building local legitimacy into corporate social responsibility: Gold mining firms in developing nations. Journal of World Business 45: 304–311.

Giurco D., Littleboy A, Boyle T., Fyfe J. and White S. 2014. Circular Economy: Questions for Responsible Minerals, Additive Manufacturing and Recycling of Metals. Resources 3: 432–453.

Golev A., Lebre E. and Corder G. 2016. The contribution of mining to the emerging circular economy. AusIMM Bulletin August 2016.

Govindan K. and Hasanagic M. 2018. A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective. International Journal of Production Research.

Gregson N., Crang M., Fuller S. and Holmes H. 2015. Interrogating the circular economy: the moral economy of resource recovery in the EU. Economy and Society 44(2): 218–243.

GTK. 2010. Finland’s mineral strategy, 19 pp. Available at www.mineraalistrategia.fi.

Homrich A.S., Galvao G., Abadia L.G. and Carvalho M.M. 2018. Review. The circular economy umbrella: Trends and gaps on integrating pathways. Journal of Cleaner Production 175: 525–543.

Hsieh H.-F. and Shannon S.E. 2005. Three Approaches to Qualitative Content Analysis. Qualitative Health Research 15: 1277–1288.

de Jesus A., Antunes P., Santos R. and Mendonça S. 2018. Eco-innovation in the transition to a circular economy: An analytical literature review. Journal of Cleaner Production 172: 2999–3018.

de Jesus A. and Mendonça S. 2018. Lost in transition? Drivers and barriers in the eco-innovation road to the circular economy. Ecological Economics 145: 75–89.

Jiménez-Rivero A. and García-Navarro J. 2017. Exploring factors influencing post-consumer gypsum recycling and landfilling in the European Union. Resources, Conservation and Recycling 116: 116–123.

Johnson D.B. 2014. Biomining - biotechnologies for extracting and recovering metals from ores and waste materials. Current Opinion in Biotechnology 30: 24–31.

Kirchherr J., Reike D. and Hekkert M. 2017a. Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation & Recycling 127: 221–232.

Kirchherr J., Piscicelli L., Boura R., Kostense-Smit E., Muller J., Huibrechtse-Truijens A. and Hekkert M. 2018. Barriers to the circular economy: Evidence from the European Union (EU). Ecological Economics 150: 264–272.

Kinnunen P., Kyllönen H., Kaartinen T., Mäkinen J., Heikkinen J. and Miettinen V. 2017. Sulphate removal from mine water with chemical, biological and membrane technologies. Water Science & Technology, Bonus issue 1: 194–205.

Kinnunen P. and Kaksonen A. 2019. Towards circular economy in mining: Opportunities and bottlenecks for tailings valorization. Journal of Cleaner Production, in press.

Lèbre E, Corder G. and Golev A. 2017. The Role of the Mining Industry in a Circular Economy. A Framework for Resource Management at the Mine Site Level. Journal of Industrial Ecology 0 (0): 1–11.

Lombardi D.R., Lyons D., Shi H. and Agarwal A. 2012. Industrial Symbiosis. Testing the Boundaries and Advancing Knowledge. Journal of Industrial Ecology 16 (1): 2–7.

Lottermoser B.G. 2011. Recycling, reuse and rehabilitation of mine wastes. Elements 7: 405–410.

Lovins A.B., Lovins L.H. and Hawken P. 1999. A road map for natural capitalism. 85 (7/8): 145–158.

McDowall W., Geng Y., Huang B., Barteková E., Bleischwitz R., Türkeli S., Kemp R. and Doménech T. 2017. Circular economy policies in China and Europe. Journal of Industrial Ecology 21(3): 651–661.

Meyer J.W. and Rowan B. 1977. Institutionalized organizations: formal structure as myth and ceremony. American Journal of Sociology 83(2): 340–363.

Moreau V., Sahakian M., van Griethuysen P. and Vuille F. 2017. Coming full circle. Why social and institutional dimensions matter for the circular economy. Journal of Industrial Ecology 21(3): 497–506.

Murray A., Skene K. and Haynes K. 2017. The circular economy: An interdisciplinary exploration of the concept and application in a global context. Journal of Business Ethics 140: 369–380.

Nelson, R.R. 2006. What makes an economy productive and progressive? What are the needed institutions? LEM Working Paper Series, No. 2006/24, Scuola Superiore Sant'Anna, Laboratory of Economics and Management (LEM), Pisa.

Neuendorf K.A. 2017. The content analysis guidebook. Second edition. SAGE Publications, Los Angeles.

Nikolaou I.E. and Evangelinos K.I. 2010. A SWOT analysis of environmental management practices in Greek Mining and Mineral Industry. Resources Policy 35: 226–234.

Nuss P. and Blengini G.A. 2018. Towards better monitoring of technology critical elements in Europe: Coupling of natural and anthropogenic cycles. Science of the Total Environment 613–614: 569–578.

Oliveira M.S., Santana R.C., Ataide C.H. and Barrozo M.A.S. 2011. Recovery of apatite from flotation tailings. Separation and Purification Technology 79(1): 79–84.

Osterwalder A., Pigneur Y. and Clark T. 2010. Business model generation: A handbook for visionaries, game changers, and challengers. John Wiley and Sons.

Parker C.M., Redmond J. and Simpson M. 2009. A review of interventions to encourage SMEs to make environmental improvements. Environment and Planning C: Government and Policy 27: 279–301.

Potting J., Hekkert M., Worrell E. and Hanemaaijer A. 2017. Circular economy: Measuring innovation in the product chain. PBL Netherlands Environmental Assessment Agency, January 2017.

Prno J. and Slocombe D.S. 2012. Exploring the origins of ‘social license to operate’ in the mining sector: Perspectives from governance and sustainability theories. Resources Policy 37: 346–357.

Punkkinen H., Räsänen L., Mroueh U.-M., Korkealaakso J., Luoma S., Kaipainen T., Backnäs S., Turunen K., Hentinen K., Pasanen A., Kauppi S., Vehviläinen B. and Krogerus K. 2016. Guidelines for mine water management. VTT Technology 266, June 2016.

Ranta V., Aarikka-Stenroos L., Ritala P., Mäkinen S.J. 2018. Exploring institutional drivers and barriers of the circular economy: A crossregional comparison of China, the US, and Europe. Resources, Conservation & Recycling 135: 70–82.

Ritzén S. and Sandström G.Ö. 2017. Barriers to the Circular Economy – integration of perspectives and domains. The 9th CIRP IPSS Conference: Circular Perspectives on Product/Service-Systems. Procedia CIRP: 7–12.

Rizos V., Behrens A., Kafyeke T., Hirschnitz-Garbers M. and Ioannou A. 2015. The circular economy: Barriers and opportunities for SMEs. CEPS Working document, No. 412, September 2015.

Roos G. 2014. Business model innovation to create and capture resource value in future circular material chains. Resources 3: 248–274.

Salmi O. 2007. Eco-efficiency and industrial symbiosis - a counterfactual analysis of a mining community. Journal of Cleaner Production 15: 1696–1705.

Sauvé S., Bernard S. and Sloan P. 2016. Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. Environmental Development 17: 48–56.

Scott W.R. 2004. Institutional theory: Contributing to a theoretical research program. Great Minds in Management: The Process of Theory Development, Ken G. Smith and Michael A. Hitt, eds. Oxford UK: Oxford University Press.

Scott W.R. 2008. Approaching adulthood: the maturing of institutional theory. Theory and Society 37: 427–442.

Scott W.R. 2014. Institutions and organizations: ideas and interests. SAGE Publications, Inc.

Simate G.S. and Ndlovu S. 2014. Acid mine drainage: Challenges and opportunities. International Journal of Engineering Research and Applications 2: 1785–1803.

Singh J. and Ordonez I. 2016. Resource recovery from post-consumer waste: important lessons for the upcoming circular economy. Journal of Cleaner Production 134: 342–353.

Sitra. 2015. The opportunities of a circular economy for Finland. Sitra studies 100. October, 2015.

Sitra. 2016. Leading the cycle. Finnish road map to a circular economy 2016-2025. Sitra Studies 121.

Stahel W.R. 2013. Policy for material efficiency — sustainable taxation as a departure from the throwaway society. Philosophical Transactions of the Royal Society A 371, 20110567.

Suddaby R. 2010. Challenges for institutional theory. Journal of Management Inquiry 19(1): 14–20.

Stål H.I. and Corvellec H. 2018. A decoupling perspective on circular business model implementation: Illustrations from Swedish apparel. Journal of Cleaner Production 171: 630–643.

Söderholm K., Söderholm P., Helenius H., Pettersson M., Viklund R., Masloboev V., Mingaleva T. and Petrov V. 2015. Environmental regulation and competitiveness in the mining industry: Permitting processes with special focus on Finland, Sweden and Russia. Resources Policy 43: 130–142.

Tao J. 2016. A literature review on institutional change and entrepreneurship. Open Journal of Business and Management 4: 629–648.

Taylor S.J., Bogdan R. and DeVault M. 2015. Introduction to qualitative research methods: A guidebook and resource. John Wiley & Sons, Inc., Hoboken, New Jersey, 403 pp.

Trianni A. and Cagno E. 2012. Dealing with barriers to energy efficiency and SMEs: Some empirical evidences. Energy 37: 494–504.

UNEP. 2013. Metal recycling: Opportunities, limits, infrastructure. A report of the working group on the global metal flows to the international resource panel. Reuter M.A., Hudson C., van Schaik A., Heiskanen K., Meskers C. and Hagelüken C. April 2014. 316 p.

US patent. 2012. 114538A. Method for extracting rare earth elements from phosphogypsum.

Velis C.A. and Vrancken K.C. 2015. Which material ownership and responsibility in a circular economy? Waste Management & Research 33 (9): 773–774.

de Villiers C., Low M. and Samkin G. 2014. The institutionalization of mining company sustainability disclosures. Journal of Cleaner Production 84: 51–58.

VTT. 2016. Policy Brief. New ways of thinking will lead to economic growth. Bringing circular economy into play. 1/2016.

Wang C., Harbottle D., Liu Q. and Xu Z. 2014. Current state of fine mineral tailings treatment: A critical review on theory and practice. Minerals Engineering 58: 113–131.

Weik E. 2011. Institutional entrepreneurship and agency. Journal for the Theory of Social Behavior 41: 466–481.

West J. 2011. Decreasing metal ore grades. Are they really being driven by the depletion of high-grade deposits? Journal of Industrial Ecology 15 (2): 165–168.

Wijen F. and Ansari S. 2006. Overcoming inaction through collective institutional entrepreneurship: Insights from regime theory. Organization Studies 28(07): 1079–1100.

World Economic Forum. 2016. Mapping Mining to the Sustainable Development Goals: An Atlas. Available at: http://unsdsn.org/wp-content/uploads/2016/11/Mapping_Mining_SDGs_An_Atlas.pdf

Zhao Y., Zang L., Li Z. and Qin J. 2012. Discussion on the model of mining circular economy. Energy Procedia 16: 438–443.

Other references

BacTech. 2018. http://bactechgreen.com/projects /#snowlake [referred 8.3.2018]

Bard F. and Ntemiris S. Co creation lab. How can autonomous transport systems bring value in cities? https://goteborg.se/wps/wcm/connect/bc6930a0-968d-4905-8b65-e7d736f62c3c/Slutrapport-Co-creation_lab_170831.pdf?MOD=AJPERES [referred 9.1.2018]

Center for Mathematical Modeling. 2018. A new dam for tailings disposal. http://www.cmm.uchile.cl/?p=22156 [referred 8.3.2018]

Cox J.J., Ciuculescu T., Goode J.R. and Hains D.H. 2011. Abalon Rare Metals Inc. Technical report on the Thor Lake project, northwest territories, Canada. NI 43–101 Report.

CSIRO, 2018. ASPIRE: Advisory System for Processing, Innovation & Resource Exchange. https://aspire.csiro.au/ [referred 8.7.2018]

EIT Raw Materials. 2018. http://eitrawmaterials.eu [referred 9.3.2018]

Firesteel Resources Inc. 2017. News release. Firesteel Resources Inc. and Nordic Mines sign JV agreement for Laiva Mine in Finland. Vancouver, BC, 11.9.2017.

Kirchherr J., Hekkert M., Bour R., Huibrechtse-Truijens A., Kostense-Smit E. and Muller J. 2017b. Breaking the barriers to the circular economy. October 2017.

Metals X Limited. 2017. Renison tailings retreatment project (“Rentails”) updated DFS confirms high margin project. ASX release. 4.7.2017.

Official Statistics of Finland (OSF): 2015. Waste statistics [e-publication]. Helsinki: Statistics Finland [referred: 5.1.2018]. Access method: http://www.stat.fi/til/jate/2013/jate_2013_2015-05-28_tie_001_en.html

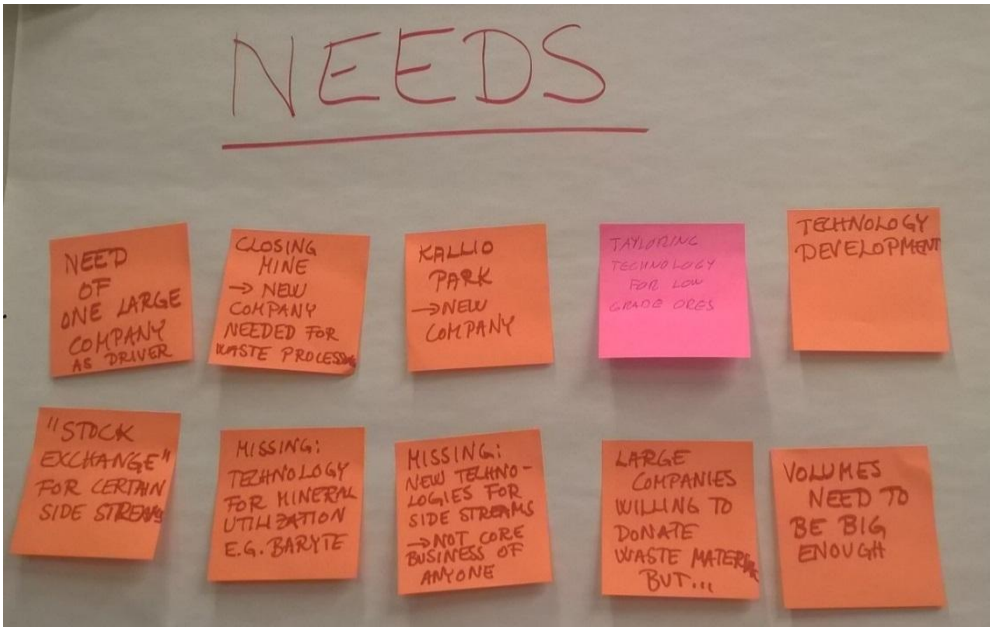
Salminen J. and Olaussen S. 2018. SOCRATES Policy Brief. Overcoming challenges in the circular economy: A thermodynamic reality-check.

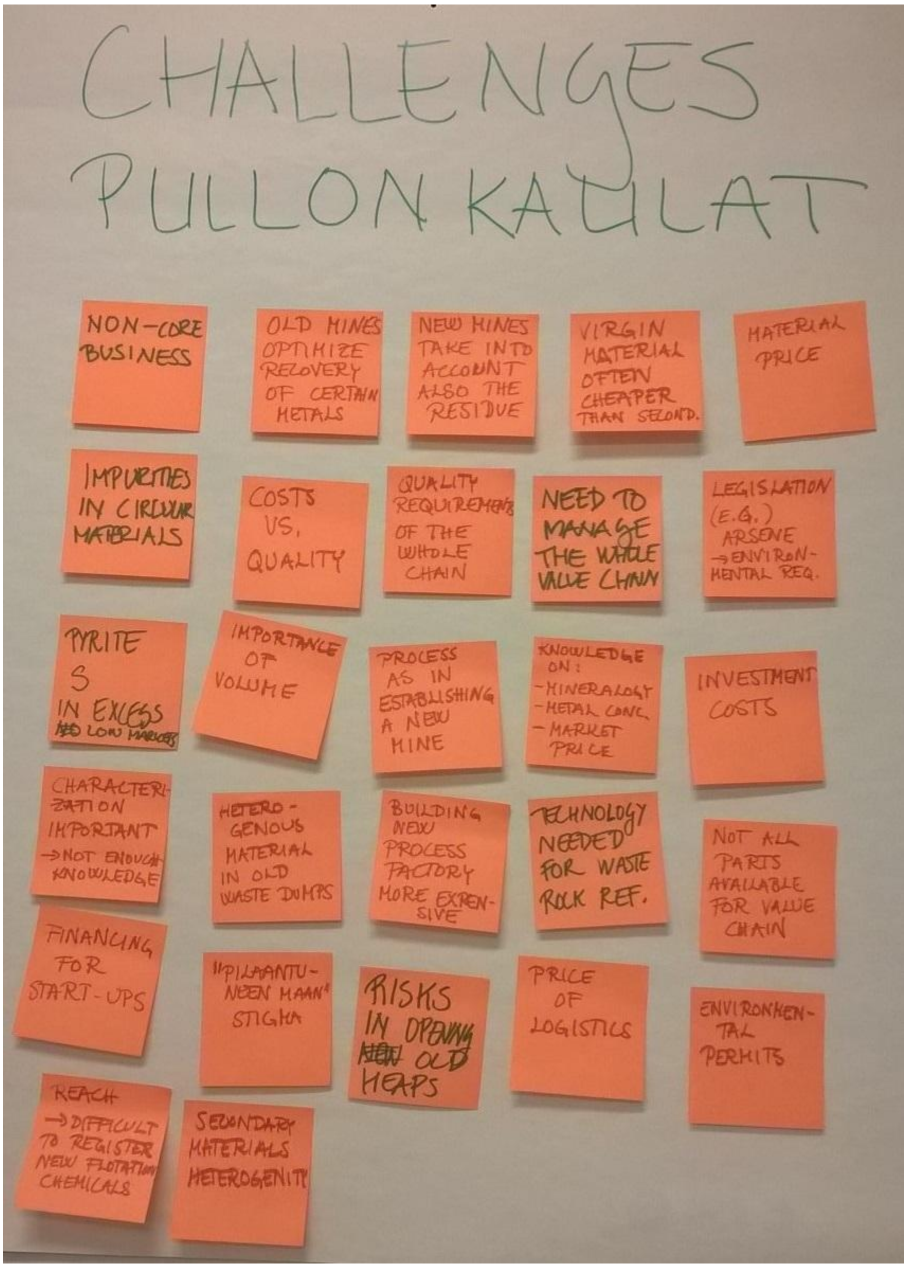
Scott H. 2016. Outcomes of the INNO-4-AGRIFOOD Co-creation Workshop: Curriculum concept and key training topics. October, 2016. http://inno4agrifood.eu/assets/content/newsletter/D2.1_CCWS%20Outcomes%20on%20e-training_vPublic.pdf [referred 9.1.2018]

Solomons I. 2017. Mine tailings recovery can be value generator, says Council for Geoscience. Mining Weekly 9.6.2017. http://www.miningweekly.com/article/mine-tailings-recovery-can-be-value-generator-reduces-enviro-impact-2017-06-09

van Zyl D., Shields D., Agioutantis Z. and Joyce S. 2016. Waste not, want not - rethinking the tailings and mine waste issue. AusImm Bulletin, December 2016.

APPENDIX 1. Workshop results.





CHALLENGES
PULLON KAULAT

NON-CORE BUSINESS

OLD MINES OPTIMIZE RECOVERY OF CERTAIN METALS

NEW MINES TAKE INTO ACCOUNT ALSO THE RESIDUE

VIRGIN MATERIAL OFTEN CHEAPER THAN SECOND.

MATERIAL PRICE

IMPURITIES IN CIRCULAR MATERIALS

COSTS VS. QUALITY

QUALITY REQUIREMENTS OF THE WHOLE CHAIN

NEED TO MANAGE THE WHOLE VALUE CHAIN

LEGISLATION (E.G.) ARSENE → ENVIRONMENTAL REQ.

PYRITES IN EXCESS ~~AND~~ LOW MARKETS

IMPORTANCE OF VOLUME

PROCESS AS IN ESTABLISHING A NEW MINE

KNOWLEDGE ON:
- MINERALOGY
- METAL CONC.
- MARKET PRICE

INVESTMENT COSTS

CHARACTERIZATION IMPORTANT → NOT ENOUGH KNOWLEDGE

HETEROGENOUS MATERIAL IN OLD WASTE DUMPS

BUILDING NEW PROCESS FACTORY MORE EXPENSIVE

TECHNOLOGY NEEDED FOR WASTE ROCK REF.

NOT ALL PARTS AVAILABLE FOR VALUE CHAIN

FINANCING FOR START-UPS

"PILAANTUNEEN MAAN" STIGMA

RISKS IN OPENING ~~NEW~~ OLD HEAPS

PRICE OF LOGISTICS

ENVIRONMENTAL PERMITS

REACH → DIFFICULT TO REGISTER NEW FLOTATION CHEMICALS

SECONDARY MATERIALS HETEROGENITY

APPENDIX 2. Theme interview questions.

1. What possibilities do you see for the valorization of the side streams of the mining and metals industry? Are there any trends?

2. What are the needs in the valorization of side streams?

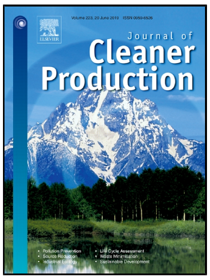
3. What are the main challenges and bottlenecks in valorizing the side streams?

4. What kinds of new business opportunities do you recognize for your business? How do you consider the circular economy potential in your business development?

APPENDIX 3. Article published based on the results of this thesis in the Journal of Cleaner Production.

Kinnunen P.H.-M. and Kaksonen A. 2019. Towards circular economy in mining: Opportunities and bottlenecks for tailings valorization. Journal of Cleaner Production. Available online since 16.4.2019. (in press)

https://doi.org/10.1016/j.jclepro.2019.04.171



Towards circular economy in mining: Opportunities and bottlenecks for tailings valorization

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PII: S0959-6526(19)31250-8
DOI: 10.1016/j.jclepro.2019.04.171
Reference: JCLP 16527
To appear in: *Journal of Cleaner Production*

Received Date: 24 August 2018
Accepted Date: 15 April 2019

Please cite this article as: Päivi.H.-M. Kinnunen, Anna H. Kaksonen, Towards circular economy in mining: Opportunities and bottlenecks for tailings valorization, *Journal of Cleaner Production* (2019), doi: 10.1016/j.jclepro.2019.04.171

Wordcount: 8657 words

Declarations of interest: none

Towards circular economy in mining: Opportunities and bottlenecks for tailings valorization

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ABSTRACT

Current management of mining waste is based on linear economy thinking. However, the use of mining waste as a raw material resource can be one solution to the limited metal supply. The objective of this study was to fill in the knowledge gaps of business opportunities, drivers, needs and barriers for tailings valorization, since the transformation towards a circular economy needs advancements in understanding these factors. Based on a workshop and theme interviews, the utilization of tailings in the mining industry is currently in its infancy, but there is clear raw material potential for the future. The handling of sidestreams at mine sites depends on mine lifecycle. The identified opportunities and drivers were categorized under the circular economy mindset, technological, environmental, institutional and economic drivers. The needs were new value chains, technology development, the decrease in the amount of waste, stability, taxation, and predictability of regulation. Challenges and bottlenecks were categorized under new value chains, technological, environmental, institutional, economic and knowledge bottlenecks. The identified needs and barriers need to be properly addressed to speed up the transformation towards the circular economy in the mining industry.

Keywords: circular economy, mining, tailings, valorization, waste

1 INTRODUCTION

Metals are crucial for a modern society. The growth and prosperity have been based on finite mineral resources and fossil fuels (UNEP, 2013; European Union, 2016; Sauvé et al., 2016). Sustainable development goals of the United Nations, as well as the implementation of the Paris Agreement, resulted in the vast utilization of a wide range of minerals for green technologies (Ali et al., 2017) such as low-carbon applications. The global demand for raw materials has increased during the last decades, and the resource use is expected to even double between 2010 and 2030 (UNEP, 2013; European Union, 2016). At the same time with the demand increase, the ore grades in the mining industry have decreased over the years in terms of both quality and concentration (Giurco et al., 2014; Esposito et al., 2017).

In addition to clear economic and societal benefits, mining has also created environmental challenges via significant amounts of mining and quarrying waste, such as tailings (Bellenfant et al., 2013; Edraki et al., 2014). The term mine tailings is used for the remaining rock and process solutions, after the extraction of valuable minerals from the mined ore (Edraki et al., 2014). Approximately 2-12 tons of overburden material is removed as waste for each ton of metal extracted from ores (Mohanty et al., 2010). In Chile, 1.6 million tons of tailings are produced every day (ACT Williams, 2017). In South Africa, there is estimated to be 17.7 million tons of tailings from gold mining (Breytenbach, 2017). In China, approximately 33,000 hectares of land has been estimated to be affected by mining activities (Chen et al., 2016), of which 13% by tailings dams (Miao and Marrs, 2000). In 2012, a total of 52,532 abandoned mines were reported to exist in Australia, although the actual number is likely to be higher because data sets of many states are incomplete (Unger et al. 2012). Over 1.2 billion tonnes of tailings waste have already been stored in the European Union (BRGM, 2001) and billions of tonnes globally (Wang et al., 2014) with the amount growing at a rate of 5-14 billion tons per year via new production (Schoenberger 2016). The major environmental risks related to mining waste are potential pollution, such as acidification and heavy metal contamination, and the stability of the tailings dam (Bellenfant et al., 2013; Simate and Ndlovu, 2014; Bascetin et al., 2016). Severe tailings dam accidents have occurred, e.g., in Spain (Aznalcollar) and Romania (Baia Mare) (BRGM, 2001) and more recently in Canada (Mt Polley) (Chambers, 2015) and in Brazil (Fundao) (do Carmo et al., 2017). Tailings are thus an enormous liability issue to mining companies (Wang et al., 2014).

However, the valorization of tailings is aligned with the United Nations' Sustainable Development Goals (SDGs). Mine tailings mining can contribute especially to the SDG11 "Sustainable Cities and Communities" and to the SDG12 "Responsible Consumption and Production" by minimizing the output of waste (World Economic Forum, 2016). Tailings valorization means the recovery of residual metals and utilization of the mineral matrix. Hazardous waste can be transformed into valuable secondary metal sources (van Zyl et al., 2016; Solomons, 2017) combining metals recovery and environmental management (Bellenfant et al., 2013) with developed technologies, such as biomining (Johnson, 2014). One single tailings area can contain valuable and critical metals worth up to hundreds of millions of euros (e.g., Metals X Ltd, 2017). Tailings have already been quarried and crushed, which significantly lowers the actual treatment costs compared to primary ores needing mining since mining and processing can constitute 40–60% of the total mineral processing costs (Cox et al., 2011; Zhao et al., 2012; Patent US2012/0114538 A1). Mine wastes contain mineral and energy resources, which may become valuable, e.g., through the development of new technologies, new market demands or improved commodity prices (Lottermoser, 2011). Currently, it is estimated that approximately 75 major tailings re-mining projects are taking place globally on the reclamation of gold, diamonds, and copper (van Zyl, 2016).

Current systems for managing mining waste are based on linear economy thinking ('take-make-waste') (Lèbre et al., 2017). Liu et al. (2019) suggest that also the undesired output should be taken into account in the eco-efficiency evaluations for the circular economy system in the mining industry. The development of a circular economy model for the mining industry has significant potential to solve the challenges of shortage of mineral resources, waste of resources (Zhao et al., 2012) and environmental pollution (Lottermoser, 2011; Bellenfant et al., 2013; van Zyl et al., 2016), and to minimize waste (Balanay and Halog, 2016) with subsequent generation of economic profits (Bellenfant et al., 2013; van Zyl et al., 2016). The use of mining waste as a raw material resource can be one solution to the limited metal supply (European Union, 2016; Nuss and Blengini, 2018). Even though the current extractive waste problem can be an opportunity to recover raw materials and significant economic value, only very little efforts have been made to move the mining industry towards circular economy (Lèbre et al., 2017). For example in the circular economy model of the Ellen MacArthur Foundation (2013) widely cited by the academics and practitioners, the mining industry is apart and excluded from restorative loops (Lèbre et al., 2017). According to the study of Ruokonen and Temmes (2018), mining companies' contribution to a circular economy is largely missing from the mining companies' environmental programs. There is limited research on sustainability issues addressed by the European mining industry (Ranängen and Lindman, 2017). If the mining sector is not included in the circular economy concept, opportunities will be lost for technically and economically feasible materials recovery (Lèbre et al., 2017).

As pointed out by the European Commission (2014), the utilization of circular economy concepts will need advancements in filling the knowledge gaps in business opportunities, drivers and barriers. Several previous studies have focused on giving a helicopter view on circular economy implementation in general and admitted the potential differences from sector to sector (Kirchherr et al. 2018). Therefore, more details from various sectors are required in addition to the general view, to enhance the sectorial understanding of the circular economy potential.

This research work focuses on the development of knowledge of possibilities to loop back some of the largest waste streams in the world (Wang et al., 2014) in the mining context, which has not been widely studied. The objective of the work is the identification of drivers, needs and barriers, which could accelerate the transformation to tailings valorization in the mining industry.

2 MATERIAL AND METHODS

This study analyses the business potential related to tailings valorization in the circular economy based on a workshop and semi-structured in-depth stakeholder interviews. Themes were pre-prepared (Eriksson and Kovalainen, 2008) for circular economy potential in the mining industry, as well as for opportunities, needs, and challenges in tailings valorization. The workshop was held in the ideation and concept development phase to gather a diversity of opinions on the topic and to integrate different viewpoints before the theme interviews. In total ten participants including five representatives from mining industry (e.g., research and development (R&D) manager, chief metallurgist, and chief executive officer) and five raw materials related academic experts participated the workshop. The workshop (four hours) focused on three separate predefined theme section discussions for new business for side and waste streams in mining and metallurgical industries in the order of 1) drivers/opportunities, 2) needs, and 3) challenges and bottlenecks.

In total seven interviewees from mining companies, technology companies, and related institutions were selected for the study based on their expertize in the mining and tailings related issues and recommendation by the company. Selected themes about the circular economy in mining, opportunities, drivers, needs, challenges, and bottlenecks were discussed with all interviewees. The interviews were held in Finnish. The interviews were transcribed, translated into English and the data was categorized. In inductive content analysis like in this study, empirical data generated was the basis for the formation of categories (Elo and Kyngäs, 2008) as a systematic element to data analysis (Alhojailan, 2012). Section 3 summarizes the results from the workshop and interviews. In section 4, the identified main categories are discussed in relation to the current literature.

3 RESULTS

The key results of four aspects: i) circular economy in mining, ii) opportunities and drivers, iii) needs and iv) challenges and bottlenecks for tailings valorization were summarized. They are presented in the following sub-chapters.

3.1 Circular Economy in mining

The mining industry was considered crucial as part of the circular economy discussion in the interviews. The products of the mining industry are specifically recyclable and indestructible. However, it was also noted, that the circular economy discussion has focused on the food industry and wastewater, and mining industry is often lacking from the circular economy discussion. The circular economy in the mining industry was considered somewhat unclear with the need to communicate it more efficiently.

Based on the interviews the valorization of tailings in the mining industry is currently in its infancy even globally. The mining companies have not always even considered and evaluated new possibilities around tailings in addition to the ways they are used to nowadays. A substantial amount of energy is used in the milling of the material, but the milled waste fraction is left unused. Up to 99% of energy may be used for the milling of the side rock and not the actual valuable mineral. Even though the tailings valorization potential has remained underexplored, the interviewees saw a clear potential for the future. Long-term thinking was emphasized in the interviews differentiating mines with various life expectancies. In the operations with longer life expectancies, the long-term thinking and utilization of materials are more likely in a wider perspective.

3.2 Opportunities and drivers

The opportunities and drivers identified in the workshop and interviews (Table 1) were categorized under the circular economy mindset and technological, environmental, institutional and economic drivers. The circular economy as such and the transformation from waste to raw material were drivers for the mining industry to utilize tailings as a source of raw materials. Cleaning of the environment and subsequent removal of the environmental hazards were considered important as environmental drivers. Because of the declining grade of primary ores, the mining industry has to recover metals from increasingly challenging ores, and tailings can become a technically and economically competitive option as a raw material source. Previously some metals were not recovered, as there was no use and demand for them. New commercial technologies have been developed for the low-grade ores and wastes. When the market needs and technologies change, the valuable components in sidestreams have turned interesting. However, the current technologies have focused only on main metals, such as Ni, Zn or Cu, leaving the rest of the material unused. Closed mines can be used for a wider spectrum of new business possibilities beyond the recovery of metals. Tailings have been used in the mines as material in backfilling, but also novel applications for the mineral matrix were suggested in geopolymers and some novel high-tech applications such as 3D printing. Industrial symbiosis was mentioned as a possibility to utilize, e.g., municipal waste for the needs of the mining industry. Non-conventional business opportunities can arise even outside of the recovery of metals, e.g., in the fields of energy, aquaculture, wine cellars, and holiday resorts.

Institutions, such as the society, international networks, and EU collaboration were considered to drive the mining industry towards a circular economy. In addition, economic drivers were recognized. The demand and price for certain elements have increased. Waste area investments are a few euros per tonne of waste material. These costs would be avoided if the material could be valorized instead of depositing it into the waste area. Also, business from sidestreams could contribute to the final waste treatment costs. When the amounts and concentrations of recoverable elements are known, the recovery of metals from tailings can be faster and easier than from ores, since the Greenfield projects (no prior work) require a lot of time. Since the transformation to tailings utilization was expected to take time, the idea of storing them for the future uses was suggested.

Table 1. Drivers and opportunities, needs, and challenges and bottlenecks related to tailings valorization identified in the co-creation workshop and theme interviews, and categorized into groups.

WORKSHOP	***INTERVIEWS***	***CATEGORIZATION***
Drivers/opportunities		
From waste to raw material/ Storage of potential materials for the future/ Waste waters may contain significant amounts of metals/ Willingness to collaborate with a circular economy as a target	*Primary production needs to be part of the larger circular economy/ Effect of the mine life for long-term thinking/ Storing the waste for the future*	*Circular economy mindset*
Available commercial technologies/ Processes have been developed for some valuables, not for the whole material/ New analytical methods reveal new sources/ Pre-treatment and logistics to another place	*New technologies enable the metal recovery from lower concentrations than before/ New technological use for some metals/ New applications for whole tailings material, e.g., in 3D printing and geopolymers*	*Technological drivers*
Removal of environmental hazard/ Cleaning of the environment		*Environmental drivers*
Involvement of the society/ International networks and EU collaboration	*Recovery of metals from tailings inside an existing restricted industrial area can start faster than in Greenfield projects*	*Institutional drivers*
Low-grade ores/ Waste area investments a few euros per tonne/ Possibility to pay a part of final waste treatment costs with business from sidestreams/ New business in storage/ Possibility for geoenergy (other business)/ Industrial symbiosis, e.g., municipal waste utilization/ Unidentified business, e.g., phlogopite, rare earth elements (REE) in gypsum/ New business: aquaculture, wine cellars, holiday resort, electricity, energy utilization	*Demand and prices for certain elements have increased/ New needs in the society transform certain elements economically valuable/ Cheaper after-treatment after tailings valorization*	*Economic drivers*
Needs		
Need of one large company as driver organization/ In a closing mine, a new company is needed for waste processing/ Not core business of anyone/ Large companies are willing to donate waste material, but volumes need to be high enough	*Incomplete value chains for tailings valorization/ Entrepreneurs, commercializing companies and especially small and medium-size enterprises (SMEs) are missing/ Lack of new companies having the capital or able to get the capital for starting the service business/ Various company strategies related to core business and outsourcing/ Role of technology providers crucial in the planning phase to consider also minor elements*	*New value chains, partnerships*
Technologies for sidestreams missing/ Tailoring technologies for low-grade ores/ Technology for mineral utilization missing	*Increase the technology readiness levels/ Faster renewal of technologies/ Basic research*	*Technological needs*

	Decrease in the amount of waste/ Isolation of harmful components/ Increase of waste stability/ Better final disposal	*Environmental needs*
Stock exchange type of instrument for sidestreams	*Logical and predictable regulation/ Legislation should favor the utilization of sidestreams/ Taxation to give an advantage to the circular product in the competition*	*Institutional needs*
Challenges and bottlenecks		
Old mines optimize the recovery of certain metals/ New mines take into account also the residue	*Tailings valorization potential should be taken into account before finally closing the mine site/ Mining companies focus more on current operational activities than on the recovery of minor elements*	*Circular economy mindset*
Non-core business/ Quality requirements and management of the whole value chain/ Importance of volume/ Incomplete value chains	*Knowledge creation for profit, value, and usability requires the expertise of several companies/ Networking and new value chains/ SMEs needed, as for big mining companies the business can be too small and not their core business or competence/ Collaboration mechanism for the mining company and the other operator*	*New value chains, partnerships*
Impurities in materials/ Materials characterization important/ Technology needed for waste rock refinery/ Heterogeneous material in old waste dumps/ Secondary materials heterogeneity	*Wide technology gap for upscaling/ Pushing new technologies forward is like going upstream with the need to do it with small steps and good justifications*	*Technological bottlenecks*
Risks in opening old heaps		*Environmental bottlenecks*
Legislation, e.g., arsenic environmental requirements/ Process as in establishing a new mine/ Contaminated land stigma/ Environmental permits/ Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH); difficult to register new flotation chemicals	*Environmental permits and the issues related to the ownership likely restrict the valorization/ Permitting process relatively extensive/ Permitting has clear effects on the selection of solutions/ Regulation determines, how tailings can be disposed of/ Liabilities / More predictable and fair regulations/ Global market with different regulation in different areas*	*Institutional bottlenecks*
Virgin material often cheaper than secondary/ Material price/ Costs versus quality/ Pyrite and sulfur in excess; low markets/ Investment costs/ Building new process factory expensive/ Financing for start-up companies/ Price of logistics	*Concentrations and masses of recoverable elements not economically high enough/ High investment costs and long payback times for processing plants/ Lacking capital/ Logistics costs often dominant in remote areas*	*Economic bottlenecks*
Knowledge gap on mineralogy, metal concentration, and market price	*Knowledge gap on the tailings content*	*Knowledge gaps*

3.3 Needs

The needs identified in the co-creation workshop and interviews are listed in Table 1. The results were categorized under new value chains, technological, environmental and institutional needs. Even though the technological development was considered as a driver for mine waste valorization, there is also a clear need to develop the technologies further. Technology readiness levels of sidestream processing technologies were considered too low slowing down the enthusiasm in the uptake of technologies in the near future. The renewal of technologies is slow due to the investment-intensive nature. When a mining company invests in the recovery technologies, they need to be tested and functional. As long as the conventional technologies, such as chemical acid leaching and precipitation are used, also the related challenges need to be solved. In addition to the metal recovery, technology for the utilization of the whole mineral matrix needs to be developed. Further, the technology development for the sidestream valorization was not seen as the core business of any existing industrial stakeholder, and even the basic research at the universities was considered insufficient.

Current value chains for tailings valorization were considered lacking or incomplete, where especially innovative and agile small and medium-size enterprises (SMEs) are missing. At least one large company would need to act as the main driver company and include other stakeholders in the value chain. New companies, which would already have the capital or which would be able to get the capital for the creation of service business, do not exist. Several mining companies would be willing to provide the sidestream for use for another company. The company strategy determines the company’s core business and outsourcing activities. One interviewee considered the role of technology providers as the most crucial already in the planning phase to consider the selection of processes and potential recovery of minor elements. The mining companies tend to focus only on the main product, whereas technology providers could consider actively also the minor elements. Sometimes it is not clear, which materials would be available for other companies, and a stock exchange type of instrument was suggested for the efficient knowledge transfer of what is available.

Other needs mentioned in the interviews were a decrease in the amount of waste and increased waste stability, which relate to the management of storage needs and better water management. The legislation would need to be logical and predictable, and favor the utilization of sidestreams. Taxation could give an advantage to the circular product in the competition, as it has a significant effect on the profitability of the business.

3.4 Challenges and bottlenecks

Challenges and bottlenecks identified in the workshop and interviews were categorized under the circular economy mindset, new value chains, technological, environmental, institutional, economic and knowledge bottlenecks (Table 1). Secondary materials are heterogeneous and contain impurities, which need to be addressed in the technology development. Pushing new technologies forward proceeds with small steps and requires excellent justifications.

The management and quality of the whole value chain is a prerequisite of successful sidestream utilization. Networking is needed for the calculation of profit, value, and usability since the expertize is widely distributed among various professionals and companies. New value chains including SMEs were also emphasized by interviewees. SMEs could have a higher financial incentive than the big mining companies, for which the business could be too marginal and out of the range of their core business and scope. The raw materials potential would need a collaboration mechanism, in which also the mining company would benefit from the other operator.

The handling of mine sidestreams depends on the mine lifecycle. New mines also take the residue into account, whereas the old mines tend to focus on optimizing the recovery of certain metals only. The valorization potential should be taken into account before closing the mine site. When the old tailings ponds have already been landscaped, it is more unlikely that they would be opened again for resource recovery.

Despite the environmental risks of already existing tailings disposal areas, there are also environmental risks in opening old heaps. Institutional bottlenecks relate to legislation, environmental permits, REACH, processes and the views of the society. Interviewees emphasized that regulation can make development faster, but it needs to be more predictable and take into account the global market. Regulation can affect geographical areas where mining companies want to operate. An environmental permit is required, when companies start to recover valuables from tailings. The permitting process was considered relatively extensive and similar as in establishing a new mine. However, one interviewee considered permitting process lighter in tailings processing, since the material is already inside an industrial area. Permitting has clear effects on the selection of solutions, and it determines how tailings can be disposed of. The ownership and potential transfer of liabilities with the material are bottlenecks, which restrict the business potential. Mine tailings areas were considered to have a certain kind of contaminated land stigma, which could affect the opinion of the nearby societies on reprocessing the tailings.

Several market- and economics-related bottlenecks exist for tailings valorization. One of the biggest bottlenecks is the low concentration and mass of recoverable elements for economical processing. Investment costs of processing plants are high, and it takes time to break even. It was noted that profitability requires certain size operations. Suitable capital financing models might be lacking for service companies needed in new value chains. Virgin materials are still often cheaper than secondary materials. Material price has a direct effect on the profitability of secondary materials valorization. Some minerals and elements are in excess in the market creating low demand for these products. However, the benefits may be wider than the value of the recovered metal, if the disposal is cheaper after the recovery of metals. Logistics costs are often dominant in remote areas as one of the main bottlenecks to be tackled.

Knowledge gap of the tailings content was considered as a significant bottleneck in the interviews. Better knowledge would increase the research about utilization possibilities. In addition, the lack of resources was considered as a bottleneck. Mining companies tend to focus on urgent operational activities with no resources to focus on minor components.

4 DISCUSSION

As de Jesus and Mendonça (2018) pointed out, typically there is a mixture of factors, which either facilitate or hinder the adoption of the circular economy. The same factor can be a driver, a need and a barrier (Figure 1). Therefore, the categories are not mutually exclusive and typically more than one driver or barrier is important (de Jesus and Mendonça, 2018). Various categories of opportunities, needs and barriers can have interactions (Kirhherr et al. 2018; de Jesus and Mendonça, 2018), which was also detected in this study. The main identified categories of drivers, needs and barriers in the tailings valorization are discussed more in detail in the following sub-sections based on the results of this study and literature.

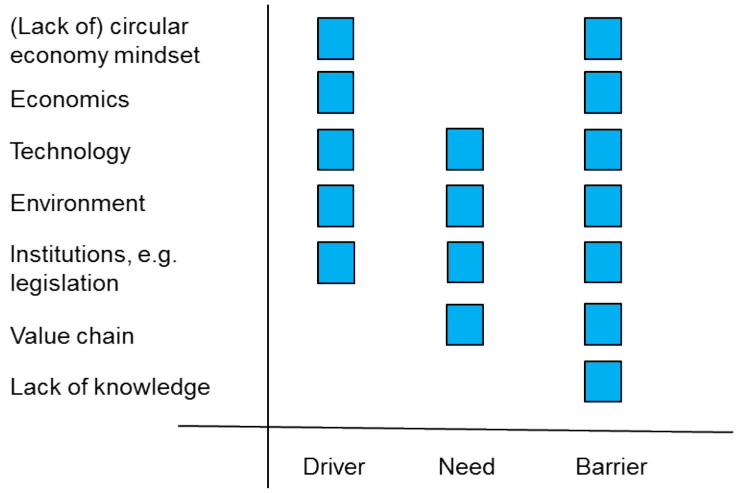

Figure 1. Complementarity and mutual inclusiveness of the categories of drivers, needs and barriers.

4.1 The circular economy in mining

According to Bechtel et al. (2013), a reluctance to adopt circular economy thinking can act as a barrier in the transformation to a circular economy, which makes circular economy thinking crucial in the transformation. Based on the workshop and interviews the mining industry is aware of circular economy thinking and also willing to transform towards a circular economy. The interviewees considered primary metal production as part of the larger circular economy. However, it was not clear to interviewees how the circular economy could be implemented in mining. Including the mining industry more clearly into the circular economy concept would bring the transformation forward and enable better communication of the role of mining in the circular economy.

Mining industry produces various waste materials such as waste rocks, mine waters, mine drainage sludges and tailings (Lottermoser, 2011). Technologies and legal framework are different for solid materials and mine water (Directive 2006/21/EC; Punkkinen et al. 2016). Hence, the opportunities, drivers, and bottlenecks likely differ between these different waste streams. Therefore, this work focused on tailings, which are considered as one of the most potential waste based sources of metals.

The interviewees considered that the utilization of tailings in the mining industry is currently only in its infancy, but also a clear potential for the future was identified. Since the transformation to tailings utilization was expected to take time, long-term thinking and storing raw materials for the future were emphasized. Wider thinking would be necessary already in the planning and research phase to consider the metal and minerals recovery in a broader context. In addition, the valorization potential for the recovery of metals and utilization of the mineral matrix should be taken into account before finally covering and closing the mine site.

4.2 Technology development

According to Velis and Vrancken (2015) not only advancing new business models is required, but also more effective reprocessing technologies are needed for closing the material loops. Technological barriers were also reported as a barrier to adopt the circular economy concept by Bechtel et al. (2013). Technology development was identified as a clear need in this study, although it was also considered as a driver for mine waste valorization. Technology readiness levels were considered low and technology gap for upscaling wide. Moreover, the technology development for waste valorization was not seen as the core business for any stakeholder. The renewal of technologies was considered slow because the uptake of new technology is not very simple and easy and technology needs to be tested, functional and evaluated for profit, value, and usability to justify intensive investments.

According to West (2011), the decrease in utilizable metal grades has been a direct result of innovations, which turned previously worthless waste into valuable ore. Technology development needs to address the low grades, heterogeneity, and impurities in secondary materials. Ali et al. (2017) suggested investment support and research efforts for technology development as actions for sustainable raw materials production. Some commercial technologies have been developed for the low-grade ores and wastes. However, the technologies have mostly allowed the recovery of certain valuables and not the utilization of whole material matrix.

Metal values have traditionally been extracted from virgin ores through physical, pyrometallurgical, hydrometallurgical and electrometallurgical approaches, such as grinding, flotation, roasting, smelting, pressure oxidation, chemical leaching and electrowinning. Some of these methods may be suitable also for recovering metals from waste materials; however, low metal grades and the presence of impurities such as arsenic may cause problems for traditional processing methods. Biomining through bioleaching, biooxidation, and bioprecipitation have been successfully applied to low-grade ores and waste streams such as mine tailings (Falagán et al., 2017; Vardanyan et al., 2018). Bioleaching with acidophilic iron- and sulfur-oxidizing microorganisms has been commercially applied for extracting metals from low-grade sulfide ores and explored mine wastes which cannot be economically processed through traditional pyrometallurgical or hydrometallurgical methods. However, processing times may be longer (Kaksonen et al., 2018). Biooxidation has found a commercial use for pre-treatment of sulfidic gold ores and concentrates upstream of leaching gold with chemical lixiviants as it can decrease the consumption of the lixiviants (Kaksonen et al., 2014). Biogenic hydrogen sulfide generation and metal sulfide precipitation have been applied to recover metals from mine drainage. Metal sulfides enable easier recovery of metals than corresponding hydroxides formed during chemical mine water treatment. Moreover, biogenic sulfide precipitation allows the concomitant removal of sulfate and acidity from mine waters (Kaksonen and Puhakka, 2007). However, the operation of bioreactors requires more expertize than chemical metal precipitation with alkaline chemicals.

Examples of other methods proposed for removing or recovering metals from tailings are magnetic roasting (Liu et al., 2013), chlorination roasting (Li et al., 2018), and electrokinetic leaching (Karaca et al., 2017). The energy costs of these processes may be higher than those in biomining due to the use of elevated temperature and electricity to drive desired reactions. However, chlorination roasting has been suggested by Li et al. (2018) as an energy efficient approach for gold- and silver-containing processing tailings as it harnesses the low boiling point and high volatility of metal chlorides. In a lab-scale study, electrokinetic leaching was shown to be able to leach Fe and Pb from exchangeable, weakly absorbed, hydrous oxide bound and organic linked fractions. However, it did not remove metals in the mineral lattice were not removed (Karaca et al., 2017). Possible uses for tailings matrices include for example blending desulfurized tailings with organic materials to produce fabricated soils (Filho et al., 2018), and the use of tailings to create geopolymers for use as backfill material for underground cavities and water and oxygen tight covers (Kinnunen et al., 2018). Networking and long-term planning are essential to identify possible technologies for waste valorization already in early stages of the mine life, as mining waste disposal methods can either make the utilization of waste possible in the future or make the waste unsuitable for any future purpose (Lèbre et al., 2017).

4.3 Value chains

There can be a lack of appropriate value chains in the transition from a linear model to the circular one (Sauvé et al., 2016). Based on the workshop and interviews the value chains and especially SMEs for the sidestream valorization in the mining industry are currently missing. Companies have various strategies related to outsourcing. As waste valorization is not a core business for big mining companies, many of them would be willing to partner with other organizations. The challenges are so complex that only one person or one company is rarely able to find solutions, which makes networking necessary.

Partnerships are generally based on the reuse and recycling of mining wastes, but also other resources could be shared (Balanay and Halog, 2016). Some actors might be unwilling to use waste as a raw material source since current processes have been optimized for virgin resources (Sauvé et al., 2016). Even though most companies in the mining sector focus solely on their core business, there are some examples of vertical integration in the value chains, where mining companies have enlargened their participation to integration into refining and recycling. Boliden is an example of a mining and smelting company, which has both materials extraction and recycling creating synergy in materials sourcing and resource recovery (Florin et al., 2015) of, e.g., copper and gold.

4.4 Institutional influence

In the global context, the particular driving forces to the circular economy have been social, regulatory or institutional factors via, e.g., institutional framing, legal set-ups, R&D support and social awareness (de Jesus and Mendonça, 2018). Institutions, including the influence of the society, international networks, and collaboration, were considered as drivers for the mining industry in the transition towards a circular economy. Identified institutional bottlenecks were legislation, environmental permits, REACH, processes in establishing a mine for the metal recovery from waste materials and the views of the society. These institutions can thus drive the circular economy transformation, but also restrict the use of waste materials as raw material sources depending on their opinions.

Permitting, regulations and taxation were considered to have clear effects on the selection of solutions in the mining industry both as drivers as well as bottlenecks, which is consistent with previous studies. The interviewees emphasized the need for predictable regulations to avoid uncertainties. Increasing waste disposal costs, concerns over environmental degradation and stricter environmental regulations, and potential profits of by-product and waste utilization were drivers for companies to reconsider their strategies in the study of Lombardi et al. (2012). According to van Beers et al. (2007), environmental regulations can be a barrier to the practical implementation of industrial symbiosis, which sometimes has been haltered by uncertainties in the legislative framework. Also, Bechtel et al. (2013) noted, that the complexity of regulations as well as discrepancies of regulations can create barriers during the transformation to a circular economy. To "remove regulatory barriers for the circular economy" is one of the aims of the Circular Economy Package of the European Union, as the removal of barriers can have significant positive economic effects. However, not all regulatory barriers can be removed. Certain case studies have shown, that the removal of regulatory barriers does not always lead to circular economy adaptation because of other still existing barriers, such as economic or technological barriers (van Barneveld et al., 2016). Stahel (2013) considered sustainable taxation decisions to boost the benefits of the circular economy.

4.5 Environment

Tailings disposal creates environmental risks, such as acid mine drainage (Simate and Ndlovu, 2014), heavy metal contamination (Bascetin et al., 2016) and tailings dam accidents (Bellenfant et al., 2013; Chambers, 2015; do Carmo et al. 2017). Reprocessing of tailings has the potential to remove the environmental hazards and clean the environment (Bellenfant et al., 2013) as well as to decrease the amount of waste (Oliveira, 2016), resulting in better waste and water management. Even though there are environmental risks in the existing tailings disposal areas, the environmental risks for opening old heaps need to be also considered (Edraki et al., 2014). If the tailings have already been stabilized and covered, there may be more environmental risks in reprocessing them compared to leaving them in the current state. If the tailings are recycled for use in new consumer and industrial applications, the potential environmental impact needs to be properly assessed (Edraki et al., 2014)

4.6 Economics

The formulation of a circular economy business case can be challenging to companies (Bechtel et al., 2013). Several economics related drivers and bottlenecks were identified for tailings valorization. When the grades of primary ores decrease, mining wastes can become a technically and economically competitive option (van Zyl et al., 2016). However, concentrations and masses of recoverable elements need to be high enough to allow economic feasibility. Materials prices directly affect the profitability of secondary materials valorization. The economic benefits go beyond the value of the recovered metal, as the disposal costs of the final residue after the metal recovery might be lower. Increasing waste disposal costs and potential profits of by-product and waste utilization have been drivers for companies to reconsider their strategies (Lombardi et al., 2012). Tailings disposal operational costs vary depending on the used technology (Bascetin et al., 2016). Mining sites are generally in remote areas, where logistics costs can be dominant. Investment costs of processing plants are relatively high, which can create a lack of capital, as was stated by some interviewees. Therefore, recovery techniques that have low capital costs are required. The lack of capital was seen as a potential challenge in the transformation from linear to the circular economy also in the study of Roos (2014).

4.7 Knowledge gaps

Knowledge gaps on mineralogy, metal and impurity concentrations in tailings as well as market price were identified in the co-creation workshop and interviews as one of the challenges and bottlenecks for tailings valorization. Also, Nuss and Blengini (2018) have previously noted that information on potential stocks, e.g., on mine waste dumps, is not yet widely available. The lack of knowledge makes the planning for the valorization of tailings challenging. When the analytics methods get better and cheaper, the knowledge about tailings can be increased. Stock exchange type instruments were suggested to facilitate knowledge transfer on available resources. An example of an existing instrument is the Advisory System for Processing, Innovation & Resource Exchange (ASPIRE) online marketplace (https://aspire.csiro.au/) developed by CSIRO, Australia (CSIRO, 2018a). The ASPIRE is a web-based tool that provides active match-making service for waste generating and utilizing businesses by suggesting potential relationships and investment opportunities (Ayre et al., 2014) thus supporting industrial symbiosis for SMEs (CSIRO, 2018b). The benefits of ASPIRE for businesses include access to new collaboration opportunities, business connections, and information that supports sustainable business opportunities, reduction of waste costs and input resource costs, diversion of waste from waste disposal sites, and reputational merit by demonstrating environmental sustainability initiatives (CSIRO, 2018c). Another example of a secondary resource database is Urban Mine platform (www.urbanmineplatform.eu), which contains datasets on flows, stocks and compositions of battery, electrical and electronic device and vehicle wastes. The database provides information for the recycling industry to evaluate the raw material potential of waste stocks in the urban mine and for developing innovative recycling strategies (Swiss Federal Laboratories for Materials Science and Technology, 2018).

4.8 Future perspectives

The circular economy potential in the mining industry needs to be actively communicated since the mining companies have not often evaluated the opportunities around tailings. Tailings valorization will likely become economically and technically more feasible in the future. However, information about tailings contents is lacking. Therefore, databases of existing tailings are needed. Better knowledge about the tailings contents can also enhance the research about utilization possibilities to increase the technology readiness levels for sidestream processing technologies. Since the value chains for tailings valorization are currently incomplete, the establishment of SMEs to complement the value chains should be encouraged. Institutions can remove identified barriers related to permitting, legislation and attitudes, and support information flow, new business establishment and needed technology development.

5 CONCLUSIONS

The transformation towards a circular economy needs advancements in filling the knowledge gaps of the factors that affect the way waste is managed. Business opportunities/drivers, needs and challenges/barriers in the mining industry to valorize tailings were identified in this study. The valorization of tailings in the mining industry is still at its infancy, but the situation is expected to change in the long-term. The transformation from a linear economy to circular one requires addressing the challenges and demonstration of possible solutions. Currently, knowledge about the contents and amounts of tailings is limited. Knowledge of available resources should be efficiently created and collected to allow the industry to understand better the possibilities of tailings valorization. One of the critical requirements is also to create suitable business cases, which might be influenced by factors, such as material price development, market demand, lower disposal costs and liabilities after the treatment. Institutional influence, such as taxation, might change the profitability and boost the circular economy transformation. Technology development has the potential to turn lower-grade materials into a raw material source and make the whole raw material valuable; minor metals could be recovered in addition to the main metals, and the residual mineral matrix has the potential to be used in the mine as geopolymers or in novel applications such as 3D printing. The value chains for tailings valorization are incomplete, which may hinder the circular economy transformation, but at the same time provide business opportunities for new stakeholders.

This study enables a better understanding of possibilities, needs, and bottlenecks for waste valorization in the mining industry. A mixture of factors either facilitate or hinder the circular economy adoption. There is clear business potential for metal recovery from mining waste in the future, but the identified barriers need to be addressed to speed up the transformation.

Acknowledgments

The work of Päivi Kinnunen was supported by the Academy of Finland [EcoTail, Decision no. 306079]. The work of Anna Kaksonen was supported by CSIRO Land and Water and CSIRO Mineral Resources. The organization of the workshop was supported by the KIC Raw Materials.

REFERENCES

ACT Williams, 2017. Overview of tailings management practice in Chile. Accessed 6.11.2018 from http://atcwilliams.com/news/overview-of-tailings-management-practice-in-chile.

Alhojailan, M.I., 2012. Thematic analysis: A critical review of its process and evaluation. West East J. Soc. Sci. 1 (1), 39–47.

Ali, S.H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enrique,z M.A., Kinnaird, J., Littleboy, A., Meinert, L.D., Oberhänsli, R., Salem, J., Schodde, R., Schneider, G., Vidal, O., Yakovleva, N., 2017. Mineral supply for sustainable development requires resource governance. Nature. 543, 367–372.

Ayre, M., Dunstall, S., King, S., Stubbs, A. 2014. ASPIRE to change the way you deal with waste, in: Australian Industrial Ecology Network. Leishman Associates, Melbourne, 2014, 20.

Balanay, R., Halog, A., 2016. Charting policy directions for mining's sustainability with circular economy. Recycling. 1, 219–231.

van Barnefeld, J., van der Veen, G., Enenkel, K., Mooren, C., Talman-Gross, L., Eckartz, K., Ostertag, K., Duque-Ciceri, N., Fischer, T., Gama, M., Scheidt, L., Wilts, H., Schäfer, L., Fischer, S., 2016. Regulatory barriers for the circular economy. Lessons from ten case studies. Final report, 13 July 2016, 169 pp.

Bascetin, A., Tuylu, S., Adiguzel, D., Ozdemir, O., 2016. New technologies on mine process tailing disposal. J. Geol. Res. Eng. 2, 63–72.

Bechtel, N., Bojko, R., Völkel, R., 2013. Be in the loop: Circular economy & strategic sustainable development. Master Thesis, Blekinge Institute of Technology, Karlskrona, Sweden.

van Beers, D., Corder, G., Bossilkov, A., van Berkel, R., 2007. Industrial symbiosis in the Australian minerals industry. The cases of Kwinana and Gladstone. J. Ind. Ecol. 11 (1), 55–72.

Bellenfant, G., Guezennec, A.G., Bodénan, F., D'Hugues, P., Cassard, D., 2013. Re-processing of mining waste: Combining environmental management and metal recovery? Mine Closure 2013, Cornwall, United Kingdom, pp. 571–582.

Breytenbach, M., 2017. Farming for minerals. Mining Weekly 24 Nov 2017. Accessed at: http://www.miningweekly.com/article/agromining-may-provide-new-opportunities-to-extract-remaining-value-from-mined-land-2017-11-24/rep_id:3650

BRGM., 2001. Management of mining, quarrying and ore-processing waste in the European Union, 79 p.

do Carmo, F.F., Kamino, L.H.Y., Junior, R.T., de Campos, I.C., do Carmo, F.F. Silvino, G., da Silva Xavier de Castro, K.J., Mauro, M.L., Rodrigues, N.U.A., de Souza Miranda, M.P., Pinto, C.E.F., 2017. Fundão tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context. Persp. Ecol. Conserv. 15, 145–151.

Chambers, D.M., 2015. A Review of the “Report on Mount Polley Tailings Storage Facility Breach, Independent Expert Engineering Investigation and Review Panel”. Available online: http://www.csp2.org/files/reports/Mt%20Polley%20Tailings%20Dam%20Failure%20Report%20Summary%20-%20Chambers%20rev%20Aug15.pdf

Chen, F., Yao, Q., Tian, J., 2016. Review of ecological restoration technology for mine tailings in China. Eng. Rev. 36 (2), 115–121.

Cox, J.J., Ciuculescu, T., Goode, J.R., Hains, D.H., 2011. Abalon Rare Metals Inc. Technical report on the Thor Lake project, northwest territories, Canada. NI 43–101 Report.

CSIRO, 2018a. ASPIRE: Advisory System for Processing, Innovation & Resource Exchange. https://aspire.csiro.au/ (accessed 8 July 2018).

CSIRO, 2018b. What is ASPIRE? https://research.csiro.au/aspire/what-is-aspire/ (accessed 8 July 2018).

CSIRO, 2018c. What are the benefits of ASPIRE? https://research.csiro.au/aspire/what-are-the-benefits-of-aspire/ (accessed 8 July 2018).

Directive 2006/21/EC of the European Parliament and of the Council on the management of waste from the extractive industries.

Edraki, M., Baumgartl, T., Manlapig, E., Bradshaw, D., Franks, D.M., Moran, C.J., 2014. Designing mine tailings for better environmental, social and economic outcomes: a review of alternative approaches. J. Clean. Prod. 84, 411–420.

Ellen MacArthur Foundation., 2013. Towards the circular economy. Economic and business rationale for an accelerated transition.

Elo, D., Kyngäs, H., 2008. The qualitative content analysis process. J. Adv. Nurs. 62 (1), 107–115.

European Commission, 2014. Scoping study to identify potential circular economy actions, priority sectors, material flows and value chains. August 2014.

European Union, 2016. European Innovation Partnership on Raw Materials. Raw materials scoreboard. Publications Office of the European Union, Luxembourg.

Eriksson, P., Kovalainen, A., 2016. Qualitative methods in business research: A practical guide to social research. 2nd edition. SAGE Publications Ltd, London.

Esposito, M., Tse, T., Soufani, K., 2017. Is the circular economy a new fast-expanding market? Thunderbird Int. Bus. Rev. 59 (1), 9–14.

Falagán, C., Grail, B.M., Johnson, D.B., 2017. New approaches for extracting and recovering metals from mine tailings. Min. Eng. 106, 71–78.

Filho, J.R.A., Firpo, B.A., Broadhurst, J.L., Harrison, S.T.L. 2018. On the feasibility of South African coal waste for production of ‘FabSoil’, a Technosol. Sustainable Minerals, Windhoek, Namibia, 14-15 June 2018, pp. 1–15.

Florin, N., Madden, B., Sharpe, S., Benn, S., Agarwal, R., Perey, R., Giurco, D., (2015) Shifting business models for a circular economy: Metals management for multi-product-use cycles, UTS, Sydney.

Giurco, D., Littleboy, A., Boyle, T., Fyfe, J., White, S., 2014. Circular economy: Questions for responsible minerals, additive manufacturing and recycling of metals. Resources. 3, 432–453.

de Jesus, A., Mendonça S., 2018. Lost in transition? Drivers and barriers in the eco-innovation road to the circular economy. Ecol. Econ. 145, 75–89.

Johnson, D.B., 2014. Biomining - biotechnologies for extracting and recovering metals from ores and waste materials. Curr. Opin. Biotech. 30, 24–31.

Kaksonen, A.H., Boxall, N.J., Gumulya, Y., Khaleque, H.N., Morris, C., Bohu, T., Cheng, K.Y., Usher, K.M., Lakaniemi, A.-M. 2018. Recent progress in biohydrometallurgy and microbial characterisation. Hydrometallurgy 180, 7-25.

Kaksonen, A.H., Mudunuru, B.M., Hackl, R. 2014. The role of microorganisms in gold processing and recovery – A review. Hydrometallurgy 142, 70-83.

Kaksonen, A.H., Puhakka, J.A. 2007. Sulfate reduction based bioprocesses for acid mine drainage treatment and metal recovery. Eng. Life Sci. 7(6), 541-564.
Karaca, O., Cameselle, C., Reddy, K.R., 2017. Acid pond sediment and mine tailings contaminated with metals: physicochemical characterization and electrokinetic remediation. Environ. Earth. Sci. 76, 408.

King, S., Ayre, M., Simpson, G., Lusher, D., Hopkins, J. 2016. Sustainable regional development through networks. The case of ASPIRE (Advisory System for Processing, Innovation and Resource Efficiency) to support industrial symbiosis for SMEs. CSIRO, Australia. http://www.uncrd.or.jp/content/documents/4446Background%20paper-CSIRO-Ms.Sarah%20King-PS-5.pdf (accessed 8 July 2018).

Kinnunen, P., Emler, R., Raatikainen, J., Guignot, S., Ciroth, A., Guimerà, J., Paajanen, M., Heiskanen, K., 2018. Towards closed water loops, ore sorting and tailings valorization for more sustainable raw materials supply. Sustainable Minerals, Windhoek, Namibia, 14-14 June 2018, pp. 1–13.

Kirchherr, J., Piscicelli, L., Boura, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., Hekkert, M., 2018. Barriers to the circular economy: Evidence from the European Union (EU). Ecol. Econ. 150, 264–272.

Lèbre, E., Corder, G., Golev, A., 2017. The role of the mining industry in a circular economy. A framework for resource management at the mine site level. J. Ind. Ecol. 0 (0), 1–11.

Li, H., Ma, A., Srinivasakannan, C., Zhang, L., Li, S., Yin, S., 2018. Investigation on the recovery of gold and silver from cyanide tailings using chlorination roasting process. J. Alloy. Compd. 763, 241–249.

Liu, B.L., Zhang, Z.H., Li, L.B., Wang, Y.J., 2013. Recovery of gold and iron from the cyanide tailings by magnetic roasting. Rare. Met. Mat. Eng. 42(9), 1805–1809.

Liu, X.,Guo, P. and Guo, S. 2019. Assessing the eco-efficiency of a circular economy system in China's coal mining areas: Emergy and data envelopment analysis. J. Clean. Prod. 206, 1101–1109.

Lombardi, D.R., Lyons, D., Shi, H., Agarwal, A., 2012. Industrial symbiosis. Testing the boundaries and advancing knowledge. J. Ind. Ecol. 16 (1), 2-7.

Lottermoser. B.G., 2011. Recycling, reuse and rehabilitation of mine wastes. Elements. 7, 405–410.

Metals X Limited, 2017. Renison tailings retreatment project ("Rentails") updated DFS confirms high margin project. ASX release. 4.7.2017.

Miao, Z. and Marrs, R., 2000. Ecological restoration and land reclamation in open-cast mines in Shanxi Province, China, J. Env. Manag., 59 (3), 205–215.

Mohanty, M., Dhal, N., Patra, P., Das, B., and Reddy, P., Phytoremediation: a novel approach for utilization of iron-ore wastes, Reviews of Environmental Contamination and Toxicology, Springer-Verlag, New York, 2010.

Nuss, P., Blengini, G.A., 2018. Towards better monitoring of technology critical elements in Europe: Coupling of natural and anthropogenic cycles. Sci. Total. Environ. 613–614, 569–578.

Oliveira, M.S., Santana, R.C., Ataíde, C.H., Barrozo, M.A.S., 2011. Recovery of apatite from flotation tailings. Sep. Pur. Tech. 79, 79–84.

Punkkinen, H., Räsänen, L., Mroueh, U.-M., Korkealaakso, J., Luoma, S., Kaipainen, T., Backnäs, S., Turunen, K., Hentinen, K., Pasanen, A., Kauppi, S., Vehviläinen, B., Krogerus, K., 2016. Guidelines for mine water management. VTT Technology 266, June 2016.

Ranängen, H., Lindman, Å., 2017. A path towards sustainability for the Nordic mining industry. J. Clean. Prod. 151, 43–52.

Roos, G., 2014. Business model innovation to create and capture resource value in future circular material chains. Resources. 3, 248-274.

Ruokonen, E., Temmes, A., 2018. The approaches of strategic environmental management used by mining companies in Finland, J. Clean. Prod.

Sauvé, S., Bernard, S., Sloan, P., 2016. Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. Environ. Dev. 17, 48–56.

Schoenberger, E., 2016. Environmentally sustainable mining: The case of tailings storage facilities. Resources Policy 49, 119–128.

Simate, G.S., Ndlovu, S., 2014. Acid mine drainage: Challenges and opportunities. Int. J. Eng. Res. Appl. 2, 1785–1803.

Solomons, I., 2017. Mine tailings recovery can be value generator, says Council for Geoscience. Min. Wkly. 9.6.2017. http://www.miningweekly.com/article/mine-tailings-recovery-can-be-value-generator-reduces-enviro-impact-2017-06-09

Stahel, W.R., 2013. Policy for material efficiency — sustainable taxation as a departure from the throwaway society. Phil. Trans. R. Soc. A. 371, 20110567.

Swiss Federal Laboratories for Materials Science and Technology, 2018. First European database for secondary raw materials. Phys.org 2003 - 2018, Science X network. https://phys.org/news/2018-04-european-database-secondary-raw-materials.html (accessed 8 July 2018).

UNEP, 2013. Metal recycling: Opportunities, limits, infrastructure. A report of the working group on the global metal flows to the international resource panel. Reuter, M.A., Hudson, C., van Schaik, A., Heiskanen, K., Meskers, C., Hagelüken, C., April 2014. 316 p.

Unger, C., Lechner, A.M., Glenn, V., Edraki, M., Mulligan, D.R., 2012.Mapping and prioritising rehabilitation of abandoned mines in Australia. Life-of-Mine Conference. Brisbane, QLD, 10-12 July 2012. Pp. 259–265.

US patent. 2012. 114538A. Method for extracting rare earth elements from phosphogypsum.

Vardanyan, N., Sevoyan, G., Navasardyan, T., Vardanyan, A. 2018. Recovery of valuable metals from polymetallic mine tailings by natural microbial consortium. Environ. Tech. DOI: 10.1080/09593330.2018.1478454

Velis, C.A., Vrancken, K.C., 2015. Which material ownership and responsibility in a circular economy? Waste. Manage. Res. 33 (9), 773-774.

Wang, C., Harbottle, D., Liu, Q., Xu, Z., 2014. Current state of fine mineral tailings treatment: A critical review on theory and practice. Min. Eng. 58, 113–131.

West, J., 2011. Decreasing metal ore grades. Are they really being driven by the depletion of high-grade deposits? J. Ind. Ecol. 15 (2), 165-168.

World Economic Forum, 2016. Mapping Mining to the Sustainable Development Goals: An Atlas. Available at: http://unsdsn.org/wp-content/uploads/2016/11/Mapping_Mining_SDGs_An_Atlas.pdf

Zhao, Y., Zang, L., Li, Z., Qin, J., 2012. Discussion on the model of mining circular economy. Energy Procedia. 16, 438–443.

van Zyl, D., Shields, D., Agioutantis, Z., Joyce, S., 2016. Waste not, want not - rethinking the tailings and mine waste issue. AusImm Bulletin, December 2016.

Highlights

- Mining industry is aware of circular economy thinking
- Drivers, needs and barriers for tailings valorization were identified
- Knowledge of available resources and finding suitable business cases are crucial
- Technology and value chain developments may turn tailings into valuables