Valorisation of heterogeneous industrial residues towards a circular economy

A systems-oriented investigation on how to facilitate shredder fines valorisation in the Swedish context

Tharaka Gunaratne

Linköping Studies in Science and Technology

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Abstract

In the context of the circular economy in the European region, the role of the recycling industry has become ever important. Shredder fines (or fines) is a heterogeneous residue of the shredding industry, which presents a disposal problem and incurs handling costs to the shredding industry. More importantly, its current handling reduces the resources efficiency of our society. This thesis aims to contribute systems-oriented knowledge to facilitate the valorisation of shredder fines in the Swedish context. In doing so, it contributes to two complementary knowledge areas: Knowledge Area 1 portrays the current picture concerning fines management, whereas Knowledge Area 2 showcases a potential approach to initiate process development for fines valorisation.

The findings of Knowledge Area 1 show that the studied shredding company is more inclined towards continuing the current disposal-oriented management of fines due to incentives for utilising fines as landfill cover materials as well as disincentives for valorising fines, created by various policy, market, and organisational factors. On the other hand, there is a significant need to improve the market prospects for recycling, especially when it comes to using fines as a secondary aggregate in the construction sector. The market is chiefly characterised by processes and underlying institutions that sustain dominant and systematic primary aggregates utilisation, whereas secondary aggregates utilisation is ad-hoc and only driven by situational benefits to different supply chain actors due to different individual reasons.

The findings of Knowledge Area 2 show that process development for fines valorisation has several technical and environmental challenges. The resource potential assessment of fines shows that the initial technical feasibility of fines valorisation is considerable. However, the realisation of this potential necessitates integrated and like costly processes to upgrade the material quality recover resources. The life cycle assessment of prospective fines valorisation shows that fines valorisation is generally more environmentally promising compared to landfill-related disposal; still, different resource recovery strategies would create different levels of environmental impacts and present different needs for improvements.

Generally, this thesis demonstrates the use of portraying the current picture concerning the present management and market prospects of a given heterogeneous industrial residue to elicit the challenges of and necessary measures for initiating changed practices. It also showcases a potential approach in terms of assessing the resource potential, formulating alternative process schemes for material upgrading and resource recovery, and assessing their environmental potential to guide sustainable investment decisions for and governance of the valorisation of a given heterogeneous industrial residue. Overall, this thesis demonstrates how systems-oriented interdisciplinary knowledge could be generated to facilitate the valorisation of heterogeneous industrial residues towards a circular economy.

Sammanfattning

I samband med den cirkulära ekonomin i EU-regionen blir återvinningssektorns roll allt viktigare. Shredder fines (eller fines) är en heterogen restprodukt som uppkommer vid fragmenteringsindustrin och utgör idag ett kvittblivningsproblem och betydande hanteringskostnader för industrin. Dessutom så bidrar dagens hantering av fines till att vi förlorar värdefulla resurser ur kretsloppet. Syftet med avhandlingen är att bidra med kunskap för att underlätta valorisering av fines i Sverige. Detta har gjorts genom studier inom två kompletterande kunskapsområden. Inom område 1 analyseras bakomliggande faktorerna som påverkar den nuvarande hanteringen av fines. Kunskapsområde 2 innefattar ett potentiellt angreppssätt för att underlätta utvecklingen av processer för valorisering av fines.

För kunskapsområde 1 visar resultaten att det studerade fragmenteringsföretaget är mer benäget av att fortsätta den nuvarande hanteringen av fines än att utveckla olika återvinningsalternativ. Detta beror både på starka incitament för att fortsätta använda fines som deponitäckningsmaterial och flera politiska, marknadsmässiga och organisatoriska hinder för valorisering. Å andra sidan finns det ett stort behov av att förbättra utsikterna för återvinning, framför allt när det kommer till att använda fines som sekundärt ballastmaterial inom bygg- och anläggningssektor. För närvarande kännetecknas dock denna marknad av processer och underliggande strukturer som framför allt bidrar till att upprätthålla en dominerande användning av primära ballastmaterial. Användningen av sekundära ballastmaterial är ytterst begränsad och sker endast i situationer när aktörerna inom leveranskedjan har tydliga skäl.

Inom kunskapsområde 2 visar resultaten att utvecklingen av processer för valorisering av fines innefattar flera tekniska och miljömässiga utmaningar. Bedömningen av resurspotential för fines visar på en betydande möjlighet att valorisera fines. Men för att realisera denna potential krävs integrerade och sannolikt kostsamma processer för att uppgradera materialets kvalitet och utvinna resurser. Resultaten från livscykelanalysen av olika återvinningsalternativ visar sammantaget att valorisering av fines i många avseende skulle leda till miljövinster jämfört med dagens användning som deponitäckningsmaterial. Olika återvinningsstrategier leder dock till olika grader och typer av miljöpåverkan och det finns ett tydligt behov av förbättringar.

Generellt visar denna avhandling genom att skildra den nuvarande praktiken både vad gäller hanteringen av fines och marknadsutsikterna för återvinning hur kunskap som kan bidra till en förändrad hantering av heterogena restprodukter tas fram. Avhandlingen bidrar även med ett potentiellt tillvägagångssätt för att bedöma resurspotentialen för heterogena restprodukter, formulera alternativa processscheman för uppgradering och resursåtervinning, och analysera deras miljöpotential för att vägleda hållbara investeringsbeslut och policyutveckling inom

området. Sammantaget visar denna avhandling hur systemorienterad tvärvetenskaplig kunskap kan skapas för att underlätta valoriseringen av heterogena industriella restprodukter mot en cirkulär ekonomi.

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List of appended articles

Article I:

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Article III:

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Article IV:

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Article V:

Gunaratne, T., Krook, J., Andersson, H., 2020. Market prospects of secondary construction aggregates in Sweden. Submitted to the *Journal of Cleaner Production*.

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1 Introduction

This chapter presents the wider context and motives of the research, followed by a description of the aim and research questions.

The global economic activity has been continuously and increasingly stressing the Earth's planetary boundaries due to natural resource depletion and pollutant emissions (International Resource Panel, 2017). The circular economy is a concept that refers to restoring the environmental balance of economic activity (Ghisellini et al., 2016). In that regard, deviating from the traditional linear model and closing industrial material loops is of prime significance. However, at present, our handling of materials typically involves considerable losses along their entire life cycles, both in terms of matter and resource quality (Material Economics, 2018). At the end of product life, current collection and recycling processes are capable of retaining the value of only a fraction of the materials contained in the waste streams, while the main amounts are either down cycled to low-quality resources or disposed of (Baccini and Brunner, 2012). Many recycling processes focus on only one or a few targeted outputs despite many incoming materials, and hence, result in generating large quantities of heterogeneous residues (Baccini and Brunner, 2012; Fellner et al., 2015). Such residues, i.e. the *waste of the waste*, are often technically challenging and economically unappealing to recover (Fischer, 2006), hence disposed of into landfills in many parts of the world (Lam et al., 2010; Vermeulen et al., 2011). This practice causes several undesirable repercussions in realising our vision of a circular economy. First and foremost, it causes a continuous loss of resources to society. On the other hand, landfilling generates hazardous emissions and takes up space. Additionally, the industries generating these residues must bear substantial costs associated with the disposal.

Since the mid-20th century, the shredding of complex end-of-life products to recover some targeted valuable resources has gradually evolved, and today, this practice plays an important role in the recycling industry in several parts of the world. In this industry, waste streams such as end-of-life vehicles (ELVs), municipal white goods, and industrial metallic scrap are shredded (Santini et al., 2012; Vermeulen et al., 2011), primarily for the subsequent recovery of metals such as iron, aluminium, and copper. Upon the initial separation of these metals, a heterogeneous residue stream consisting of a mixture of the non-recovered materials (e.g. metals, plastics, textile and fibre, rubber, foam, glass, wood, and gravel) is generated (Cossu et al., 2014; Vermeulen et al., 2011). This material, called shredder residue, is often landfilled around the world (Cossu and Lai, 2015; Vermeulen et al., 2011). In certain countries, for example, in Sweden and Belgium, advanced processing is used for further recovery of materials such as metals and plastics from the larger size fractions of this residue. Nevertheless, the fine-granular fraction of the shredder residue, which is called *shredder fines* or merely *fines*, is virtually always disposed of (Allen and Fisher, 2007; Santini et al., 2012).

Shredder fines, like other heterogeneous industrial residues, are typically regarded as low-quality materials due to that they constitute a blend of valuable materials such as base metals, other useful materials, for example, organic, inert, and hazardous components like heavy metals and organic pollutants (Ahmed et al., 2014; Fiore et al., 2012; Morselli et al., 2010). Without further processing, this material offers limited utility. The materiality of fines can significantly vary between different shredding plants due to differences in the feed material, shredding units, and post-shredder resource recovery processes. In previous literature, fines have been commonly recognised as the 0-20 mm fraction of the shredder residue (Vermeulen et al., 2011). The share of fines could comprise 10-30% of the material input to the shredder and 25-70% of the shredder residue (Cossu et al., 2014; Cossu and Lai, 2015). Globally, about four million tonnes of fines are generated annually from the shredding of ELVs alone (calculated from Fiore et al. (2012) and Vermeulen et al. (2011)). The total amount of fines generated is expected to be a couple of times more than that because most shredding plants typically shred a mix of waste streams.

In Sweden, the advancement in post-shredder treatment processes has gradually enabled the shredding industry to recover materials from the smaller fractions of shredder residue over time. Consequently, in some plants, the particle size of fines has been reduced from 20 mm to less than 10 mm during the last two decades. At present, fines is primarily utilised as landfill cover material in the country, whereas on certain occasions, it is also landfilled. This practice, however, causes the loss of resources such as metals, energy carriers, and minerals to society, whereas it also incurs significant disposal costs like transportation, administrative fees, and taxes to the shredding companies. On the other hand, several other factors are making the continued fines disposal difficult for the shredding companies. Sweden's policy decision to gradually phase out landfills two decades ago (Swedish EPA, 2010a) has rapidly decreased landfill availability, which is the current outlet for the material. Stricter implementation of the EU targets for recovery and recycling¹ of end-of-life vehicles (European Commission, 2000), one of the main input streams to the shredding plants, might require the further processing of fines. Additionally, the stakeholders increasingly require improved environmental sustainability of companies, which indirectly compels the resource recovery and recycling of fines. Hence, this disposal-oriented practice of fines management is unlikely to be an option in the long run. Several other countries in the region, such as the Netherlands, Denmark, Belgium, and Finland, which are socio-economically comparable to Sweden, have already drastically reduced the disposal of similar heterogeneous industrial residues via waste-reutilisation policies and practices (Johansson, 2018). Thus, in order to improve resource efficiency, reduce costs, and avoid future disposal problems, the Swedish shredding industry should seek alternative management options based on value-addition (upgrading) and resource recovery—also referred to

¹ "Recovery" is any operation by means of which a waste is used or being prepared to serve a particular function by replacing other materials. "Recycling" means any recovery operation by which waste materials are reprocessed into products, materials, or substances, whether for the original or other purposes (European Commission, 2008).

as valorisation (Martin, 2013; Pontikes and Malfliet, 2016)—of fines. Additionally, to address these objectives, valorisation should target the full resource recovery of fines, that is, the recovery of specific materials to increase resource efficiency and retain economic value and bulk materials to avoid disposal.

At present, very little is happening in practice when it comes to improving fines management, and the research on fines valorisation is still in an early phase. The potential valorisation of fines can be influenced by factors related to multiple aspects; hence, its development and implementation require multi-faceted knowledge. Previous research concerning other heterogeneous industrial residues, such as shredder residues and municipal waste incinerator bottom ash (municipal bottom ash), show various aspects on the technical, actor, and institution levels. The technical aspects are related to the materiality of fines and process development for fines valorisation. Materiality-related aspects, such as the chemical and physical composition (Ahmed et al., 2014; Dou et al., 2017), are necessary to establish in order to assess the occurrence of potentially recoverable resources and material contaminants. Such knowledge enables the identification of the potential users and the need for process development to deliver various fines-derived secondary raw materials (SRMs). Process-related aspects, such as resource recovery efficiency (Šyc et al., 2018), economic feasibility (Jody et al., 2011), and environmental impacts (Allegrini et al., 2015), are necessary to formulate and assess valorisation strategies. The actors primarily constitute waste producers and raw material users. Waste producer-related aspects, such as capacities to influence material flows (van Beers et al., 2009) and how they have internally organised for it, determine the actual practice of managing fines. Raw material user-related aspects such as SRM demand (Bertils and Elvingson, 2019) and gate requirements (Johansson et al., 2017) are essential to assess the market prospects of SRMs and the need for valorisation of the different residues. The institutions primarily constitute formal institutional (governmental policy and regulation) aspects. Administrative instruments (Nayak and Apelian, 2014) and local-authority regulation (Johansson, 2018) would provide the overall governance of valorisation applications, while market instruments (Dubois et al., 2015) could be used to provide external stimulation for such applications.

Two main gaps of systems-oriented knowledge exist regarding such aspects in relation to fines management. One is that systems-oriented knowledge on how such aspects influence the current situation concerning fines management is lacking. The realisation of fines valorisation would involve institutional conditions and responsive actors, conducive to investing in knowledge and technology development for resource recovery of fines and utilising fines-derived SRMs in industrial applications. Enabling such circumstances and settings naturally requires knowledge that can explain the prevailing disposal-oriented practice of managing the residue (Omran et al., 2007) and the market prospects of secondary raw materials (Bertils and Elvingson, 2019). A systems perspective here facilitates viewing the current practice of residue management (Andersson et al., 2019b) and the market rationale of raw

materials (Iacovidou et al., 2021) as consequences of various factors of the aforementioned different aspects acting together and influencing each other. The lack of such knowledge renders the identification of challenges and necessary measures and setting priorities for initiating changed practices towards fines valorisation largely difficult.

Initiating changed practices by itself is not sufficient to realise fines valorisation. Technological processes need to be developed for upgrading and resource recovery. Even though technical aspects such as material characterisation and process development have been the primary focus of virtually all previous fines research, systems-oriented technical knowledge that enables the development of cost-efficient and environmentally justifiable valorisation processes is lacking. For instance, one of the key prerequisites of process development for fines valorisation is knowledge of the resource potential, that is, the likeliness of deriving materials to fulfil a particular utility (Taylor and Steven, 1983) commercially. Assessing the composition of potentially recoverable resources and material constraints that need to be resolved in recovering them is essential to assess the resource potential of a given material, particularly a heterogeneous one such as fines. However, previous research concerning the resource potential of fines (Allen and Kolb, 2009; Bareel et al., 2006; Edo et al., 2013; Johansson et al., 2017; Konetschnik and Schneeberger, 2009; Péra et al., 2004) is confined to assessments of a few targeted constituents out of many, and are performed based on one or few randomly collected or representative samples and involving particular size fractions of the material. Consequently, our knowledge of the resource potential, even at the plant level, is largely limited. The lack of systems-oriented knowledge on the resource potential makes the identification of valorisation options and formulating upgrading and resource recovery processes for fines difficult. This is reflected in the lack of systems-oriented approaches in the previous research concerning process development for recovering fines. Generally, these studies are confined to either the recovery of one or few targeted specific valuable materials such as base metals (Allen and Fisher, 2007; Furuyama and Bissombolo, 2005; Konetschnik and Schneeberger, 2009; Lewis et al., 2011; Mallampati et al., 2018; Singh et al., 2016) or utilisation as bulk materials in applications such as construction (Péra et al., 2004; Rossetti et al., 2006) and plastics moulding (Cain et al., 2000; Robson and Goodhead, 2003). A large share of the material is left for disposal in the case of the former, whereas the opportunity to recycle valuable resources is lost in the latter. Consequently, the full resource recovery of fines is overlooked.

Another key prerequisite of process development for fines valorisation is knowledge of the expected performance of such processes. Thus, the performance assessment of alternative valorisation strategies is necessary to identify the most promising path for technology development. In this regard, certain studies have performed economic assessments of certain individual resource recovery processes (Allen and Fisher, 2007; Allen and Kolb, 2009); nevertheless, there is a general lack of

environmental assessments of fines valorisation. The environmental impact of novel processes such as potential fines valorisation is largely determined in the early stages of their development (Villares et al., 2017) and would eventually determine the functional requirements and costs (Jeswiet and Hauschild, 2005) of operating them. Previous research totally lacks environmental impact assessments of fines valorisation, whereas only the environmental impacts of shredder residue valorisation are addressed (Boldrin et al., 2015; Ciacci et al., 2010; Høstgaard et al., 2012; Vermeulen et al., 2012). Consequently, investment decisions regarding fines valorisation and the identification of possibilities for their sustainability improvements have become difficult.

1.1 Aim and research questions

The overall aim of this thesis is to contribute systems-oriented knowledge to facilitate the valorisation of shredder fines in the Swedish context, that is, to unveil the influence of the various technical, actor-related, and governmental aspects and their inter-relations on fines valorisation and how to address such aspects to realise fines valorisation. In doing so, a two-fold approach referring to two knowledge areas has been undertaken. Knowledge Area 1 addresses one of the two aforementioned main knowledge gaps in fines research, the lack of systems-oriented knowledge on the current situation concerning fines management. Thereby, the challenges and necessary measures to initiate changed practices are identified. Knowledge Area 2 addresses the other main knowledge gap, the lack of systems-oriented technical knowledge to develop environmentally justifiable processes for fines valorisation. Thereby, guidance is provided towards sustainable investment decisions and policy and regulation. This research involves contributing knowledge to facilitate fines valorisation. Neither the implementation of changed practices nor the development of valorisation processes is part of it.

Knowledge Area 1 portrays the current picture concerning fines management in terms of the underlying factors of the current practice of fines management and the market prospects for secondary raw materials. In that regard, the following research questions (RQs) are addressed.

RQ1: Why is the current disposal-oriented management of shredder fines sustained in Sweden?

This research question intends to establish the underlying factors of the current practice of fines management in Sweden in terms of the incentives for shredding companies for the disposal-oriented management of fines and the disincentives for valorisation-based alternatives. Thus, the shredding company perspective on the influence of external aspects, that is, related to government policy and regulation and secondary raw material (SRM) markets, and company-internal aspects, that is, related to landfill construction material (LCM) markets, and internal organisational aspects, on the current management of the residue was established. The producer (shredding

company) perspective is focused on as they are considered the most central actor in the issue of fines management. The study itself is confined to a single shredding company, and therefore, the internal organisation factors are specific to that company. Nevertheless, the insights drawn on the factors created by the policy (and regulation), market, and technical aspects are plausibly more generalisable in the Swedish context.

RQ2: What are the market characteristics that determine the construction aggregates utilisation in Sweden?

This research question intends to establish the underlying factors determining the dominant primary aggregates and the situational secondary aggregate utilisation in the country in terms of supply chain processes and the structural components supporting them. The construction sector, even though it only involves one type of potential fines-derived SRMs, that is, the bulk material of fines-derived construction aggregates, represents a very large market, which is also one of the most likely ones to open valorisation possibilities for heterogeneous industrial residues such as fines in the near future. The primary focus in addressing this research question is the user perspective because they interact with both upstream and downstream actors and also have a prominent role in terms of the selection of construction materials, and any changes towards increased utilisation of secondary aggregates will have to be implemented by them. Thus, the user perspective on the main market processes related to aggregates utilisation - material choice, supplier selection, and purchase - and the formal and informal institutions occurring on various levels that facilitate such processes are addressed. The user perspective is complemented with customer and supplier perspectives on the same aspects.

The two research questions complement each other to portray the current picture and thereby guide the initiating of changed practices. RQ1 provides insights to identify the challenges and possible measures for encouraging shredding companies towards knowledge and technology development for fines valorisation. RQ2 provides insights into a specific market sector to identify the challenges of and possible measures for the increased utilisation of secondary raw materials in that sector so that an established outlet with significant demand for potential fines-derived construction aggregates could be made available.

Knowledge Area 2 showcases a potential approach to initiate process development in terms of assessments of the resource potential of fines, formulation of alternative valorisation process schemes, and the assessment of the environmental impact of fines valorisation. In that regard, the following research questions are addressed.

RQ3: How could the resource potential of fines be assessed to enable full resource recovery?

This research question intends to develop a systematic methodological approach to comprehensively assess the resource potential of fines. Even though it is the resource potential itself that is required to develop valorisation processes, it is highly plant-specific, and the development of a generally applicable methodological approach for assessing the resource potential is deemed more useful. The resource potential of fines is assessed as part of it. The developed methodological approach consists of three main parts: strategic sampling and characterisation of the distribution and variation of a range of chemical and physical properties, selection of applications targeting both the potential recovery specific resources and the potential reutilisation of bulk materials, and benchmarking the established material compositions against the user and regulatory requirements of the selected applications. Thereby, the resource potential of fines is assessed, and the specifications are provided on the need for upgrading (resolving material constraints) and the potentially recoverable quantities of fines in each application. Such knowledge provides the basis for formulating valorisation alternatives based on different resource recovery strategies.

RQ4: What is the environmental potential of the different valorisation options for shredder fines?

This research question intends to assess the life cycle environmental impacts of fines valorisation alternatives. Three valorisation alternatives are formulated based on the resource recovery strategies: 1) maximising copper recovery, 2) maximising construction aggregates recovery, and 3) optimising full resource recovery. The targeted resources in each alternative are selected based on the assessed resource potential fines (in RQ3). The net life cycle impacts (i.e. the difference of the life cycle impact of fines-derived secondary raw materials (SRMs) and substituted primary raw materials (PRMs) of the three alternatives were compared against that of the status quo (i.e. the current handling of fines) to identify whether fines valorisation is environmentally benign, and against each other to identify their relative environmental potential. A streamlined life cycle assessment is used to indicate the potential environmental consequences of the different valorisation alternatives. Thus, environmental hot spots of the valorisation alternatives are identified in relation to the different operations taking place along the life cycles of fines-derived SRMs. Given that the formulated process schemes are conceptual and process parameters could vary, and the compositions of fines is subjected to significant variations, an uncertainty analysis of the environmental impact is performed. The assessed environmental potential is specific to the formulated processes and fines generated at the particular shredding plant.

The two research questions consist of two sequential parts of a methodological approach for initiating process development for fines valorisation. The assessed resource potential in RQ3 provides fundamental information to formulate and assess fines valorisation in RQ4. The empirical contributions of addressing the research questions, that is, the resource potential of fines and the environmental impact of

potential fines valorisation, guide sustainable investment decisions and governance of fines valorisation.

1.2 Thesis outline

Chapter 2: Background

This chapter presents the background context of heterogeneous industrial residues in terms of the state of the art of their management.

Chapter 3: Research journey

This chapter presents how the different research activities unfolded along the way and led to the writing of the scientific articles the thesis is based on, followed by extended abstracts of those articles with emphasis on the employed data collection and analytical approaches.

Chapter 4: Theoretical approaches

This chapter presents the theoretical background pertaining to how the key concepts of the thesis, namely, circular economy, industrial ecology, and systems perspective, were approached.

Chapter 5: Methodology

This chapter presents the methodological approach of the thesis in relation to the two knowledge areas and the research questions, study objects and research methods in the articles, the employed systems perspectives, the synthesis of the article findings to address the research questions, and the discussion.

Chapter 6: Knowledge Area 1: The current picture of fines management

This chapter addresses the first and second research questions. The current practice of fines management is elaborated from the producer perspective (RQ1) and the rationale of the construction aggregates market is elaborated from the user perspective (RQ2).

Chapter 7: Knowledge Area 2: A potential approach for fines valorisation

This chapter addresses the third and fourth research questions. The resource potential of fines is assessed (RQ1) and valorisation alternatives are formulated and their environmental potential assessed (RQ4).

Chapter 8: Discussion

This chapter presents a discussion on the contribution of the key findings of the thesis in providing knowledge for facilitating fines valorisation in relation to previous research, followed by a synthesising discussion on the implications of the thesis contributions in realising fines valorisation.

Chapter 9: Reflections

This chapter presents a general reflection on the significance of heterogeneous industrial residue valorisation for the circular economy and the thesis contributions in facilitating heterogeneous industrial residues valorisation.

Chapter 10: Conclusions

This chapter presents the major takeaway points from addressing the knowledge areas and the corresponding research questions in facilitating fines valorisation and concludes with an overall reflection on the research's contribution to heterogeneous residue valorisation.

2 Background

This chapter presents the background context of heterogeneous industrial residues in terms of the state of the art of their management.

This section refers to the context of shredder fines and municipal bottom ash. The latter is referred to for several reasons. It is a comparable residue to fines in terms of materiality (heterogeneity and particle size) and composition. It is also similar to fines in that the material characteristics can vary significantly depending on the input materials and the recycling process (i.e. incineration). Furthermore, it has a mature presence in research and industrial applications.

Since early 2000, the EU has announced the long-term vision of becoming a recycling society (European Commission, 2005). Later on, an action plan for the circular economy was published (European Commission, 2015), manifesting the need for an increase in closing material loops via value-added resource recovery and recycling, which is now vitalised in the EU Green Deal (European Commission, 2019). In this context, the management of heterogeneous industrial residues poses a challenge. For instance, in the EU region, shredder fines and municipal bottom ash² are generated in millions of tonnes (Blasenbauer et al., 2020; Vermeulen et al., 2011), whereas the material complexity makes resource recovery and recycling difficult both technologically and economically (Fischer, 2006). Additionally, given the differences in policy and market-related circumstances, the actual practice of handling such residues, for example, municipal bottom ash (Blasenbauer et al., 2020), differs significantly among different countries.

Sweden, in conjunction with the EU landfill directive (European Commission, 1999), drafted several legislations to discourage the disposal of potentially recoverable residues/wastes at the beginning of this century. For instance, landfilling is subjected to a tax of 500 SEK/tonne (Sveriges Riksdag, 1999) and prohibited if the material contains more than 10% organic matter (Sveriges Riksdag, 2001). However, after two decades, the management of heterogeneous industrial residues is still rarely practiced outside landfills. Waste producers often seek an outlet for such residues through landfill covering and other landfill-related constructions. Nevertheless, the future possibilities with such applications are rapidly decreasing, especially given that the country has the policy to phase out landfills (Swedish EPA, 2010a), and the waste producers foresee the need for alternative outlets. Yet, the reutilisation of heterogeneous industrial residues is still emerging, and replacing primary material with such waste-based materials is not yet a priority in the country (Eklöf, 2018). Only a few projects, such as municipal bottom ash utilisation in some ground construction applications like filling and laying a foundation (Kjellsson, 2007; Ribbing, 2007), have been undertaken so far.

² In this thesis, the term municipal bottom ash should be understood as municipal bottom ash upon initial metals separation, which is common practice in Europe (Blasenbauer et al., 2020).

When it comes to the regulation of such residue reutilisation applications, the Swedish Environmental Protection Agency (EPA) has developed guiding values regarding the maximum allowable contaminant levels. These guiding values are specified in three application categories: construction on sensitive grounds such as playgrounds and parks, construction on less sensitive grounds like parking lots and noise barriers, and landfill covering (Swedish EPA, 2010b). However, the application of these guiding values varies throughout the country. In Sweden, the reutilisation of waste-classified materials in construction is considered a hazardous activity, and hence, requires permission from the respective local authorities if the minimum contamination levels set by the EPA are exceeded (Sveriges Riksdag, 1998). These applications are assessed on a case-by-case basis (Swedish EPA, 2010b). Uniform criteria are, however, absent for such assessments, and hence, different local authorities interpret the guidelines differently (Bertils and Elvingson, 2019; Johansson, 2018). This leads to long and uncertain authorizing processes, often compelling waste producers to go for disposal options, which are more certain, and waste users to select conventional materials. Additionally, the guiding values for allowable contamination levels are based on a total hazard approach where the emphasis is put on regulating the total concentration of hazardous substances - particularly heavy metals (Swedish EPA, 2010b) - occurring in the waste. Many heterogeneous industrial residues cannot fulfil such total concentration limits, and therefore, waste producers argue that the guiding values should instead be based on a risk approach where the allowable contamination is regulated by leaching concentrations. There are also studies (Avfall Sverige, 2017; Hedenstedt, 2015) that proclaim that fulfilling such requirements is more practical in residue-derived SRM utilisation.

Several other countries in the region, such as Denmark, Belgium, Finland, and the Netherlands, which are socio-economically comparable to Sweden, widely practise the reutilisation of municipal bottom ash in ground construction applications (Dou et al., 2017; Johansson, 2018; Van Gerven et al., 2005). Unlike Sweden, these countries have developed specific and nationwide standards that are binding and thus not subject to varying interpretations by local authorities (Johansson, 2018). Another important feature of these regulatory frameworks is that they are often differentiated, allowing fairly high contamination levels in applications with low exposure risk and vice versa. The former, however, is often combined with requirements on different safety and control measures, such as the maximum allowed quantity and layer-thickness of residues and the minimum distance and elevation from water sources (Dou et al., 2017; Van Gerven et al., 2005). Such centralised regulations lead to more foreseeable and consistent conditions for utilisation of residues, which is beneficial both for their producers and the users of residue-derived SRMs. Several of these countries also regulate the allowable contamination levels by using a risk-based approach and emphasising the leaching concentrations (Danish EPA, 2016; Flemish Government, 2012).

In certain countries, governments have intervened at the actor level to facilitate the utilisation of waste by creating a market. For instance, in Denmark, the authority responsible for national transportation uses bottom ash as sub-base materials in road construction (Johansson, 2018). The Dutch government has initiated the Green Deal program, where government enters into partnerships with and encourages voluntary solutions by market actors to solve a waste situation (Dutch Economic Affairs Ministry, 2015). There, the government's primary role is to exert recovery demands and facilitate the removal of implementation barriers (Ellen Macarthur Foundation, 2017). Furthermore, same regulatory requirements are shared between primary and secondary construction materials in the country, which creates an equal playing field for the materials in the marketplace. The governmental policy and market-related conditions in the aforementioned countries are deemed to have created more encouraging circumstances and settings than in Sweden for applications based on SRMs, and hence, are more conducive to attaining the regional resource objectives.

3 Research journey

This chapter presents how the different research activities unfolded along the way and led to the writing of the scientific articles the thesis is based on, followed by extended abstracts of those articles with emphasis on the employed data collection and analytical approaches. An overview of the articles is provided in Tables 1 and 2 at the chapter's conclusion. The full articles are appended to the thesis.

The research presented in this thesis has been conducted as part of an ongoing research project entitled Mistra Fines, which is funded by the Mistra Closing the Loop II program. The Mistra Fines project aims to contribute a framework of knowledge, methods, and necessary circumstances and settings that could facilitate the development and implementation of shredder fines valorisation. Even though shredder fines has been generating for decades, the issue of the need for its improved management has only been recently identified. Shredder fines could carry a significant amount of potentially recoverable valuable resources, and therefore its disposal could be a significant lost resource opportunity. Realising the valorisation of this residue is a complex task that involves initiating change in the current disposal-oriented practice by its owners, processing it for upgrading and resource recovery, and having the raw material user utilising fines-derived SRMs. Knowledge creation for facilitating such change inherently necessitates a systems perspective, which has also influenced the overall approach to the research work presented in this thesis. Following is a brief description of how the different research activities unfolded and led to the writing of scientific articles.

The lack of systematically concerted knowledge on a recently-developed body of knowledge makes it difficult to guide future research on the matter. Therefore, it was first necessary to establish the current knowledge levels regarding fines management. Hence, the research work started with a systematic review of globally published scientific literature that concerned the management of fines. The overall aim of the study was to review and assess the contributions and limitations of previous studies on shredder fines to provide a coherent overview of current knowledge levels. This study led to the writing of the first article of the thesis.

One of the two main findings of Article I was that current global knowledge does not provide a coherent understanding of the materiality of fines. That is, different studies have investigated the occurrence of different constituents and involved different particle size fractions. Additionally, the variation of material composition is unknown. The lack of comprehensive knowledge of the material characteristics makes the identification and development of feasible alternatives for the full resource recovery of fines difficult. In addressing this issue, it was recognised that the materiality of fines is quite plant-specific due to the differences in feed material and employed shredding and post-shredder resource recovery processes. Thus, fines generated at a particular shredding plant in Sweden was strategically sampled and characterised to provide a comprehensive understanding of the materiality of fines

generated at a specific shredder plant and an approach for identifying and evaluating the initial technical feasibility of different upgrading and resource recovery approaches. The overall aim of the study was to provide knowledge that could guide future research on integrated process development for the upgrading and resource recovery, and thereby, the full resource recovery of fines. This study led to the writing of the second article of the thesis.

As far as process development for fines valorisation is concerned, Article I also revealed that the environmental and economic feasibility impact of potential processes, which provides indispensable knowledge regarding their performance, are currently lacking. Consequently, policy making, regulation, and investment decisions for fines valorisation become difficult. In addressing this issue, integrated process schemes for upgrading and resource recovery of fines were formulated based on different levels of motivations based on the findings of the second study and assessed using life cycle environmental impact assessment. The overall objective of the study was to systematically assess the environmental potential of alternative fines valorisation strategies. Economic assessments were considered somewhat far-fetched given the early stage of process development where the actual costs of commercial operations would fluctuate rapidly, and especially, the revenues of potential fines-derived resources are unknown. This study led to the third article of the thesis.

Another main finding of Article I was that previous fines research was almost entirely technically focused, involving material characterisation and process development. There, knowledge on various societal-level aspects such as government policy and regulation, actors of potential fines valorisation, and raw material markets are scantily addressed. The lack of focus on the societal-level aspects in fines research makes the understanding of the underlying factors of the current disposal-oriented practice of fines management limited. Consequently, the identification of challenges and necessary measures to initiate change towards fines valorisation becomes difficult. In addressing this issue, it was recognised that the circumstances and settings that have resulted in a certain practice on fines management are quite context specific. Thus, a study on the underlying factors of the current practice of fines management in the Swedish context was carried out. In order to enable an in-depth understanding, the study involved interviews with selected employees of a specific shredding company (the same company that owns the aforementioned shredding plant) in the country. The overall aim of the study was to provide systems-oriented knowledge on the influence of policy, market, and organisational aspects on the current practices of fines management in the Swedish context. This study led to the writing of the fourth article of the thesis.

The lack of focus on the societal-level aspects in fines research also makes the understanding of the market prospects of fines valorisation limited. Consequently, the identification of strategies to initiate increased utilisation of secondary raw materials by industries becomes difficult. In addressing this issue, it was recognised

that in-depth knowledge of the market rationale of raw materials, that is, market processes and the underlying institutions concerning raw material utilisation, is necessary. Hence, the construction aggregates sector was studied given that large quantities of materials are utilised in this sector, and it is also one of the likely ones to increase SRM utilisation in Sweden due to increasing regional trends and policy initiatives. The overall objective of the study was to analyse the present Swedish construction aggregates market. This study led to the writing of the fifth article of the thesis.

3.1 Appended articles

Article I presents a study based on a systematic review of the previous fines literature. The objective of the study was to guide future research concerning the valorisation of shredder fines. In performing the review, the previous research concerning fines was systematically searched and selected. Internationally published literature during the last four decades was searched using keywords in the Scopus database. The abstracts of the resulting literature were read to screen those related to shredder fines. A maximum particle size of 20 mm was used to select the literature dealing precisely with fines. The selected literature was reviewed for what has been studied, in what ways, and to what extent. Subsequently, three research topics, material characteristics, process development, and policy and regulation, were identified. The topical research was assessed regarding its scope and applicability. The scope was identified with respect to the objectives and the breadth and depth of the studied aspects within the topic. The assessment of scope was performed by benchmarking against research on municipal bottom ash, a similar residue in terms of heterogeneity and particle size, yet with a more mature and established field of research compared to fines. The applicability was identified with respect to how specific aspects related to fines were studied within each research topic. The assessment of applicability was performed in relation to the specific situations and settings under which the generated results are valid. Thereby, knowledge gaps, as well as limitations in empirical and methodological approaches in previous studies, were identified and discussed.

The previous studies on fines are largely technically focused. That is, they have almost only involved material characterisation and process development. The material characterisation studies are largely confined to the assessment of a few out of many potentially recoverable resources and potential contaminants. Furthermore, these studies have often employed one or few randomly collected samples, which cannot show the variation of material composition. Additionally, the findings are confined to either one specific size fraction or a few fractions with large size ranges. The process development studies are often confined to the investigation of operating parameters, resource recovery efficiencies, and reutilisation grades. Other important process attributes, such as pre-treatment requirements, output characteristics, and economic feasibility, remain largely unaddressed. Furthermore, the developed

processes are mostly limited to lab-scale studies. Such isolated and limited-focus findings are inadequate to comprehensively establish the materiality of fines and develop upgrading and resource recovery processes. A couple of studies have performed top-down investigations on policy and regulation; nevertheless, they concern shredder residues in general. On the one hand, specific issues related to fines management remain unaddressed in these studies. On the other hand, the actor-level implications of various policy, market, and organisational aspects are yet to be investigated. In addition to the scope and applicability improvements within the topical research, a systems-oriented understanding of their interrelations is necessary to facilitate the potential valorisation of fines.

Article II presents a study based on a systematic approach to integrated process development for the full resource recovery of fines. The objective of the study was to guide process development for fines valorisation. The study was performed using a mixed method consisting of quantitative and qualitative approaches. Fines generated at a specific shredding plant in Sweden was strategically sampled according to Swedish standards and characterised with the objective of identifying potential applications for the recovery of fines based on the occurrence of potential resources and material constraints. Samples were collected twice a week to capture the weekly average. Six sub-samples, representing the primary sample (*primary fraction*) and five incremental size fractions (*sieved fractions*), were prepared and sent for analysis in an accredited laboratory in Sweden. The primary fraction was analysed to establish the average chemical and physical composition in fines as a whole, whereas the sieved fractions were analysed to establish the distribution of chemical and physical composition within the material. The intention of characterisation with respect to a range of particle sizes was that potential applications could be possibly identified with respect to different particle sizes of the material, and the subsequent development of valorisation processes could be based on that. The analysis consisted of 25 metals, and fuel properties. This procedure was continued over a period of 10 weeks to establish the over-time variation of composition.

Five potential reutilisation applications were selected based on the established material characteristics with the objective of addressing the full resource recovery of fines. Copper recovery in smelting and energy recovery in cement kilns and municipal waste incinerators were selected to address the recovery of specific resources. Copper recovery was selected given the significant occurrence of the material in most of the analysed fractions and its high market value. Energy recovery was selected given the significant heating value, especially in the larger sieved fractions. To address the avoided disposal of the material, bulk utilisation (to substitute primary aggregates such as sand and gravel) in ground constructions (such as filling, preparing foundation layers, and laying ballast) and landfill covering were selected. Subsequently, the established material characteristics were benchmarked against the gate and regulatory requirements pertaining to each application, which were obtained primarily through interviews with companies involved in such applications. The

benchmarking revealed the upgrading requirement and resource recovery potential of the different fractions in the different applications. Thus, the initial feasibility of fines valorisation was assessed. The feasibility assessment was further complemented with the recoverable share of fines in each application. Thus, it was shown that the integration of various upgrading and resource recovery processes is necessary for the full resource recovery of fines. The initial feasibility assessment is specific to fines generated at the involved shredding plant. Nevertheless, the developed methodological approach to process development is generally applicable.

Article III presents a study based on a systematic approach to the environmental assessment of fines valorisation. The objective of the study was to facilitate sustainable policy and regulation concerning fines valorisation. A streamlined life cycle assessment was performed on the three valorisation strategies of 1) maximising copper recovery, 2) maximising construction aggregates recovery, and 3) optimising full resource recovery, which were formulated based on the previously assessed resource potential of fines generated at the involved shredding plant (in Article II). The upgrading and resource recovery process schemes of the different strategies were designed with a panel of experts from the involved shredding company (that owns the involved shredding plant). Given that the objective is a preliminary environmental assessment of the design-stage processes and the identification of possible environmental hot spots of such processes, a streamlined LCA, but not a detailed and comprehensive approach, was opted for. Material flow analyses were performed to quantify the flows of fines-derived SRMs of each valorisation alternative regarding the different life cycles stages; fines processing, SRM recycling, waste disposal, and in-between transportation. Based on the material flows related to fines-derived SRMs, the elementary flows (i.e. material and energy requirements and emissions) of unit operations and the corresponding flows of substituted PRMs were calculated. The latter was calculated using substitution ratios for the different utilisation applications obtained from the literature. The impact categories climate change, ozone depletion, acidification, and resource depletion were used. Mid-point impact factors of the different life cycle stages were sourced from the EcoInvent database, Version 3, using the software SimaPro 9.

The net life cycle impact of each valorisation alternative was calculated by subtracting the life cycle impacts of the substituted PRMs from that of fines-derived SRMs. Thus, the environmental potential of each valorisation alternative was compared against that of the status quo (i.e. the current handling of fines). The calculation of the net environmental impacts of each valorisation alternative was disintegrated to show the environmental impacts of the different life cycle stages. Thus, environmental hot spots were identified. The assessed life cycle environmental impact is specific to the valorisation of fines generated at the involved shredding plant; nevertheless, the developed methodological approach is generally applicable.

Article IV presents a study based on the underlying factors of the current practice of fines management in Sweden. The objective of the study was to elicit challenges

of initiating fines valorisation. The shredding company perspective was focused on since it is the most central actor in the issue of fines management. The study was performed with a qualitative approach based on semi-structured, face-to-face interviews with selected employees from a specific shredding company in Sweden. Employees representing different functional areas of the company were selected to ensure all the operations of the company related to the generation and management of fines were addressed. The functional area of *corporate management* involves overall strategic decision-making. *Processing* involves the core business activity of shredding and post-shredder resource recovery, where fines is generated. *Regulatory affairs* involves issues related to waste policy and legislation and local authorities that govern and regulate the handling of fines. *Environmental permits* works together with local authorities regarding environmental assessments as part of the authorisation of handling fines. Finally, *sales* involves the investigation of SRM markets, and hence, the potential users of fines-derived SRMs. The interviews were transcribed and processed with tags in order to list various aspects of relevance to fines management. In the case of obscure or doubtful content, the author's interpretation of such content was verified with the respective respondents. Subsequently, themes that represent the implicit topics characterised by a group of tags were developed to identify the various policy, market, and organisational factors influencing the current practice of fines management. The factors of influence consisted of both incentives for the studied shredding company to utilise fines in landfill covering and disincentives to develop valorisation options. In this analysis, special emphasis was given to the interrelations between the different factors.

Challenges of facilitating change and initiating investments in knowledge and technology development for fines valorisation were elicited based on the analysis of the current practice of fines management. The means to address the challenges are discussed primarily by relating to literature concerning the valorisation of other similar heterogeneous industrial residues, such as municipal bottom ash, shredder residues, and construction and demolition residues. Thereby, recurring issues in residue valorisation in general and specific issues concerning shredder fines valorisation in Sweden were identified. The discussion was further facilitated with empirical information obtained from the regional and national waste legislation and the shredding company perspective of the necessary circumstances and settings for fines valorisation. The organisation-related findings of the study are specific to the involved shredding company. Nevertheless, the implications of policy and market factors are quite generalisable to the shredding industry in the Swedish context. Sweden's waste policies are largely based on the EU directives, and therefore policy-related findings are, to a reasonable extent, deemed generalisable in the regional context as well.

Article V presents a study based on the rationale of the construction aggregates market in Sweden. The objective of the study was to establish the market prospects of increased utilisation of secondary construction aggregates. The user perspective

was the focus since they are the most central actors in the aggregate supply chain. The study was performed with a qualitative approach based on semi-structured, face-to-face interviews with a selected group of aggregate users. The user group primarily consisted of three infrastructure constructors because infrastructure construction, that is, constructions such as roads and railways and public and industry areas, and the ground constructions (e.g. filling, preparing foundation layers, and laying ballast) are necessary for such constructions and buildings. The user groups also included one asphalt producer and one concrete producer as a significant amount of aggregates is also used in these applications. The user perspective was complemented with the customer (i.e. entities such as companies, organisations, and authorities that entrust the construction work to the infrastructure constructors and own the completed construction work) perspective on the aggregates utilisation because users' raw material choice for aggregates is presumably influenced by various aspects related to the customers' practices and requirements. The user perspective was also complemented with the supplier (i.e. companies that produce and sell construction aggregates) perspective on the secondary aggregates production, particularly because the users' material choice for aggregates is presumably influenced by various aspects related to the quality and availability of secondary alternatives. The interviews were transcribed and processed with tags in order to list various aspects of relevance to construction aggregate utilisation. In the case of obscure or doubtful content, the author's interpretation of such content was verified with the respective respondents. Subsequently, themes that represent the implicit topics characterised by a group of tags were developed to identify various market processes and the underlying institutions pertaining to the dominant utilisation of primary aggregates and the situational utilisation of secondary aggregates. In this analysis, special emphasis was given to the interrelations between the different supply chain actors (suppliers, users, and customers) and the processual and institutional aspects.

Challenges and possible measures towards increased utilisation of secondary construction aggregates were discussed based on the analysis of the market rationale. The discussion focuses on the utilisation of three main types of potential secondary aggregates, that is, the existing company and sector-internal residues and external industrial residues. The discussion was facilitated by referring to literature concerning aggregates markets and sustainable markets, as well as waste management literature in general and once concerning the utilisation of industrial residues as construction aggregates in particular.

Table 1: Overview of the Articles I-III of the thesis. The full papers are appended.

	Article I	Article II	Article III
Background	<ul style="list-style-type: none"> Incoherent knowledge about fines and its management deters common knowledge building. 	<ul style="list-style-type: none"> Harnessing the full resource recovery potential of fines has so far been overlooked. Market requirements of potential fines-derived secondary raw materials are largely unaddressed. 	<ul style="list-style-type: none"> Previous research concerning fines processing overlooks the full resource recovery of the residue. The environmental performance of fines valorisation remains unassessed.
Aim	<ul style="list-style-type: none"> Review and assess previous studies on shredder fines to guide future research on its valorisation. 	<ul style="list-style-type: none"> Guide future research on integrated process development for fines valorisation to achieve full resource recovery. 	<ul style="list-style-type: none"> Assess the environmental potential of alternative valorisation strategies to enable sustainable investments, policies, and regulations regarding fines valorisation.
Research questions	<ul style="list-style-type: none"> Which topics of fines management have been studied, in what ways, and to what extent? How have these research approaches influenced the breadth and depth of current knowledge? 	<ul style="list-style-type: none"> How can the resource potential of fines be identified via systematic sampling and characterisation? What are the market requirements and the material constraints of different reutilisation applications? How can the exploitation of the full resource potential in shredder fines be facilitated? 	<ul style="list-style-type: none"> What are the life cycle environmental potentials of fines valorisation alternatives targeting different levels of resource recovery? What are the environmental hot spots of such alternatives?
Method	<ul style="list-style-type: none"> Desktop search and selection of scientific articles based on pre-determined criteria. Establishing research topics, objectives, methodological approaches, and contributions. Assessment of scope and applicability of the topical findings to draw future research guidelines. 	<ul style="list-style-type: none"> Strategic sampling and material characterisation. Interviews to establish market (gate and regulatory) requirements of the potential applications. Benchmarking material characteristics against the market requirements for initial feasibility assessment. 	<ul style="list-style-type: none"> Formulation of valorisation alternatives based on the assessed resource potential (in Article II) and together with industry experts. Streamlined LCA in relation to the impact categories of climate change, ozone depletion, acidification, and resource depletion. Identification of environmental hot spots in relation to life cycle stages.
Findings / Results	<ul style="list-style-type: none"> Three topics: material characteristics, process development, and policy and regulation. Topical research is confined to investigating one out of many issues at a time. Research areas such as marketability of fines-derived resources and actor-level implications of policy are unaddressed. 	<ul style="list-style-type: none"> Distribution of over-time average variation of total metals, leaching metals, and fuel properties in and across five size fractions of fines. Different applications prefer different fractions and involved different material constraints. Valorisation targeting one single application would significantly overlook the full resource recovery potential. 	<ul style="list-style-type: none"> Alternatives 1 and 3 are preferable to Alternative 2 with respect to all the impact categories. Alternative 3 is preferable to Alternative 1 regarding climate impact, with a fairly small margin. Alternative 1 is preferable to Alternative 3 regarding ozone depletion, acidification, and resource depletion with fairly large margins.
Conclusions	<ul style="list-style-type: none"> Significant room for improvement exists concerning the scope and applicability of the findings within the studied topics. A systems-oriented approach is necessary to capture the interrelations between the research topics and other aspects. 	<ul style="list-style-type: none"> Fines valorisation should be initiated based on systematically created knowledge of material characteristics and market specifications. Integrated process development is necessary to harness the full resource recovery potential. 	<ul style="list-style-type: none"> Sustainable investments and policies regarding fines valorisation should be based on knowledge of environmental potential. Life cycle assessment is necessary to reveal the holistic environmental potential of valorisation alternatives.

Table 2: Overview of the Articles IV-V of the thesis. The full papers are appended.

	Article IV	Article V
Background	<ul style="list-style-type: none"> • Previous fines research is largely technically focused. • Knowledge of the influence on societal-level factors is necessary to realise fines valorisation. 	<ul style="list-style-type: none"> • The Swedish construction aggregates market is dominated by the systematic supply and utilisation of primary aggregates, whereas secondary aggregate representation is minimal. • Previous studies concerning markets for secondary aggregates are few and confined to selected structural aspects, whereas market processes are largely unaddressed.
Aim	<ul style="list-style-type: none"> • Analyse fines management by the involved shredding company to contribute knowledge to initiate investments in knowledge and technology development towards fines valorisation. 	<ul style="list-style-type: none"> • Analyse the rationale of the current Swedish construction aggregates market to better understand the challenges related to an increased utilisation of secondary aggregates.
Research questions	<ul style="list-style-type: none"> • What are the underlying policy, market, and organisational factors that sustain the current practice of shredder fines management in Sweden? 	<ul style="list-style-type: none"> • Why are primary construction aggregates currently utilised to the extent they are utilised? • In what situations are different secondary construction aggregates currently utilised?
Method	<ul style="list-style-type: none"> • Interviews to establish the shredding company perspective on different aspects that influence the fines management. • Thematic analysis of the policy, market, and organisational factors underlying the current practice of managing fines • Eliciting challenges of facilitating fines valorisation and a literature-based discussion of means to addressing them. 	<ul style="list-style-type: none"> • Interviews to establish the user perspective of different aspects that influence the processes of the construction aggregates market. • Thematic analysis of the market processes and the underlying institutions • Eliciting challenges and necessary measures towards increased utilisation of secondary construction aggregates.
Findings / Results	<ul style="list-style-type: none"> • Secure outlets, legislative recognition, and low costs create incentives to utilise fines in landfill covering. • Absence of established outlets, lack of clear regulatory and market playing rules, and lack of internally organising, and capacities to influence material flows create disincentives to valorise fines. 	<ul style="list-style-type: none"> • Dominant primary aggregate utilisation is characterised by user discretion in material choice, convenient and economical aggregate sourcing, and economical intra-corporate trading. • Situational secondary aggregate utilisation is characterised by user initiatives due to economic and administrative benefits, customer initiatives due to opportunities for enhanced environmental performance, and supplier initiatives due to economic benefits of avoided disposal.
Conclusions	<ul style="list-style-type: none"> • Drastic measures in governmental policy are necessary to challenge the current fines disposal. • Established market demand and clear regulatory and market playing rules are necessary to initiate actor investments for knowledge and technology development. • Governmental intervention is key to the overall realisation of fines valorisation. 	<ul style="list-style-type: none"> • Incorporation of governmental resource policies into industry standards and local authority regulation is to key high user acceptance • Recognition of the significance of resource conservation into sustainability policies by actors is essential to embed secondary aggregates into the supply chain. • Supply chain collaborations are essential for the streamlining of market processes regarding secondary aggregate utilisation

4 Theoretical approaches

This chapter presents the theoretical background pertaining to how the key concepts of the thesis, namely, circular economy, industrial ecology, and systems perspective, were approached.

4.1 Circular economy

The overall notion of this research is based on the concept of circular economy, which aims for the restored environmental balance of economic activity (Ghisellini et al., 2016) attained via innovation based on reduced material throughputs (Korhonen et al., 2018; Webster, 2013). This thesis fundamentally views circular economy as an ends to complement sustainable development, whereas the means to achieving it is not part of the concept itself but a decision up to its practitioners. According to the Ellen MacArthur Foundation's (2019) interpretation of circular economy being "on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems" manifests that the realisation of the concept necessitates focusing on the entire life cycle of materials.

Research in the context of circular economy could stem from different theoretical perspectives, depending on which life cycle stage of the raw materials is involved. The *cleaner production* approach (Hens et al., 2018) focuses on pollution prevention using end-of-pipe environmental technologies, which are typically undertaken in the mining (Hilson, 2000) and production phases (Sousa-Zomer et al., 2018). The *regenerative design* approach (Lyle, 1994), on the other hand, focuses on resource conservation via proactive design measures. One divaricate of this approach is the avoided primary raw material production via design-phase strategies such as *design for recycling* (Kriwet et al., 1995) and production-phase strategies such as *design from recycling* (Lore et al., 2017). Another main divaricate of the *regenerative design* approach is dematerialisation, which involves strategies such as *design for dematerialisation* (Skillington and Crawford, 2020) in the production and use phases. The *performance economy* approach (Stahel, 2016) focuses on the reduction of environmental impact via servitisation strategies such as *repair*, *remanufacturing* in the production and use phases (Gelbmann and Hammerl, 2015; Sundin and Bras, 2005), and *product sharing*, particularly in the use phase (Stahel, 2016). The *industrial ecology* approach (Frosch and Gallopoulos, 1989) focuses on resource conservation attained via industries utilising each other's residues. It is commonly undertaken in the production phase, such as in industrial symbiosis (Chertow, 2000), where production residues are reutilised as raw material in other industries, as well as in the end-of-life phase, such as in landfill mining (Baas et al., 2010), where disposed residues (wastes) are dug out, reprocessed, and used as raw material in other industries. The approach to circular economy of this research falls within the domain of *industrial ecology*. That is mainly because the focus is on the upgrading and resource recovery of end-of-life-phase materials (fines), which are bound for disposal, for the subsequent utilisation by other industries as raw materials.

4.2 Industrial ecology

The concept of industrial ecology refers to a network of industrial activity that mimics the interdependencies and linkages in natural ecosystems (Erkman, 1997) by utilising each other's residues as resources in production. Thus, it represents a transformation from the traditional isolated industry approach of raw material input, production, and waste disposal to a more integrated and resilient industrial ecosystem. Today, industrial ecology is broadly conceptualised and applied to all the life cycle stages in relation to improving material and energy efficiencies. This thesis approaches the concept from the perspective of closing material loops at the end of product life.

As far as addressing the closing of material loops in an industrial ecology context, two main approaches, the *geographical approach* and the *product-based approach* (Korhonen, 2002), could be identified. The former approach refers to the development and organisation of the practice of exchanging material and energy residue flows between companies, typically within close geographical proximity, and thus involves disciplines such as eco-industrial parks (Lowe, 1997) and industrial symbiosis (Ehrenfeld and Gertler, 1997). The latter approach refers to the metabolism of materials in industrial processes and the development and implementation of strategies for the management of specific material (and energy) residue flows to increase resource efficiency and reduce environmental impact (Saavedra et al., 2018), largely based on technological innovation. The domain of this research is the *product-based approach*, given that it focuses on a particular residual flow (fines) and facilitating the development of proven technological processes for its valorisation.

Historically, industrial ecology research is dominantly characterised by studies focused on the materials and processes (Erkman, 1997) aiming to facilitate technical innovation. However, in its broader sense, the concept has also evolved to address the societal context (Saavedra et al., 2018; Seuring, 2004a), within which such innovation should take place and be implemented. Yet, industrial ecology research on this societal dimension, or more specifically, how actors and institutions influence technical innovations (Boons and Howard-Grenville, 2009) such as residue valorisation, is still rather uncommon. This thesis is based on the notion that the realisation of fines valorisation needs to be facilitated by addressing both the aforementioned technical and societal dimensions of industrial ecology. The gaining of such an understanding, which involves addressing multiple aspects related to institutions, actors, materials, and processes and their interactions, calls for an interdisciplinary systems perspective.

However, in realising industrial ecology, it also recognises the idea of first understanding the occurrence of a given problem and interactions with the natural environment of dealing with it - two knowledge areas - in order to determine restructuring possibilities (Graedel and Allenby, 1995) and make it more

environmentally sustainable. The two knowledge areas deal with two inherently different issues of the same problem, which are equally relevant to enable and drive change towards fines valorisation. Addressing such principally different knowledge areas in parallel could provide more value rather than integrating them (Wallsten, 2015) in terms of specific knowledge to facilitate fines valorisation. In-depth knowledge on the present situation concerning fines management is key to initiate changed practices, while knowledge on the environmental implications of fines valorisation is required to initiate process development.

4.3 Systems perspective

A systems perspective is simply viewing a given object or a situation in terms of a set of components and their interrelations occurring within a certain boundary (Meadows, 2008). Undertaking a systems perspective provides a mode for holistic contextualisation and analysis of an often complex real-world problem situation (Olsson and Sjöstedt, 2005). Systems perspectives have been previously employed for the analytical work in various sustainability-oriented research contexts, such as the environmental impact of eco-industrial developments (Feiz, 2016) and the resource efficiency impacts of servitisation (Wasserbaur, 2020). In the context of this thesis, two principally different systems perspectives are deemed necessary to address its two knowledge areas. First, a socio-technical systems perspective enables addressing Knowledge Area 1: portraying the current picture concerning fines management, which refers to understanding the occurrence of the problem situation. Second, an environmental engineering perspective enables addressing the Knowledge Area 2: showcasing a potential approach for fines valorisation, which refers to understanding the environmental interactions of dealing with the problem. A key limitation in employing interdisciplinary (i.e. involving multiple aspects on different societal and technical levels and their interactions) systems-oriented approaches in research like this, which focuses on change towards fines valorisation, is that it only allows a certain depth of investigation and may lack detailed knowledge on the individual disciplines involved (Olsson and Sjöstedt, 2005) that are necessary for the actual development and implementation of fines valorisation, which nevertheless, are beyond the scope of this thesis.

4.3.1 Socio-technical systems perspective

According to Churchman (1968), understanding the occurrence of a given problem situation could be based on knowledge of the different system constituents. However, a comprehensive systems-oriented understanding that enables the explanation of the occurrence of a particular situation should see a system not only in relation to its individual constituents but also their interrelations (Sundberg et al., 1994). A socio-technical system (STS) perspective facilitates the analysis of a technically relevant societal issue, such as fines management, in relation to a dynamic network of different actors and institutions and the various flows (e.g. material, knowledge, information, and money) between them (Geels, 2004; Markard et al.,

2012). Thus, it would enable the identification of the influence of multiple factors due to various institutional and actor-related aspects and their interrelations on initiating change towards technical solutions (Hughes, 1987) such as fines valorisation.

A major potential drawback of employing an STS approach is that the system could include too many system constituents and their interactions could get too complicated, making it overwhelming to deal with. Therefore, system boundaries must be drawn to exclude the aspects that are too peripheral to influence the focus of the study.

Institutions could be seen as the playing rules that govern actor behaviour in a given context (Giddens, 1984). According to North (1990), such institutions could be both formal and informal. Formal institutions constitute written conditions such as policies, legislation, regulations, and agreements that govern actor behaviour by holding them legally responsible and accountable for their actions. Informal institutions constitute norms and habits that shape the practice of doing things. Given this thesis' focus on initiating changed practices towards fines valorisation, formal institutions are presumably the most relevant. For instance, according to Payne (1973), governmental policy and regulation, together with markets, are the most important factors in making prospective resources into proven resources. While having favourable institutional conditions is fundamental to the success of every industry (Wrigley, 1962), specific policy interventions could be particularly beneficial for potential new developments. In particular, cases such as potential fines valorisation do not have apparent direct market advantages for the participating individual actors due to the inferior material quality and low user demand, but only for society due to any environmental benefits (Johansson, 2016). Hence, governmental interventions are likely necessary to drive investments towards knowledge and technology development for upgrading and resource recovery as well as the utilisation of fines-derived SRMs. Given the aforementioned significance of the actors towards fines valorisation, this thesis focuses on the actor perspective when it comes to the influence of institutional factors. The undertaking of such bottom-up approaches usually characterises industrial ecology research that has close relationships with the industry (Graedel and Allenby, 1995), such as the one presented in this thesis.

Given that the objective of Knowledge Area 1 is to contribute knowledge for initiating changed practices, the employed STS approach of this thesis focuses on the actor perspective concerning the current situation regarding fines management. Such actor focus is chiefly grounded in the theory of integrated chain management, which refers to the significance of key actors (together with other stakeholders) actively taking part in improving the environmental sustainability of the supply chain (Held, 1994; Seuring, 2004b). When it comes to the potential valorisation of a currently disposed of residue such as fines, which involves significantly changing the current supply chains of different raw materials, a strong focus on the potential suppliers and

users of the residue-derived SRMs is necessary as they play a central role in initiating the valorisation of the residue. The significance of the actor focus is particularly emphasised concerning the realisation of industrial ecology practices (Saavedra et al., 2018) because it is not merely a means to do things more sustainably but also a cultural phenomenon (Boons and Roome, 2000).

When it comes to the utilisation of fines-derived SRMs, the potential users, that is, the companies that utilise raw materials in different production and construction-related applications, must be willing to accept such materials and substitute their currently-utilised primary raw materials (PRMs). The user acceptance of fines-derived SRMs would strongly depend on the competitiveness of such materials in the marketplace. Increasing competitiveness and enabling and driving industrial actors to utilise fines-derived SRMs would thus necessitate knowledge on the key characteristics of the existing aggregates market. In that regard, market organisation, which refers to the actions, interactions, and exchanges between actors (Ahrne et al., 2014), market rationality, which refers to strategic value orientations of actors (Biggart and Delbridge, 2004), and market development, which refers to the level of cohesion between market structures and processes (Aspers, 2009), are crucial. As far the potential supply of fines-derived SRMs is concerned, it will have to be initiated via shredding companies because they own the material and have the responsibility of managing it. The external conditions related to formal institutions and raw material markets would influence the shredding companies on investing in knowledge and technology development towards valorising fines.

The organisations actors represent are equally important to look at in understanding the actor perspective. Shredding companies and raw material users are profit-seeking organisations whose responses are not entirely determined by institutional and market conditions. They interpret the socio-technical environment and design their actions and networks (Schneidewind, 2003) based on strategic choice (Child, 1997) and other organisational factors related to structure and culture (Rogers, 1983). Additionally, a focus on the socio-materiality aspect of the materials that different actors' operations involve, which is typically lacking in traditional STS approaches (Johansson, 2013), is particularly important because the knowledge of residue owners and potential SRM users on the material, and their perception of the materiality of such materials, could largely influence how they choose to deal with it.

4.3.2 Environmental engineering perspective

Traditionally, environmental engineering approaches have been employed to develop holistic technological solutions to a given environmental problem situation, such as pollution due to emissions from an industrial plant (Reible, 2010). There, measures such as end-of-pipe treatment of air, water, and solid emissions prior to their release to the environment (Reible, 2010), which typically associates concepts such as cleaner production (Nilson et al., 2007), have been addressed. In this thesis, the environmental engineering concept is used in association with closing industrial

material loops via addressing holistic approaches to the development of technological processes for upgrading and resource recovery of industrial residues.

One of the main problems concerning previous fines research in addressing the technical aspects related to the potential valorisation of the residue is that only selected aspects of material characteristics have been studied. This limits our knowledge of resource potential and our ability to develop processes for the full resource recovery of fines. Another main problem is that the environmental performance of fines valorisation is left unaddressed. As the environmental performance of new technologies is largely determined at the early stages of their development (Villares et al., 2017), the lack of such knowledge impedes sustainable investment decisions and government policy and regulation concerning fines valorisation. In addressing the former, a traditional material-based approach, that is, one that employs tools such as material characterisation and material balance for holistically understanding and solving environmental problems (Davis and Cornwell, 2008), is undertaken. In addressing the latter, an environmental systems analysis approach, that is, one that views and assesses the occurrence of an environmental problem in relation to a system of related activities (Feiz, 2016), is carried out.

Material-based process development

The development of valorisation processes for full recovery requires a thorough understanding of the resource potential of fines. The resource potential can be defined as the likeliness of making a specific material available to fulfil a particular utility (Taylor and Steven, 1983). Traditionally, for primary reserves, this likeliness has been assessed in terms of the material composition, the technical feasibility, and economic prospects of extracting and refining the raw material to deliver marketable outputs (Falkie and McKelvey, 1976). The assessment of the resource potential of secondary resources needs a similar type of information (UNECE, 2018). Therefore, knowledge concerning the technical feasibility of retrieving resources as well as their marketability is needed. However, such a full-fledged exploration is beyond the scope of this research, whereas the objective has been to perform an early phase prospection of the occurrence of potentially recoverable resources, and the initial feasibility of utilising the material in potential reutilisation applications.

In certain studies, the assessment of the resource potential of residues has been limited to the occurrence of a specific resource type such as metals (Jung and Osako, 2009). Certain studies have also included the occurrence of contaminants/undesirables like heavy metals (Allegrini et al., 2014). However, such assessments are limited to the occurrence of one or a few of many potential resources and contaminants/undesirables in residues. Conversely, establishing a range of potential resources and material constraints enables the identification of multiple recovery possibilities. It increases the chances of the full resource recovery of the material. Various other characteristics, such as the level of speciation and mechanical properties, have also been studied regarding the materiality in relation to other

residues such as municipal bottom ash (Dou et al., 2017; Le et al., 2017). However, such detailed material properties are understandably more important when it comes to actual process development, which is not part of this research and hence omitted.

The handling of the heterogeneity of the material can exert significant influence on the identification of reutilisation options and the subsequent process development for upgrading and resource recovery. Therefore, given the significant over-time variations of the material input to the shredder, this research recognises that knowledge on the level of variation of the composition of fines provides better information (Allegrini et al., 2014; European Commission, 2004) in terms of both materiality and subsequent processing requirement.

The materiality of fines alone is not sufficient to assess the resource potential. The technical feasibility and marketability of potential fines-derived SRMs need to be assessed too. The technical feasibility is determined by the availability of technological know-how, the maturity and scale of technology development, and so on (Mankins, 1995). The marketability would be determined by various structural and processual aspects of different raw material markets. Given that, the actual valorisation of fines is not part of the research work of this thesis, and neither a full technical feasibility assessment nor a marketability assessment is performed. Instead, an assessment of the initial feasibility of the potential valorisation of fines in terms of the gate and regulatory requirements pertaining to potential reutilisation applications that could indicate the necessary levels of upgrading and resource recovery in process development is deemed sufficient at this early stage of fines valorisation. A similar view on the resource potential, that is, based on materiality and an initial indication on the technical feasibility, has been employed in previous research concerning secondary residues (Iacovidou et al., 2017; Johansson, 2013).

Environmental systems analysis

The concept of environmental systems analysis (ESA) refers to a systematic and systems-oriented assessment and analysis of the interactions between anthropogenic objects and the natural environment. ESA enables the decision-making in societal processes, such as capital investments, policy making, and regulation, more sustainable (Moberg, 2006; Neto et al., 2008) by allowing us to assess the environmental impacts of activities and objects via viewing them as systems. There are various ESA tools (Finnveden and Moberg, 2005; Ness et al., 2007) that could be chiefly categorised into procedural and analytical tools. Procedural tools such as environmental impact assessment (EIA) and strategic environmental analysis (SEA) typically concern qualitative assessments of policies, projects, and programs. Analytical tools such as material flow analysis (MFA) and life cycle assessment (LCA) involve the modelling and quantitative assessment of different aspects of physical objects such as products, industrial processes, and infrastructure as well as political objects such as nations and regions. Detailed technical assessments performed via analytical tools could also be used to complement the more generic assessments

performed via procedural tools (Moberg, 2006). Given the focus on the environmental assessment of potential fines valorisation processes, this thesis concerns the LCA.

LCA involves a quantitative and holistic assessment of the environmental impact, that is, the local and global impacts of resource use and emissions in relation to multiple impact categories (Baumann and Tillman, 2004) over the entire life cycle of different objects. LCA is arguably the most comprehensive environmental systems analysis tool available today, and its use could contribute to potential residue valorisation in several ways. The extended focus beyond the immediate object into the other life cycle phases and the incorporation of multiple environmental impact categories enable the overcoming of possible methodological challenges such as problem shifting due to limited scope (Finnveden, 2000). It also allows comparative assessments between several alternative solutions and gaining knowledge about potential areas for improvements (Moberg, 2006). LCAs could be used to perform initial, often streamlined (Todd and Curran, 1999), environmental assessments of prospective technologies in order to select the most promising ones for actual development (Arvidsson et al., 2018) and to identify needs for further improvements, for example, environmental hot spots (Joyce et al., 2018), which is the focus of this thesis.

There are also several challenges associated with performing an accurate LCA. One of them is the choice of environmental impacts. For instance, mid-point indicators (close to the environmental intervention) would make the modelling less uncertain but also less environmentally relevant, and end-point indicators (close to the impact) vice versa. A common argument against LCAs is that they are based on single observations as the model is run with a certain set of data, which makes it unqualified to make universal statements (Finnveden, 2000). Therefore, possible uncertainties of an LCA need to be addressed to provide a broader picture. Previous studies have specified model, scenario, and parameter uncertainties involved in LCAs (Finnveden et al., 2009; Huijbregts, 1998; Lloyd and Ries, 2007), which are expected to be particularly high when new technologies such as potential fines valorisation are involved (van der Giesen et al., 2020; Villares et al., 2017). For instance, model uncertainties could arise as the characterisation factors relevant for the incumbent and new technical systems could change over time. Scenario uncertainties could occur due to changes in the applicable background system conditions such as the origin of PRM production and the level of technological development by the time the valorisation is operational. Parameter uncertainties refer to variations in aspects such as material compositions and efficiencies and resource requirements of processes. While the difficulty of addressing the two former uncertainty types due to practical reasons is understood, parameter uncertainty remains commonly addressed in research (Feiz, 2016). A plausible means to address parameter uncertainty would be to run the model with possible input data variations using, for instance, a Monte-Carlo simulation (Heijungs and Huijbregts, 2004).

5 Methodology

This chapter presents the methodological approach of the thesis in relation to the two knowledge areas and the research questions, the study objects and research methods in the articles, the employed systems perspectives to synthesise the article findings, the synthesis of the article findings to address the research questions, and the discussion.

The compilation of the thesis involved putting the aforementioned articles together, aiming to provide new and synthesised knowledge to facilitate fines valorisation (Figure 1). The different study objectives of the articles led to the devising of the two separate knowledge areas representing two separate issues related to fines valorisation and their research questions in catering to the aim. Knowledge Area 1 is based on the idea of investigating the occurrence of the problem situation concerning fines management, and Knowledge Area 2 on investigating how it could be technologically addressed. Given that the different articles address different issues related to multiple aspects occurring on different societal and technical levels, systems-oriented approaches were necessary for their synthesis in addressing the research questions, and hence, the knowledge areas.

The research questions of the two knowledge areas are addressed by synthesising the empirical contributions of the appended Articles II-V in different ways. In Knowledge Area 1, Articles IV and V provide findings from qualitative analyses of actor perspectives concerning institution and actor-related aspects that concern the initiating of changed practices. In Knowledge Area 2, Articles II and III contribute with findings from quantitative analyses of technical aspects that concern the process development for fines valorisation. The empirical contributions of Article I provided the foundation for the two systems approaches and influenced the design and focus of the other articles. The contributions of Articles II-V are based on specific cases, that is, a specific shredding plant in Articles II and III, a specific shredding company in Article IV, and a specific construction sector in Article V. Such a case-based approach was employed as it enables in-depth and multifaceted knowledge development regarding a given issue and allows for the examination and interpretation of data in the context of their use (Feagin et al., 1991).

Finally, the key contributions of the thesis towards providing knowledge for facilitating fines valorisation were discussed in relation to previous research concerning fines and similar heterogeneous residues. A synthesising discussion was also performed on the implications of the thesis contributions in realising fines valorisation.

Figure 1: The analytical approach of the thesis.

5.1 Knowledge areas

Knowledge Area 1 portrays the current situation concerning fines management. There, the underlying factors of the present management of fines (refers to RQ1) were investigated to identify challenges and necessary measures for initiating investments in knowledge and technology development by shredding companies towards valorising fines. To complement this, the rationale of the construction aggregates market (refers to RQ2) was investigated to identify challenges and necessary measures to initiate increased utilisation of secondary aggregates in the construction sector, which has a high potential for fines-derived SRMs. A socio-technical system focusing on the actor perspective was used to contextualise and explain the occurrence of the technically relevant issues of fines management (disposal, potential valorisation, and potential reutilisation) as consequences of societal context such issues occur. This knowledge area is particularly important in identifying the challenges of and necessary measures for initiating changed practices.

Knowledge Area 2 showcases a potential approach to process development for fines valorisation. There, the resource potential of fines (refers to RQ3) was assessed to enable the development of integrated processes for upgrading and resource recovery. Since there were many methodological gaps in previous fines research, a systematic methodological approach for assessing the resource potential was developed. The environmental impact of fines valorisation (refers to RQ4) was assessed to provide guidance for sustainable investment decisions and policy and regulation. In facilitating this assessment, three alternative valorisation process schemes were formulated based on the assessed resource potential, particularly because integrated upgrading and resource recovery processes for fines valorisation are absent in previous research.

An environmental engineering perspective was used to facilitate dealing with the technical aspects of materiality and processes. There, a traditional material-based approach was used to systematically and comprehensively assess the resource potential of fines and formulate alternative valorisation process schemes targeting different resource recovery strategies. An environmental systems analysis approach was used to systematically and comprehensively assess the environmental impact of valorisation alternatives. This knowledge area is particularly important in identifying the specific challenges and targeted measures for facilitating the development of specific valorisation strategies.

5.2 Study objects

RQ1 refers to knowledge of the underlying factors of the current disposal-oriented practice of fines management, which is fundamental in initiating changed practices towards knowledge and technology development for valorising the residue. In addressing this research question, the shredding company perspective was focused on because they (shredding companies) are the most central actors in the issue. The studied company was selected for several reasons: It is a large-scale company that operates in many parts of the country and owns multiple shredding plants and landfills. Having been involved in advanced post-shredder resource recovery, it also already supplies secondary raw materials to several markets. The large-scale operations and involvement with various local authorities and raw material markets mean that possible variations in policy and market conditions related to the management of fines can be covered. Additionally, given its involvement in shredding operations for about four decades, the company was presumed to have vast knowledge and experience about the material and its handling.

RQ2 refers to the rationale of the construction aggregates market in Sweden, which is fundamental in initiating changed practices towards the utilisation of fines-derived construction aggregates. In addressing this research question, the perspective of construction aggregate users was the focus because they are the most central actors in aggregates utilisation in various construction-related applications. Companies with large-scale and wide-spanned operations were selected, as they would have a vast amount of experience and knowledge and cover the possible variance regarding different market aspects. The user perspective was complemented with the customer (i.e. entities such as companies, organisations, and authorities that own the completed construction work) and supplier (i.e. companies that produce and sell construction aggregates) perspectives. The customer perspective was involved because users' raw material choice for aggregates is presumably influenced by various aspects related to the customers' practices and requirements. The supplier perspective was involved particularly because the users' material choice for aggregates is presumably influenced by various aspects related to the quality and availability of secondary alternatives.

RQ3 and RQ4 refer to knowledge concerning the assessment of the resource potential of fines and the environmental potential of fines valorisation alternatives that are formulated based on the assessed resource potential. In addressing these research questions, fines generated at a major shredding plant, which belongs to the involved shredding company (in RQ1), was used. A specific plant was selected because the composition of fines is highly plant specific (i.e. it depends on the input materials and the involved shredding and post-shredder resource recovery processes). That means the resource potential of fines and the required processes for fines valorisation would also be plant specific.

5.3 Research methods

The scientific articles of this thesis have employed different methods. Article I has employed a systematic bibliometric analysis. Articles IV and V, which have been primarily used in Knowledge Area 1, are based on qualitative methods whereas Articles II and III, which have been primarily used in Knowledge Area 2, are based on quantitative methods. All the methods employed in the articles of this thesis are recognised methods in the respective fields, which increases the credibility of the research (Shenton, 2004).

5.3.1 Qualitative methods

A qualitative approach was preferred, for instance, over a quantitative one, in Articles IV and V mainly because the research questions are oriented towards the societal level, and the qualitative approach could better refer to meanings, descriptions, and characteristics (Bell et al., 2019), which enable effective capturing of the targeted actor perspective. Face-to-face interviews were deemed appropriate to capture the idiosyncrasies and complex perceptions associated with the issue in question (Miles and Huberman, 1994) and expressions and body language necessary to interpret the data accurately. Semi-structured interviews were opted for, for instance, over fully-structured interviews, as they allow for flexibility and create more opportunities for uninfluenced responses (Bell et al., 2019). Thus, the employed method could enable the capturing of how different actors perceive the issues in question and act in relation to it, which are necessary to elicit challenges and possible measures to initiate change (Seuring, 2004b). A thematic analysis approach was used to analyse the interview data in accordance with the process of data reduction, data display, and drawing conclusions (ibid.). A thematic analysis could facilitate the aggregation of qualitative data scattered throughout the interviews and thereby identify factors underlying the issue in question. In order to improve the credibility of the analysis, that is, to make the findings more congruent with reality (Merriam, 1994), the interpretation of certain ambiguous responses were confirmed with the interview respondents, and the interview findings were complemented with findings from the study of relevant documents such as companies' sustainability reports, external consultant reports, and legislation. An inherent and unavoidable problem regarding reproducibility in qualitative research is the constant change of research subjects (Fidel, 1993). In an attempt to partially address it, the data collection and analytical procedures are thoroughly described (Bassey, 1981; Firestone, 1993) in Articles II and III.

The main possible generalisability-related limitation of Article IV is that the findings are based on the case of an individual shredding company and the perspectives of the other shredding companies operating in Sweden are not captured regarding the factors influencing their approaches to managing fines. Nevertheless, given that currently there are only three main shredding companies operating in Sweden and that the studied company accounts for a substantially higher share of the shredding

industry than the others and is operational throughout the country, it was deemed the best case to represent the Swedish context. One of the possible generalisability-related limitations of Article V is that the findings are based on users representing selected applications of aggregate utilisation. For instance, applications such as cement mortar and potty production are not represented. In such applications that are auxiliary to the mainstream construction works such as infrastructure and buildings, the extent of the utilisation of different primary and secondary aggregates may be determined by different market processes initiated by different actors due to different motives. Nevertheless, the selected applications account for approximately 85 percent of the country's aggregates utilisation, and hence, studying the user perspective of such applications would provide a reasonable explanation of the rationale of the Swedish aggregates market. Other possible limitations could occur due to the selection of customers and suppliers to complement the user perspective. For instance, only one customer, also state-owned (Swedish Transport Administration), was selected, whereas there are multiple municipal and private customers. Similarly, only one supplier, which operates on a large scale and is a subsidiary of one of the involved construction corporates, was selected, despite plenty of independent and often medium to small-scale suppliers. These other customers and suppliers omitted from the study are plausibly characterised by different internal policies and practices to those of the selected large-scale counterparts and thus may have different levels of influence on the aggregates utilisation by users than the selected ones.

5.3.2 Quantitative methods

Quantitative approaches consisting of numerical analyses were preferred, for instance, over qualitative ones in Articles II and III, which are inclined towards the technical level of the fines management issue and target the assessment of resource potential and environmental impacts because they can generate concrete and physically measurable results. In Article II, to assess the resource potential, shredder fines were systematically sampled and comprehensively characterised regarding the distribution of average as well as over-time variation of a range of chemical and physical properties across incremental size fractions of the material. Assessing the occurrence of a range of chemical and physical properties would allow the identification of multiple potentially recoverable resources and the applicable material constraints. The over-time variation, in addition to facilitating the resource potential assessment, would provide an important parameter for the designing of upgrading and resource recovery processes. In Article III, a streamlined life cycle assessment focused on global environmental impacts of selected fines valorisation alternatives was assessed. An assessment of the environmental impacts occurring throughout the entire life cycles of fines-derived SRMs and substituted PRMs would provide more holistic information for decision-makers. A streamlined LCA approach (Todd and Curran, 1999) was undertaken, given that the objective is the preliminary environmental assessment of the design-stage processes. Streamlined LCAs are

commonly used for assessing the environmental impacts of secondary resources against their primary counterparts (Woolridge et al., 2006) and comparing residue valorisation alternatives for decision support (Curry et al., 2011). The focus on global impacts would provide knowledge for a more balanced environmental assessment of fines valorisation by local authorities, which is currently focused on the local impacts. Three alternative valorisation process schemes were formulated to represent principally different resource recovery strategies based on the assessed resource potential in Article II.

The main generalisability-related issue in both articles is that the findings are confined to fines generated at the involved shredding plant. This limitation, however, is unavoidable because the material characteristics of fines are quite plant specific due to the differences in input material qualities and the employed shredding and post-shredder resource recovery processes in different plants. Consequently, the resource potential becomes plant specific. That also means fines generated at different plants would require tailored processes for upgrading and resource recovery, and hence, the environmental impact of potential fines valorisation would also become plant specific. Nevertheless, the developed methodological approach for assessing the resource potential of fines and formulating upgrading and resource recovery routes remain generally applicable irrespective of the geographical context.

5.4 Systems approaches

5.4.1 The employed socio-technical systems approaches

In addressing the first research question, the current disposal-oriented practice of fines management by shredding companies is viewed as a consequence of both incentives for continued utilisation as landfill cover material (LCM) and disincentives for adopting valorisation options. Such motives (incentives and disincentives) are understood as being influenced by external factors due to governmental policy and raw material (RM) markets as well as company-internal factors due to LCM markets, organisational aspects, and fines' materiality (Figure 2). Therefore, one of the units of analysis in the employed STS approach is the fines management by the studied shredding company. Other possible operations of the shredding company that do not concern fines management are thus not studied. The focus is particularly on the shredding company because it owns the responsibility for the material and its management. Any changes to this practice, such as the development of resource recovery processes and reutilisation applications, would presumably have to be initiated by this actor.

Figure 2: Employed socio-technical systems view of fines management. The thick arrows represent the internal and external factors influencing the shredding company's incentives for fines management. The thin continuous arrow represents the current utilisation of fines as landfill cover material, whereas the thin dashed arrows represent the potential valorisation of fines.

One of the main factors that externally influence fines management by the shredding company is governmental policy and regulation. Regional policies, such as the EU waste framework directive (European Commission, 2008), define terms such as recovery and recycling that are generally applicable to residues, whereas the end-of-life vehicles directive (ELV directive) imposes recovery and recycling targets for ELVs (European Commission, 2000) that specifically concern shredder fines. In conjunction with the regional policies, Sweden has introduced administrative, legislative instruments, such as the landfill ban on organic-rich waste (Sveriges Riksdag, 2001) and landfill tax (Sveriges Riksdag, 1999). Previous fines research concerning governmental policy (Dubois et al., 2015; Nayak and Apelian, 2014) is confined to a top-down perspective. However, when it comes to dealing with fines in practice, it is important to understand how the actors interpret and react to different policy stimuli. The regulation of fines management in Sweden, similar to other residues, takes place via guiding values developed by the national Environmental Protection Agency (EPA), which are exercised on the municipal level (Swedish EPA, 2010b). The addressing of regulatory aspects in previous fines research is limited to the identification of regulatory requirements on material quality for certain ground construction applications (Allen and Fisher, 2007; Johansson et al., 2017). Given the aforementioned Swedish context, it is important to investigate the specificity of regulatory requirements and local authority practices in regulating waste reutilisation applications, which indicate the extent to which the potential fines recovery is facilitated in the country. The other main factor that externally influences fines management by the shredding company is raw material markets. Previous fines research concerning raw material markets is confined to the investigation of user requirements and regulatory standards on a few potential fines-derived SRMs (Allen and Fisher, 2007; Johansson et al., 2017). However, these markets are understandably more characterised by the supply, demand, and competition related to secondary as

well as primary raw materials. Despite the significance of investigating these aspects of a market as such (Porter, 1985), what is more interesting, given the early stage of fines valorisation, is how such aspects create motives for shredding companies to process fines and produce fines-derived SRMs. Certain governmental policy instruments, for instance, once targeting induced SRM demand, could also influence the raw material markets.

The shredding company, which remains entirely unaddressed in previous fines research (Gunaratne et al., 2020), is important to address regarding two main types of aspects for their influence on fines management. One is the company-internal organisational aspects. In that regard, strategic management is relevant as it makes decisions concerning the long-term approaches to managing the residue. As much as it is of own choice, the strategic management is understandably influenced by the external policy, regulation, and market-related circumstances and settings. Another relevant organisational aspect is the operational management of fines, which is addressed in relation to the company's capacities to influence material flows and the extent to which the company is organised for handling the material. These operational management aspects, which are understandably influenced by the choices made by the strategic management, are particularly relevant for the potential valorisation of the fines. Developing valorisation processes necessitates capacities such as knowledge and technological know-how and financial and human resources. Implementing valorisation, which implies adopting changed practices, necessitates structural reorganisation measures (Rogers, 1983) such as setting priorities and defining responsibilities. Change management, in turn, implies issues related to internal communication and coordination (ibid), especially in large organisations that have been in operation for a long time, presumably involving a scattered departmental structure (Luthans, 2011). The materiality of fines is a key aspect that is strongly related to the operational management of fines. The shredding company's knowledge on fines' materiality could largely influence its perception of fines and how it chooses to deal with it. The other main type of aspects regarding the shredding company that needs to be addressed is the internal markets for landfill construction materials (LCMs), which is the current outlet for fines. The LCM markets are considered a company-internal affair primarily because the shredding company's own landfills, and occasionally, third-party landfills that are operationally within their control, are used for the purpose of utilising fines in landfill covering. The LCM markets are particularly susceptible to governmental waste policies' fostering of landfilling.

In addressing the second research question, the utilisation of construction aggregates by users, that is, the companies that utilise aggregates in various construction-related applications, is viewed as a consequence motives created at the main market processes related to aggregates utilisation, namely, procurement of construction projects and sourcing of construction aggregates (Figure 3). Such processes, in turn, are understood to be supported by different institutions. Previous fines research

lacks any sort of market analysis (Gunaratne et al., 2020). The focus is particularly on the users because the utilisation of fines-derived construction aggregates has to be initiated through them.

Figure 3: Employed socio-technical systems view on the construction aggregates market. Aggregates utilisation is influenced at two main market processes of a construction project supported by Institutions occurring internally within as well as externally to the construction sector (thick arrows). The thin black arrows represent both existing (continuous) and potential (dashed) supply of supply of construction aggregates internally within and externally to the construction sector.

The different market processes would involve different supply chain actors playing different roles. For instance, the raw material choice for aggregates is presumably influenced by various aspects related to the customers’ practices and requirements, and the supplier selection is influenced by factors such as the availability and quality of raw materials and transportation requirements. Purchasing chiefly involves negotiations on the terms of the contract, such as prices, quantities, delivery, and duration of the trade. Institutions could occur on the governmental level in terms of policy and regulation, which particularly concern the handling of wastes and using secondary raw materials. Institutions could also occur on the sector level, such as application standards and contractual agreements between actors that largely determine the feasibility of the utilisation of different types of aggregates; the former particularly concerns the technical feasibility, whereas the latter influences the financial feasibility. Finally, there could be organisation-level institutions that could occur in the form of policies regarding aspects such as trade and sustainability and systems regarding activities such as procurement, purchase, and transportation, which largely influence the actual practice of aggregates utilisation.

5.4.2 The employed environmental engineering approaches

Material-based approach

The resource potential of the residue needs to be assessed comprehensively (Figure 4) to enable full resource recovery of fines. The occurrence of a variety of potential resources is necessary to assess in order to identify different types of potential reutilisation applications, which is necessary to address the full resource recovery of fines. Certain previous fines studies have limited the assessment to a single material type such as metals (Konetschnik and Schneeberger, 2009) and energy carriers (Edo et al., 2013). Certain other fines studies have assessed the occurrence of multiple resources such as metals, minerals, and energy carriers (Allen and Kolb, 2009; Gent et al., 2015); however, material constraints such as contaminants like heavy metals, and other undesirables such as inert and clogging substances that could hinder reutilisation applications, remain unassessed. Assessing the occurrence of such material constraints is necessary to identify the need for upgrading.

Knowledge is also required on the over-time variation of the different constituents, which is an important design parameter (Allegrini et al., 2014) for valorisation. Yet, certain fines studies have characterised the material based only on either one or few randomly collected samples (Edo et al., 2013; Morselli et al., 2010) that can only provide a snapshot, or representative samples (Fiore et al., 2012) that can only provide an average, of a continuous flow of the material. It is also desirable to gain knowledge on the distribution of constituents across incremental size fractions based on which valorisation processes might need customisation. Yet, certain studies have restricted the composition assessment to either a single size fraction (Börjeson et al., 2000; Gonzalez-Fernandez et al., 2008) or a couple of size fractions with broad ranges (Fiore et al., 2012; Morselli et al., 2010).

As far as the reutilisation applications are concerned, the full resource recovery of fines should be the overall focus. However, previous fines studies are confined to either the recovery of specific materials (Lewis et al., 2011; Santini et al., 2012) or bulk materials that are down-cycled in applications such as ground construction (Péra et al., 2004; Rossetti et al., 2006). A large share of the material is left for disposal in the case of the former, whereas the opportunity to recycle valuable resources is lost in the latter. Therefore, different types of potential applications for the reutilisation of both specific as well as bulk secondary materials should be selected.

The resource potential assessment would then require benchmarking the user and regulatory requirements of such reutilisation applications against the established material characteristics. Thereby, the required level of process development for upgrading fines and deriving different fines-derived SRMs could be identified. Based on that, alternative strategies for fines valorisation based on different resource recovery objectives could be formulated.

Figure 4: Employed material-based approach in assessing the resource potential of fines. The material is comprehensively characterised and benchmarked against the user and regulatory requirements of selected multiple reutilisation applications to identify the need for process development of material upgrading and resource recovery.

Environmental systems analysis approach

The environmental potential of potential valorisation needs to be comprehensively assessed to enable sustainable investment decisions and governance concerning fines valorisation. Hence, an LCA-based environmental systems analysis approach (Figure 5) has been employed in this thesis. In holistically assessing the life cycle impact, it was recognised that not only the environmental burdens (positive impacts) due to fines-derived SRMs but also the environmental savings (negative impacts) due to substituted PRMs need to be considered.

Given that the focus of the thesis is valorisation fines but not any measures upstream of fines generation, the main stages of the life cycle of fines-derived SRMs should be fines processing, utilisation (of SRMs in industrial applications such as metal smelting, heating, cement production, and road construction), landfilling (of processing and utilisation waste), and transportation (of SRMs, processing wastes, and utilisation waste) between them. The equivalent life cycle stages for the substituted PRMs are PRM mining, utilisation (of PRMs in the same industrial applications of SRMs), landfilling (of mining and utilisation waste), and transportation (of PRMs, mining waste, and utilisation waste) between them. Transportation is important to consider, particularly given that there could be significant distances between valorisation plants and the utilisation sites that are originally located close to PRM sources. The end products of SRM/PRM utilisation, that is, materials such as copper, steel, and cement and infrastructure such as roads, were not considered for the assessment.

Figure 5: Employed environmental systems analysis approach in assessing fines valorisation. The net environmental impact of the formulated valorisation alternatives was obtained by calculating the life cycle impact of fines-derived SRMs subtracted by the life cycle impact of substituted PRMs.

5.5 Article synthesis

5.5.1 Knowledge Area 1: The current picture

RQ1 is addressed primarily in Article IV by investigating how different internal and external factors influence the management of fines at the studied shredding company via creating incentives for continued utilisation of the material in landfill covering and disincentives for adopting valorisation options. Internal factors were established by addressing the LCM markets and internal organisational aspects. Organisational aspects were addressed both in relation to the strategic management and operational management of fines. Regarding the operational management of fines, how the shredding company perceives the material complexity of fines and in what ways that influenced its management was particularly addressed. Since Article IV did not involve an in-depth study on the influence of fines' materiality on its management by the involved company, this socio-material perspective was substantiated with findings from Article II in terms of the heterogeneity and variation in material composition. External factors influencing fines management were established by addressing the raw material markets and governmental policy and regulation. In addressing this research question, special emphasis was given to the interrelations between the different aspects.

RQ2 is addressed in Article V by investigating the factors that sustain the dominant primary aggregate utilisation and the situations determining the unsystematic secondary aggregate utilisation. This is done by addressing the organisation and decision-making of the mainstream market processes, that is, material choice, supplier selection, and purchase, and how such processes are supported by different institutions occurring at the governmental, sector, and organisation levels. The user perspective, which was the primary focus, was complemented with customer (i.e. entities such as companies, organisations, and authorities that own the completed

construction) and supplier (i.e. companies that produce and sell construction aggregates) perspectives regarding these aspects. Similar to RQ1, the socio-material perspective of users regarding the utilisation of secondary raw materials, in general, was addressed.

5.5.2 Knowledge Area 2: A potential approach

RQ3 refers to necessary knowledge on the resource potential of fines to enable the development of integrated processes for the full resource recovery of fines. The resource potential is assessed in three parts. First, the chemical and physical material characteristics of fines were established. There, the average composition and over-time variation of the total concentrations of 25 metals, leaching concentrations of regulated metals, and fuel properties (energy content, ash, etc.) in fines as a whole and across five size fractions were established. Second, potential reutilisation applications representing the recovery of specific resources as well as the utilisation of bulk materials were selected. Third, the initial feasibility of utilising fines in the selected applications was assessed by benchmarking the material characteristics against the user and regulatory requirements of the applications. The benchmarking enabled the identification of the initial technical feasibility and the required level of technology development for upgrading and resource recovery pertaining to each application. The actual valorisation of fines was not part of the research work of this thesis. Hence, a full technical feasibility assessment of utilising fines in the selected applications was not performed.

RQ4 refers to knowledge concerning the approach to assess the environmental potential of alternative strategies for fines valorisation, which is necessary to enable sustainable investment decisions and policy and regulation regarding fines valorisation. The research question is addressed by performing a streamlined initial assessment of the life cycle environmental impact of three valorisation alternatives: 1) copper recovery, 2) construction aggregates recovery, and 3) full resource recovery. The three alternatives were formulated based on three resource recovery strategies: 1) maximising the recovery of specific raw materials, 2) maximising the recovery of bulk materials, and 3) optimising the full resource recovery. The targeted materials in each valorisation alternative were based on the assessed resource potential of fines in RQ3. The process schemes for upgrading and resource recovery in each alternative were designed together with the involved shredding company given its previous knowledge and experience in handling the material, the valorisation. The practical significance of technology development together with the industry is widely recognised in LCA literature concerning the assessment of prospective technologies (Arvidsson et al., 2018). The net life cycle impact (i.e. life cycle impact of fines-derived SRMs subtracted by that of substituted PRMs) of each valorisation alternative and the status quo (i.e. the current handling of fines) is thus calculated. The net environmental impacts of the most promising alternatives are also disintegrated to show the environmental impacts of the different life cycle stages in order to identify environmental hot spots. Given that the formulated process

schemes are conceptual and the actual environmental potential of the processes could vary, and the compositions of fines are subjected to significant variations, the effect of the parameter uncertainty on the LCA results is addressed.

5.6 Discussion

First, the key contributions of the appended articles in facilitating fines valorisation were discussed by revisiting the research questions. The discussion was performed by comparing and contrasting the article findings to mainly previous research concerning fines and similar heterogeneous residues such as municipal bottom ash, shredder residues, construction and demolition residues, and slag. Generic waste management literature was also used to further facilitate the discussion.

Subsequently, a synthesising discussion was performed on the implications of the article findings towards the realisation of fines valorisation. The main challenges of realising fines valorisation were identified based on the article findings. Potential measures to address such challenges were then discussed in relation to literature concerning other heterogeneous residues in particular and waste management in general, and by referring to specific article findings regarding their implications towards facilitating such measures.

6 Knowledge Area 1: The current picture on fines management

This chapter portrays the current picture concerning fines management by addressing the first and second research questions. The underlying factors of the current practice of fines management are presented from the shredding company perspective in addressing the first research question, while the rationale of the construction aggregates market is presented from the aggregates user perspective in addressing the second.

6.1 Factors underlying the current practice of fines management

This section addresses the first research question and presents the motives for the studied shredding to sustain the current disposal-oriented management of fines. Such motives consist of both incentives for continued utilisation of fines in landfill covering and disincentives for opting for fines valorisation, created by different external and company-internal factors (Figure 6). In the following subsections, the internally and externally created incentives for continued utilisation of fines in landfill covering are first presented. The disincentives for valorisation follow. These disincentives are primarily externally created, which in turn influence the internally created disincentives. The presented findings are based on Article IV unless specifically mentioned otherwise.

Figure 6: Factors underlying the current practice of fines management. Illustration of the externally and internally created motives due to policy, market, organisational, and materiality-related factors on the current fines management at the studied shredding company.

6.1.1 Incentives for utilising fines in landfill covering

One of the primary incentives for the studied company to utilise fines in landfill covering is that such use offers a secure outlet for the material due to readily accessible and internal LCM (landfill construction material) markets. In the studied company, its own landfills are primarily used for this purpose. Third-party landfills, with which the company has close relationships, are occasionally used. Decades of operations have allowed these disposal routes to gradually evolve and establish administratively and logistically. According to the interviewed personnel responsible for environmental permits, the company has continuously been striving to open up new landfills and will most likely continue to do so, despite the government's policy to phase out landfills. Even though it was not explicitly mentioned by any of the interviewees that the company prefers to get rid of this problematic material via these available outlets, such an inclination was implicitly clear. For instance, although several of the interviewees stress that a more in-depth understanding of the materiality is needed to facilitate valorisation, the legal representative claims that such detailed investigations of fines could also risk jeopardising the current landfill covering practice. Such a cautious approach towards dealing with fines is mainly influenced by their negative perception of the materiality of fines. Such a perception could be explained in that the periodic assessments of the occurrence of the regulated metals, which are required by local authorities as part of authorising the use of the material in landfill covering, have made it aware of the problematic nature of fines. The negative perception is further substantiated by the findings of Article II, which shows that the average total concentrations of regulated metals in fines largely exceed the guiding values of the Swedish environmental protection agency (EPA) for reutilisation in landfill covering (details presented later in Section 7.1.1). In addition, the high level of heterogeneity and over-time variation in the chemical and physical composition make fines a challenging material to handle in terms of continuous and standardised processes for quality assurance.

As far as the externally-created incentives for utilising fines in landfill covering are concerned, one of the primary factors is that such use allows the company to achieve the targets of the ELV directive (European Commission, 2000). The directive requires 95% recovery of the end-of-life vehicles, and the recovery of fines is paramount to comply with this target, given that fines represent around 10% of the feed material to the shredder. According to the involved recycling facility manager of the studied company, the plant has conducted a dedicated trial on ELVs for which the share of fines has been much less than 10%. Nevertheless, achieving the directive's recovery target is more or less still dependent on the fines' recovery. There, landfill covering, which is currently recognised under backfilling (European Commission Eurostat, 2011), an operation classified as recovery in the waste framework directive (European Commission, 2008), offers a good opportunity for doing so. The other primary externally created incentive for utilising fines in landfill covering is that such utilisation of waste is tax-exempt in Sweden due to the recovery classification (Statens Ofentliga Utredningar, 2005), thus making the operational costs of handling fines much lower

than those of landfilling, which is the currently available alternative for the material. The current costs of landfill covering range from 100 to 300 SEK/ton for the company, and given today's landfill tax of 500 SEK/ton (Sveriges Riksdag, 1999), the operational costs would be significantly higher if fines were landfilled.

6.1.2 Disincentives for valorising fines

Disincentives for valorising fines primarily occur in the external environment. One of the most prominent externally created disincentives for valorising fines is the inconsistent application and lack of clear regulatory requirements, which makes the shredding companies generally uncertain regarding the realisation of potential applications for fines-derived SRMs. According to one of the interviewed process managers, the environmental risk of fines reutilisation in ground construction is “a very local and case-specific question, but there are only general guiding values”. At present, regulatory requirements are only available in the form of guiding values developed by the Swedish EPA on the allowable contamination levels in secondary raw materials (SRMs) to be used in ground construction applications (Swedish EPA, 2009), which cannot accurately address the varying material and site-specific conditions of individual applications.

Another regulation-related disincentive is the inconsistent application of regulatory requirements. The actual regulation of SRM utilisation in ground construction takes place on a case-by-case basis by local authorities (Swedish EPA, 2010b), and according to the interviewed legal representative, the company has previously experienced large inconsistencies in how these guiding values are interpreted by local authorities in different situations. Such claims could be further supported in that even the Swedish Transport Administration, which is the largest potential user of fines-derived SRMs in ground construction, has been unaware of the applicable regulatory conditions for such use (Johansson, 2018). A plausible explanation for this situation could be that local authorities often lack experience, resources, and qualified personnel to perform accurate environmental assessments (Bertils and Elvingson, 2019).

Furthermore, the aforementioned environmental assessment by local authorities has created unfavourable circumstances for waste reutilisation applications. According to the interview respondents responsible for environmental permits, “the biggest problem is that the authorities are seeing waste as an environmental burden”. The unfavourable regulatory conditions are mainly evident in that the EPA guiding values are primarily based on a hazard-based approach that puts the focus on the total concentration of metals (Swedish EPA, 2009), and the studied fines largely exceeds the total concentration limit values (Article II). In contrast, if a risk-based approach was undertaken, the focus would be on the leaching concentrations since the actual environmental and health impacts are caused by their biological availability (Singh and Lee, 2015), of which leaching concentrations are a stronger indicator (Blasenbauer et al., 2020). The studied fines could more or less conform to the leaching concentration limit values (Article II). Additionally, the current authorising processes by local

authorities emphasise local impacts and pollution risks of waste reutilisation, whereas the global benefits of avoided impacts from primary production remain somewhat neglected. Such local risk-prudent regulation could, to a large extent, be explained by the strong emphasis put in the waste framework directive on minimising hazards of waste handling (European Commission, 2008). The aforementioned regulation generates a lack of trust at the studied shredding company, which foresees that any attempt to valorise fines will not undergo a fair trial in the authorising processes.

Continuing on the externally created disincentives, the market conditions for SRMs in Sweden render fines valorisation a high investment risk for shredding companies. According to the interviewed manager of the secondary raw materials division, the market prospects of fines are very small. One of the main reasons underpinning the very low market prospects of fines-derived SRMs is the abundant primary materials at competitive prices and potential users having adapted their technical processes, knowledge, and regulatory understanding for such materials. Additionally, the authorisation processes involve quality assurance for each and every occasion fines are to be reutilised, which is an arduous, time-consuming process for shredding companies and makes them unable to maintain timely deliveries. These quality assurance requirements are partly due to the aforementioned lack of specific regulatory requirements to govern such applications. The aforementioned factors also explain the general lack of user willingness for secondary raw materials in Sweden (Johansson, 2018). What would further reduce the user demand for SRMs would be the availability of more homogeneous and less-contaminated alternatives such as iron sand, steel slag, and construction and demolition residues in the country. This disadvantageous situation for fines was expressed by the interviewed legal representative as “fines will never be a gold mine”.

There is also a significant lack of market specifications regarding secondary raw materials. One part of the market specifications is the user requirements concerning material quality, the lack of which is related to the aforementioned absence of demand for SRMs. The other part of market specifications is the regulatory requirements for SRM applications, the lack of which is also presented earlier in this section. According to all the involved process managers of the company, despite the availability of a certain level of technology and know-how at their disposal, they are unable to develop tailored upgrading and resource recovery processes due to the lack of market specifications.

A major internally created disincentive for valorising fines is the lack of focus on the material on the corporate management level of the company. This situation is primarily due to the circumstances and settings in the external environment that foster fines disposal and are uncondusive to fines valorisation. According to the interviewed manager of the secondary raw materials division, the company would rather continue with the current disposal-oriented approach for fines until it is no longer an option. As stated by the interviewed process managers, there are also existing issues and potential for improvement in the company's mainstream processes involving the

larger fractions of shredder residues that carry higher resource yields and economic prospects. Hence, corporate management has so far prioritised investments in improvement measures to these mainstream processes.

Plausibly explained by the lack of focus on the strategic management of fines at the corporate level, the operational management of the material is somewhat in limbo, which creates further disincentives for developing valorisation options. One such disincentive is the limited capacities for improved handling of the material. As mentioned previously, the company's current knowledge on fines' materiality is somewhat focused on the occurrence of a few regulated substances. According to the involved process managers, knowledge and technology development towards fines recovery has been deprived of necessary financial and human resources, which are instead channelled to the prioritised mainstream processes, a direct consequence of priority setting at the strategic level. Consequently, the company's knowledge of the potentially recoverable resources and material constraints in fines is limited, making the development of tailored technical processes for upgrading and resource recovery difficult

Another disincentive is the lack of internally organising for the handling of the material. Currently, the responsibility of handling fines is not formally recognised in the company's organisation structure, and consequently, a substantial lack of communication and coordination exists between the different functional units of relevance for the management of the residue. The lack of coordination is evident in that all the respondents claimed the improved management of fines is someone else's responsibility, whereas the lack of communication is evident in that the interview respondents were either unaware or unsure of fines valorisation initiatives taken elsewhere within the company. Despite the aforementioned lack of capacities, a few such initiatives have been undertaken in a scattered and isolated manner, however within individual functional units of the company, for example, *processing, research and development, and sales*, and none of them have led to successful implementation. The failures could be attributed to the lack of a structured and coordinated approach towards handling the material. That is because such an approach is necessary to overcome various implementation barriers (Lozano, 2009) due to a presumably high embeddedness in aspects such as routines and protocols of obtaining environmental permits, generating contractual agreements with landfill owners, and logistical arrangements, which have sustained over decades of utilising fines in landfill covering.

6.2 Rationale of the construction aggregates market

The previous section showed that market prospects are a key factor in creating motives for fines valorisation. This section provides in-depth insights into a selected market by addressing the second research question. Thus, this section presents the rationale of the construction aggregates market in terms of the main market processes and the underlying institutions that determine the utilisation of construction aggregates. The construction aggregates market is selected because it is a likely future market for fines-derived SRMs with a potential for the utilisation of large quantities in Sweden. The findings are based on Article V and presented from the user perspective unless other actors are specifically mentioned.

Currently in Sweden, approximately a total of 100 million tonnes of primary and secondary aggregates are annually utilised in three main types of applications: approximately 10 million tonnes in concrete production, 8 million tonnes in asphalt production, and 82 million tonnes in different ground construction (filling, preparing foundation layers, and laying ballast). The major suppliers and users (i.e. companies that utilise aggregates in the different construction-related applications) of aggregates in Sweden are also subsidiaries of the three large corporations that constitute the majority of the country's construction sector. To a very large extent, the aggregate utilisation applications are part of infrastructure constructions, a larger share of which is owned by governmental (state-owned, regional, and municipal) customers (i.e. companies, organisations, and authorities that award the construction to users and own the completed construction work).

The current rationale of the Swedish construction aggregates market is characterised by dominant and systematic primary aggregate utilisation and situational and ad-hoc secondary aggregate utilisation. Such utilisation is determined by various user motives created at the main market processes related to aggregates utilisation in a construction project, that is, project procurement and aggregate supply (Figure 7). These market processes are supported by various institutions occurring on the customer, user, sector, and national levels.

Figure 7: Rationale of the construction aggregates market. Different user motives created at the main market processes sustain the dominant primary aggregates utilisation and situational secondary aggregates utilisation. Such motives are facilitated by various institutions occurring at the customer, user, sector, and national levels.

6.2.1 Dominant primary aggregates utilisation

Primary construction aggregates represent approximately 85% of the aggregates utilisation in Sweden, which could be split into around 77% crushed rocks (and moraine) and 8% gravel (and sand). Several factors create motives for users to utilise primary aggregates. One such motive is the straightforward material choice due to the availability of specific sectoral application standards. For instance, the AMA infrastructure standard (Svensk Byggtjänst, 2020) is virtually always referred to regarding aggregates for ground constructions and asphalt production and the BBC standards (NORDCERT, 2021) for concrete production. Particularly, the governmental customers, who own approximately 80% of infrastructure construction projects, require these standards to be met by users in their public procurement. That these standards mainly facilitate primary aggregates provides users with a natural motive to choose such materials by default.

The choice of primary aggregates also makes aggregates sourcing economical and convenient for users. This is especially the case in the relatively densely populated southern (Götaland) and middle (Svealand) regions of Sweden, where all the major cities are located, most of the construction work takes place, and a large number of quarries are located (Swedish Geological Survey, 2019). The high supplier competition and low aggregate prices make the aggregates sourcing economical. According to one of the interviewed purchasing managers, they “usually find three or four suppliers to create competition and influence the price”. On the other hand, the users have

supplier databases at their disposal, containing information such as material types, product quality certificates, and distance, thus making the sourcing of aggregates convenient.

Users have also gained the upper hand in aggregates trading due to the aforementioned high supply completion. Thus, they have been practicing the use of different types of supply contracts to suit different situations. Framework contracts are often entered into in relation to large-scale aggregates sourcing (e.g. > 10,000 thousand tonnes) for lower prices over an extended period. Project-based contracts are often used targeting the medium-scale use of aggregates (e.g. 100 – 1,000 tonnes) in certain projects. Contingent contracts, on the other hand, are used for small-scale aggregates sourcing (e.g. < 10 tonnes) towards projects of private customers such as individuals or small enterprises. The two latter contracts, given their smaller budgets, do not involve strict conditions as in the framework contracts, and hence, allow the user a greater degree of freedom in terms of suppliers and prices.

A particular user motive that explains the dominant primary aggregates utilisation is the economic benefits of intra-corporate trading. The involved users source a significant share of their primary aggregates (70-90 percent) via suppliers who are subsidiaries of the same construction corporations. Even though they are informal, internal purchasing policies are practiced explicitly, given the opportunity to retain the money within the corporation. The purchasing managers would only source aggregates externally when “special types of aggregates that we (the users) don’t have are required (e.g., railway Macadam) or when it’s less costly transportation wise”. The costs of aggregates transportation usually exceed the cost of the material itself and hence is prioritised over the internal purchasing policy.

6.2.2 Situational secondary aggregates utilisation

Secondary aggregates are derived by the crushing and sieving of natural construction residues such as blasting and excavation masses, and anthropogenic residues such as demolition asphalt and concrete masses as well as other external industrial residues. Secondary aggregates utilisation represents around 15% of the total aggregates utilisation, which can be split into 10% natural residues-derived and 5% anthropogenic residue-derived, which mostly consist of internally generated demolition masses. A small amount, in contrast, also comes from external industrial residues such as steel slag.

Unlike primary aggregates, secondary aggregates are utilised non-systematically in isolated situations driven by different actors due to different reasons. Even though the customers generally do not specifically require secondary aggregates, there is somewhat interest in material reuse to improve their environmental performance. According to one of the interviewed purchasing managers, “customers in their so-called green projects require that we reuse materials”. However, such projects are focused on climate impact objectives, which are only indirectly related to secondary

aggregates due to reduced transport requirements, whereas resource efficiency objectives, which are directly related to secondary aggregates utilisation, apparently do not play a recognisable role. What is more, such reutilisation aspirations are chiefly driven by economic benefits of avoided material and transportation costs. For instance, secondary aggregates utilisation is required by the STA only when the economic benefits are obvious. According to the interviewed STA project manager, “unfortunately, between environment and economy, it is the economy that governs”.

Given the lack of significant customer demand, the users do not systematically source secondary aggregates because they do not have the same incentives for doing so as with primary aggregates. Consequently, secondary aggregates are opportunistically opted for by users. For instance, users source secondary aggregates generated on the construction site to avoid material and transportation costs. Such on-site secondary aggregates are derived from the construction and demolition residues. Any involved processing costs (of crushing and sieving) would be insignificant compared to the avoided costs in such situations.

A similar opportunity, that is, avoided or reduced material and transportation costs, exists in sourcing secondary aggregates based on residues that occur in close proximity to the construction site. Unlike primary aggregates, formal suppliers are absent for secondary aggregates. According to the interviewed supplier’s recycling manager, “secondary aggregates suppliers are often ones in possession of a waste and facing a disposal problem” due to lack of landfill space and high costs. Such residue owners could simply eliminate the disposal problem by giving away their residues to be used as secondary aggregates: a win-win situation for both users and the so-called suppliers. The sourcing of secondary aggregates is informal, and contractual agreements of any sort are currently not used.

Another factor that generally motivates users to utilise secondary aggregates is to fulfil the national policy target for 70 percent reutilisation of construction and demolition residues (European Commission, 2008). This also gives a plausible explanation to why secondary aggregates, including in-proximity ones, are chiefly sourced internally within the construction corporations. Nevertheless, the enforcement of the aforementioned policy target and how such enforcement actually influences secondary aggregates utilisation by users is currently somewhat unclear. Yet, what is particularly noteworthy is that such utilisation currently requires proven economic benefits of doing so.

7 Knowledge Area 2: A potential approach for fines valorisation

Given that the knowledge needed for initiating changed practices is provided in the previous chapter, this chapter showcases a potential approach to initiate process development for valorising fines by addressing the third and fourth research questions. The assessment of the resource potential of fines is presented in addressing the third research question, while the formulation of valorisation alternatives and the assessment of their environmental potential are presented in addressing the fourth.

7.1 Resource potential assessment method

This section addresses the third research question and the findings based on Article II. The resource potential of fines is assessed in terms of the initial feasibility of the reutilisation of fines in selected applications. This is done by developing and applying an approach involving systematic sampling of the material, comprehensive characterisation of the chemical and physical composition, followed by an initial technical feasibility assessment by benchmarking the assessed composition against the user and regulatory requirements of selected potential reutilisation applications. The selected applications represent both the recovery of specific resources such as copper and energy and the recovery of bulk materials so that the full resource recovery of fines is addressed.

7.1.1 Sampling, characterisation, and application selection

First, fines were strategically and systematically sampled to capture the variation in composition, which was presumed to be quite high given that the input material mixture to the involved shredding plant changes continuously. The primary samples were prepared for analysis by isolating a part of the primary sample and sieving the remainder into five incremental size fractions. The objective of analysing the incremental size fractions was to identify how fines' composition is distributed across them and possible needs for or opportunities in processing them separately.

The occurrence of the total concentration of 25 total metals were assessed because of two main reasons. One is that fines is generated from multiple metal-bearing materials and presumably contains a significant metals recovery potential. The other reason is that the total concentration of metals is strongly looked for in user and regulatory requirements in commercial waste reutilisation applications in Sweden in general. The occurrence of leaching concentration (L/S 10, Swedish standard) for 12 regulated metals of 12 Swedish regulated metals was also assessed. This is particularly because the Swedish EPA regulatory guiding values for waste reutilisation in ground construction (e.g. filling, preparing foundation layers, and laying ballast) is a commonly investigated reutilisation application for similar heterogeneous in Sweden. Energy properties, that is, heating value, ash content, moisture content, chlorine concentration, and sulphur concentration, were particularly assessed because fines

contains organic materials and presumably contains a significant energy recovery potential.

Based on the assessed material characteristics and the common practice for commercial waste reutilisation in the country, different types of potential reutilisation applications, which could collectively encompass the full resource recovery of fines, were selected. As far as the recovery of specific resources is concerned, copper smelting and energy recovery applications were selected. Copper smelting was selected because it is currently practiced for the metals-rich larger fractions of shredder residues as well as for electrical and electronic waste, and certain sieved fractions of shredder fines contained considerable amounts of copper. Energy recovery in cement kilns and municipal waste incinerators were also selected because they are common practice for plastics and foam-rich larger fractions of shredder residues and many other types of organic-rich industrial residues, and certain fines fractions were found to contain a substantial energy content. Bulk recovery via utilisation in ground construction and landfill covering were selected to avoid the disposal of fines. Even though landfill covering is the most-practiced bulk utilisation application for heterogeneous residues in Sweden, other European countries are widely utilising residues such as municipal bottom ash in various ground construction applications (see Section 2.1).

7.1.2 Assessing the initial feasibility of reutilisation applications

Copper recovery in smelting

A copper smelting plant in Sweden was involved regarding the initial feasibility assessment of copper recovery from fines. The highest average copper concentration in the different fractions (both the primary fraction and the size fractions ZA-ZE) was between 2 and 3 percent, significantly below the 8 percent gate requirement (Figure 8). The variation levels suggest that it could reach copper concentrations of 6 to 7 percent occasionally in size fractions ZA and ZD, but less reliably. Therefore, the enrichment of copper content is necessary to be acceptable. However, the user is willing to accept a fee (paid by the shredding company) to compensate for the low copper concentration. Even though the gate requirements are flexible regarding the copper content, they are rigid regarding contaminants due to the potential damage certain metals can cause to the smelting process. The concentration of the most critical metals, namely, mercury (Hg), cadmium (Cd), and beryllium (Be), were generally well under the maximum limits. The occurrence of mercury concentrations in all the fractions was well below the gate limit value of 2 milligrams per kilogram (mg/kg) for all weekly samples except for one week, where the concentrations were an order of magnitude higher. Such unpredictable over-time variations make upgrading difficult and need to be avoided via upstream measures addressing waste collection and sorting.

Figure 8: Total concentrations of copper in fines (d.b.). Average and variation over nine weeks in the primary and sieved fractions of shredder fines. The dashed line represents the gate requirement of the smelting plant.

Energy recovery in cement kilns and municipal waste incinerators

Two cement kilns and a municipal waste incineration facility in Sweden were involved regarding the initial feasibility assessment of energy recovery from fines. The gate requirements for secondary fuels in cement kilns, as well as in municipal waste incinerators, primarily concern the heating value, ash content, moisture content, and chlorine concentration (Figure 9). As far as the cement kilns are concerned, none of the fines fractions meet the requirement of 18 megajoules per kilogram (MJ/kg) heat content. Therefore, the enrichment of organic content is required. When it comes to municipal waste incineration, the size fractions ZA-ZC fulfilled the 10-14 MJ/kg requirement. There are no such strict limit values on the ash content in either application, yet the current levels were considered too high and need to be significantly reduced, which means some separation of metals and minerals is required. Due to the issue of clogging, chlorine concentration is rather seriously regarded in both applications. The larger size fractions ZA-ZC, despite their higher energy content, need pre-treatment for chlorine reduction as the concentrations exceed the maximum tolerable values. The concentrations of the metals cadmium, thallium, mercury, arsenic, cobalt, chromium, copper, manganese, nickel, lead, antimony, vanadium in the fuel are regulated in Sweden in both applications. Generally, the average concentrations of these metals largely exceed the limit values in all the fractions of fines, and thus, metals separation is required.

Figure 9: Composition of fuel properties in fines. Average composition and over-time (nine weeks) variation in the primary and sieved fractions of shredder fines. The dashed lines and dotted lines represent the gate requirements for cement kilns and municipal waste incinerators, respectively.

Bulk recovery in ground construction and landfill covering

Two construction companies in Sweden were involved regarding the initial feasibility assessment of utilising fines as a bulk aggregate (to substitute primary aggregates such as sand and gravel) in ground construction and landfill covering applications. Generally, the users' primary concern is the mechanical properties, such as the strength and stability of the material when put into use. Even though the aforementioned mechanical properties of fines are apparently not widely studied, the material is of interest to them, given that it is currently utilised as a landfill cover material. However, the significant levels of organic materials (above 10%) could be problematic. There are no certain gate requirements as such concerning contaminants. Instead, such issues are chiefly governed by regulatory requirements. Currently, the pollution concerns of ground construction applications are handled individually by the respective local authorities based on the guiding values of the Swedish EPA. These guiding values primarily refer to the total and leaching concentrations of the metals cadmium, mercury, lead, copper, zinc, chromium, nickel, and arsenic (Table 3). The average total metal concentrations of all the regulated metals (Figure 10) surpass the limit values for all the fractions of fines. There, it is noteworthy that the high positive variations of the three critical metals recognised by the Swedish EPA (i.e. cadmium, mercury, and lead) are higher than the limit values by orders of magnitude. In contrast, the leaching concentrations of metals (Figure 10) are generally under the limit values in many of the fractions. Unlike total concentrations, the leaching concentrations also do not display as much of a characteristic variation across the different size fractions. What is particularly noteworthy is that the large variations in the concentrations of lead - a critical metal classified by the Swedish EPA - in the primary and ZD fractions, which could exceed the maximum limit values for both applications. Even though the influence is not as critical as of lead, the high variations in the zinc concentration in

the primary fractions and the ZC-ZD fractions could also exceed the limit values in both applications. Generally, pre-treatment in the form of organic material separation, metal separation, and stabilisation are deemed required prior to these applications.

Table 3: Swedish regulatory guidelines for waste reutilisation in construction. The guiding values on the maximum total and leaching concentrations of metals for ground construction and landfill covering are provided (Swedish EPA, 2010b, 2009).

Metals	Total concentration (mg/kg)		Leaching concentration L/S 10 (mg/kg)	
	Ground construction	Landfill covering	Ground construction	Landfill covering
Copper (Cu)	40	80	0.8	0.6
Zinc (Zn)	120	250	4	3
Lead (Pb)	20	200	0.2	0.3
Chromium (Cr)	40	80	1	0.3
Nickel (Ni)	35	70	0.4	0.6
Cadmium (Cd)	0.2	1.5	0.02	0.007
Mercury (Hg)	0.1	1.8	0.01	0.01
Arsenic (As)	10	10	0.09	0.4

Figure 10: Total and leaching concentrations (L/S 10) of Swedish regulated metals in fines. The average and over-time (nine weeks) variation in the primary and size fractions of shredder fines. The leaching concentration of certain metals could not be shown because their concentrations were below the detectable limits of the tests.

7.1.3 Guiding process development

The overall resource potential of fines is illustrated in Table 4. Given that different reutilisation applications prefer certain size fractions, upgrading and resource recovery targeting different size fractions is recommended. There is also a significant need for material upgrading pertaining to the different reutilisation applications due to the high occurrence of contaminants/undesirables. The use of integrated processes to simultaneously address various material constraints and resource recoveries would be a plausible strategy to valorise fines efficiently. The different reutilisation applications also account for varying levels of the recoverable share of fines. For instance, the recovery of specific resources, that is, metals and energy carriers, would lead to large quantities of fines left for disposal. Copper recovery in smelting would only recover 2 percent of fines, having 88 percent disposed of; the remaining 10 percent material corresponds to the organic fraction that would be burnt out during smelting. Similarly, energy recovery in either of the two applications would only recover about 6 percent of fines, with 94 percent disposed of. However, the prior separation of the mineral content (about 10 percent) could directly recover that share as clinker in cement production. In contrast, bulk utilisation in ground construction would recover 100 percent of the material. Yet, the opportunity to recover specific resources is lost. The full resource recovery of fines, therefore, calls for the integration of the individual reutilisation applications, which could be done together with the aforementioned integration of upgrading and resource recovery processes.

Table 4: Overall resource potential of shredder fines. Presented in relation to the initial feasibility of utilising fines in the selected reutilisation applications.

Applications	Potential resources	User requirements	Regulatory requirements	Recoverable share of fines	Disposable share of fines
Copper recovery in smelting	Fractions: ZA-ZD Cu 2%-3%	Cu 8%	Not applicable	< 2% (as copper)	88 %
Energy recovery in cement kilns	Fractions: ZA-ZC 10-14 MJ/kg	18 MJ/kg Lower ash content Lower chlorine conc.	Lower total metal concentrations	6% (as energy carriers) 10% (as clinker)	84 %
Energy recovery in municipal waste incineration	Fractions: ZA-ZC 10-14 MJ/kg	10-14 MJ/kg Lower ash content Lower chlorine conc.	Lower total metal concentrations	6% (as energy carriers)	94 %
Bulk recovery in ground construction	Fractions: ZA-ZE	Not applicable	Lower total metal concentrations	100% (as filler material)	-
Bulk recovery in landfill covering	Fractions: ZA-ZE	Not applicable	Lower total metal concentrations	100% (as filler material)	-

7.2 Process formulation and environmental assessment of fines valorisation

This section addresses the fourth research question. It first presents the formulation of the different valorisation alternatives based on the assessed resource potential in the previous section. Subsequently, it presents the streamlined assessment of the life cycle impact of the formulated fines valorisation alternatives and the status quo (the current handling of fines). The following is based on Article V.

7.2.1 Formulation of valorisation alternatives

In line with the same thinking behind selecting potential reutilisation applications in the resource potential assessment (Section 7.1.1), three valorisation alternatives were formulated based on the resource recovery strategies: 1) maximising the recovery of specific resources to return material to production loops and retain value, 2) maximising the recovery of bulk materials to avoid disposal, and 3) optimising the full resource recovery. The targeted resources of the alternatives are selected based on the assessed resource potential of fines (Section 7.1), and the respective conceptual process schemes are designed together with the involved shredding company. The actual development of the process schemes was not part of this research.

Valorisation Alternative 1: Copper recovery

The focus is put on copper recovery given the significant (2-3 weight-% d.b.) occurrence of the metal in fines (Section 7.1.1). Copper recovery is preferred economically due to the high market value and environmentally due to the impacts of copper ore mining and refining (Dudka and Adriano, 1997). The process scheme (Figure 11) is designed to maximise the deriving of a copper-rich fraction, which is reutilised in copper smelting. Fines are separated into different size fractions in order to increase the efficiency of the subsequent unit operations. The two largest size fractions are targeted for the separation of copper-containing materials. In order to enable the effective separation of the copper-containing materials using eddy-current separators (ECS), prior removal of iron content using magnetic separators (MS) was necessary. The iron-rich fraction is reutilised in steel production. Since the largest fraction also contains a significant organic content, it needs removal prior to landfilling. The separated organic-rich fraction is therefore reutilised in cement kiln heating. The smallest fraction is to be landfilled without further processing, given that the efficient recovery of any specific resources is difficult due to the small particle size and the high concentration of undesirables (heavy metals, ash, etc.).

Figure 11: Conceptual process scheme of Valorisation Alternative 1: Copper recovery. Different size fractions are processed differently to enable the effective recovery of a copper-rich fraction. The organic-rich and iron-rich fractions are by-products.

Alternative 2: Construction aggregates recovery

The focus is put on construction aggregates recovery given that the processing is simpler and assuming it would be economical due to avoided disposal costs. The process scheme (Figure 12) is designed to derive construction aggregates for road base layer construction. In order to meet the technical requirements of aggregates in road base layers and to have the high heavy metal content contained, fines is physically bound in cementitious concrete, which is crushed to generate construction aggregates. The organic content in fines is separated using air sifting to have the desired strength in crushed concrete. The separated organic-rich fraction is utilised in cement kiln heating. The cement mortar is allowed to dry to become concrete, which is then crushed to obtain the right size of the construction aggregates.

Figure 12: Conceptual process scheme of Valorisation Alternative 2: Construction aggregates recovery. Fines are bound in crushed concrete to meet the technical requirements of and contain the contaminants in the aggregates. The organic-rich fraction is a by-product.

Alternative 3: Full resource recovery

The focus is the full resource recovery of fines. The process scheme (Figure 13) is designed to recover different types of secondary raw materials from the different size fractions. Similar to Alternative 1, the processing is based on different size fractions. The large-sized fraction is processed with the focus of retrieving iron-rich, copper-rich, and organic-rich fractions, not unlike Alternative 1. This time, the metal and mineral-rich fraction from air sifting is utilised in cement production. The medium-

sized fraction, due to its particle size, is processed with a three-way dry shaking (DS) to derive different material types based on density. The organic-rich fraction is utilised as a secondary fuel in cement kiln heating together with the organic-rich fraction from the large-sized fraction. The mineral-rich fraction and the metal-rich fraction (left upon magnetic separation) are utilised in cement production. The iron-rich fraction from magnetic separation is utilised in steel production together with the iron-rich fraction from the large-sized fraction. The < 1.00 mm size fraction, like in Alternative 2, is processed to derive construction aggregates.

Figure 13: Conceptual process scheme of Valorisation Alternative 3: Full resource recovery. Process scheme is designed to optimise the recovery of both specific valuable materials and bulk construction aggregates.

7.2.2 Environmental potential of the valorisation alternatives

Generally, the valorisation alternatives show better environmental potential in comparison to the status quo (Figure 14). The status quo shows environmental burdens (positive impacts) in all the impact categories, whereas the valorisation alternatives mostly show environmental savings (negative impacts). Alternatives 1 and 3 are the most preferable given that they display characteristically superior environmental potential to that of the status quo regarding almost all the impact categories, chiefly due to the substitution of several primary raw materials. There, Alternative 3 is preferable regarding the climate change impact category and with a rather small margin, chiefly attributed to the more than double coal substitution in cement kiln heating compared to Alternative 1. In contrast, Alternative 1 is preferable regarding the other three impact categories and with rather high margins. The smaller net ozone depletion burden in Alternative 1 is chiefly attributed to approximately half the quantity of crushing involved in deriving construction aggregates, which is a highly energy-intensive unit operation. The higher acidification savings in Alternative 1 is chiefly attributed to the approximately three times larger copper ore substitution in copper smelting. The high coal substitution does create a substantial acidification savings in Alternative 3. Yet, its per-tonne savings is much smaller than that of

copper ore substitution. The higher net resource depletion savings in Alternative 1 is chiefly attributed to the approximately three times larger substituted copper ore mining and refining. The aforementioned high coal substitution (in cement kiln heating) and the limestone substitution (in cement production) create substantial resource depletion savings in Alternative 3. Yet, their per-tonne resource depletion savings are much smaller compared to that of copper ore substitution.

Alternative 2, which is apparently less preferable to Alternatives 1 and 3 regarding all the impact categories, is somewhat special. Even though both the status quo and Alternative 2 represent bulk utilisation of fines, they show significant differences in their environmental potentials. The higher climate savings and acidification savings in Alternative 2 are chiefly due to the replacement of coal in cement kiln heating. However, it is noteworthy that Alternative 2 also shows higher ozone depletion and resource depletion burdens than the status quo. The environmental hot spots, that is, the main contributions towards the environmental burdens of the Valorisation Alternatives, are explained in relation to the different life cycle stages of the involved fines-derived SRMs in the following.

Figure 14: Overall environmental potential of the valorisation alternatives in comparison to the status quo.

Regarding Alternative 2, almost all the high net ozone depletion burden is attributed to concrete crushing involved in fines processing (Figure 15) to derive construction aggregates, which involves an order of magnitudes higher electricity requirement than the other unit operations. The net resource depletion burden is chiefly and equally attributed to concrete crushing (fines processing stage) and cement kiln

heating using fines-derived organic-rich fraction (SRM utilisation stage). The former is caused by the high energy intensity of the operation, whereas the latter is due to the energy recovery from fossil-based materials such as plastics and foam and the disposal of valuable materials such as metals.

Figure 15: Illustration of the environmental hotspots of Valorisation Alternative 2. The distribution of the environmental burdens of fines-derived SRMs across their life cycle stages (blue), the total savings of substituted PRMs (orange), and the net life cycle impact (grey) regarding the ozone depletion and resource depletion impact categories are presented.

Regarding the environmental potential between Alternatives 1 and 3, both alternatives contribute towards a significant climate change burden in different stages of the life cycles of fines-derived SRMs (Figure 16). For instance, both alternatives generate climate change burdens mostly in the SRM utilisation stage due to cement kiln heating using the organic-rich fraction, which is 70% fossil-based (Lundgren, 2018). There, Alternative 3’s contribution is much higher given that the involved quantities are more than twice the amount of Alternative 1. For instance, Alternative 3 shows a higher contribution in the fines processing stage mainly due to the energy-intensive concrete crushing. In contrast, Alternative 1 shows a higher contribution in the waste landfilling stage due to landfilling approximately 77% (Figure 11) of the fines processing waste, which contains more than 13% organic matter.

Alternative 3, like Alternative 2, generates a significant net ozone depletion burden due to the energy-intensive concrete crushing involved. In contrast, a specific life cycle stage does not stand out in alternative 1, which also involves a less ozone depletion burden compared to the savings due to substituted PRMs. When it comes to acidification, both Alternative 1 and 3 generate most of the burdens at the SRM utilisation stage due to steel production using the iron-rich fraction. Nevertheless, such burdens are insignificant compared to the saving due to substituted PRMs, particularly regarding copper smelting and coal-based cement kiln heating.

Both Alternative 1 and 3 involve significant resource depletion burdens at different life cycle stages of the fines-derived SRMs. The main reason for burdens at the SRM transportation stage is the long distance between the northern steel production plants and the southern studied shredding plant for the utilisation of the iron-rich fractions. The involved transportation distance is equally long regarding copper smelting; nevertheless, the recoverable quantities of the copper-rich fraction are an order of

magnitude less than those of the recoverable iron-rich fractions in both valorisation alternatives. The resource depletion burdens at the SRM utilisation stages are chiefly attributed to steel production mainly because of the larger per-tonne impacts involved compared to other utilisation applications. Additionally, Alternative 3 generates a resource depletion burden at the fines processing stage chiefly attributed to the energy-intensive concrete crushing, whereas Alternative 1 generates a burden due to the landfilling of fines processing waste, which contains valuable resources such as metals.

In Article V, a Monte-Carlo simulation of the parameter uncertainty is performed to capture the effect of possible variations of the input parameters in terms of the material composition of fines and the recovery efficiency and electricity requirements of the unit operations. The outcomes of the different alternatives vary considerably, chiefly due to the large variations in the material composition of fines; nevertheless, the uncertainty analysis generally confirms the preference of the valorisation alternatives from the LCA.

Figure 16: Illustration of the environmental hotspots of Valorisation Alternative 2. The distribution of the environmental burdens of fines-derived SRMs across their life cycle stages (blue), the total savings of substituted PRMs (orange), and the net life cycle impact (grey) regarding the different impact categories are presented.

8 Discussion

This chapter presents a discussion on the contribution of the key findings of the thesis in providing knowledge for facilitating fines valorisation in relation to previous research, followed by a synthesising discussion on the implications of the thesis contributions in realising fines valorisation.

8.1 Contributions towards facilitating fines valorisation

8.1.1 Establishing the current practice of fines management

Given that fines is currently disposed of, the most fundamental knowledge requirement of facilitating fines valorisation is the knowledge that facilitates changed practices. In facilitating changed practices towards fines valorisation, it is most fundamental to explain why the current practice of fines management is sustained, which is one of the key overall contributions of this thesis. Article I shows that previous fines research has not performed any investigations targeting the current practice of fines management. Certain studies concerning other residues, such as construction and demolition waste (Nitivattananon and Borongan, 2007) and incineration ash (Obernberger and Supancic, 2009), have analysed the current practice of the management of such residues but nevertheless are focused on the processing technologies, material flows, and governmental policies rather than the responsible actor in question, which is key in realising sustainable changes (Seuring, 2004b).

The overall contribution of Article IV of this thesis is an in-depth insight into the underlying factors sustaining the current disposal-oriented practice of fines management from the producer (shredding company) perspective. The producer perspective is focused on because the producer is the most central actor in fines management as it owns the material and has the responsibility of managing it. Hence, such knowledge is necessary to identify challenges and necessary measures of initiating investments towards knowledge and technology development towards fines valorisation. In addressing the producer perspective, Article IV employs a socio-technical systems approach. The producer's choice of managing fines is inevitably a consequence of various motives created due to different factors related to multiple aspects occurring at the policy, market, and organisation levels. The explanation of the occurrence of such a societally relevant technical issue necessitates a socio-technical systems perspective (Geels, 2004).

One of the main findings in Article IV is that governmental waste policy creates strong incentives for fines utilisation in landfill covering chiefly due to the recognition of landfill covering as a recovery operation, a key issue that needs to be addressed in putting ambitious regional and national resource policies into practice. Previous fines studies are confined to a couple of top-down investigations on selected administrative and market instruments (Dubois et al., 2015; Nayak and

Apelian, 2014) that do not address how the involved actors interpret and react to different policy stimuli. Another main finding in Article IV is that governmental regulation creates strong disincentives for fines valorisation due to the lack of specific applications standards and favourable local authority practices. This is a key issue, also recurring concerning municipal bottom ash management in Sweden (Bertils and Elvingson, 2019; Johansson, 2018), that needs to be addressed to reduce uncertainty and create trust among actors in valorising fines. Previous fines research totally lacks investigations concerning the regulation of fines management.

In general, similar efforts to that of Article IV in terms of establishing the bottom-up perspective of policy and regulation are evident, for instance, concerning Dutch municipal bottom ash management (Born and Veelenturf, 1997; van der Zwan, 1997). Having such early-on research somewhat explains the successful bottom ash valorisation in the Netherlands today (Blasenbauer et al., 2020; Johansson, 2018). Regarding municipal bottom ash, additional bottom-up research efforts that could further facilitate producer investments towards the valorisation of the residue are evident. Examples are the influence of policy on material composition (Lee et al., 2014), which addresses the problem upstream of residue generation, and on resource recovery potential (Huang et al., 2006), which concerns downstream measures.

Article IV also finds that the current landfill construction material (LCM) markets create incentives for fines disposal by offering a secure outlet, while at the same time, secondary raw material (SRM) markets create disincentives for fines valorisation due to the lack of demand and material specifications. Such knowledge illuminates how the current market conditions need to be reversed to drive producers (shredding companies) towards investments for fines valorisation. For instance, Khodier et al. (2018) explain how shredding companies chose to opt for other means for shredder residue recovery, despite the EU directive requirements on recycling, due to higher market demand and better economic returns. When it comes to SRM markets, previous fines research is confined to the investigation of user and regulatory requirements on a few potential fines-derived SRMs (Allen and Fisher, 2007; Johansson et al., 2017). Although such studies indicate the extent of available market specifications, they are insufficient to assess how they influence fines management by actors.

A particularly interesting finding in Article IV is that the internal organisational aspects of the shredding company at the strategic and operational management levels create disincentives for fines valorisation: the former primarily due to the lack of incentives at the external policy and market environment and the latter chiefly due to the lack of organisation and resources, which is a consequence of the lack of prioritisation of the issue at the strategic management level. Resolving such interrelated company-specific organisational issues plays an essential role not only in initiating investments towards valorisation but also in successfully adopting fines valorisation as a day-to-day business activity. Such organisational studies are entirely

lacking in previous fines research, while it is also not common concerning the waste management literature in general.

Article IV also finds that the socio-material perspective of the material creates disincentives for fines valorisation due to the perceived material complexity of fines, which is substantiated via one of the key empirical findings of Article II, that is, material characteristics of fines in terms of the distribution of average and variation of chemical and physical composition across incremental size fractions. Even though it is not common in the waste literature and totally lacking in fines research, certain previous studies, for example, landfill mining (Johansson, 2016), have emphasised its significance towards initiating valorisation investments by actors. Such knowledge is particularly helpful in identifying the need for increased societal awareness on the resource potential of fines, and thereby, having market actors and policymakers recognise the significance of its valorisation.

8.1.2 Establishing the market prospects of secondary construction aggregates

Together with the aforementioned current practice explanation, it is also fundamental to investigate the market prospects of secondary raw materials (SRMs) to facilitate fines valorisation. Decades of studies are evident concerning markets for specific valuable SRMs such as scrap metals (Hu et al., 2020; Kooi, 2010; Spoel, 1990). When it comes to heterogeneous residues such as fines, markets for bulk materials, such as construction aggregates, are equally important because they enable the bulk utilisation of large quantities of such residues that would otherwise be disposed of. Thus, it frees up landfill space and saves disposal costs. The latter could also finance valorisation investments, thus enabling the recovery of specific resources (c.f. Fellner et al., 2015). What is more, similar residues to fines, such as municipal bottom ash (Blasenbauer et al., 2020) and construction and demolition residues (Hjelmar et al., 2016), have been widely utilised as a secondary construction aggregate in the European region. The analysis of the Swedish construction aggregates market is another key overall contribution of this thesis.

Article I of this thesis shows that previous fines research totally lacks market studies as such. Generally, studies concerning the markets for heterogeneous residues are focused on selected aspects such as supply, demand, and competition (Bertils and Elvingson, 2019; Jeffrey, 2011), governmental policy (Dubois et al., 2015; Johansson, 2018), and regulation (Blasenbauer et al., 2020), which are important in understanding the constitution and governance of the market. Nevertheless, when it comes to the market prospects of residue-derived SRMs, the key is to understand how the current raw material utilisation is sustained via the different market processes by actors in a given market, which remains mostly unaddressed. Additionally, the lack of focus beyond a particular actor in such studies leaves possible actor interrelations across the supply chain unaddressed. Certain studies, for example, Shooshtarian et al. (2020), have captured the actor perspective regarding secondary construction aggregate markets: nevertheless, they are confined to macro-

level investigations that provide generic suggestions to providing incentives for different stakeholder groups for increased secondary aggregates use.

The overall contribution of Article V of this thesis is in-depth insights into the rationale of the construction aggregates market from the user (i.e. companies that purchase and utilise aggregates in different construction-related applications) perspective. The market rationale is explained in terms of the motives for utilising primary and secondary aggregates in relation to the interplay between main market processes, involved actors, and the supporting institutional structures. Given that primary aggregates utilisation is currently largely dominant in the country, contrasting between the primary and secondary aggregates provides the necessary knowledge for the identification of challenges of and possible measures for increased utilisation of secondary aggregates by creating similar market conditions to that of primaries. The user perspective is focused on because the user is the most central actor in the aggregates supply chain in terms of responsibility for utilising the materials by matching the customer requirements, material specifications, and supply. Additionally, the user perspective is complemented with the customer (i.e. companies and organisations that order and own the completed construction) and supplier (i.e. companies that produce and sell construction aggregates) perspectives to capture their influence on the user's material choice. Similarly to addressing the current practice of fines management in Article IV (Section 8.1.1), Article V addresses the rationale of the construction aggregates market by employing a socio-technical systems approach, given that the different market processes of aggregates utilisation involve different supply chain actors and are governed by institutions occurring at different societal levels.

The overarching finding of Article V is that the Swedish construction aggregates market is characterised by the dominant and systematic utilisation of primary aggregates that is sustained at the main market processes and thoroughly evolved specific institutions at the customer, user, sector, and national levels underlying them. On the contrary, secondary aggregates utilisation is opted for unsystematically and situationally and governed by scattered and non-specific institutions at the different societal levels. Such findings provide the necessary knowledge towards improving the institution structures underlying secondary aggregates to raise the competitiveness of such materials to a comparable level to that of primary aggregates.

One of the main findings in Article V is that already at the project procurement stage - the first main market process related to aggregates utilisation - users are driven to choose primary construction aggregates due to the availability of specific application standards, while secondary aggregates are only opted for to comply with specific customer requirements for improved environmental performance. This finding signifies that the Swedish construction market is chiefly governed by sectoral playing rules, which are currently absent for, and need to be matched by, secondary aggregates to enable their systematic utilisation. The influence of the lack of specific application standards deterring secondary aggregates utilisation in the country is a

recurring finding in other heterogeneous residues such as municipal bottom ash (Bertils and Elvingson, 2019; Johansson, 2018). Nevertheless, Article V provides in-depth insights on the role of sectoral standards in sustaining the dominant primary aggregates utilisation and how it compares to the secondary aggregates utilisation.

The other main finding in Article V is that in sourcing construction aggregates - the second main market process – users could enjoy economic benefits and convenience in utilising primary aggregates due to the practice of intra-corporate trading and systematic supplier selection and purchasing, whereas secondary aggregates are only opted for chiefly due to the economic benefits of avoided waste disposal. This finding particularly signifies that aggregates acquisition is chiefly driven by economies of vertical integration of supply and systematic trading of aggregates, which are a necessary means for secondary aggregates to become competitive and gain market access. Studies are generally lacking in waste research concerning how existing corporate practices influence SRM utilisation.

Even though Article V only involves infrastructure construction whereas building construction is omitted, given that the former accounts for the vast majority of aggregates utilisation and the involved user group represents all the infrastructure-related applications and the largest companies in the country, the findings are more or less generalisable to the entire construction aggregates market.

8.1.3 Process development for fines valorisation

The preceding sections discussed the thesis contributions towards providing knowledge to facilitate changed practices, which is one of the fundamental knowledge requirements in facilitating fines valorisation. Another fundamental knowledge requirement is the knowledge that facilitates the development of valorisation processes. In that regard, the overall key contribution of this thesis is a combined methodological approach for the conceptual formulation and early-stage assessment of fines valorisation processes. The developed approach consists of assessing the resource potential of fines, formulating alternative process schemes for fines valorisation, and assessing the environmental potential of the formulated valorisation processes. Even though previous research concerning fines and other heterogeneous residues such as shredder residues and municipal bottom ash have contributed numerous empirical contributions and some methodological contributions concerning the aforementioned individual aspects, waste research generally lacks an overall systematic methodological approach for facilitating process development for valorisation, such as the one presented in this thesis. A key overall feature of this methodological approach is that it recognises that process development cannot take place in isolation, whereas the upstream and downstream implications of the supply chain have to be accounted for as well.

Resource potential assessment

Comprehensive knowledge of the material should be the starting point for process development for residue valorisation. Thus, Article II of this thesis develops a systematic methodological approach for assessing the resource potential of fines. One of the main components of the developed resource potential assessment method is the assessment of the chemical and physical composition in terms of a wide range of constituents representing metals and energy properties, which enable the identification of a variety of potentially recoverable resources and possible material constraints. Some previous fines studies have limited the composition assessment to a single material type such as metals (Konetschnik and Schneeberger, 2009) or energy carriers (Edo et al., 2013). Other fines studies have assessed the occurrence of multiple resources such as metals, minerals, and energy carriers (Allen and Kolb, 2009; Gent et al., 2015); however, material constraints such as contaminants, for example, heavy metals, and other undesirables, for instance, inert, clogging, and corrosive substances that could hinder reutilisation applications, remain unassessed. Further possibilities for more advanced assessments of material properties are evident regarding, research-wise, more mature residues such as municipal bottom ash, for which actual processing and reutilisation applications are currently taking place. Examples are the analysis of organic compounds (Høstgaard et al., 2012), speciation levels (Dou et al., 2017; Lam et al., 2010), and mechanical behaviour (Le et al., 2017).

Even though the material properties are assessed, process development could not take place in isolation exclusive of the upstream and downstream implications of the SRM supply chain. Upstream implications of fines processing were addressed in terms of assessing the variation of the aforementioned material compositions, which is a necessary design parameter (Allegrini et al., 2014) for the development of upgrading and resource recovery processes. Hence, fines were strategically sampled over nine weeks to cover the weekly variation of composition. The material characterisation in previous fines research has been largely based on only either one or a few randomly collected samples (Edo et al., 2013; Morselli et al., 2010) that can only provide a snapshot, or representative samples (Fiore et al., 2012) that can only provide an average, of a continuous flow of the material. In contrast, composition variation assessment is evident in research concerning certain other residues, for example, in municipal bottom ash characterisation (Liu et al., 2008). Nevertheless, such assessments mostly focus on parameters such as leaching in order to assess the environmental risk behaviour of the residue, for instance, upon disposal, rather than to facilitate process development for valorisation.

Furthermore, the distribution of the average occurrence and variation of the assessed constituents across incremental size fractions is analysed to enable customisation of potential upgrading and resource recovery processes based on size fractions. Previous fines characterisation studies are confined to either a single size fraction (Börjeson et al., 2000; Gonzalez-Fernandez et al., 2008) or a couple of size fractions

with broad ranges (Fiore et al., 2012; Morselli et al., 2010), which do not sufficiently enable such customised process development. In contrast, similar methodological approaches to that of Article II, in terms of having incremental size fractions, are evident in municipal bottom ash characterisation research (Dou et al., 2017; Weng et al., 2010).

In addressing the downstream implications of fines processing, the assessed material characteristics, that is, the average and variation of material composition and their distribution across incremental size fractions, are benchmarked against the user and regulatory requirements pertaining to a variety of potential reutilisation applications. The objective is to address both the recovery of specific valuable resources to retain value and the bulk material utilisation to avoid disposal so that full resource recovery of fines is encompassed. Close efforts have been performed in previous fines research where user specifications for secondary metal smelting or construction aggregates have been identified (Allen and Fisher, 2007). Such studies, however, do not address the regulatory requirements and somewhat neglect the need for full resource recovery of the residue.

Process formulation and performance assessment

Given that the resource potential of fines is comprehensively assessed, the next step of facilitating process development is to formulate valorisation process schemes. Article III of this thesis formulates three alternative valorisation process schemes based on fundamentally different resource recovery strategies: 1) maximising specific valuable resources, 2) maximising bulk materials, and 3) optimising full resource recovery. The assessed resource potential of fines in Article II is used as the basis for the selection of the targeted resources in the different process schemes. Previous fines research is mostly confined to the investigation of either the recovery of specific valuable materials such as metals (Allen and Fisher, 2007; Lewis et al., 2011) or the utilisation of the residue as a substitute bulk material in applications such as ground construction (Péra et al., 2004; Rossetti et al., 2006). Additionally, such research is only focused on the recovery of a single targeted resource, whereas integrated processes for the recovery of several resources while maximising the recovery of a targeted resource, which is the approach in Article III, have been overlooked. Similar efforts to that of Article III in terms of formulating valorisation alternatives based on different resource recovery strategies and involving integrated process schemes targeting multiple resources recovery are evident in research concerning other residues such as shredder residues (Høstgaard et al., 2012) and municipal bottom ash (Holm and Simon, 2017). Given that such residues have a more mature research presence compared to fines, the mentioned studies also involve existing industrial processes for scenarios development and data collection in contrast to the assessment in Article III, which is based on conceptual process schemes. Given the substantially high occurrence of pollutants such as heavy metals and organic pollutants, process development for environmental risk reduction is also common in fines research (Mallampati et al., 2016; Singh and Lee, 2015), which is addressed in

Article III in the material upgrading involved in the process schemes of the valorisation alternatives.

When it comes to selecting the right strategy for the development of fines valorisation processes, it is crucial to assess the environmental potential of such processes because resource recovery and recycling are not necessarily environmentally benign (Geyer et al., 2016). Additionally, given that environmental performance of technological processes is largely determined in the early stages of their development (Villares et al., 2017), particularly in the design stage where the unit operations are decided and functional requirements set (Jeswiet and Hauschild, 2005), it is important to perform the environmental assessments already in the design stage of the fines valorisation processes. Article III of this thesis, using a streamlined approach, assesses the life cycle environmental impacts of alternative conceptual approaches to fines valorisation, and thereby provides an initial indication of the environmental potential of the valorisation alternatives, which enables sustainable investment decisions in terms of selecting the most environmentally promising valorisation options and identifying the need for further improvements. Previous research concerning environmental assessments of fines valorisation is absent. However, possibilities for more elaborate LCAs for emerging technologies such as ex-ante LCAs (Cucurachi et al., 2018), which could more accurately facilitate the selection of environmentally preferable valorisation options, particularly upon lab or pilot-scale processing, have been demonstrated in relation to other residues such as e-waste (Villares et al., 2016).

To complement the extensive focus on the local impacts of residue valorisation by Swedish local authorities (Swedish EPA, 2009), Article III focuses on the global impact categories in its LCA. Thereby, necessary knowledge for more environmentally holistic assessments of such applications is provided. Otherwise, it would have been more natural to choose both local and global impact categories to provide a more balanced environmental assessment, which has usually been the approach in the LCA studies concerning other residues such as shredder residues (Boldrin et al., 2015; Ciacci et al., 2010; Vermeulen et al., 2012), municipal bottom ash (Margallo et al., 2014; Sou et al., 2016), and municipal fly ash (Huber et al., 2018).

Different shredding plants would generate fines that carry different resource potentials and (hence) would require different tailored processes of which the exact environmental impacts need to be assessed separately. Nevertheless, as far as the use of principally different valorisation strategies such as the ones used in this thesis is concerned, the difference in the involved processing level between them could be expected to be similar irrespective of the origin of fines, meaning that the characteristic differences in the environmental potentials between the different valorisation strategies would still remain. It also needs to be borne in mind that the environmental assessments are subjected to changes in background system conditions such as the origin of PRM production and the level of technological development, and therefore, need to be assessed for different national contexts

regularly to provide accurate investment and policy guidance. As far as the selection of the right valorisation strategies is concerned, economic assessments are also essential. Nevertheless, such assessments are deemed far-fetched at this early stage of fines valorisation as the actual future investment costs are uncertain and the expected revenues of potential fines-derived SRMs unknown.

8.2 Implications in realising fines valorisation

The preceding section (Section 8.1.) presented a discussion on the contribution of the key findings of the thesis in providing knowledge for facilitating fines valorisation in relation to previous research. This section presents a synthesising discussion on the implications of the thesis contributions in realising fines valorisation.

The findings of Article III show that the current fines disposal by the studied shredding company is primarily determined by the strategic significance of doing so, which, in turn, is strongly motivated by the prevailing governmental policy- and raw material market-related conditions. Such conditions need to be challenged to initiate investments in knowledge and technology development towards valorisation by shredding companies.

8.2.1 Challenging the prevailing conditions sustaining fines disposal

One of the most practical means of compelling shredding companies to seek valorisation-based alternatives in managing fines would be the declassification of landfill covering as backfilling, a measure that has been recognised regarding other residues as well (Arm et al., 2017). It will strip landfill covering of its current status as a recovery³ operation, which is one of the key reasons driving such practice (Article III). That would strengthen the ELV directive's requirements for only thermal recovery other than recycling in ELV management, thus necessitating alternative recovery strategies for fines to fulfil the ELV directive targets. Additionally, it would automatically remove the existing landfill tax concessions in Sweden that are currently enjoyed by shredding companies in utilising fines in landfill covering (Article III). That would render the disposal of fines in landfill covering significantly more expensive, thus making value-added recovery strategies economically worthwhile to consider.

A direct and more drastic means to challenge the current practice of managing fines would be to impose bans or higher punitive taxes on fines disposal that would render LCM markets, the current outlet, economically not worthwhile. An example can be taken from the Netherlands, where the landfilling of several potentially recoverable wastes has been banned (Lieten, 2018). Municipal bottom ash is one such material for which valorisation applications have been consequently developed in the country

³ "Recovery" is any operation by means of which a waste is used or being prepared to serve a particular function by replacing other materials (European Commission, 2008).

(Kahle et al., 2015). The Dutch success story has also been due to the availability of well-established SRM markets. In contrast, a disposal ban on fines in Sweden would be an isolated one, as the fines-derived SRMs would most likely not be equally well received by end users, and thus, might only penalise shredding companies. The aforementioned policy measures could also be complemented with resource recovery mandates. The assessed resource potential in Article II could be eye-openers for the authorities to recognise the significance of fines and thereby develop tailored policy measures.

8.2.2 Creating favourable conditions for fines valorisation

Challenging fines disposal alone would not suffice to realise the valorisation of the material. It is equally important to create favourable and more predictable policy- and market-related conditions to drive and enable actor innovation of applications based on fines valorisation, and thereby, the development of environmentally feasible and cost-effective upgrading and resource recovery processes. That would involve creating secure outlets for fines-derived SRMs and developing clear market and regulatory playing rules for their applications.

8.2.2.1 *Secure outlets for fines-derived SRMs*

Adequate and predictable demand

Article III shows that the availability of an adequate and predictable demand is one of the most important aspects of creating secure outlets for fines-derived SRMs. It is usually not a big problem to find outlets for specific fines-derived SRMs such as metals and organics. The shredding industry already has somewhat established access to markets for such materials through the existing resource recovery from the shredder residue. However, as far as bulk materials such as fines-derived construction aggregates are concerned, user acceptance is currently quite low in Sweden (Bertils and Elvingson, 2019).

Governmental intervention via state-owned users could play a central role in inducing market demand. Examples of such cases can be taken from Denmark and the Netherlands – countries with comparable socio-economic contexts to Sweden – where governmental authorities responsible for transportation utilise bottom ash-derived construction aggregates in the construction of roads and pavements (Johansson, 2018). The same could be implemented regarding fines-derived construction aggregates in Sweden involving the Swedish transport administration (STA). The analysis of the Swedish construction aggregates market in Article V clearly shows that requirements from a customer such as the STA with large bargaining power are a key determinant of the material chosen by the Swedish aggregates users. However, the findings of Article V also show that secondary aggregates are currently only sourced from the existing construction and demolition residues (CDRs), and sourcing from external industrial residues (EIRs) is virtually

non-existent. The utilisation of fines-derived secondary aggregates would therefore require specific measures for the increased utilisation of EIR-derived aggregates.

As much as governmental interventions, innovation based on fines valorisation driven by shredding companies and industrial raw material users is also necessary to create demand for fines-derived SRMs. The government could then take part in facilitating such innovation. An example is the Green Deals program of the Dutch government, where the government enters into partnerships with and encourages voluntary solutions by market actors to solve a waste situation (Dutch Economic Affairs Ministry, 2015), and the government's primary role is to exert recovery demands and facilitate the removal of various implementation barriers (Ellen Macarthur Foundation, 2017), especially related to policy and regulatory conditions.

The assessed resource potential of fines in Article II contributes to the demand creation. On the one hand, it enables authorities to create targeted policy-induced demand (Fellner et al., 2018). However, given that the assessed resource potential in Article II is plant specific, similar assessments for other shredding plants are advisable to support national policymaking. On the other hand, the resource potential assessment increases the knowledge on the resource possibilities and reduces the prevailing negative perceptions regarding aspects like material complexity and contamination potential - such as the once held by the studied shredding company (Article III) - thus enabling better actor initiatives for valorisation-based applications.

Economic competitiveness

The economic competitiveness of fines valorisation is equally important in creating secure outlets for fines-derived SRMs. The assessed resource potential in Article II generally indicates that the economic prospects of fines valorisation could be quite low, given the significant material constraints that need to be resolved by presumably costly upgrading processes. Exogenous support would therefore be needed to justify investments in such valorisation processes. In that regard, market-based policy instruments such as tradeable credits based on amounts recycled and punitive taxes on primary raw materials have been proposed, for example, concerning shredder residues in Belgium (Dubois et al., 2015) to make secondary raw materials (SRMs) economically attractive to potential users. In the context of Sweden and targeting fines, the former, which targets reduced SRM prices, could be a good starting point. The latter, which targets increased PRM prices, is somewhat too early to expect, given that Sweden, unlike Belgium, has plenty of primary raw materials, and its production is a significant part of its economy. Additionally, policy support via financial instruments such as interest-free loans and revenue tax subsidies have been generally proposed to further strengthen and anchor residue valorisation as a general means to facilitate a circular economy (Uusitalo et al., 2020).

Given the right economic conditions, the studied shredding company has clearly shown its will in investing in residue valorisation by investing close to a hundred million Euros within a couple of years for the advanced processing of shredder residues (Article III). That is a strong indication that policy instruments could be used to encourage shredding companies to choose the most environmentally benign valorisation strategies. For instance, despite that the valorisation strategy targeting the bulk materials recovery is the least environmentally preferred (Article III), shredding companies might want to proceed with it given that it is the simplest and quickest option to get rid of fines. There, the aforementioned market and financial instruments could be tailored to encourage valorisation strategies targeting specific resources recovery or full resource recovery, which showed better environmental potential (Article III). Policy measures, however, should consider the fact that the assessed environmental potential is susceptible to different factors that could vary over time. One such factor origin of the substituted PRMs. For instance, the superior environmental potential of the first and third valorisation alternatives is chiefly attributed to the substitution of copper ore and coal. However, these primary raw materials are usually bought in a global market, and there could be substantial differences in the environmental impacts of their production in different parts of the world.

Another factor that could change over time is that the involved process schemes of the different valorisation strategies are conceptual, and future changes could occur in their design.

For instance, the inferior environmental potential of the second valorisation strategy is chiefly attributed to the use of energy-intensive concrete crusher, which may be avoided due to technological innovation.

. Another important factor that could change over time is the potential changes to substitution ratios of the different fines-derived SRMs. For instance, the substitution of current concentration-grade-based substitution ratios could change to economic-value-based ones upon commercial-scale production (Reap et al., 2008) of fines-derived SRMs.

8.2.2.2 Clear market playing rules

One of the key market playing rules is quality specifications for fines-derived SRMs, which are necessary to enable process development for upgrading and resource recovery by residue producers. The studied shredding company clearly indicates that such specifications are lacking (Article III), a challenge generally recognised in the waste management literature (Shahbazi et al., 2013). The analysis of the construction aggregates market in Article V particularly shows that secondary aggregates are not incorporated into the AMA infrastructure standards, which is the key determinant of users' material choice. Collaborative platforms, such as in the aforementioned Dutch Green Deals program, are therefore needed where residue producers could identify

potential user requirements. In that regard, having major actors such as the STA developed specific application standards for secondary aggregates (Article V) would be a key enabler. Assessing the resource potential, as demonstrated in Article II, then provides instrumental knowledge for different users to develop tailored standards to accommodate fines-derived SRMs.

What is more needed to improve upon such initiatives and to internalise secondary raw materials in different industrial sectors is enhanced actor collaborations across the supply chain. For instance, the lack of access to SRMs is a typical challenge in the enhanced utilisation of such materials (Andersson, 2018). The analysis of the construction aggregates market in Article V shows that the convenience of systematic supplier selection and purchase via the use of sophisticated databases and portals are among the main reasons why users would choose to utilise primary raw materials. Given the already-existing economic benefits of avoided material and transportation costs of sourcing primary aggregates, the users would be more driven to utilise secondary aggregates when the systematic sourcing of such materials is enabled via investment in similar systems for the sourcing of SRMs or incorporating them into the existing systems.

Another key market playing rule is pricing mechanisms for fines-derived SRMs, which are necessary for accurate economic assessments, and thus reduce the uncertainty of valorisation investments. As profit-seeking business entities, shredding companies would naturally opt for more economically predictable affairs. The evolving of clear pricing mechanisms would, on the one hand, rely on having established supply and demand structures for fines-derived SRMs, which could, to a certain extent, be facilitated via the creation of secure outlets, as discussed above. On the other hand, the pricing mechanisms also depend on user willingness to pay for such materials. For instance, the analysis of the construction aggregates market in Article V shows that one of the main incentives for users to utilise secondary aggregates is the opportunity to capitalise on the suppliers' disposal problem and source materials for free. Similarly, different potential users of fines-derived SRMs would also want to capitalise on the shredding companies' fines disposal problem and gain an advantage by sourcing fines-derived SRMs as cheaply as possible. However, having secure outlets for fines-derived SRMs would also mean that shredding companies are less likely to have a big disposal problem, and fines-derived SRMs are more likely to have a price tag, at least to break even the costs. The users will then have to be prepared to recognise the value of and be willing to pay for such materials, which are currently uncertain in Sweden given abundant access to primary raw materials such as construction aggregates (Swedish Geological Survey, 2019) and iron and copper (Swedish Government Offices, 2013), which are among the main potential fines-derived SRMs.

8.2.2.3 Clear regulatory plying rules

Similar to user requirements, regulatory requirements also enable the development of upgrading and resource recovery processes. Article III shows that the most prominent regulatory challenge concerning fines valorisation is the lack of specific regulatory requirements on the allowable contamination levels for the utilisation of potential fines-derived construction aggregates in ground construction applications. Examples of specific regulatory requirements of soil contamination levels are found in countries such as Denmark, Netherlands, and Belgium (Flanders region), where application-specific requirements, which are nation/region-wide applicable and binding, are available. In order to minimize pollution concerns, the limit values in these countries are often combined with different safety measures and requirements, such as maximum allowed quantity and layer-thickness of residues in Denmark and the Netherlands, and minimum distance and elevation from water sources in Belgium (Dou et al., 2017; Van Gerven et al., 2005). Urgent recognition of the possibility of a rapid increase in the demand for SRMs and the consequent drafting of legislation by governmental institutes are necessary to implement such regulatory requirements in Sweden. Policy initiatives, such as classifying wastes/residues as anthropogenic stocks (UNECE, 2018), can drastically enable the development of such legislation. Nevertheless, in contrast to the aforementioned countries, the recognition of the need for increased use of secondary construction aggregates is so far limited in Sweden, plausibly owing to the abundance of primary aggregates and landfill space.

Article III also shows that another regulatory challenge is the local authorities' extensive focus on the local environmental impacts of residue valorisation. The life cycle assessment of fines valorisation alternatives in Article V clearly shows that there are significant differences in the global environmental impacts between the different resource recovery strategies. Thus, it is advisable that such global impacts be considered in the environmental assessments in regulating residue valorisation. That would put fines-derived SRMs into a fair trial against the corresponding primary counterparts and, thereby, gain actor trust in SRM-based applications, which is generally lacking in the country (Johansson, 2018). To make the environmental assessments even fairer towards residue-derived SRMs, the local impacts of PRM utilisation should also be taken into account, which is also currently lacking in Sweden, plausibly due to the erroneous perception of natural materials as somehow safe (Skene, 2018). Such facilitation of fines valorisation within the regulatory practice would not only enhance the legitimacy, and thereby, the market acceptance of fines-derived SRMs, but also encourage the development of clear material specifications by users.

Generally, governmental interventions are paramount in both challenging the current practice disposal and enabling favourable conditions for fines valorisation regarding heterogeneous residues in general in Sweden. Therefore, it is worth noticing that such interventions are more likely to first target relatively higher-value residues, for example, electric and electronic residues or larger-volume residues, for example,

municipal bottom ash and slag. Specific interventions targeting fines valorisation would plausibly have to wait. Nevertheless, initiating residue valorisation initiatives in Sweden would first require state-level recognition and the fostering secondary raw materials as a new demand paradigm.

9 Reflections on heterogeneous industrial residue valorisation in a circular economy

This chapter presents a general reflection on the significance of heterogeneous industrial residue valorisation for the circular economy and the thesis contributions in facilitating heterogeneous industrial residues valorisation.

9.1 Significance of heterogeneous industrial residue valorisation in a circular economy

Recycling industries such as shredding will remain well-established sectors in the EU economy in the foreseeable future, and therefore, heterogeneous industrial residues (HIRs) such as fines will continue to be generated. Additionally, in the case of shredding, the discarded products, especially end-of-life vehicles, are getting more and more materially complex (Andersson et al., 2019a), meaning that the high heterogeneity of fines is likely to remain or even increase. Given that the current landfill-related options for their disposal are disappearing in the long term, the recycling industry needs to have secure outlets for its residues. Therefore, dealing with HIRs will be part of the EU's transition towards a circular economy.

Valorising HIRs entails two central dichotomies in the context of a circular economy. One is environment versus economy. From an environmental point of view, the recovery of specific SRMs such as metals, plastics, and minerals is important as it aids in closing the material loops and avoids the production of primary raw materials (PRMs). The findings of Article III of this thesis show that the recirculation of specific secondary raw materials (SRMs) such as metals and organics can also generate significant environmental savings, which is a recurring finding in relation to other HIRs, for example, shredder residues (Ciacci et al., 2010). Metals recovery and recycling are also important from an economic point of view given their high market value compared to bulk materials, for instance. Nevertheless, the general low occurrence of such resources in heterogeneous residues and the unknown processing costs for their recovery imply a high economic uncertainty. In contrast, the recovery of bulk materials for utilisation in applications such as ground constructions could provide an outlet for the whole of the residue and hence avoid disposal costs for the recycling industries. Yet, such utilisation would only substitute PRMs such as sand, gravel, and bedrock, and the findings of Article III show that the environmental savings per tonne of avoided primary production is much less than what could be achieved by recycling metals, for instance. Therefore, the recovery of bulk materials might not be seen as environmentally interesting as the recovery of specific resources. This dilemma of recyclable quantity vs. per-tonne environmental saving between bulk materials is also evident in relation to the valorisation of other HIRs, for example, as municipal bottom ash (Allegrini et al., 2015). A plausible argument for bulk utilisation, however, could be that large quantities of substituted PRMs could still make the absolute environmental savings substantial, which is somewhat

confirmed in the findings of Article III in relation to climate change and acidification impact categories. What is more, the avoided disposal costs of the bulk utilisation could be used to finance the recovery of specific SRMs (cf. Fellner et al., 2015), and thereby relieve the investors of the aforementioned economic uncertainty of such processes. Ultimately, the practice of HIR valorisation would come down to a trade-off between the involved economic and environmental costs and benefits.

The other main dichotomy of HIR valorisation in the context of a circular economy is resource efficiency versus toxicity. A common misconception of recycling is that it is always environmentally benign (Geyer et al., 2016) due to the avoidance of PRM production. However, due to the generally high occurrence of contaminants in heterogeneous residues, resource recovery processes and recycling applications based on such materials could inherently generate environmental and human toxicity impacts due to hazardous dispersals and emissions (Johansson and Krook, 2021). Landfilling, the current mainstream option for managing such residues, is plausibly a less-risky option, at least in the short term, as the leachate is collected and treated in EU landfills (Brennan et al., 2016). However, it comes at the cost of lost resources.

9.2 Thesis contributions towards heterogeneous industrial residue valorisation

A significant opportunity for the valorisation of HIRs seems to exist in our societies, considering the material compositions of such residues and the large amounts in which they are generated and disposed of. Nevertheless, research and development are still evolving for such residues, and only a few valorisation initiatives have taken place. This thesis, via the case of shredder fines, provides key methodological and empirical contributions towards knowledge creation to facilitate the valorisation of HIRs in general.

The overarching contribution is the use of a two-fold, systems-oriented approach for knowledge creation. This thesis demonstrates the use of having, side by side, the two principally different knowledge areas representing two fundamentally different issues of facilitating the valorisation of heterogeneous residues.

One knowledge area involves investigating the present situation concerning a given HIR: knowledge most fundamental to initiate changed practices. Given that both societal and technical factors would naturally influence the management of complex materials such as heterogeneous residues, this thesis demonstrates the use of a socio-technical systems approach to elaborate the present situation in relation to the producer-user duality. The producer perspective, that is, the current practice of managing a given HIR, needs to be investigated to identify the challenges of and possible measures for initiating investments in knowledge and technology development towards valorisation. There, although the individual findings on the underlying factors of the current practice are specific to fines management, the overall empirical contribution that signifies the need for policy and market-related

measures to challenge disposal and create favourable conditions for valorisation is more or less generalisable to different HIRs in the country. The user perspective of the present situation, that is, the market's prospects of SRMs, needs to be investigated to identify the challenges of and possible measures for increased utilisation of a given HIR. In that regard, both the individual findings concerning the rationale of the construction aggregates market and the overall empirical contribution that signifies the need for improved institutional conditions on the different societal levels to increase secondary aggregates utilisation are generalisable to different HIRs in the country.

The second knowledge area of this thesis, provided changed practices are initiated, involves demonstrating a combined methodological approach for initiating process development for the valorisation of HIRs. Given the holistic focus, that is, process development to facilitate full resource recovery, an environmental engineering perspective is used in the method development. The first part of the method involves a systematic assessment of the resource potential of a given HIR to enable the development of integrated processes for material upgrading and resource recovery. There, the focus is put on facilitating full resource recovery, that is, the recovery of both specific valuable materials and bulk materials. The second part of the method involves the formulation of alternative valorisation process schemes based on the assessed resource potential and principally different resource recovery strategies and their environmental assessment. A key overall feature of this combined methodological approach is that it recognises that process development cannot take place in isolation, whereas the upstream and downstream implications of the supply chain must be accounted for as well.

The empirical knowledge generated using the developed method is necessary to guide sustainable investment decisions for and governance of the valorisation of such residues. The resource potential assessment of a given HIR guides governmental policy-making targeting its resource recovery. The environmental potential assessment of the valorisation strategies of the HIR guides investments towards selecting the most promising valorisation strategies for development and identifying the need for further improvements. It also guides national policymaking towards creating favourable market conditions for targeted valorisation strategies and local authorities towards more favourable regulation of fines valorisation.

10 Conclusions

This chapter presents the major takeaway points from addressing the knowledge areas and the corresponding research questions in facilitating fines valorisation and concludes with an overall reflection on the research's contribution to heterogeneous residue valorisation.

This thesis provides knowledge to facilitate the valorisation of shredder fines, or just fines, a heterogeneous residue of one of the prominent Swedish recycling industries, namely the shredding industry. Thus, interdisciplinary, systems-oriented knowledge is contributed to two principally different knowledge areas, that is, the current picture concerning fines management and a potential approach for fines valorisation.

The current picture concerning fines management is portrayed by employing a socio-technical systems perspective. It reveals that in the present Swedish context, the sustained disposal-oriented approach to managing fines seems rational. Multiple factors created due to government policy and regulation, raw material markets, and internal organisational aspects collectively provide shredding companies with incentives for utilising fines in landfill covering and disincentives for opting for valorising the residue. On the other hand, the market prospects of residue-derived secondary construction aggregates, which is a significant potential application for fines valorisation, are also quite low in the country. Various market processes and supporting institutions create several economic and administrative motives for the users towards a dominant and systematic utilisation of primary construction aggregates. Secondary aggregates are opted for unsystematically, driven by situational benefits for different actors. This present situation concerning fines management suggests that strong measures that challenge fines disposal, as well as favourable policy and market conditions that support fines valorisation, are necessary to initiate changed practices.

A potential approach to fines valorisation is showcased by employing an environmental engineering perspective. It demonstrates how the development of valorisation processes could be initiated based on a systematic and holistic methodological approach for the assessment of the resource potential and the formulation and assessment of valorisation alternatives. The employing of the developed methodological reveals that fines generally carries a considerable resource potential, which is an eye-opener for policymaking targeting its resource recovery. It also shows that there are characteristic differences between the alternative approaches to fines valorisation due to the fundamentally different resource recovery strategies they are based on. Such knowledge is essential to guide investments towards the selection of the most sustainable valorisation strategies for development, national policymaking towards creating favourable market conditions for targeted valorisation strategies, and local authorities towards more favourable regulation of applications based on fines valorisation.

Generally, this thesis demonstrates the use of portraying the current picture concerning the present management and market prospects of a given heterogeneous industrial residue to elicit the challenges of and necessary measures for initiating changed practices. It also showcases a potential approach in terms of assessing the resource potential, formulating alternative valorisation process schemes, and assessing their environmental potential to guide sustainable investment decisions for and governance of the valorisation of a given heterogeneous industrial residue. Overall, this thesis demonstrates how systems-oriented knowledge could be generated to facilitate the valorisation of heterogeneous industrial residues. Thus it enables the industries to avoid the disposal problem and reduce the handling costs of such residues and the society in general to improve resource efficiency, which are key in our path towards a circular economy.

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