Opening the black box of material criticality
Heterogeneity and interrelations of companies within and across industrial sectors

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Abstract

The concept of ‘material criticality’ has been introduced to examine availability and accessibility of natural resources that underlie industrial competitiveness and deployment of strategic technologies, such as electric mobility or wind turbines. The academic and policy discourse conceptualised material criticality rather as a black box, assuming industrial sectors to be monolithic, homogeneous and independent entities, neglecting complexity of the company dimension. The thesis questions appropriateness of these assumptions and aims to achieve the following objectives: 1) to examine the influence of heterogeneity and interrelations of companies on identification and mitigation of material criticality; and 2) to demonstrate their relevance for understanding material criticality.

Through the exploratory case based research, the thesis highlights the importance of the company dimension for examination of critical materials. The findings indicate the need to extend the criticality analysis to consider power relations of companies along supply chains, and competitive relations of companies across industrial sectors at a shared resource market. These relations influence a company’s ability to identify and mitigate material criticality, which in turn affects an industrial system’s ability to withstand supply disruptions. Heterogeneity of companies within and across industrial sectors suggests against utility of generic outcomes of the criticality analysis at the national/global levels.

The thesis provides implications for policy-makers regarding selective support for companies and industrial sectors to assist their efforts to mitigate material criticality. The results serve to raise awareness of practitioners about material criticality and to assist with the decision-making for development of mitigation strategies. Finally, the thesis calls for the need to establish a dialogue between policy-makers, industrial actors and researchers to advance understanding and analysis of material criticality.

**Key words:** critical materials, identification, mitigation, company, supply chain, inter-sectoral competition, buyer-supplier power relations.
Sommario

La nozione di “materiali critici” è stata introdotta in anni recenti per governare sul piano industriale le problematiche legate alla disponibilità e accessibilità di risorse naturali che stanno alla base dello sviluppo di tecnologie strategiche, quali la generazione eolica o la mobilità elettrica. Istituti di ricerca e governi hanno finora approcciato il problema considerando la dimensione industriale come una “scatola nera”, ovvero assumendo i settori industriali come entità monolitiche, omogenee e indipendenti, trascurando così la possibile rilevanza delle specificità aziendali. Partendo da questi presupposti, la tesi si pone due obiettivi: 1) esaminare l’influenza di eterogeneità e interrelazioni tra imprese sui processi di identificazione e mitigazione dei materiali critici; e 2) dimostrare la rilevanza dell'eterogeneità e delle interrelazioni tra imprese nella comprensione del fenomeno nel uso complesso.

Attraverso ricerca empirica basata su casi, la tesi mette in evidenza un insieme di fattori di natura industriale fondamentali per la piena comprensione e la gestione dei materiali critici. In particolare, i rapporti di forza cliente-fornitore (power regime), lungo le catene di fornitura, e la competizione tra imprese che agiscono sullo stesso mercato dei materiali critici. Questi aspetti condizionano, inoltre, il grado di consapevolezza dell'azienda circa la criticità dei materiali e la fattibilità di diverse possibili azioni di mitigazione. Ne deriva per le imprese una scarsa utilità di analisi generaliste, quali elenchi di materiali critici redatti periodicamente da centri di ricerca ed altri enti pubbliche.

La tesi fornisce raccomandazioni per i decisori politici per quanto riguarda il sostegno selettivo a imprese e a settori industriali, al fine di assistere in modo mirato e appropriato gli sforzi per mitigare i rischi legati all’uso di materiali critici. I risultati raggiunti servono anche a sensibilizzare i manager circa la complessità del fenomeno, aiutandoli nel prendere decisioni razionali circa le strategie di mitigazione. Infine, si sottolinea la necessità di stabilire un dialogo tra diversi attori per progredire nella comprensione e nello sviluppo di adeguati strumenti di analisi della criticità dei materiali.

Sammanfattning

Begreppet materialkritikalitet (material criticality) har införts för att undersöka tillgänglighet och åtkomlighet till naturresurser som bär upp industriell konkurrenkskraft och insatser av strategiska tekniker, såsom elektrisk mobilitet eller vindturbiner. Den akademiska och politiska diskursen har konceptualiserat materialkritikalitet närmast som en ”black box” utifrån antagandet att näringsgrenar är monolitiska, homogena och oberoende enheter, och bortser från komplexiteten i bolagsdimensionen. Avhandlingen ifrågasätter dessa antagandens lämplighet och avser att uppnå följande mål: 1) att undersöka hur heterogenitet och bolags inbördes förhållanden inverkar på identifiering och motverkande av materials kritikalitet; och 2) att påvisa deras relevans för att förstå materialkritikalitet.


Avhandlingen tillför återverkningar för beslutsfattare när det gäller selektivt stöd åt bolag och näringsgrenar som hjälp till deras insatser att motverka materialkritikalitet. Resultaten bidrar till att höja medvetenheten hos praktiskt verksamma om materialkritikalitet och att bidra i beslutsfattandet om utveckling av strategier för motåtgärder. Slutligen manar avhandlingen till att inleda en dialog mellan beslutsfattare, näringslivets aktörer och forskare för att förbättra förståelsen och analysen av materialkritikalitet.

Nyckelord: kritiska material, identifiering, motåtgärder, bolag, leveranskedja, intersektoriell konkurrens, maktförhållande köpare-säljare
List of appended papers

This thesis is based on four papers that are enclosed at the end.

Paper A


An earlier version of this paper was presented at the GCPC Conference, November 2015.

Paper B


An earlier version of this paper was presented at the EurOMA conference, July 2017.

Paper C


An earlier version of this paper was presented at the World Resources Forum, October 2017 and is to be presented at the EurOMA conference, June 2018.

Paper D


An earlier version of this paper was presented at the EurOMA conference, July 2017 and at the Circular Materials Conference, May 2016
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1. Introduction

This is the cover essay of the thesis that seeks to open the black box of current conceptualisation of material criticality by focusing on examination of the company dimension. This chapter introduces the research problem, presents objectives and the main research question, and provides a structure of the cover essay.

1.1. Research background and motivation

For centuries, natural resources such as minerals have been key elements of industrial competitiveness and prosperity of nations. Unequal distribution of resources on the planet forced the need to secure access to resources via explorations of new lands, population migrations to resource-rich areas, development of trade across the globe and even lead to geopolitical conflicts. Nowadays, increasing world population together with growing demand from newly industrialised countries have been raising concerns of both governments and industries about ensuing availability of natural resources and their appropriate management. The current resource management at the international arena stems from the fear of nationalization of resources, increased government control, protectionism in favouring domestic industries via decreased export rates or pricing policies (e.g., Buijs and Sievers, 2012; Humphreys, 2013). Such resource management measures affect the international trade and mineral supply chains. For example, the civil war in Zaire (now the Democratic Republic of Congo) in 1970s lead to shortage of cobalt in the global scale (Alonso et al., 2007). China’s reduction of export rates of rare earth elements in 2010 resulted in escalation of their prices (Buijs and Sievers, 2012a).

The concerns over availability of and accessibility to resources are not new. For example, in 1798 Thomas Malthus examined the growth trends of population versus farmlands and warned about incapacity of supply to catch up with increasing demand for food (Malthus, 1978). In addition in 1865 Stanley Jevons raised concerns about scarcity of coal due to rising extraction rates and its possible impact on British economy (Jevons, 1865). These examples stress concerns about physical availability of resources in respect to
demand and population growth. This view is often called the fixed-stock paradigm, as the argument is grounded on the finite stocks of exhaustible resources on the planet and their decrease over time (Tilton, 2003, 1996).

An alternative perspective has also been proposed. The opportunity-cost paradigm highlights price mechanisms as regulators of resource scarcity (Tilton, 2003, 1996). For example, price increase of minerals may serve as an incentive for investments in capacity development or exploration of new reserves, as well as reduction of demand due to more efficient use and substitution. The supporters of this perspective argue that throughout history price mechanisms proved to be efficient in mitigation of resource scarcity. Indeed, as we know, the predictions of Malthus and Jevons did not materialise due to technological advances and substitutions. However, the fixed-stock paradigm questions adequacy of reliance on new possible technologies and market incentives. The past is no guaranty for the future, and market mechanisms often fail to consider environmental and social externalities associated with production of exhaustible resources (Krautkraemer, 2005; Söderholm and Tilton, 2012; Tilton, 1996).

So far, neither the fixed stock nor the opportunity cost paradigm has managed to prove the other completely wrong. For example, Henckens et al. (2014), supporting the fixed-stock paradigm, calls for inter- and intra-generational responsibility for resource exploitation and the need for sustainable extraction rates. Tilton et al. (2018) brings arguments in favour of the economic perspective on scarcity. This multiplicity of views on scarcity is sustained by uncertainty regarding future trends in mineral supply and demand, uncertainty of future technological changes, the difficulty measuring environmental and social impacts, and unknown amount of resources in the Earth’s crust (Tilton, 2003).

The examination of resource scarcity has also attracted the attention of policymakers. In particular, the debate over resource scarcity in the academic circles translated into a policy discourse with the introduction of the so called ‘material criticality analysis’ (European Commission, 2010; NRC, 2008). That is an instrument for identification of problems that might arise over the access
to resources, and for development of raw materials policy (Blengini et al., 2017; Buijs and Sievers, 2012a).

Throughout the last century, different materials were considered as critical at different periods of time even though the fundamental concerns were and still are the same. This is mainly due to changes in technologies and economic development trends, changes in supply and demand structures, political conditions (Buijs and Sievers, 2012b). Nowadays, the materials labelled as critical have particular impact on emerging technologies that are indispensable to abate climate change and to ensure sustainable development, such as photovoltaic panels, wind turbines, electric mobility etc. (European Commission, 2017, 2014a).

The concept of material criticality incorporates both physical and economic aspects of scarcity: geological availability and accessibility of materials (e.g., reserve/production rate, rate of exploration, recycling rate) and economic impacts/vulnerability to supply disruption (ability of an industrial system to obtain materials and to address the supply-demand imbalance) (European Commission, 2010; NRC, 2008). Initially the debate has been dominated by governance/policy documents and reports, but in recent years the topic has grasped the attention of researchers and many academic studies have been published (Jin et al., 2016; Peck et al., 2015). The research effort has been mainly focused on identification of factors that influence material criticality (Achzet and Helbig, 2013; Helbig et al., 2016), development of assessment methodologies (Bach et al., 2017; Glöser et al., 2015; Graedel et al., 2012; Roelich et al., 2014) and suggestions of mitigation actions (Wäger et al., 2012; Weiser et al., 2015; Wellmer and Dalheimer, 2012).

So far, material criticality studies have examined industrial systems with different geographical scopes (European Commission, 2017; Hatayama and Tahara, 2015; NRC, 2008), various technologies and industrial sectors (Moss et al., 2013; U.S. Department of Energy, 2011; Widmer et al., 2015). Available studies tend to conceptualise the system under examination considering industrial sectors as homogeneous and even monolithic entities, just formally acknowledging their composition and complexity. Moreover, industrial sectors are assumed to be independent entities, as interconnections of end-
use applications of the same material are neglected. Although several studies propose an assessment methodology for a company (Graedel et al., 2012; Kolotzek et al., 2018), the company dimension is positioned as an independent layer of the material criticality, suggesting that a criticality factor relevant for an industrial system might not be relevant for a company and vice versa. Such an “isolation” of a certain dimension is problematic as that limits a phenomenon and disengages it from a full spectrum of influencing factors.

Figure 1 characterises the common assumptions of the academic and policy discourse regarding their approach to conceptualise the system under examination. It is evident that these assumptions significantly simplify the reality. However, the question is if the assumptions allow to properly examine the essence of material criticality or if they lead to its incomplete conceptualisation and operationalisation?

The concept of material criticality was established and is driven by the policymakers interested in the development of a governance tool. As a result, the discourse has been primarily focused on development of the factors and assessment methods, rather than on understanding the phenomenon, the mechanisms and nuances that drive supply and demand. Such an approach does not allow for further development/understanding of the concept (Wacker, 2004; Whetten, 1989). Instead, the understanding of material criticality requires scrutiny and raises the following questions among many. How critical are critical materials for different industrial actors? Are there any differences among industrial sectors as regards material criticality? Is criticality an issue that spans along the value chains? This thesis attempts to empirically examine some of these aspects focusing on the company dimension and its role in identification and mitigation of material criticality.
Figure 1. The discourse assumption vs complexity of the reality.
1.2. Research objectives and question

The current policy and academic debate on material criticality tends to either neglect the company dimension considering industrial sectors rather as a black box, or conceptualising the company dimension as an independent level of analysis, not connected to an industrial system. In this thesis, I argue that both approaches are problematic. Companies face supply disruptions and develop strategies to secure supply of materials, and thus, can directly affect material criticality. Their views on material criticality can differ from what the literature and policy documents stipulate. The examination of material criticality, overlooking the complexity of industrial sectors, might provide unreliable results and the corresponding mitigation actions might lead to final effects different from the intended ones.

Companies are indispensable elements of any industrial system, and should be considered as such in the criticality analysis. It is necessary to bring in complexity of the company dimension starting from the characteristics that have been neglected with the current assumptions: heterogeneity and interrelations of companies (see Figure 1). The heterogeneity of companies refers to differences among companies in relation to identification and mitigation of material criticality. The assumption of the independence of industrial sectors suggests examination of interrelations of companies across industrial sectors. However, companies are not independent within an industrial sector either. They are tied in buyer-supplier relations along supply chains. Therefore, it is also necessary to consider intra-sectoral company relations. Figure 2 depicts transition from the assumptions that prevail the current discourse to the focus of examination of this thesis.

This thesis has two interrelated aims. Firstly, it aims at examining the influence of heterogeneity and interrelations of companies within and across industrial sectors on identification and mitigation of material criticality. As it was discussed above, the heterogeneity and interrelations of companies comprise the attributes of the reality as opposed to the assumptions currently employed in the discourse. Together they characterise the company dimension that has been rather neglected so far. Secondly, the thesis seeks to demonstrate the
relevance of inter-/intra-sectoral heterogeneity and interrelations of companies for the material criticality conceptualisation. This aim allows examining if consideration of the company dimension is indispensable for understanding material criticality.

Figure 2. Positioning of research objectives and questions (the arrows indicate the logical connection, not the cause-effect connection).

In order to achieve the aims stipulated above, this thesis poses the following overall research question:

*How do heterogeneity and interrelations of companies within and across industrial sectors influence identification and mitigation of material criticality?*

With this research question, the thesis intends to bring attention to the importance of the company dimension for understanding and management of material criticality.
1.3. Structure of the thesis

The thesis is composed of the cover essay and four appended papers. Figure 3 below illustrates the structure of the thesis.

The cover essay consists of six chapters. Chapter 1 introduces the research background, sets the research problem and presents objectives and research question of the thesis. Chapter 2 provides an overview of material criticality discourse and discusses implications from resource oriented organisational theories. Chapter 3 describes the research design of the thesis, including empirical settings, data collection and analysis, and research rigour. Chapter 4 presents the summary of appended papers. Chapter 5 discusses the obtained findings in the context of research objectives and the main research question. Chapter 6 concludes the thesis providing implications for theory, practice and policy makers, discussing limitations and indicating prospects for further research.
Chapter 1
Introduction:
Research background; research objectives and research question

Chapter 2
Conceptual foundations of materials criticality

Chapter 3
Research methodology: empirical settings, data collection and analysis, research rigour

Chapter 4
Overview of appended papers

Chapter 5
Discussion

Chapter 6
Conclusions, implications, limitations and further research

Paper A
Business perspective on materials criticality

Paper B
Intra-sectoral mechanisms: role of power relations across supply chain tiers

Paper C
Inter-sectoral mechanisms: role of competition at resource markets

Paper D
Closed-loop supply chain as a strategy to mitigate materials criticality

Figure 3. Structure of the thesis.
2. Theoretical background

While the introduction presented the research background and shaped the scope of the thesis, this chapter provides an overview of the discourse on material criticality in order to set a proper ground for the research investigation and the analysis of obtained results. Given that material criticality is rather a new concept, this chapter starts with examination of its key antecedent – resource scarcity. Then, the discourse on material criticality is presented and limitations of its current conceptualisation and analysis are discussed. The chapter ends with introduction of two organisational theories that serve as lenses for examination of the company dimension, and in particular, interrelations of companies within and across industrial sectors.

2.1. From resource scarcity to material criticality

The term “criticality” in the context of raw materials can be tracked back to 1939, when the “Critical Material Stockpiling Act” was issued in the US, which was followed by different acts in the US and Europe (Buijs and Sievers, 2012b; NRC, 2008). This term was employed in relation to the debate on availability and accessibility to natural resources that are important to the national economy. However, until the 21st century “criticality” did not have its own identity, but was rather viewed as a policy alternative to the academic term “scarcity”. In 2008 Natural Resource Council in the US introduced the material criticality assessment methodology (NRC, 2008) that brought a new perspective on resource scarcity and the term “criticality” started to take its position in the academic discourse. But is “criticality” principally different from “scarcity”? The following paragraphs introduce the discourse on resource scarcity and its relation to current research on material criticality.

In the academic literature, resource scarcity has been discussed from two distinctive perspectives: geologic (physical scarcity) and economic (economic scarcity). Each perspective takes a particular approach for conceptualisation and measurement of scarcity. The geologic perspective examines scarcity by analysing quantity and quality of known resources and their exploration rates in relation to demand trends for resources and their extraction rates. Based on these data, predictions are made about reserve life expectancy, which serves as an indicator of scarcity and depletion (Henckens et al., 2014;
Krautkraemer, 1998; Tilton, 1996). However, this view has been argued to be not reliable, because quantities of known available resources are constantly changing (Tilton and Lagos, 2007; Tilton, 1996). Explorations of new reserves and technological advances that allow processing of resources with lower quality bring in new supplies.

Although the absolute geological scarcity might be claimed as unlikely (Graedel et al., 2014), periods of temporal shortage are indicated as an unavoidable feature of exploitation of exhaustible resources such as minerals. The mining industry is characterised by high investment costs and long time required for capacity development and exploration of new reserves (Humphreys, 2014; Nuur et al., 2018). Therefore, supply cannot be easily adjusted to changes in demand and prices (Humphreys, 2014). In addition, minerals produced as by-products are subject to the structural scarcity. Their extraction depends on demand dynamics for a primary material, rather than their own demand (e.g., indium is extracted from zinc ore). When extraction of a primary mineral does not produce sufficient amount of a by-product to meet its demand the structural scarcity occurs (Henckens et al., 2014).

According to the economic perspective, a resource will become unaffordable long before its shortage occurs. Therefore, price/cost increase due to supply-demand imbalance is argued to be a better indicator of scarcity (Cleveland, 1993; Tilton, 1996). In particular, three economic indicators of scarcity are usually distinguished in the literature: i) natural resource extraction cost (the labour/capital cost per unit of output); ii) market price of natural resource commodity; and iii) user cost (value of future profits forgone by producing the last unit now rather than exploiting it in the future) (Brown and Field, 1978; Cleveland, 1993; Hall and Hall, 1984). These indicators have been criticised for various conceptual flaws such as assumptions about rational economic behaviour and awareness of scarcity when decisions regarding resource allocation are made (Cleveland, 1993). Other factors such as technological change, taxation, change of market structure etc. may also influence the price and thus mask resource scarcity (Brown and Field, 1978; Cleveland, 1993; Hall and Hall, 1984; Krautkraemer, 1998). Although it is assumed that price/cost encompasses all factors influencing scarcity, there are no studies that would demonstrate so. Henckens et al. (2016) show the market
failure to signal mineral exhaustion with commodity price increase. This is particularly an issue when environmental impacts of resource extraction are not considered in the price mechanisms (Krautkraemer, 2005).

The examination of both perspectives demonstrates complexity and multiplicity of resource scarcity. Each perspective addresses particular aspects of the phenomenon, and is subject to assumptions, uncertainties and criticism. Regardless of the perspective, indicators raised concerns about their ability to embody all relevant forces that lead to resource scarcity (Brown and Field, 1978). For decades researchers have called for necessity to examine supply and demand factors that influence scarcity, rather than to focus only on an indicator that supposedly represents those factors (Brown and Field, 1978; Cleveland, 1993). Since then, publications have discussed plethora of factors affecting resource scarcity related to supply and demand conditions, interests of stakeholders, institutional arrangements etc. (Poulton et al., 2013; Wäger and Classen, 2006).

It is possible to argue that the concept of material criticality is a translation of the original concept of resources scarcity from a perspective of policy-makers. Both resource scarcity and material criticality aim to capture the same phenomenon, but with different scopes of conceptualisation. In particular, material criticality steps away from the resources scarcity discourse over the best perspective and the best indicator. Instead, material criticality focuses on identification of influencing factors converging geologic, economic, geopolitical, sustainability and other aspects. Such conceptualisation brings its own limitations, which are discussed in the following section.

2.2. Material criticality: identification and mitigation

Although there is no broadly accepted definition of material criticality, there seem to be a general agreement that two dimensions define criticality. They are: likelihood of supply disruptions (supply risk) and economic impact of (vulnerability to) supply disruptions (Erdmann and Graedel, 2011; Graedel and Reck, 2015; Jin et al., 2016; Peck et al., 2015). However, studies differ greatly in terms of factors considered for conceptualisation of each dimension. Achzet and Helbig (2013) and Helbig et al. (2016) reviewed
existing frameworks of the criticality analysis and summarised the most common criticality factors. They are presented in Figure 4 below. Recent publications introduced more factors related to environmental and social impact taking inspiration from the sustainability research domain (Bach et al., 2017; Kolotzek et al., 2018). However, little attention has been given to justification of the factors employed in the assessments. Studies do not tend to explain how the factors are selected, why they are necessary and sufficient to grasp material criticality.

The first criticality assessment methodology was developed in the policy circles by National Research Council (NRC, 2008). The proposed method introduced the criticality matrix of two dimensions: supply risk and impact of supply restrictions (see Figure 5). Position of a material in the matrix is determined by its values at two dimensions, while its criticality status depends on an established threshold. Similar approach was further adopted for criticality assessment in the EU (European Commission, 2017, 2014a, 2010). However, a number of other methodologies have emerged. For example, Moss et al. (2013) performed the analysis assessing only one dimension (supply disruption). Graedel et al. (2012) extended the criticality matrix to the criticality space by introducing ‘environmental impact’ as the third dimension (see Figure 5). Kolotzek et al. (2018) suggested the following three dimensions for the criticality analysis: supply risk, environmental and social. However, Glöser et al. (2015) and Frenzel et al. (2017) point out that such developments are problematic due to deviation from the two-dimensionality, which is the key premise for the risk assessment.

The criticality analysis frameworks differ in terms of weights of factors considered, procedures for aggregating factors into final scores of key dimensions, calculations of the overall criticality indicator, thresholds to delineate when materials become critical etc. Given this diversity, the studies are usually criticised for the lack of transparency of calculations and justification of methodological choices (Erdmann and Graedel, 2011; Graedel and Reck, 2015; Lloyd et al., 2012).
Factors of the vulnerability dimension (Helbig et al., 2016)
- Substitutability
- Value of products affected
- Future demand/supply ratio
- Value of the utilised materials
- Spread of utilisation
- Change in demand share
- Import dependence
- Target groups demand share
- Strategic importance
- Ability to innovate
- Change in imports
- Company concentration of production
- Consumption volume
- Mine production change
- Recyclability

Factors of the supply risk dimension (Achzet and Helbig, 2013)
- Country concentration of production
- Country governance
- Depletion time
- By-product dependency
- Company concentration in mining corporations
- Demand growth
- Import dependence
- Recycling/recycling potential
- Substitutability
- Volatility of commodity prices
- Exploration degree
- Production costs in extraction
- Stock keeping
- Market balance
- Mine/refinery capacity
- Future market capacity
- Investment in mining
- Climate change vulnerability
- Temporary scarcity
- Risk of strategic use
- Abundance in earth’s crust

Figure 4. Criticality factors.
Materials criticality has dynamic nature, as it is subject to changes in demand and supply conditions, changes of society’s view on certain materials, technological change and political vision (Erdmann and Graedel, 2011; Graedel and Reck, 2015). For example, the EU criticality analysis in 2014 indicated that some materials lost their criticality status comparing to the assessment in 2010 (European Commission, 2014a, 2010). Consideration of different time horizons in the analysis also may lead to different assessment outcomes, what was demonstrated by U.S. Department of Energy (2011). Buijs et al., (2012) indicate the current discourse fails to distinguish short-term and long-term problems related to criticality, and warn about poor predictive power beyond the short-term criticality assessment.

Researchers argue that outcomes of the assessment depend on a system under considerations (Erdmann and Graedel, 2011; Lloyd et al., 2012), meaning that a material critical for France is not necessarily critical for Japan due to different industrial sectors comprising national economies, different supply and demand conditions etc. Moreover, some researchers suggest that assessment methodologies should be different for systems with different boundaries, such as a company and a nation. For example, Graedel et al. (2012) proposed a methodology with different frameworks of factors for criticality analysis at global, nation and company levels. Such division might

Figure 5. Examples of criticality assessment approaches.
jeopardise conceptualisation of material criticality and generate confusion regarding meaning and relevance of various criticality assessments. The suggestion that companies need a specific assessment methodology is problematic, because a) companies may disregard outcomes of the criticality analyses conducted at the nation level; and b) the criticality analysis at the global/national level does not need to consider company dynamics because they have to be addressed within a specific methodology for companies. Both are conceptually problematic. Companies are parts of an industrial system, and therefore, the impact of material criticality on that system is inevitably passed on companies and vice versa.

However, there are just a few papers that either propose methodologies for companies (Graedel et al., 2012; Kolotzek et al., 2018) or bring insights from empirical examination of companies (Mroueh et al., 2014; Slowinski et al., 2013). The majority of studies examine global materials flows, analyse industrial systems with different geographical scopes (European Commission, 2017; Hatayama and Tahara, 2015; NRC, 2008), or focus on particular industrial sectors and technologies. Table 1 provides an overview of different types of criticality studies.

The criticality analysis focuses on examination of materials flows in terms quantities of materials entering and leaving an industrial system (or absolute quantities when analysis is performed at the global level). Criticality studies tend to consider key processes along the value chain of a material (in terms of quantities), distribution of material’s extraction and production among countries and distribution of material’s employment among final applications (industrial sectors) (e.g., European Commission, 2017; U.S. Department of Energy, 2011). For example, the EU assessment formally acknowledges different industrial sectors in order to estimate their contribution to European economy. Very few studies identify key industrial actors along supply chains (e.g., Mroueh et al., 2014). And no studies consider companies and their relations that develop and drive materials flows (expect publications explicitly focused on empirical examination of companies).
Table 1. Different types of criticality studies.

<table>
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<tr>
<th>Scope of analysis</th>
<th>Characteristics</th>
<th>Examples of studies</th>
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<tr>
<td>Global materials flows</td>
<td>Examination of materials flows, considering global supply and demand conditions and trends, overall impact on the environment. Analysis of ability of global supply to meet demands of growing world population. Not considered: distribution of materials use among applications (industrial sectors) and geographic regions, their interconnection, supply chain structures, heterogeneity and interconnection of industrial actors.</td>
<td>(Graedel et al., 2012) (Graedel et al., 2015) (Nassar et al., 2015) (Panousi et al., 2015) etc.</td>
</tr>
<tr>
<td>Industrial system (a country, a region)</td>
<td>Examination of materials flows, considering global availability of materials, supply structure of a specific industrial system, demand of a specific industrial system, global demand trends, distribution of materials use among applications (industrial sectors), economic importance/vulnerability of a specific industrial system. Focus on materials employed in industrial sectors important for a specific industrial system. Not considered: interconnections of industrial systems utilising the same critical material, heterogeneity and interrelations of companies within and across industrial sectors.</td>
<td>(NRC, 2008) (European Commission, 2017, 2014a, 2010) (Graedel et al., 2012) (Morley and Eatherley, 2008) (Hatayama and Tahara, 2015) (Nassar et al., 2015) (Panousi et al., 2015) etc.</td>
</tr>
</tbody>
</table>
Examination of materials flows, considering global availability of materials, supply structure of a company, demand of a company, economic importance/vulnerability of a company. Focus on materials employed in a company. Not considered: interconnections of companies utilising the same critical material within and across industrial sectors. (Graedel et al., 2012) (Slowinski et al., 2013) (Rosenau-Tornow et al., 2009) (Kolotzek et al., 2018)

In summary, it appears that the current criticality analysis is conducted under implicit assumptions that industrial sectors, which comprise an industrial system under examination, are:

- monolithic: focus on attributes of the whole industrial sector, no considerations of its composition (typical for studies at the global level), or
- homogeneous: focus on attributes of the whole industrial sector; acknowledgement of materials value chain structures and multiple industrial actors; no consideration of differences among the actors (typical for studies at industrial system/sector level), and
- independent: acknowledgement of distribution of a material among its end uses (industrial sectors); no consideration of interrelations of industrial sectors utilising the same material(s) (typical for studies at al levels).

Same assumptions are also notable when mitigation of material criticality is discussed. The approaches are usually proposed with an industrial system in mind, and it is possible to find only a few fragmented implications for companies (e.g., Graedel et al., 2014; Morley and Eatherley, 2008). Buijs and Sievers (2012b) point out that the suggested mitigation options have not changed since first reports were published decades ago, and that they rely on basic economic principles as material efficiency, efficient use of products, substitution of materials and products, finding new sources of primary supply, increasing secondary sources of supply (recycling). Several publications integrate proposed solutions into comprehensive frameworks (Wäger et al., 2012; Weiser et al., 2015; Wellmer and Dalheimer, 2012) (see Table 2).
<table>
<thead>
<tr>
<th>Authors</th>
<th>Mitigation actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wäger et al. (2012)</td>
<td><strong>Mining</strong>:&lt;br&gt;• Recovery of historical materials&lt;br&gt;• Certification/labelling&lt;br&gt;• Sustainability standards&lt;br&gt;• Good governance and transparency&lt;br&gt;• (Eco-)efficient mining/refining processes</td>
</tr>
<tr>
<td></td>
<td><strong>Manufacturing</strong>:&lt;br&gt;• Recycling of manufacturing scrap&lt;br&gt;• Leasing/selling functions&lt;br&gt;• Product design&lt;br&gt;• Materials efficiency&lt;br&gt;• Substitution</td>
</tr>
<tr>
<td></td>
<td><strong>Product use</strong>:&lt;br&gt;• Sufficiency&lt;br&gt;• Product lifetime</td>
</tr>
<tr>
<td></td>
<td><strong>Recycling</strong>:&lt;br&gt;• Certification/labelling&lt;br&gt;• Stockpiling&lt;br&gt;• (Eco-)efficient end-of-life product collection and recovery systems&lt;br&gt;• Recycling chain interfaces</td>
</tr>
<tr>
<td>Wellmer and Dalheimer (2012)</td>
<td><strong>Supply mechanisms</strong>:&lt;br&gt;• Primary Raw Materials (Exploration, Investment in new production, Increase of recovery of raw material out of the deposits and in beneficiation/metallurgy)&lt;br&gt;• Secondary Raw Materials (Improvement of Recycling, Use of lower grade scrap)</td>
</tr>
<tr>
<td></td>
<td><strong>Demand mechanisms</strong>:&lt;br&gt;• Thrifter consumption of materials&lt;br&gt;• Substitution&lt;br&gt;• New Technologies with totally different raw material profile</td>
</tr>
<tr>
<td>Weiser et al. (2015)</td>
<td><strong>Governance interventions</strong>:&lt;br&gt;• Support programs&lt;br&gt;• Legislation&lt;br&gt;• Taxation&lt;br&gt;• Monitoring and other data sampling&lt;br&gt;• Political strategies&lt;br&gt;• Private industry initiatives and networks&lt;br&gt;• Standard-setting incl. resource top-runner&lt;br&gt;• Consumer education and awareness programs&lt;br&gt;• International institutionalization and global governance&lt;br&gt;• Good governance and transparency initiatives</td>
</tr>
</tbody>
</table>
Wäger et al. (2012)’s life cycle perspective points out that different actions are suitable for different actors along a supply chain and that all actors should take mitigation actions to address such a complex issue. Wellmer and Dalheimer (2012) support Wäger et al. (2012) indicating that both demand and supply conditions should be addressed simultaneously to mitigate material criticality. Weiser et al. (2015) highlight importance of governance mechanisms to assist technology options. These researchers indicate that a combination of strategies, taken by different industrial actors and policymakers is required to mitigate material criticality. In addition, Weiser et al. (2015) point out the need for a materials specific approach for mitigation, as there is no an ideal set of strategies applicable for all possible materials.

Given the multiplicity of possible actions and heterogeneity of actors, it is not clear how the mitigation actions are to be selected from a list, what actors should apply which actions along a supply chain and across industrial sectors, and how to ensure compatibility (long-term alignment) of actions taken by different companies. For example, Allwood et al. (2013) highlight trade-offs between different material efficiency strategies. Furthermore, little research efforts have been put to examine feasibility of proposed strategies and their relevance to companies that comprise an industrial sector. Need for governmental intervention is another open issue. For example, Buijs and Sievers (2012b) point out that the list of critical materials might bring attention to issues that could be resolved through market mechanisms without policy support.

| Technology options | - Primary production efficiency  
|                    | - Product manufacturing efficiency and pre-consumer recycling  
|                    | - Material efficiency  
|                    | - Eco-design and life-cycle management  
|                    | - Substitution  
|                    | - Innovative end-of-life recycling technologies |
The overview of the literature demonstrates that the current discourse on material criticality does not provide sufficient explanations of the phenomenon involving the company dimension. The employed assumption about industrial sectors (monolithic, homogeneous, independent) considerably simplify the reality and raise questions regarding thoroughness of conceptualisation of material criticality and validity of assessment results. Industrial sectors are not monolithic and homogeneous, they are comprised of a plethora of different industrial actors. These actors are interconnected via exchanges of resources that form supply chains. Moreover, no company is independent, and therefore, it would be erroneous to neglect the role of its relations with other actors in the criticality analysis. As each material is employed in more than one industrial sector, these sectors are not independent: each sector may affect as well as be affected by other industrial sectors that employ the same material. The overall discussion over identification and mitigation of material criticality lacks consideration of the company dimension.

2.3. Leveraging organisational theories to enhance the notion of material criticality

The thesis attempts to examine the role of the company dimension in material criticality, in particular, focusing on heterogeneity and interrelations of companies within and across industrial sectors. The previous section indicated that the current discourse on material criticality does not provide a sufficient ground for examination of the company dimension. This requires bringing in an organisational perspective to the current discourse. The organisational theories serve as appropriate theoretical lenses for this purpose, because they have been employed for examination of company operations and relations for decades.

Many organisational theories can provide implications for the company dimension of material criticality in general and for interrelations of companies in particular. However, just a few theories conceptualise company relations around resource employment and offer implications applicable to natural resources. Therefore, it is deemed worthless to revise all organisational
theories on their relevance to the company dimension of material criticality. Instead, this section focuses on theories that assist in addressing the research objectives of the thesis. In particular, two theories are discussed: resource dependence theory for intra-sectoral company relations and factor-market rivalry for intra-sectoral company relations.

Interrelations of companies within an industrial sector are considered in terms of direct resource exchange relations that are formed along a supply chain. Such relations are conceptualised by resource dependency theory (RDT) from dependence and power perspective (Pfeffer and Salancik, 1978). RDT postulates that a company cannot be self-sufficient in relation to resources indispensable to operations, and therefore, its survival depends on the ability to obtain resources from external environment (Pfeffer and Salancik, 1978). In particular, Pfeffer and Salancik (1978) indicate that resources create dependence when they are important and scarce. Conceptualisation of power (or dependence) attributes as ‘importance’ and ‘scarcity’ can be traced back to Emerson (1962). Since then power attributes have been further developed by various researchers (Kähkönen and Virolainen, 2011; Meehan and Wright, 2012). The most common attributes can be summarized as: relative magnitude of the resource exchange to a company's business, regularity and stability of the exchange, availability of equivalent resources from other companies, availability of a resource substitute, ease of switching to another partner and/or a resource substitute, information asymmetry advantage.

Although the power attributes resemble some criticality factors, they bring attention to aspects that have not been considered in the material criticality analysis yet: actual conditions in buyer-supplier relations and influence of these conditions on companies’ ability to identify and mitigate material criticality.

RDT postulates that a company will try either to minimise its dependence on other organisations or to maximise their dependence on itself (Pfeffer and Salancik, 1978). However, literature suggests that ability of a company to take such actions is directly linked to its power-dependence position (Bode et al., 2011; Casciaro and Piskorski, 2005; Maloni and Benton, 2000; Mena et al., 2013). Therefore, in the context of critical materials power relations may be
an enabler or an inhibitor for a company’s ability to take criticality mitigation actions as well as identify supply constraints.

As RDT’s assumptions and implications are valid within boundaries of direct resource exchange relations (Pfeffer and Salancik, 1978), the theory is not applicable for examination of interrelations of companies across industrial sectors. Companies that operate in different industrial sectors and utilize the same critical material are connected via the common resource market. Such companies are potential competitors for a critical material in terms of its availability and affordability. Competition was suggested as a factor affecting material criticality by several publications (Bell et al., 2013; Graedel et al., 2012; Speirs and Gross, 2014; Wäger and Classen, 2006). However, it has been considered in the criticality analysis only by a few studies (Nieto et al., 2013; U.S. Department of Energy, 2010).

Therefore, interrelations of companies across industrial sectors are examined through the lens of competition. Factor-market rivalry theory (FMR) conceptualises competition over access to resource at the factor (resource) market (Markman et al., 2009). FMR allows examining competition through drivers of competitive behaviour, types of competitive actions and types of competition.

Capron and Chatain (2008) indicate two key strategies at resource market: focal firm resource oriented strategies (upgrade its own resources) and competitor's resource oriented strategies (degrade rival’s resources by reducing the quantity and efficiency (value creating ability) of available resources). These competitive actions provide implications for potential criticality mitigation actions.

Chen (1996) introduced the awareness-motivation-capability framework of drivers of competitive behaviour, indicating that companies will take actions (or respond to competitor’s action) only when they are aware about a problematic situation and have motivation and capability to do so. However, Chen and Miller (2015) highlighted that the gaining advantage might not be the only or primary objective of companies, and they indicated three views of competitive dynamics: rivalrous, competitive-cooperative and relational.
RDT and FMR provide important lenses for analysing the influence of interrelations of companies within and across industrial sectors on the identification and mitigation of material criticality. They provide a necessary lever for gaining better understanding of the company dimension in material criticality. Given that the discourse on material criticality has been developed without explicit theoretical and conceptual grounding, it is especially important to relate to and build on already established theories.
3. Methodology

This chapter presents the overall research design of the thesis, including particularities of empirical settings, procedures for data collection and analysis and control for the research rigour.

3.1. Research approach

Material criticality is a complex and multidisciplinary phenomenon. The great variety of criticality factors and assessment methodologies have been introduced, and, so far, the discourse is characterised by significant divergence in conceptualisation of material criticality. The dominant research approach can be characterised as conceptual development of criticality factors and assessment instruments, with their further employment for examination of material flows. The analysis is usually performed within a scope of an industrial system of a country or a region, paying little to no attention to the company dimension. Only a few empirical studies that explore a company perspective on material criticality are available. They adopted a case based research design, engaging with different business stakeholders through interviews and round tables (Mroueh et al., 2014; Peck and Bakker, 2012; Slowinski et al., 2013).

Given the lack of considerations of the company dimension in the material criticality discourse and fragmented empirical evidence, examination of the research objectives of the thesis require a rather exploratory investigation. In particular, the exploratory qualitative case study research approach is argued to be beneficial (Eisenhardt and Graebner, 2007; Stuart et al., 2002; Yin, 2009).

In addition, the research takes inspiration from multisited ethnography approach (Burrell, 2009; Green, 1999; Nadai and Maeder, 2005). This approach allows to examine particularities of a phenomenon occurring at different sites (e.g., companies) as if collecting a puzzle of many pieces. Therefore, in this thesis the companies involved serve both as points of comparison to identify differences and commonalities in identification and mitigation of material criticality; and as ‘sites’ in order to pull together
evidence about what constitutes material criticality and its mitigation from a company perspective.

The exploratory nature of the research argues in favour of the inductive logic (Eisenhardt, 1989; Ketokivi and Choi, 2014). This implies that no specific hypotheses were developed from the existing literature before the data collection, and the examination is primary based on obtained empirical evidence. However, several organisational theories and concepts are employed for framing the focus and dimensions of analysis. For example, resource dependence theory and conceptualisation of buyer-supplier relations via power regimes assist in developing the framework for analysing intra-sectoral interrelations of companies (see Paper B).

The overall research approach leans toward the interpretative paradigm of research inquiry, as compared to the positivistic one (Hirschman, 1986). This means that there is no a priori conceptualisation of material criticality, heterogeneity and interrelations of companies as a scheme of causes and effects. Instead, the thesis aims to understand the role of the company dimension in material criticality, admitting a possibility for alternative interpretations, which is an important characteristic of the interpretative paradigm (Hirschman, 1986).

The thesis addresses the research objectives through four studies presented in four papers (see Chapter 4). Each paper examines particular aspects of the company dimension and their influence on identification and/or mitigation of material criticality. The level of analysis in four papers is a company and unit of analysis varies between a supply chain (Papers B and D) and a company (Papers A and C). The summary of the appended papers is presented in Table 3.
Table 3. Summary of the appended papers.

<table>
<thead>
<tr>
<th></th>
<th>Paper A</th>
<th>Paper B</th>
<th>Paper C</th>
<th>Paper D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Topic</strong></td>
<td>The business perspective on material criticality</td>
<td>Intra-sectoral interrelations: role of power relations along a supply chain</td>
<td>Inter-sectoral interrelations: role of competition at resource market</td>
<td>Closed-loop supply chain as a strategy to mitigate material criticality</td>
</tr>
<tr>
<td><strong>Level of analysis</strong></td>
<td>Company</td>
<td>Company</td>
<td>Company</td>
<td>Company</td>
</tr>
<tr>
<td><strong>Unit of analysis</strong></td>
<td>Company</td>
<td>Supply chain</td>
<td>Company</td>
<td>Supply chain</td>
</tr>
<tr>
<td><strong>Companies engaged</strong></td>
<td>Five manufacturing companies (component and final product)</td>
<td>Four manufacturing companies representing three tiers in two supply chains (component and final product)</td>
<td>Three component manufacturers (Siemens, Vestas, Continental)</td>
<td>Six operators of reverse supply chain and four manufacturing companies (component and final product)</td>
</tr>
<tr>
<td><strong>Research questions (RQ) in the paper</strong></td>
<td>• How do manufacturing companies view and mitigate material criticality?</td>
<td>• How do the power regimes between supply chain tiers affect identification of material criticality?</td>
<td>• How do companies across different industrial sectors interact to obtain critical materials?</td>
<td>• How do factors for implementation of closed-loop supply chain for critical materials manifest themselves on different companies along the supply chain?</td>
</tr>
<tr>
<td></td>
<td>• How do material criticality factors and the mitigation strategies employed by companies relate to the factors and strategies established in the literature at the industrial system level?</td>
<td>• How do the power regimes between supply chain tiers affect mitigation of material criticality?</td>
<td>• How do inter-sectoral interactions influence identification and mitigation of material criticality?</td>
<td>• What are the key enabling and bottleneck conditions for implementation of closed-loop supply chain for critical materials from the perspective of practitioners?</td>
</tr>
<tr>
<td><strong>Main RQ</strong></td>
<td>How do heterogeneity and interrelations of companies within and across industrial sectors influence identification and mitigation of material criticality?</td>
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</tbody>
</table>
3.2. Empirical setting

For the purpose of this thesis, the company selection is bounded to geographical boundaries of the European Union (EU), and to the industrial sectors that employ materials indicated as critical by European Commission, (2014a). It should be noted that according to the updated criticality analysis at the EU level, materials (and applications) considered in the thesis are confirmed as critical (European Commission, 2017).

In 2014 the EU study generated a list of 20 critical materials. Each material is used in several applications, and some products use several critical materials (European Commission, 2014b). As this thesis is an exploratory study that aims to understand the phenomenon of material criticality, it is important not to focus on specificities of a particular material, but instead, examine criticality attributes common for various materials. The appended papers perform examination in the context of different materials, companies and industrial sectors (see Table 4 for details). The selection of empirical setting for each paper is driven information-oriented logic: materials, companies and industrial sectors are selected in order to ensure that obtained data is suitable for the intended investigation (Eisenhardt, 1989; Flyvbjerg, 2006; Yin, 2009).

Table 4. Empirical settings of papers.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Rationale</th>
<th>Empirical settings</th>
</tr>
</thead>
</table>
| A     | The paper aims to gain understanding of a company's perspective on identification and mitigation of material criticality. Focus on obtaining implications common for different critical materials rather than a particular critical material, a particular supply chain, industry or a particular company. | Different critical materials.  
Multiple industrial sectors.  
Five manufacturing companies with different supply chain position. The companies belong to different industrial sectors and supply chains. Some companies employ one critical material, others employ several different ones. |
| **Paper B** | The paper examines cross-tier buyer-supplier relations. Therefore, it is important to focus on established supply chain and technology (comparing to emerging technologies and developing supply chains) | PGMs in automotive sector (catalytic convertors in an exhaust system) 
Automotive sectors is major application of PGMs. 
Four manufacturing companies that belong to two supply chains: two final product manufacturers (niche and large) that share two component manufacturers located at two consecutive tiers. |
|---|---|---|
| **Paper C** | The paper examines cross-application relations from a perspective of competing demand for a critical material. Therefore, it is important to focus on a case of significant supply disruption of a critical material. | REE in wind turbine and automotive sectors. 
REE crises: rapid price increase due to export quotas reduction by China during 2010-2014. 
Wind turbine and automotive sectors are major applications of REE. 
Three component manufacturers that utilise REE. All three companies share resource market, but only two of them share also product market. |
| **Paper D** | The paper examines conditions for implementation of closed-loop supply chain for critical materials, but it does not focus on a particular critical material or a particular closed-loop supply chain. | Different critical materials 
Wind turbines and photovoltaic panels: they are important industrial sectors for enabling sustainable development and reduction of environmental impact. 
Four manufacturing companies and six reverse supply chain operators. Companies belong to different supply chains, have different positions in forward and reverse supply chains. |
3.3. Data collection and analysis

The data collection was focused on obtaining evidence on experienced supply constraints (e.g., availability and affordability) of materials under examination expressed by companies (as indication for identification of material criticality); and evidence on actions taken by companies to resolve supply constraints (as indication for mitigation of material criticality). Additional data was collected to achieve particular research objectives of each paper (see Table 5 for details).

The data collection was performed via two types of sources: primary – semi-structured interviews; and secondary – different types of documents publicly available on webpages of companies. Both types of data sources are used in all papers, except Paper C that particularly examines only secondary sources. The multiple sources of data collection (be it primary vs secondary, or secondary vs secondary) allowed to obtain rich evidence and check for possible contradictions of evidence (triangulation) (Eisenhardt, 1989).

The data collection in each paper followed the preliminary developed protocols with outlined the key topics and questions. These protocols were employed in data collection process for both interviews and document analysis. The semi-structured type of interview was employed because it allows ensuring flexibility in data collection, which is particularly important for the exploratory research. Semi-structured interviews ensured that key research topics would be addressed and also allowed obtaining additional information specific to a certain material, a company, its supply-chain position or industrial sector (Eisenhardt, 1989; Saunders et al., 2009). Table 5 summarise attributes of data collection in all appended papers.

The interviewees were selected based on their expertise, understanding of operations of their companies and ability to provide information about the use of critical materials, related risks and employed mitigation strategies. Interviews were conducted with the middle managers responsible for purchase and supply management, sustainability, and senior managers with an overall knowledge of a company’s business operations.
The obtained data was analysed qualitatively through pattern matching and coding (Miles and Huberman, 1994). The analysis was conducted in the respect to particular dimensions of analysis of each paper (see Table 5 for details). The framework of analysis in each paper was developed grounding on theoretical and conceptual implications from relevant research domains.

Lukka and Vinnari (2014) characterise such an approach as an application of a method theory to a domain theory, where a method theory is referred to a theoretical lens, a lever for providing new insights for investigating a certain set of knowledge (domain theory). For example, resource dependence theory (RDT) and factor-market rivalry theory (FMR) can be considered as method theories for examination of material criticality.
Table 5. Data collection and analysis in papers

<table>
<thead>
<tr>
<th>Paper</th>
<th>Data collection</th>
<th>Data analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper A</td>
<td>Five manufacturing companies (component and final product).</td>
<td>The obtained data was analysed:</td>
</tr>
<tr>
<td></td>
<td>Six interviews with company representatives (one-two interviewees per a company).</td>
<td>- within each company, in order to investigate the presence of specific risk factors, connected to the use of critical materials and mitigation strategies,</td>
</tr>
<tr>
<td></td>
<td>Company’s documents: annual reports, sustainability reports, information on the</td>
<td>- within each dimension of analysis (risk factors and mitigation strategies), in order to highlight commonalities and differences as suggested by different companies.</td>
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<tr>
<td></td>
<td>company’s webpage, presentations.</td>
<td>Theoretical/conceptual lens: supply and supply chain risk research domain.</td>
</tr>
<tr>
<td></td>
<td>Key topics: the use of critical materials, experienced supply constrains connected</td>
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<tr>
<td></td>
<td>with critical materials, and strategies taken to secure supply of critical materials.</td>
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<tr>
<td></td>
<td>Data collection period: Spring 2015.</td>
<td></td>
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<tr>
<td>Paper B</td>
<td>Four manufacturing companies representing three tiers in two supply chains (component and final product).</td>
<td>- Each company was examined on criticality factors associated with PGMs, actions taken for PGM management and relevant power attributes.</td>
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<td></td>
<td>Three interviews with company representatives (one interviewees per a company, data</td>
<td>- Each dyad was examined on the power relation.</td>
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<td></td>
<td>from one company is collected only from secondary sources).</td>
<td>- Power positions of companies were examined against their ability to identify and mitigate materials criticality.</td>
</tr>
<tr>
<td></td>
<td>Company’s documents: annual reports, sustainability reports, information on the</td>
<td>Theoretical/conceptual lens: resource dependence theory.</td>
</tr>
<tr>
<td></td>
<td>company’s webpage.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Key topics: experienced PGMs supply constraints; actions taken to secure PGMs</td>
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<tr>
<td></td>
<td>supply; PGMs supply and purchasing structure, possibility to substitute PGMs and/or suppliers, information available an exchange partner and an external environment.</td>
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<td></td>
<td>Data collection period: Spring 2017.</td>
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</tbody>
</table>
| Paper C | Three component manufacturers.  
Company’s documents: annual reports, sustainability reports, information on the company’s webpage, presentations, press-releases.  
Key topics: experienced REE supply constraints; actions taken to secure REE supply; information available about resource market and other industrial sectors employing REE.  
Data collection period: Spring 2017. | The obtained data was analysed:  
• within each company, for examination of REEs supply constraints, mitigation actions taken, types of actions taken;  
• across companies, for examination of the presence and nature of inter-sectoral interactions, similarities and differences between companies that share only resource market and those that share both markets.  
Theoretical/conceptual lens: factor-market rivalry theory |
|---|---|---|
| Paper D | Six operators of reverse supply chain and four manufacturing companies (component and final product).  
Ten interviews with company representatives (one interviewee per a company).  
Company’s documents: annual reports, sustainability reports, information on the company’s webpage.  
Key topics: engagement of a company in recycling of critical materials and development of closed-loop supply chain; factors influencing implementation of closed-loop supply chain; current enabling and bottleneck conditions; changes required to foster closed-loop supply chain development; a company’s perspective toward recycling of critical materials and development of closed-loop supply chain as a strategy for mitigation of material criticality.  
Data collection period: Autumn 2015 - Spring 2016. | The obtained data was analysed:  
• within each company, for investigating the presence of specific factors connected to development of closed-loop supply chain for critical materials and their roles;  
• within each supply-chain position, for examining commonalities and differences regarding specific factors and their roles;  
• within each factor, for highlighting commonalities and differences as indicated by different companies.  
Theoretical/conceptual lens: closed-loop supply chain research domain. |
3.4. Research rigour

Hirschman (1986) and Guba (1981) present and discuss two main paradigms for research inquiry: interpretative (humanistic/naturalistic) and positivistic (rationalistic/scientific). The researchers highlight that different types of inquiries require different criteria for evaluation of the research rigour. In particular, the criteria of internal validity, external validity, reliability and objectivity, born from the positivistic tradition, are not suitable for the interpretative inquiry. Guba (1981) introduced alternative criteria. They are: credibility, transferability, dependability and confirmability. Later Wallendorf and Belk (1989) added the fifth criteria of integrity. Given that the overall research approach of the thesis leans towards the interpretative paradigm, the associated criteria are considered as appropriate to discuss the research rigour of the thesis.

Credibility refers to an extent to which the findings appear to be acceptable (adequate and believable) representations of the reality (Guba, 1981; Hirschman, 1986). In order to achieve credibility, data were collected from multiple data sources of different nature: primary (interviews) and secondary (documents publicly available on webpages of companies). Triangulation of the data sources allowed to verify the obtained evidence through various sources and identify contradictions (if any). Nevertheless, the data collection process is inevitably limited by availability of documents and number of interviews conducted. The richness of the data was ensured by diversity of data sources. In addition, credibility criterion was addressed by verification of the interpretations of data obtained from primary and secondary data sources with the interviewees during and after the interviews.

Confirmability refers to an extent to which the findings are not subject to biases of different nature (Guba, 1981; Hirschman, 1986). As the interviews were conducted mainly with one interviewee per a company, respondent bias was possible. In order to reduce it, various secondary data sources were also analysed. Triangulation of data was also conducted among multiple secondary sources. In order to address possible researcher bias, the findings were reviewed by all co-authors of each paper independently and then collectively;
and the interpretations of data obtained from primary and secondary data sources were verified with the interviewees during and after the interviews.

Transferability refers to an extent to which findings obtained in one context are applicable to other contexts (Guba, 1981; Hirschman, 1986). The conducted research examined characteristics of material criticality in the context of different materials, companies and industrial sectors; and each paper has a specific empirical setting (see section 3.2). The obtained finding were analysed in order to understand the nature of material criticality, rather than examine how a certain materials should be managed in a certain context. Nevertheless, the importance of the context should not be neglected. For example, Paper B shows the relevance of power relations on identification and mitigation of material criticality; and this finding is transferable to any other material (analytical generalisability). However, the example of the power distribution in the automotive supply chain provide implication for a) a similar power structure in relation to materials employed in already established technologies with established supply chain structures; and for b) a future power structure for currently emerging technologies.

Dependability refers to an extent to which the findings are subject to time and place, or could be repeated under similar examination (Guba, 1981; Hirschman, 1986). In order to ensure replicability of obtained findings, the protocols for the data collection were preliminary designed (key research themes and questions for semi-structured interviews), the data analysis followed preliminary developed procedures (dimensions of analysis), and interpretation of obtained evidence was explained. Dependability was also addressed by conducting interviews with experienced and knowledgeable managers, and analysing documents at least over the last five years.

Integrity refers to an extent to which findings are influenced by misinformation or lies by interviewees. To achieve integrity, the data was collected from multiple sources (and their triangulation). In addition, confidentiality was assured for all engaged interviewees.
4. Overview of appended papers

The research question and objectives are addressed through investigations reported in four appended papers. They examine different aspects of inter-/intra-sectoral heterogeneity and interrelations of companies in relation to identification and mitigation of material criticality. Table 6 indicates the key themes of the thesis addressed by each paper. This chapter follows by presenting summary of the papers.

Table 6. Relevance of thesis themes for each paper (indicated by an asterisk).

<table>
<thead>
<tr>
<th>Main RQ</th>
<th>Thesis theme</th>
<th>Paper A</th>
<th>Paper B</th>
<th>Paper C</th>
<th>Paper D</th>
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<tbody>
<tr>
<td>How do heterogeneity and interrelations of companies within and across industrial sectors influence identification and mitigation of material criticality?</td>
<td>Identification of material criticality</td>
<td>**</td>
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<tr>
<td></td>
<td>Mitigation of material criticality</td>
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</tr>
<tr>
<td></td>
<td>Intra-/inter-sectoral heterogeneity</td>
<td>**</td>
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</tr>
<tr>
<td></td>
<td>Intra-sectoral interrelations (cross-tier)</td>
<td>*</td>
<td>**</td>
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<tr>
<td></td>
<td>Inter-sectoral interrelations (across sectors)</td>
<td>*</td>
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4.1. Paper A

The business perspective on material criticality

Purpose: The purpose of this paper is to examine how manufacturing companies view and mitigate material criticality, how their concerns and taken actions differ from implications of the literature and policy documents.

Methodology: Using an explorative case study approach, the paper analyses companies in different positions of the supply chain. In total five manufacturers (three components/materials manufacturers and two final product manufacturers) were studied. The main sources of data collection were semi-structured interviews conducted with managers responsible for purchasing and supply management and sustainability. In addition, secondary data such as different companies’ sustainability and annual reports were analysed.

Findings: The paper presents the criticality factors and employed mitigation strategies through the lens of supply and supply chain risks literature. The results point out the limited scope of the criticality factors and employed mitigation strategies considered, compared to those established in the literature. Examined companies do not tend to consider criticality factors characterising upstream supply chain operation, but they bring in new aspects of factors related to demand and competition. The results provide implications for interconnection of companies along a supply chain and across industrial sectors. Although manufacturers employ limited portfolios of mitigation strategies, the most common strategies (relational and contractual mechanisms) are not considered in the material criticality discourse. The findings indicate that governmental interventions might be required for strategies seen as irrelevant or challenging at the company level.

Relevance/contribution: The results highlight that companies’ perspective on framing material criticality differs from the existing models at the industrial system level. Moreover, the differences among manufacturing companies are indicated in relation to both identification and mitigation of material criticality.
4.2. Paper B

Intra-sectoral interrelations: role of power relations along supply chain

Purpose: The purpose of the paper is to empirically examine the cross-tier company relations through the lens of power regimes, and examine the influence of such power structures on a company’s awareness and concerns about material criticality and ability to respond to supply disruptions.

Methodology: The paper takes exploratory case study approach. Four manufacturing companies from the automotive sector were engaged. In particular, the companies belong to three tiers in two supply chains, and the focus of examination is the material flows of PGMs: catalytic converter (tier-2) – exhaust system (tier 1) – OEM (niche and large automotive manufacturers). Both primary (interviews) and secondary data (company’s reports) were collected and analysed. The semi-structured interviews were conducted with both final product manufacturers and the tier-2 supplier who provided evidence for the overall supply chain.

Findings: The paper describes the power regimes between supply chain tiers, based on identified power attributes of each examined company. The findings show that advanced power position provides better awareness of supply constraints and allows for a bigger scope of feasible mitigation actions. Moreover, it appears that power dominance rises upstream in a supply chain and with bigger magnitude of materials exchange.

Relevance/contribution: The study provides indication for the power regimes between supply chain tiers as mechanisms for shaping identification and mitigation of material criticality. The materials criticality analysis require extension to include examination of power positions of companies and their relations.
4.3. Paper C

Inter-sectoral interrelations: role of competition at resource market

Purpose: The purpose of the paper is to examine inter-sectoral interactions of companies through the lens of competing demand, and examine the influence of such relations on a company’s awareness and concerns about material criticality and ability to respond to supply disruptions.

Methodology: The paper takes exploratory case study approach, and the examination is focused on the period of REEs price increase triggered by export quotas reduction by China in 2010. The paper examines three companies: Vestas that use REEs for production of generators for wind turbines, Continental that use REEs for motors for electric mobility and Siemens that manufacture both products. Various secondary data was collected: reports, press releases, presentations publicly available on the webpages of the companies and in the internet. The documents were collected for the period over 2009-2016 in order to consider also the state of risks before and after the supply disruption of REEs.

Findings: The obtained results indicate that the examined companies are rather focused on their own industry and supply chain and do not take into considerations demand for REEs from other industrial sectors as a potential threat to limit REEs availability. Companies do not explicitly engage in competition at the resource market and take actions to reduce their dependence on REEs. However, the taken actions have indirect effect on other industrial sectors by affecting availability and affordability of materials at the resource market. In addition, the findings provided implications for the synergetic effect of cross-sectoral collaborative efforts.

Relevance/contribution: The obtained results indicate the importance of inter-sectoral interrelations of companies for identification and mitigation of material criticality, and provide implications for extension of the criticality analysis to include examination of competitive position at the resource market.
4.4. Paper D

Closed-loop supply chain as a strategy to mitigate material criticality

Purpose: The paper aims to examine enabling and bottleneck conditions for development of the closed-loop supply chain (CLSC) for critical materials; and analyse how the factors manifest themselves in different companies along the supply chain.

Methodology: The research questions are examined via exploratory case study research, which is based on six recycling operators and four manufacturers of green energy technologies (wind turbines and photovoltaic panels) from different positions in the supply chain. Building on the literature on CLSC, recycling systems and critical materials, ten factors influencing development of CLSC for critical materials are identified. These factors are further examined in the context of companies with different SC positions. The main sources of data collection were semi-structured interviews conducted with informants responsible for purchase, supply management and sustainability, and senior managers with an overall view of their business. In addition, secondary data such as different companies’ sustainability and annual reports were analysed.

Findings: The findings indicate that companies at different supply chain positions perceive differently the factors influencing implementation of CLSC for critical materials. While manufacturers are concerned primarily with technical feasibility of recycling, recycling operators provide implications for all set of factors indicating that challenge for CLSC for critical materials lies beyond technological issues. Examination of enabling and bottleneck conditions indicated by the interviewed companies for each factor allows implying that the following is required if CLSC for critical materials is to be implemented: development of interfaces within SC, development of sound competition environment for recycling operations, introduction of incentives for investments in infrastructure, stability of the market of critical materials. Legislation has great power to frame operational environment for companies and thus determine ultimate feasibility of CLSC for critical materials.
Relevance/contribution: This study examines factors influencing implementation of CLSC from a material perspective, as opposite to product as a unit of analysis, with recycling, as opposite to commonly addressed remanufacturing. The paper indicates the actions required for development of additional sources of supply of critical materials from recycling. Moreover, the findings highlight importance of collaborative efforts between companies to mitigate material criticality.
5. Discussion

This chapter synthesizes the findings of the appended papers in order to address the overall research question: "How do heterogeneity and interrelations of companies within and across industrial sectors influence identification and mitigation of material criticality?" The relevance of heterogeneity and interrelations of companies are discussed firstly in relation to the identification and then in relation to the mitigation of material criticality. Finally, the interplay of identification and mitigation is discussed.

5.1. The relevance of heterogeneity and interrelations of companies for the identification of material criticality

The findings demonstrate heterogeneity of companies regarding their considerations of material criticality. This heterogeneity is notable along a supply chain (Papers B and D), within an industrial sector (Papers B and C) and across different industrial sectors (Papers A and C). The nature of these differences can be explained by two counterparts of the identification of material criticality: awareness and concerns.

Awareness about material criticality issues is tightly related to the scope of considerations (monitoring) of companies. The findings highlight that this scope is rather narrow comparing to the existing frameworks of material criticality analysis (see criticality factors in Figure 4). Paper A indicates that companies do not tend to examine the upstream supply chain, what is in line with available fragmented empirical evidence (Mroueh et al., 2014; Slowinski et al., 2013). The factors related to geological availability, capacity of mines and smelter, or the by-product character of materials are usually neglected by companies (Paper A), but are commonly included in the criticality assessment methodologies (European Commission, 2014a; NRC, 2008). However, the case of PGMs in the automotive industry in Paper B suggests that when supply disruptions persist over time companies are more inclined to engage into upstream supply chain examination and management. Paper C indicates that a need for larger amount of a material brings companies' attention to the resource market. However, companies do not tend to consider other end uses
(industrial sectors) of a material as risk sources for its availability or affordability (Paper C).

Companies might be aware of supply disruptions, but not consider them as problematic. The obtained evidence indicates that this may happen when certain material criticality issues are not regarded as relevant for planning horizons of companies (Paper A), when a supply disruption is regarded as suppliers’ duty (Paper A) or when it can be transferred to another actor (Paper B). Alternative explanations are also possible, such as company's approach to risk management: risk-averse, risk-seeking, or risk-neutral (Heckmann et al., 2014).

The diversity of companies' awareness and concerns serves also as an implication for presence of other factors influencing criticality that are not yet considered in the current assessment, such as inter- and intra-sectoral interrelations of companies examined in Papers B and C.

Intra-sectoral relations of companies are formed by direct resource exchanges, which tie companies into supply chains. These relations can be examined through various perspectives, and Paper B employed the lens of resource dependence theory (Pfeffer and Salancik, 1978), according to which exchanged resources put companies in dominant or dependent positions in relation to exchange partners. Paper B indicates that a power position of a company has an impact on its ability to identify material criticality. More advanced power position is associated with better identification of material criticality because of easier access to information about the external environment that such position warrants. Differences in power positions of companies along a supply chain provide indications for differences in identification of material criticality along supply chains within an industrial sector.

The power position is defined through analysis of power attributes characterising the resource exchange. Information is indicated as an important power attribute that can improve visibility and assists with restructuring of power positions (e.g., Munson et al., 1999). The importance of transparency of operations and information exchange is also highlighted in
the supply chain research domain, for example, in order to minimise supply and demand uncertainties (Lee et al., 1997; Lo, 2013; Yi et al., 2011). However, information uncertainty and asymmetry among companies are not considered in material criticality analysis as influencing factors. This can be explained by its original aim to provide information about supply and demand conditions easily available to all interested parties. It is possible to argue to which extend the aim has been fulfilled so far, but quite all studies highlight the problem of data availability and calls for transparency of operations and enhanced information exchange (Buijs et al., 2012; Erdmann and Graedel, 2011).

Although some other power attributes may appear similar to the criticality factors (e.g., availability of substitutes, revenue impacted), they are conceptually different: power attributes characterise not supply continuity or supply-demand imbalance, but buyer-supplier relations. However, power attributes bring attention to issues that have not been considered in the criticality analysis yet. Given that a company’s power position is related to its ability to identify material criticality, power attributes provide important implications for the criticality analysis. In particular, the current criticality analysis requires extension to include examination of actual supply chain structures instead of rather abstract indicators such as ‘company concentration’ (Achzet and Helbig, 2013; Helbig et al., 2016). For example, several suppliers might be available at the market, but a company might choose to source a material from a single supplier anyway. In a similar manner, availability of a substitute is not an indication for its employment. Therefore, analysis at the industrial system level without considering the company dimension might provide more optimistic outlook than the actual situation.

The obtained evidence in Paper B points out that power position of a company is formed by relations with both suppliers and customers, and that a company’s relations with a supplier influence its relations with a customer and vice versa (c.f. Kähkönen and Virolainen, 2011). This indicates for a necessity to examine demand and supply aspects in their interplay. Although the current discourse on material criticality take into consideration both supply and demand aspects, they are examined as independent factors
(European Commission, 2014a; NRC, 2008). When a supply chain is considered, Paper B provides implications for more dominant power position of upstream supply chain. This finding is in line with Buijs and Sievers (2012b)'s indications about a power shift to resource producers (resource producing countries).

Paper C brought attention to interrelations of companies across industrial sectors. Although criticality studies usually acknowledge plethora of end-use applications of each material and complexity of materials flows (European Commission, 2014a; NRC, 2008; U.S. Department of Energy, 2011), only a few existing assessment frameworks consider cross-application interrelations in the analysis in terms of a possible threat for constrained availability of materials from demand growth in other industrial sectors (Nieto et al., 2013; U.S. Department of Energy, 2010). The findings of Paper C suggest that the current conceptualisation is not sufficient. Demand increase might serve as an indication for potential competition at the resource market, but it says nothing about whether a certain industrial sector will still manage to obtain a material given an increased overall demand. Paper C indicates that competitive position of a company at the resource market is influenced not only by a market share and demand trends. It is necessary to take into consideration changes in supply structures, development of substitutes, product and process innovations etc. Material criticality factors such as ‘substitutability’, ‘concentration in producing countries or companies’, ‘ability to innovate’ (Achzet and Helbig, 2013; Helbig et al., 2016) appear to be useful to examine competitive positions of companies. However, the findings indicate that it is important to examine these factors in their interplay between industrial sectors, meaning that substitutability of one application might affect substitutability of another one, not necessarily form the technological perspective, but its actual implementation.

Interrelations of companies within and across industrial sectors influence the state of material criticality and help understand differences between companies in the way they view supply disruptions. Heterogeneity of companies implies that it is wrong to assume that criticality is equally problematic for all the industrial sectors and companies that use the same material.
5.2. The relevance of heterogeneity and interrelations of companies for the mitigation of material criticality

The heterogeneity of companies is also evident when mitigation actions are considered. In the same manner as identification, mitigation of material criticality differs along a supply chain (Papers B and D), within an industrial sector (Papers B and C) and across different industrial sectors (Papers A and C). It is possible to imply that the identification of material criticality frames mitigation efforts, as companies take actions to address the problems they are aware of and concerned about. The findings show that both companies’ concerns and mitigation actions are limited to the supply chain and the industrial sector where they operate.

The obtained evidence points out that awareness and concern are not sufficient conditions for companies to take actions. Only those actions are taken that are feasible and regarded as relevant to business operations. These conditions resemble awareness-motivation-capability framework of Chen (1996) initially developed for analysis of competitive behaviour. Various internal and external factors may affect feasibility of a certain action for a certain actor. Papers B and C demonstrate that inter- and intra-sectoral interrelations of companies influence the mitigation of material criticality.

Paper B shows that advanced power position of a company is associated with a broader scope of feasible actions (c.f. Casciaro and Piskorsk, 2005), allowing for a broader set of feasible criticality mitigation actions to choose from. The diversity of power positions provides implications for differences in mitigation efforts among companies along supply chain within an industrial sector. Paper B indicates that companies put efforts to maintain or to improve their power positions against the partners, and information, being an important power attribute, may help with power restructuring. The findings show that after supply disruptions companies put efforts to improve their risk management system or even develop own criticality assessment methodology (Paper A and C). Examples of companies developing their own assessment methodologies indicate that existing assessment frameworks do not sufficiently reflect their business reality. However, given that companies have
rather limited scope of considerations and lack of awareness regarding resource constraints, the development of such an assessment instrument could generate faulty results as well as devalue assessments performed at the national level.

Paper C brings evidence for interconnections of companies across industrial sectors through their resource decisions and actions that affect resource market. Securing a material source for one company (e.g., via a joint venture or vertical integration) can limit its availability for another company. Decisions to substitute a material in one industrial sector may ease supply conditions for another sector. Although, as Paper C shows, actions of companies have competitive nature, they compete against the market itself rather than against a particular company, meaning that companies aim to secure their resource market position rather than attack another company. The findings of Papers A and C provide implications for a competitive position at a resource market to be a limitation for feasibility of mitigation actions. In particular, Paper A indicates that companies with small share at resource market (e.g., use small amount of a material) are not able to influence that market and may only adjust to its conditions. These findings provide indications for differences in mitigation of material criticality between companies from different industrial sectors. In addition to competitive conditions at resource market, Paper C shows that competition at the product market also impose limitations on a company’s ability to take actions. For example, price competition might restrain a company’s ability to pass material’s price increase on customers; and competition on a product functionality might restrain a company’s ability to substitute a material and cause product’s performance deterioration.

Some actions, although potentially feasible, can be considered as not relevant to business operations. For example, recycling and closing the loop of operations are often considered as such by manufacturing companies (Papers A and D). As Paper C shows, competitive priorities of a company at a product market may also guide selection of mitigation actions. The findings indicate that companies employ multiple mitigation actions usually leaning to supply/supplier management and product and process innovation to decrease of dependence on a material. Relational and contractual instruments are also
indicated as important means to mitigate material criticality. However, such strategies are not included in suggestions for material criticality mitigation (Wäger et al., 2012; Weiser et al., 2015).

Example of closed-loop supply chain in Paper D indicates how important alignment and collaborations are for mitigation of material criticality. Croxton et al. (2001) pointed out that any supply chain processes would be neither effective nor efficient without collaborations. The same is true for actions taken across supply chains and industrial sectors to address supply conditions of a certain material. Paper D highlights importance of alignment of interests and actions of companies across all industrial sectors that employ the same material for development of closed-loop supply chain, as recovery of a material from its all end uses is required for truly closed-loop operations. Paper C provides an example of how inter-sectoral interrelations within a company led to synergetic efforts for research on material efficiency, substitutes and recycling. This indicates a potential to approach mitigation of material criticality through cross-sectoral collaborations.

Material criticality is shaped by all actors that use a material. Being created by everyone, it cannot be mitigated by a single company. Given the plethora of possible mitigation actions and differences among companies in relation to their interests and capabilities, coordination might be important to ensure alignment of the actions taken and to avoid conflicts among the actions.

5.3. Synthesis

The findings highlight that inter- and intra-sectoral heterogeneity and interrelations of companies are indispensable attributes of industrial systems that require careful examination in the criticality analysis. Consideration of heterogeneity of companies reveals important diversifying aspects of identification and mitigation of material criticality, they are: awareness and concerns of criticality factors and feasibility and relevance of mitigation actions (see Figure 6). Interrelations of companies within and across industrial sectors influence the identification of material criticality by facilitating/impeding ‘awareness’ of supply disruptions, and affect the mitigation of material criticality by enabling/impairing the ‘feasibility’ of
various options. ‘Concern’ and ‘relevance’ are elements that rather relate to strategic priorities and planning horizons of each company, and are subject to companies’ interpretation (Daft and Weick, 1984) and sensemaking (Kiesler and Sproull, 1982).

As the findings indicate, inter-/intra-sectoral heterogeneity and interrelations of companies are important aspects influencing material criticality that should not be neglected. This highlights the importance of incorporation of the company dimension in the material criticality analysis. The findings provide implications for the importance of detailed examination of supply chain structures, buyer-supplier relations, power positions of companies against their supply chain partners and competitive positions of companies at the resource market. Employment of the power attributes (e.g., information asymmetry, feasibility to switch to alternative source) in the criticality analysis may improve the current assessment methodology. In addition, the findings suggest that criticality factors are not independent. The obtained evidence allow to imply for the interrelation of factors characterising demand and supply conditions, and the interrelation of factors characterising employment of a material across industrial sectors (end use applications).

Figure 6. Influence of inter-/intra-sectoral heterogeneity and interrelations of companies on material criticality (the arrows indicate the logical connection, not the cause-effect connection).
Plethora of suggested mitigation actions indicate a great potential for mitigation of material criticality. The current material criticality analysis does not examine feasibility of recommended actions and their implementation. However, companies have diverse interests and capabilities, and the same action might not be applicable or might not make a business case for all companies. The findings provide implications for the following limiting conditions: a power position against suppliers and customers, a competitive position at resource product markets. Moreover, influence from actions taken by companies in other industrial sectors have to be also taken into consideration in the development of criticality mitigation strategy. In addition, the findings indicate that the current frameworks of possible mitigation actions miss to consider relational and contractual instruments that are favoured by companies.

Furthermore, the list of suggestions might remain just a list as there are no implications for implementation and division of responsibilities among companies along a supply chain and across industrial sectors. This is particularly important for complex strategies as development of closed-loop supply chain. Given that one company cannot mitigate material criticality, there is a need to provide guiding principles that would foster the alignment of efforts of different companies.

Heterogeneity of companies in relation to both identification and mitigation of material criticality indicates against utility of generic outcomes of material criticality analysis, such as the lists of critical materials and mitigation options.
6. Conclusions

The thesis brought attention to the company dimension in the material criticality discourse. The performed examination highlighted the importance of heterogeneity and interrelations of companies for understanding and management of critical materials. This chapter concludes the thesis by offering implications for the discourse on material criticality, for industrial actors and policy-makers; and by discussing limitations of the conducted research and prospects for further investigations.

6.1. Implications for material criticality discourse

The current discourse on material criticality tends to consider industrial sectors as monolithic, homogeneous and independent entities. The thesis highlights that such conceptualisation is oversimplistic and problematic, as it misses to consider operational reality of companies that form and drive materials flows through supply chains, industrial sectors and geographic regions. In particular, the thesis indicates the importance of consideration of heterogeneity of companies and their interconnections in material criticality analysis. The current approaches to material criticality analysis should be extended to consider power relations of companies that directly exchange resources (along supply chain), and competitive relations of companies from different industrial sectors at shared resource market. These aspects, among others, influence company’s awareness about material criticality and feasibility to take mitigation actions.

The urgency to revise the current assessment methodology is indicated by initial attempts of companies to develop own criticality analysis (e.g., Siemens and General Electric). This evidence implies that companies do not rely on outcomes of the performed assessments: the lists of critical materials vary from region to region, and the recommended actions are too generic. Development of own assessment instruments by companies is problematic because companies tend to disregard some factors and introduce new ones (comparing to already existing methodologies at the national level). This leads to further divergence of the attempts to grasp and analyse material criticality. Dewulf et al. (2016) calls for a need for an internationally uniform criticality assessment methodology, and this thesis highlights a necessity for common
understanding of material criticality among industrial actors and policy makers.

The thesis also indicates that the current material criticality analysis is problematic in how the methodology is being developed. Studies juggle with criticality factors and their various mixes and aggregations. However, selection of factors, their necessity and sufficiency are not justified. The discourse lacks theoretical grounding. This was also indicated by Glöser et al. (2015), who discussed material criticality analysis from classical risk theory perspective. The thesis employed several organisational theories and concepts that proved to be beneficial to outline previously neglected aspects of the phenomenon.

The current discourse tends to develop an assessment tool rather than understand the phenomenon in its full complexity. The thesis calls for extension of the scope of analysis to include companies dynamics, employment of existing theories for setting ground for factors development and performing empirical research for both validation of the deduced factors and examination of new ones. In the same manner further examination of mitigation of material criticality is required.

6.2. Implications for industrial actors

The findings of the thesis indicate that the scope of considerations (monitoring) of companies is narrower than the current analysis suggests as necessary to grasp and examine material criticality. This may result in overlooking some factors that restrict availability and affordability of materials. Therefore, it is necessary to raise awareness of companies about materials flows to improve their identification of material criticality. Particular attention should be given to the upstream of supply chain and other industrial sectors employing the same material. The findings highlight importance of transparency of operations and information exchange along supply chain and industrial sectors.

The findings warn against development of own equivalent of material criticality assessment methodology by companies because of their selective
consideration of factors and primary focus on own supply chain and industrial sector. It is necessary to ensure uniformity and consistency of the material criticality assessment methodology, rather than simply disregard factors that do not appear relevant to the scope of business operations. Given that the material criticality analysis is under development, companies are encouraged to contribute to its development by bringing empirical evidence and indications for factors important to their operations that are missed in the current analysis. The dialogue between policy-makers, researchers and industrial actors is required in order to gain better understanding of the phenomenon.

The literature suggests various actions to mitigate material criticality, but not all of them are employed by companies. They tend to rely on traditional instruments that can be deployed independently. However, the findings allow to imply for benefits of collaborations along supply chains and across industrial sectors. Closed-loop supply chain serves as an example of strategy that cannot be successfully developed by a single company, and for which collaboration between forward and reverse supply chain operators is a prerequisite. Other strategies can be employed independently (e.g., product design), but given the diversity of capabilities and interests of companies, there is a need for the information exchange and dialogue among actors to ensure that in overall the taken efforts are aligned rather than impede each other. Moreover, the thesis highlights the importance of long-term proactive measures in order not only to mitigate material criticality, but also prevent it.

6.3. Implications for policy-makers

The material criticality analysis was introduced as an instrument to guide resources policy. The thesis indicates that the current analysis does not consider complexity of the reality in a sufficient manner, and thus might provide misleading results and implications. It is necessary to include heterogeneity and interrelations of companies within and across industrial sectors. The material criticality analysis should go further than producing general list of critical materials and mitigation options. There is a need for more comprehensive analysis that could include the company dimension, the heterogeneity and interrelations of companies.
Given that companies operate in multiple countries, different conceptualisation of material criticality (and therefore, different outcomes of analysis) at national level serves against validity of the concept and utility of analysis to practitioners. It is necessary to facilitate the dialogue across counties to unify the analysis. In addition, the policy-makers should provide guidance and support to the discourse development in academic circles, for example, via establishing a platform for communication and exchange of research findings, as well as for facilitating the dialogues between researchers and policy-makers. It is necessary to ensure that the efforts are taken to uniform the conceptualisation of material criticality.

Awareness is an important prerequisite for mitigation of material criticality. Policy-makers have an important role in ensuring transparency of mineral supply chains that would allow companies to have appropriate visibility of materials flows and their impediments. As material criticality is a complex phenomenon, it can be tackled only through a mix of different measures taken by different actors, both private and public. Therefore, orchestration of criticality mitigation efforts is important. Moreover, policy-makers need to provide selective support for companies and industrial sectors as well as for strategies that are currently regarded as irrelevant or challenging for companies (e.g., closed-loop supply chain), but are important at the industrial system or global levels.

However, given that the support of the government is important, it is not clear to which expend the assistance and guidance should be provided. For example, should the inter-sectoral competition be given to the market, or should the government intervene and secure industrial sectors important to a national economy? Should the policy-makers support the technology transition and substitution developments, or again it is better to leave it to companies and open market? This research does not provide explicit answers to these questions. However, careful examination of companies and their interconnections is required before issuing any selective regulatory measures, as policy effort at one industry can worsen competitive position of another one as well as can distort global supply chains.
6.4. Research limitations and prospects for further research

The thesis aimed to bring in the company dimension to the conceptualization of material criticality. This was done by examination of heterogeneity and interrelations of companies within and across industrial sectors. However, it would be wrong to assume that these aspects fully represent the company dimension or that the power perspective on buyer-supplier relations and the competition perspective on cross-sectoral relations fully address all aspects of interrelations of companies within and across industrial sectors. The choice of another theoretical perspective might unveil other inter-/intra-sectoral mechanisms that influence identification and mitigation of material criticality or that might characterize the company dimension in another way. Moreover, the performed research provides implications for new important aspects of the criticality analysis that require further examination, such as interconnection of criticality factors and alignment of mitigation actions. Finally, the neglect of the company dimension is not the only limitation of the discourse on material criticality.

In addition to the boundaries of the examination and the theoretical perspectives employed, the thesis is limited by the methodological choices in terms of the empirical settings, data collection and analysis. These issues are discussed in detail in Chapter 3. Further studies should continue pursuing empirical research, but extend the boundaries of investigation by engaging more companies from multiple industrial sectors and along full supply chains. This should assist with identification (if any) of criticality factors and/or mitigation strategies specific to certain industrial sectors, certain materials or certain kind of supply disruption. More empirical examination is needed to ensure empirical validity of proposed criticality assessment frameworks and suggestions for its mitigation.

The discourse should not be focused only on the assessment instrument development as it is now. It is necessary to challenge current assumptions and limitations in order to advance understanding of material criticality and its conceptualisation. There is a need to establish strong theoretical background
providing justifications for suggested criticality factors and mitigation options.

These limitations open multiple opportunities for further research. As the thesis does not address all possible inter-/intra-sectoral mechanisms that might influence material criticality, employment of different theoretical lenses as well as extension of the scope from relations to network may reveal other criticality factors that have not been considered yet. Examination of internal characteristics of companies and particularities of their external environment provides opportunities for better understanding heterogeneity of companies in relation to identification and mitigation of material criticality. Further research should not only investigate new (currently neglected) factors, but also validate ones that are already present in current analyses. Interrelation of factors is another aspect that requires further investigation. It would be wrong to assume their independence given interconnectedness of operations of companies.

In terms of mitigation options and strategies, further research is needed to examine decision-making for selection and development of strategies, effectiveness and efficiency of the efforts taken, suitability of different mitigation options for various circumstances be it exposure to certain criticality factors or restricted capabilities to take actions. The issues of strategy alignment and trade-offs among different actors requires thorough investigation. Furthermore, it is necessary to examine the need for and impact from governmental interventions directed towards availability and price of materials.
References


