KAUNAS UNIVERSITY OF TECHNOLOGY

MILDA MALINAUSKIENĖ

DECISION SUPPORT SYSTEM MODEL FOR RESOURCE EFFICIENCY IMPROVEMENT INTEGRATING ASSESSMENT OF RESOURCE CRITICALITY

Doctoral dissertation
Technological Sciences, Environmental Engineering (04T)

2016, Kaunas

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Table of Contents

List of figures

List of tables

Abbreviations

BAT	Best available techniques
BAU	Business-as-usual
BDW	Biodegradable waste
CN	Combined nomenclature
CP	Cleaner production
DMC	Domestic material consumption
EC	European Commission
EI	Economic importance
EPI	Environmental performance index
EU	European Union
HHI	Hirschman-Herfindahl Index
IE	Industrial ecology
IMPD	Import dependency
IPPC	Integrated Pollution Prevention and Control
LCA	Life cycle assessment
LCSA	Life cycle sustainability assessment
LCP	Large combustion plant
MFA	Material flows analysis
RE	Resource efficiency
RECP	Resource efficient and cleaner production
REEs	Rear earth elements
RP	Resource productivity
SAW	Simple additive weighting
SMEs	Small and medium enterprises
SR	Supply risk
UNEP	United Nations Environmental Programme
WGI	Worldwide governance indexes

Glossary

Agent-based model	Class of computational models for simulating the actions and interactions of autonomous agents with a view to assessing their effects on the system as a whole.
Criticality	An estimate of supply risk for elements whose shortage may endanger the functioning of a society (1).
Input-output analysis	Set of related methods that show how the parts of a system are affected by a change in one part of that system. Input-output analysis specifically shows how industries are linked together through supplying inputs for the output of an economy.
Life cycle assessment	Technique to assess environmental impacts associated with all the stages of a product's life from cradle to grave.
Material flows analysis	Analytical method to quantify flows and stocks of materials or substances in a well-defined system.
Manufacturing industry	Comprises establishments engaged in the mechanical, physical, or chemical transformation of materials, substances, or components into new products; produces goods for the end users.
Mineral reserves	Quantity that is exploitable with current technical and socioeconomic conditions.
Mineral resources	Geologically assured quantities that are available for exploitation.
Natural resources	Materials or substances such as minerals, forests, water, and fertile land that occur in nature and can be used for economic gain.
Raw materials	Transformed natural resources to feed the manufacturing sector.
Resource efficiency	Means using the Earth's limited *resources* in a sustainable manner while minimising impact on the environment. It allows more to be created with less and to deliver greater value with less input.
Statistical entropy	Entropy is a measure of the disorder or randomness in a closed system. Statistical entropy is used to measure the variance of a probability distribution (2).
System dynamics	Computer-aided approach to policy analysis and design. It applies to dynamic problems arising in complex social, managerial, economic, or ecological systems — literally any dynamic systems characterized by interdependence, mutual interaction, information feedback, and circular causality.
Technosphere	The sphere or realm of human technological activity; the technologically modified environment.

INTRODUCTION

Research relevance

The increase in the number of scientific publications concerning the analysis and assessment of resource criticality and scarcity in recent years suggests that interest in a secure and sufficient supply of natural resources has been significantly raised. This is not surprising, since, even if the availability of resources has always been one of the key factors for any successful industrial activity, nowadays, the uncertain and politicized (3, 4) supply of resources, especially non-renewable ones, along with volatile prices (5–7) requires substantially more attention from the decision-makers.

The concept of resource criticality is in general relative (8) and, as a result, the studies in this field tend to apply a broad range of system boundaries, purposes, and methodologies. Actually, if all the elements from all countries and regions mentioned somewhere in this context were summarized, then most elements used for industrial purposes would be listed (7). Although resource availability is more often discussed in a regional, national, or even in a global context, the influence of uncertain supply is, first of all, observed at the local level, and this suggests that resource availability should be critical for every industrial company. On the other hand, companies are important economic players who are able to make decisions that are related not only to their activities but also influencing the general competitiveness of industry branches or regions.

Keeping in mind the rate at which resources are exploited in order to meet the growing needs of modern society and the associated environmental impact, the efficient use of resources has become a strategic economic development trend, which is clearly outlined through a number of European Union documents, primarily in the Roadmap to a Resource Efficient Europe (9) and the Communication Towards a Circular Economy (10) published by the European Commission. Here too, the industrial companies play a major role in the implementation of the resource efficiency measures. This calls for the bottom-up approach to increase resource efficiency and meanwhile mitigate resource criticality.

Therefore, the question is, whether and how the concept of resource criticality could be integrated into decision-making, for an improvement in resource efficiency. There have been few attempts in the scientific literature to integrate these concepts, of which the most promising is the integration into the LCSA framework (11, 12). However, the suggestions are currently on the conceptual level, and the authors agree that the operationalization of the site-specific assessment would encounter significant difficulties. Thus, in order to provide the possibility for industrial decision-makers to holistically address the risks related to the supply of resources, the concept should be integrated into a widely applied framework.

This doctoral thesis aims to address the identified research gap by integrating the resource criticality assessments into the cleaner production (CP) implementation procedures for the evaluation and prioritization of resource efficiency improvement options.

Aim and tasks of the research

The *aim of the research*- to develop a decision support system model for resource efficiency improvement in the companies integrating assessment of resource criticality.

Tasks:

1. Carry out analysis of already performed research on resource criticality assessment and mitigation, analyse how the environmental implications are addressed in the existing studies, and identify the main problems in the field;
2. Perform the analysis of decision-making support methods and models for resource efficiency improvement, and identify existing proposals to integrate criticality assessment into decision-making support for sustainability improvement in industry;
3. Perform the analysis of resource use in the Lithuanian economy, in terms of resource criticality and resource efficiency, and identify the most vulnerable branches of industry;
4. Develop an integrated decision support system model for the evaluation of resource efficiency alternatives that integrates resource criticality;
5. Apply the developed model to selected companies in identified vulnerable branches of industry.

Key thesis

Integrating resource criticality assessment in terms of geostrategic supply risk and economic importance into the common procedures for cleaner production implementation allows for the identification of significant aspects related to the use of natural resources from a point of view of an industrial company; and using criticality as an additional criterion for the assessment and prioritization of resource efficiency improvement alternatives.

Research object and methodology

The research *objec*t is- the manufacturing company.

The research covers the systematic literature review and quantitative statistical analysis. An economy-wide material flow analysis was performed. The software for the statistical analysis, PC-Axis, was used for the processing of statistical data. The Excel database for the calculation of criticality indicators was created.

The development of the decision-making support system model was based on the framework of the procedures for the cleaner production implementation. The developed model was tested by applying it to two production companies. Material flow analysis was performed, and the developed Excel database was used.

Scientific novelty

The main scientific novelty of this research is the developed multi-objective decision-making support system model, which for the first time integrates the evaluation of resource criticality, in terms of the geostrategic supply risk and economic importance, into the common procedures of resource efficiency implementation. The created model extends the scope of the cleaner production implementation procedures by supplementing it with the criticality evaluation for the identification of significant aspects, and for the assessment of resource efficiency improvement alternatives.

Furthermore, the research results contribute to the inclusion of an assessment of the environmental implications into the criticality evaluation from the entrepreneurial perspective.

Practical value

The developed decision support system model can be used in production companies as a tool for identifying and evaluating resource efficiency improvement options. It allows for the identification of geostrategic supply risks related to the used resources as well as vulnerability to these risks. Meanwhile, it offers a tool for supporting decision making for resource efficiency improvement by addressing resource criticality as additional criteria for the evaluation.

The developed model was tested in two producing companies corresponding to the different industry branches of the Lithuanian economy that are vulnerable to the availability of imported natural resources.

Structure and contents of the dissertation

The dissertation consists of an introduction, five main chapters, conclusions, references and supplementary material.

The first chapter contains the systematic literature review in the fields of criticality assessment and decision-making support for resource efficiency improvement. The possibilities to integrate concepts corresponding to different fields of research are discussed and the research gaps are identified. The second chapter presents the research methodology. In the third chapter, the results of resource criticality assessment for the Lithuanian economy are presented. The fourth chapter provides the description of the developed decision support system model for resource efficiency improvement in the industrial companies. The fifth chapter presents the main results of the model application in the nitrogen fertilizer production company and metal processing company. Finally, conclusions and recommendations are presented.

1. LITERATURE REVIEW

1.1. Review of the relevant research in the field of resource criticality evaluation

1.1.1. The availability of natural resources

Stable and secure sourcing of raw materials is the key condition of any successful industrial activity. Fortunately, even if geologists claim that our current knowledge about the actual quantities of resources and reserves is still very limited (13, 14), there seems to be a consensus that the complete exhaustion of minerals is not likely to occur (13, 15, 16). Even so, there are several significant reasons why natural resources should be used with great caution. Firstly, the quantities at which natural resources are used nowadays were unimaginable only 20 years ago (13). The global extraction and use of metals increased nearly 19-fold from 1900 to 2005 (17, 18). This shift was greatly influenced by the tremendous growth of emerging economies such as China, Brazil, and India (13). Secondly, the rate at which resources are used has a direct influence on the environmental impact caused by the extraction, processing, and use of raw materials. Moreover, a significant portion of the available material stocks has been transferred from the Earth's crust to the troposphere (17). Thirdly, decreasing ore grades (19) can cause the "effective exhaustion", when the extraction of raw materials in terms of energy, water, and environmental damage will be so great, that mining activities will cease (15). Finally, the issue that attracts more and more attention is a secure and sustainable supply of raw materials, which is analysed in the studies addressing resource criticality.

The topic of resource criticality has emerged recently in the scientific literature and political agendas but is not new. The concept of criticality in terms of supply constraints appeared for the first time in 1939 when the U.S. Government released the Material Stock Piling Act that was designated to secure the supply of military relevant raw materials (20). However, until recently little research has been done in this field of study. The extensive discussion on this subject was reopened by the U.S. National Research Council in 2008 when the study on Critical Minerals for the U.S. Economy was published (20). The European Commission (EC) followed by publishing the report on the critical materials for the EU in 2010 (21). Since then, this issue has generated a great deal of debate in the scientific literature as well.

A lot of attention has been paid to the recently highlighted, so called, technology metals. There are concerns that the availability of these metals can limit the achievement of targets on CO_2 emission reduction, including the concern that it could discourage the wider scale implementation of clean technologies, such as wind turbines (15, 22–25), electric vehicles (26) and photovoltaics (15, 23, 27). Without consideration to material criticality in the planning and design phase, the transition to low-carbon infrastructure might lock society into technologies that are vulnerable to the disruption of the supply of key materials and components (27, 28). Furthermore, the development of fast-growing economies can limit the availability of economically important industrial metals, such as aluminium, copper, nickel, and zinc (21, 29), or even resources that are crucial for the functioning of ecosystems such as phosphorus (30) and water (31).

1.1.2. Defining criticality

The analysis and evaluation of the criticality in the context of the availability of natural resources is still a young and heterogeneous topic (32, 33). After analysing 29 published definitions and descriptions used for critical materials, Peck et al. (7). in line with other authors such as Alonso et al. (3), Roelich et al. (25) and Chakhmouradian et al. (8), conclude that currently there is no common definition and, therefore, there is no agreed global list of critical materials. The definitions and criteria of criticality evaluation are relative and strongly depend on the context.

Prior to defining the concept of resource criticality, first of all, one should distinguish it from the term “resource scarcity” or physical abundance, which is also sometimes used in this context. According to Skinner (34), an element is geochemically scarce if the average abundance in the Earth’s crust lies below 0.01 weight percent. Absolute scarcity (physical scarcity) is when satisfaction of an elementary need is no longer possible and cannot be met by additional production (35). However, Scholz and Wellmer (30) argue that this is a purely physical definition that does not consider the material’s functionality and societal demand and is thus unsuitable in the context of economic use of elements.

Wolfensberger et al. (36) suggest a term of relative scarcity (economic scarcity) which refers to a shortage of supply relative to the mineral’s demand. The term *criticality* represents even more aspects related to the economic use of materials and defines supply risks for elements whose shortage may endanger the functioning of a productive society (30). The term criticality in the thesis will be further used in this context. However, the concept is not straightforward (37) and there is no consistent definition throughout the literature (27). Nevertheless, there are several key aspects of which the majority of the authors seem to have a common understanding.

Firstly, the material in itself cannot be critical by definition. According to Bradshaw (15) it is a “situation, or state of a system, brought about by some attribute or property, which is said to become critical”. It is relative, therefore, it must be compared to other materials (32). The widely acknowledged (38) EU definition states that “a raw material is labelled ‘critical’ when the risks of supply shortage and their impact on the economy are higher compared with most of the other raw materials” (39).

Secondly, resource criticality assessment is a framework for holistic evaluation, which involves multidimensional criteria. Three different approaches are applied to assess the criticality of raw materials: criticality matrices, criticality indices, and quantitative future supply and demand analysis (40). The criticality matrix is an abstraction of classical quantitative risk assessment within a risk matrix, which aims to reflect the likelihood of supply disruptions (41).

In line with the U.S. National Research Council (20) and European Commission (39) most other authors also agree that criticality is a function of supply risk and vulnerability to supply restrictions (18, 33, 40). This can also be referred to the classical definition of risk (likelihood vs. consequence) (41). However, studies differ considerably in the interpretation of these two dimensions.

To name a few, the supply risk can refer to "security of supply" (42), "geological and non-geological production constraints" (19), "likelihood of supply shortage" (13), ecologic, economic and availability risks, caused by biophysical, technical, economic and social factors (43), "threats for future supply restrictions" (32), "likelihood of a material supply restriction" (44), risk within their respective supply chains (27) and a strong possibility of supply interruption (15).

Vulnerability can be determined as "concern to business and governments" (42), "addiction of economy" (19) or "economic importance" (13, 39), relevance to economic systems (32), potential impact if a restriction were to occur (44) and the level of inherent vulnerability (27).

Only some authors, like Bensch et al. (33) and Saleh et al. (45) distinguish the environmental risks as a separate dimension. Therefore, it is not clear whether and how this concept is related to the environmental implications. To address this issue, the in-depth analysis and discussion are provided in Chapter 1.2.1.

1.1.3. Causes of resource criticality

The constraints on the availability of natural resources are in many cases the result of the interplay of various factors. Wolfensberger, et al. (2008) proposed a meaningful classification of the drivers of non-energy mineral resource availability and suggests that the drivers are related to the dynamics of supply and demand (Table 1.1).

Table 1.1 Classification of the drivers of non-energy mineral resource availability (36)

Timeframe	Supply-related drivers of criticality	Demand-related drivers of criticality
Permanent	Geological (e.g. mineral depletion) Technical (e.g. dissipation)	Functional (e.g. basic needs of society)
Mid and short term	Societal (e.g. regulatory, geopolitical, social) Technological (e.g. substitutability, inefficient/no recycling, low efficiency of exploration, potential joint production) Economic (e.g. high volatility of sector, insufficient investments, interruption of trade, entrance barriers)	Demographic (e.g. population growth) Social (e.g. culture, wealth/poverty, lifestyle)

The rise in the global extraction of minerals, which has particularly increased in the last century, causes ever-decreasing ore grades (17, 18) and that forces extraction and production to move to ever-more inaccessible or sensitive areas (19). Another important issue is the spatial dilution into the environmental and the technosphere. Not only minerals used in small amounts but also conventional elements such as zinc or titanium are subject to dissipation (36). Rechberger and Graedel (2) argue that the recovery of raw materials from technogenic stocks is restricted by their increasing statistical entropy in products or the environment. Most of the authors agree that physical abundance is not the critical issue, but resource accessibility is (16). Especially, because, it is influenced by various societal, technological, economic, demographic and social factors.

A considerable number of developed nations, especially European countries, rely on imported material commodities (44). High concentrations of production both on the country and the company level (13, 41) make the supply of raw materials particularly vulnerable to the geopolitical situation. Resource availability can be influenced by political tension (43), supply monopolies (44) and taxation of certain high-tech metals (41). In addition to the uncertain raw material supply, the extraction and production of raw materials in politically unstable countries often has negative social and environmental consequences (44). Dewulf et al. (46) emphasize that conflict minerals are often endorsed by international regulations.

Amongst the technological concerns limited substitutability, recovery and finding alternative products that meet social needs (46) should be mentioned. Most of the high-tech metals are by-products of the processing of other metals (e.g. tellurium used for thin-film photovoltaic technology is a by-product of the extraction of copper) (27). The lower demand for the main metal compared to the high demand of the by-product material (41) limits the availability of such metals.

Mayer and Gleich (32) state that raw material supply is rather inflexible because capacity expansions require large investments and the duration of new mining projects is relatively long. In addition to the initial investments, the supply is influenced by the production costs, such as cash operating costs, total production costs, treatment/refining charge, energy costs, transport and freight costs, technological progress reduction, costs for exploration, mining, processing and recycling (16).

Global population growth, along with social changes, such as increasing wealth or changing lifestyle, increases the quantitative need for materials (40). The strong economic development of China and other emerging economies has contributed to a rapidly increasing demand for metals and minerals (47). Increasing internal demand results in protectionist measures, export restrictions and volatile prices (46).

Moreover, the emergence of new high-tech technologies and the transition to a low-carbon economy increases the diversification, so demand, and therefore competition for raw materials rises (41, 48, 49). The increased use of high-tech metals is also related to low recycling rates and high dissipative losses along the life-cycle, because these metals end up in other material flows, get lost in the use phase or elsewhere and evade recycling (49). Knoeri et al. (50) state that even material substitution decisions of large companies might induce changes in the supply chain.

This list of the factors that influence the supply and demand of raw materials is not exhaustive. Besides, nearly all of the mentioned characteristics are dynamic and change over time. It must be emphasized that nobody can foresee the future resource availability or prices, but it is important to understand the weaknesses of the supply chains which may lead to supply shortages (16).

1.1.4. State of the art in methodologies for resource criticality assessment

The interdependency of the drivers that influence the availability of raw materials and the dynamic nature of it makes the evaluation of resource criticality challenging. There is much variation in the methodology, scope, and depth of the studies (40). The assessments are always made from the perspective of a particular system (40) because there is no such thing as absolute criticality. One resource is more critical than others under some conditions, for some users, and for some time scales (37). Therefore, the choice of the methodology and concrete indicators depends on several factors, such as the goal of the assessment, properties, and boundaries of the analysed system, undertaken assumptions, generalizations and interpretation.

After analysing criticality studies, general methodological steps that are common to all the analysed research can be observed. First, the indicators that should represent resource criticality are selected and calculated. Second, the indicators are aggregated to represent different dimensions. Finally, in order to represent the final results, the values are aggregated as either linear, in a matrix, or 3-dimensional (51).

In terms of the scope of assessment the studies can be grouped as:

- assessments with geographical focus (global, regional or country-wide) for one or several resources,
- assessments from an entrepreneurial perspective,
- assessments to estimate the impact on the implementation or functioning of particular technologies.

The present review of criticality studies is designed to review the most influential methodological approaches and identify the main challenges of criticality assessment.

Assessments with geographical focus

The studies with geographical focus are either screening studies that aim to develop a methodology for criticality assessment and apply it to compare the criticality of several materials or the in-depth analysis of the availability of one or several specific resources. The most influential screening studies with rigorous methodologies, also acknowledged as influential by Achzet and Helbig (51), Sievers et al. (47), Habib and Wenzel (22) and other authors, were analysed in order to provide the general overview of methodologies for criticality assessment from a specific geographical perspective (global-wide, region-wide or nation-wide). These studies are listed in Table 1.2 including their geographical focus, covered dimensions, and evaluated criteria. The analyses of specific resources are mostly based on the methodologies developed in the screening studies.

Table 1.2 Evaluated dimensions and assessed criteria in the criticality studies with the geographical focus (SR- Supply Risk, Vu-Vulnerability, En-Environmental implications as separate dimensions)

Study	**Geographical focus**	**Dimensions**			**Criteria**
		SR	**Vu**	**En**	
U.S. National Research Council (2008)	US	+	+		US consumption (value), Substitutability, Emerging uses, US import dependence, Ratio of world reserves to production, Ratio of world reserve base to production, World by-product production compared with total primary production, US secondary production from old scrap compared with consumption
Morley and Eatherley (2008)	UK	+			Global consumption levels, Lack of substitutability, Global warming potential, Total material/environmental requirement, Physical scarcity, Monopoly supply, Political instability, Climate change vulnerability
European Commission (2010, 2014)	EU	+	+	+ (2010)	Concentration of supply, Governance rating of producing countries (alternatively environmental performance in 2010 study), Substitutability, Recycling rate, Value added to end-use sectors
Thomason (2010)	US	+			US self-supply
Erdmann et al. (2011)	Germany	+	+		Share of national consumption, Change in the share of national consumption in world consumption, Demand for emerging technologies, Substitutability, Change in import, Ratio of world reserve to production, World by-product production compared with total primary production, Recycling rate, Concentration of reserves, Company concentration, Country risk of producing countries, Governance of countries selling to Germany, Sensitivity of value chain

Table 1.2 (continued)

Graedel et al. (2012)	Global, national	+	+	+	National/global: depletion time, companion metal fraction, percentage of population utilization, substitute performance, substitute availability, environmental impact ratio, life cycle assessment categories “human health” and “ecosystems”; national: policy potential, human development, political stability, global supply concentration, national economic importance, net import reliance ratio, net import reliance, global innovation
Hatayama and Tahara (2015)	Japan	+	+	+	Depletion time, concentration of reserves, concentration of ore production, concentration of import trading partners, price change, price variation, mine production change, domestic demand growth, domestic demand growth for specific uses, stockpiles, recyclability, possibility of usage restrictions

The U.S. National Research Council (20) was the first study that expanded the assessment of material availability over physical scarcity. The aim of the study was to identify critical raw minerals for modern US society. Similarly Morley and Eatherley (52) identified critical materials for the UK, Erdmann et al. (54) - for Germany, European Commission (39, 56) - for the European Union, Hatayama and Tahara (55) - for Japan. The study performed by Thomason (53) analysed the potential supply shortfalls for the US in the case of war. Graedel et al. (17) provided a generic methodology for multi-level assessment from corporate to global.

Three out of the seven analyses consider factors related to all the three dimensions: supply risk, vulnerability and environmental impact. With regard to the assessed criteria, studies differ considerably. However, the concentration of supply and political stability of supplying countries, import dependence, substitutability, the ratio of world reserves to production, economic importance, and issues related to by-production and recycling are mostly considered.

The selection of criteria strongly depends on the factors that are acknowledged by the authors as drivers that make material critical to the analysed system. However, due to the very high level of complexity, most of the authors agree that it is not possible to cover all the aspects of criticality. Rather, the assessment should simplify the real world without giving decision-makers the wrong signals (51).

The aforementioned studies can be defined as screening studies. Yet, a considerable number of studies apply the criticality approach to performing more specific assessments by analysing in depth one or several resources at the national, regional or global level. Liu and Müller (57), Guyonnet, et al. (58), Leal-Ayala, et al. (59) performed comprehensive material flow analyses of investigated resources in order to provide a solid basis for further assessments and identification of policy measures. Cordell and White (60), E. M. Harper, et al. (61), E.M. Harper, et al. (62), Mason, et al. (19) provided broader analysis in terms of criticality, Beylot and Villeneuve (18) focused on economic importance and Stepanek, et al. (29) on the supply risk. The criticality concept is primarily applied to metals, in particularly high-tech metals (58, 59), but also traditional industrial metals (18, 19, 29) and nuclear metals (62). Moreover, recent studies emphasise the importance of non-metal non-renewable materials such as water (31) and phosphorus (30, 60), which is an essential element for ensuring global food security.

Criticality assessment from an entrepreneurial perspective

Resource criticality is much more widely discussed in the context of particular economies. As a result, Graedel, et al. (17) as well as Mayer and Gleich (32) emphasize that it is particularly unclear for decision-makers in companies how to interpret and practically apply the criticality assessment. Up to now, only a few studies have intended to analyse resource criticality from the point of view of industrial decision makers. These studies are listed in Table 1.3.

Table 1.3 Evaluated dimensions and assessed criteria in the criticality studies from an entrepreneurial perspective (SR- Supply Risk, Vu-Vulnerability, En-Environmental implications as separate dimensions)

Study	**Assessment focus**	**Dimensions**			**Criteria**
		SR	**Vu**	**En**	
Rosenau-Tornow et al. (2009)	Corporate (Volkswagen AG)	+			Country concentration in production, country risk, market balance, stock keeping, refinery/mine utilisation, production costs, market power, market balance in 5 years, investments, degree of exploration
Duclos et al. (2010)	Corporate (General Electric)	+	+		Country concentration in production, country risk, by-product dependency, likelihood of rapid global demand growth, substitutability, crustal abundance, historic price volatility, volume of usage compared to the world supply, impact on revenue of products containing the element, ability to pass-through cost increase
Graedel et al. (2012)	Corporate	+	+	+	Depletion time, companion metal fraction, policy potential, human development, political stability, global supply concentration, percent of revenue impacted, ability to pass through cost increases, importance to corporate strategy, substitute performance, substitute availability, environmental impact ratio, corporate innovation, life cycle assessment categories “human health” and “ecosystems”

Table 1.3 (continued)

Bensch et al.(2015)	SMEs	+	+	Concentration risk, political risk, supply reduction risk, demand increase risk, human health, biodiversity
Mayer and Gleich (2015)	Industrial decision makers	+		Supply risk, country concentration, world mine production, apparent consumption, secondary production, stocks compared to price, real interest rate, global GDP, inflation rate, future price developments

Rosenau-Tornow, et al. (16) developed a method for identifying and assessing critical raw material market situations by looking only at supply risk dimension. The method has been used by Volkswagen AG to evaluate the supply risk of mineral raw materials. The authors provide concrete benchmarks for evaluation, although they emphasize that future fluctuations in demand, supply, and prices of minerals are almost impossible to predict.

Duclos, et al. (63) was the first to adapt the U.S. National Research Council (20) approach at the corporate level. The criteria corresponding to "Price and supply risk" and "Impact of a restricted supply on General Electric" were aggregated to the matrix. The method was applied to identify critical materials for the General Electric Company.

Graedel et al. (17) emphasized that no single approach is appropriate for evaluating supply risk and vulnerability to supply restriction at each of the three organizational levels (global, national and corporation). Some factors might be crucial for a corporation but unimportant at a global level. To name a few geopolitical factors, supply potential and intensity of competition are of crucial relevance to the corporate level but not that important at a global level. Similarly to Duclos, et al. (63), Graedel, et al. (17) extended the U.S. National Research Council (20) concept by proposing an influential methodology to evaluate the criticality of metals by distinguishing the supply risk and vulnerability to supply risk according to the organizational level. For example, Graedel, et al. (17) suggest that supply risk should be divided into medium-term (5-10 years) and longer term (a few decades). The former is suggested to be more appropriate for governments as well as corporations. Meanwhile, vulnerability to supply restriction differs depending on the organizational level.

More recently, Bensch, et al. (43) identified a need for an open source environmental management information system and developed a conceptual decision and information systems integration model for the assessment of products based on their raw material composition (33). The model aims to support decision-making in SMEs with a focus on the procurement of raw materials and product development (43). The application of the model is illustrated by applying it to the SMEs from the electronics industry. The proposed tool for decision-making support allows critical materials to be identified based on the global data. The proposed methodology can be considered as a useful database, but it does not follow the Graedel, et al. (17) approach to multi-level assessment, especially when it comes to the vulnerability dimension. The authors also acknowledge that the availability of data on an annual basis is a limitation of the proposed decision-making system.

Mayer and Gleich (32) aimed at enhancing the applicability of supply risk estimation for the industrial decision makers and proposed a statistical assessment framework that is aimed at a dynamic supply risk assessment and to make forecasts.

Concerning the methodologies of the selected studies, the choice of criteria to evaluate supply risk is rather similar to the approach used in the studies with a geographical focus. Nevertheless, the estimation of vulnerability to the supply risk is neglected in most of the analysed studies. Only Duclos, et al. (63) and Graedel, et al. (17) proposed a comprehensive set of indicators to assess the vulnerability dimension. A similar conclusion can be made regarding the environmental risk, which is addressed only in two studies by introducing two life cycle assessment categories (17, 33).

Application to assess technology

Another important group of criticality studies is the studies that focus on the functioning of specific industries or technologies on a global or national level. It is important to emphasize that most of these studies are designated to perform in-depth analysis of the materials or substances that were identified as critical in previous studies with a geographical focus.

Technology-wide the emphasis in the scientific literature in clearly put on the so-called low-carbon technologies. Authors investigate whether material availability is a constraint for technology growth. Alonso, et al. (64) aimed at identifying future demand for REEs and assess the implications for REE production, Bradshaw, et al. (15) examined the issues of potential geochemical scarcity, substitutability, and by-production of elements that are essential for the transition to a low-carbon economy, Grandell and Thorenz (65) investigated the silver supply risk for the fast-growing solar sector, Viebahn, et al. (48) - for the transformation of the Germany energy system, Guyonnet, et al. (58) explored flows and stocks of certain REEs at the scale of the European Union. Furthermore, Angerer, et al. (66) analysed how emerging technologies will drive demand for materials.

Fthenakis (67), Candelise et al. (68), Jarrett, et al. (23) and Bustamante and Gaustad (27) investigated whether the availability of materials could limit the potential for photovoltaic systems, Pihl, et al. (70) for concentrated solar power technology, Habib and Wenzel (22) and Dawson et al. (24) analysed concerns related to wind turbines. In addition to the low-carbon technologies, fossil fuel based industries were also analysed. Nieto, et al. (71) assessed a case of REEs in U.S. petroleum refining and investigated the possible effect on the supply risk of three different supply/demand scenarios.

In terms of methodology, the quantitative supply and demand patterns are estimated in most of the studies, often different scenarios are analysed. Some of the chosen indicators are similar to those used in the studies with a geographical focus, such as substitutability, by-production and supply risk. Roelich, et al. (28) proposed a framework for relating local and global properties in terms of materials criticality. This multi-level approach was used in the later studies by Dawson, et al. (24) and Jarrett, et al. (23).

1.1.5. The main challenges of the criticality determination

The major aim of the criticality studies is to highlight the economically important materials that are subject to potentially restricted availability. However, different methodologies lead to different results. Actually, in this context, if all the elements mentioned somewhere, from all the countries and regions, are summarized then most elements in industrial use are listed (7). Most of the authors that aimed to assess resource criticality emphasize that this is a challenging task. The main challenges related to the criticality determination are detailed bellow.

Complexity of aspects to be addressed and corresponding indicators

Firstly, the concept of criticality is not straight forward, and it must deal with a wide variety of factors (see Chapter 1.1.3). The majority of these factors are also difficult to depict, and the choice of concrete indicators is often very subjective. This also applies to the selection of criticality dimensions to be analysed. Most of the studies agree on supply risk and vulnerability dimensions, but the inclusion of the environmental dimension is quite evenly balanced between supporters and non-supporters (72). Moreover, the factors that influence criticality are complex and interdependent, therefore, significant assumptions, and generalizations have to be made in order to provide the comprehensive simplification of the real world.

Secondly, even if only a few authors emphasize it (72), there is no universal approach. To provide meaningful insights for decision-makers from different organisational levels, criticality determination should be performed from a point of view of the system under consideration.

Criticality factors are dynamic

An important attribute of resource criticality is that it is dynamic. This is valid for the factors that influence both demand and supply of natural resources. It can change significantly over time because new technologies emerge and old ones die, the geopolitical situation alters (72), mines open and close (40), new mineral deposits are discovered and the geographical location of supply changes (22), societies and policies change, financial cycles wax and wane (40), demand from different economic sectors changes, material substitution decisions of large international companies can induce changes in the supply chain (50). Although it is obvious that most of the factors that influence criticality are dynamic, most of the studies provide static assessment and only a few opt to capture the changes over time. The European Commission in the report of critical raw materials for the EU (21) acknowledged the need for periodic assessment and provided the updated study in 2014. Recently, several conceptual approaches were introduced, such as agent-based modelling (50), system dynamics modelling (73, 74) and scenario-based risk analysis (25). Nevertheless, Glöser, et al. (41) noted that the later, model-based approaches are no longer designated to the screening of a large number of materials, but rather are very specific models to analyse the materials that have already been identified as critical in previous studies.

Criticality is relative

Criticality of materials is a matter of degree, not a state of being (47). In order to deliver a more comprehensive message for decision-makers, some studies (17, 21, 75, 76) provide thresholds to separate critical materials from non-critical ones. On one hand, imposing thresholds is certainly related to some degree of subjectivity. On the other hand, setting limits for certain indicators can help to circumvent some methodological issues such as compensation amongst the criteria in the linear summation (17).

Limited availability of data

One of the key challenges acknowledged in majority studies is a lack of pertinent data of adequate quality. This applies not only to data on material flows (77), international trade and economic indicators (21), but also to the unreliable data on mineral reserves (13). This issue often leads to various assumptions that should be acknowledged in order to provide more transparent results.

Other challenges

Amongst other limits to the critical raw materials approach Sievers, et al. (47) emphasize that most of the studies show a bias towards technology minerals, they lack predictive power, have a tendency to overestimate the economic impact, fail to distinguish between short and long-term problems and focus on risks related to the mining and export, thus disregarding the larger production chain.

1.2. Environmental aspects in the context of resource criticality assessment and mitigation

1.2.1. Environmental implications as criteria to assess resource criticality

Environmental implications are to some extent reflected in the majority of criticality studies, especially those that concern assessments with a geographical focus. However, not all the studies consider the environmental aspects and the approaches differ significantly. The studies can be divided into two major groups in terms of the underlying assumptions (Fig. 1.1).

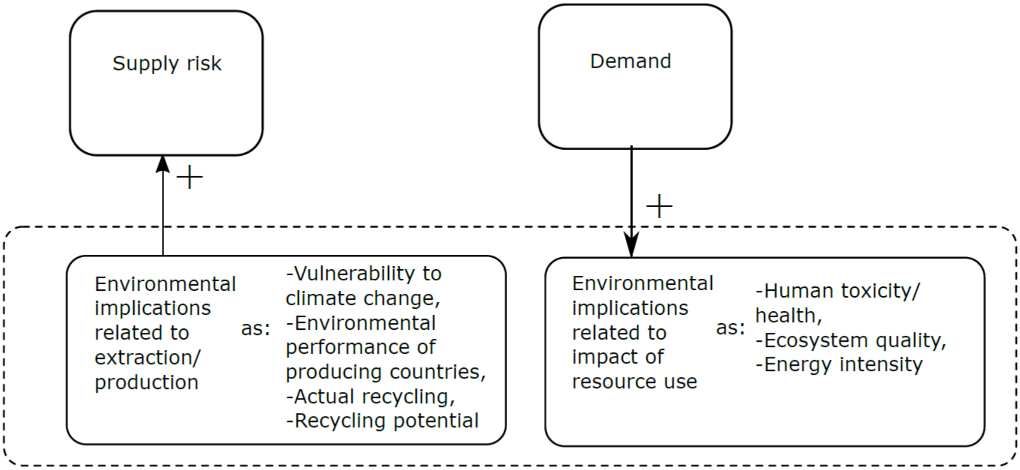

Fig. 1.1 Environmental implications as criteria in the criticality assessment studies and corresponding indicators

The first group of studies suggests that environmental implications have an influence on the supply risk of materials. Two aspects are addressed concerning this assumption. Morley and Eatherley (52), European Commission (39) and Roelich, et al. (25) state that the condition of the environment can increase the supply risk of raw materials. Morley and Eatherley (52) argue that environmental limitations are more likely to restrict supply than physical scarcity and represent this assumption by introducing the indicator of vulnerability to the effects of climate change in key supply regions. The authors argue that some regions are more vulnerable to the effects of climate change than others. Therefore, this indicator can help to predict future material insecurity. The European Commission (39) represented the Environmental Risk as a separate and equally important criticality dimension. It can be said, that this would imply the extension of the criticality definition. The Environmental Performance Index (EPI) of the producing countries was used to evaluated the environmental risks in the supply countries. However, the Environmental Risk dimension was excluded in the updated 2014 study because it was considered not relevant enough. Roelich, et al. (25) followed the EU approach and argued that due to environmental impacts related to the extraction of materials, environmental regulations are becoming increasingly stringent and thus it can become a barrier to the development of mining operations. The EPI was used in the Roelich, et al. (25) assessment of criticality of infrastructure transitions.

The second aspect addressed in the studies of the European Commission (39, 56), U.S. National Research Council (20), Hatayama (55) and Erdmann (54) is actual recycling or potential recyclability. The underlying assumption is that reducing the dependence on foreign resources by promoting domestic recycling can decrease supply risk and thus mitigate criticality (55).

The second group of studies suggests a rather different approach and proposes that the negative impact on the environment related to the use of resources should be considered as a separate dimension of criticality (17, 33, 78) or in the case of the Morley and Eatherley (52) study, it is included as a criterion under the material risk dimension. In this case the environmental implications are reflected as global warming potential caused by material extraction (52), environmental burden of the material that is assessed through LCA in terms of damage to human health and ecosystems (17, 33), human toxicity expressed as Environmental Protection Agency toxicity score, energy intensity expressed as primary embodied energy and energy saving obtained through recycling (78). In this respect, environmental implications are not intended to be viewed as a restriction to supply security, but rather as an indication to the decision-makers (17).

The environmental paradox

A significant number of environmentally friendly technologies actually rely on materials that are acknowledged as critical at the global level in various studies. Morley and Eatherley (52) call it "the environmental paradox", since in this case, environmental performance or efficiency is achieved with greater supply risk and often with significant environmental implications.

The examples could be platinum group metals (PGMs) used for catalytic converters in vehicles, production of fuel cells, low-sulphur petroleum; tellurium and indium used in solar cells, cobalt used for rechargeable lithium-ion car batteries and neodymium used for energy efficient car magnets (52).

1.2.2. Resource efficiency measures addressing criticality mitigation

Besides characterization, research into resource criticality further investigates possible strategies for reducing identified risks. Strategies to address resource criticality are related to either securing the supply or improving the management of the resources. Resource supply from a global or national point of view can be secured by forging political alliances, revising competition policy to discourage monopoly or excessive oligopoly (52), increasing mining of primary resources (40), export restrictions with a view to securing domestic supply, resource development overseas and stockpiling (55). From an entrepreneurial point of view the close cooperation with suppliers (48), strategic inventories can offer a buffer against short-term volatility in materials supply and pricing (79). Ensuring sources of primary material might be the fastest achievable strategy, but the durability of results might be questionable, and the implementation of this measure does not contribute to the reduction of dependency on primary resources or improvement of overall resource efficiency. Therefore, policy measures related to securing the supply are beyond the scope of this review.

The sustainable development concept and precautionary principle should be applied to manage material criticality (80). Thus, only the strategies related to sustainable management of resources that are addressed in the scientific literature are described in this chapter. In most of the cases, screening criticality studies only briefly mentions the possible criticality mitigation measures. Nevertheless, the studies with a focus on specific technologies in most of the cases offer possible solutions. It should be emphasized that challenges related to critical materials can be addressed in a variety of ways, depending on the specific material and its application (79). The strategies suggested in the scientific literature can be summarized to three major groups:

- Reduction of resource utilization;
- Closing material cycles;
- Substitution.

Reducing resource use

Reducing material intensity is one of the key strategies to reduce the dependence of primary resources (27) and increasing resource efficiency. With the aim to move towards a more sustainable use of resources, reducing the use of material should be the primary goal considering the whole life cycle of the material, including mining and material processing (41). From an entrepreneurial perspective, among other common practices addressed in the criticality studies, advanced manufacturing processes such as 3D printing (52) and improved product design (59) are good examples of the possibility to reduce resource use.

Closing material cycles

Retaining abiotic resources within the technosphere (Fig. 1.2) can prolong resource supplies (81). Moreover, it has considerable advantages over primary supply in terms of securing supply, decreasing the environmental impact from primary production and decreasing costs.

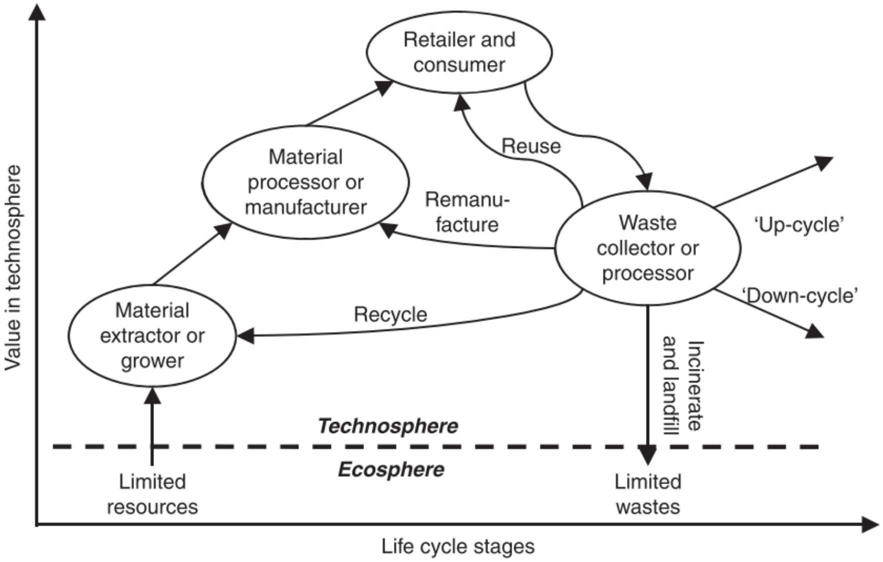

Fig. 1.2 Resource cycle and value in the technosphere (82)

Metals are a good example for demonstrating opportunities to close material cycles (81). In contrast to other non-renewable resources like oil and coal, metals can be recycled after the end of their product life without losing their properties. Also, the importance of metals is increasing due to the increasing requirement for basic metals (associated with the development of emerging economies and increasing wealth) as well as technology metals (associated with the increasing variety of required materials) (83).

In the context of criticality mitigation, scientific literature investigates opportunities to improve resource efficiency and close material cycles in every stage of the metal life cycle. Lusty and Gunn (13) proposed strategies for more efficient mining and processing, that include the application of such innovative technologies as automated drilling and mining, more selective or “smart blasting”, improved ore sorting, more effective waste removal and pre-concentration, enhanced grinding technology, in-situ mining, re-working of tailings and slags, improved water management and increased the application of bio-technology.

In terms of further life cycle stages, reuse-remanufacturing, recycling and down cycling are the most important procedures for keeping essential metals in the materials cycles (14). Innovative approaches such as product-multiple life cycles are proposed in the scientific literature (74).

Recycling and recovery

Enhanced recycling is important for ensuring the needs of society without increasing pressure on the environment (27, 40). Some metals, such as gold, silver or aluminium already have considerably high recycling rates, but many others, such as technology metals, are associated with the very low recycling rates (81). Thus, increasing recycling efficiency involves both, improving collection systems and recycling technologies.

Bradshaw, et al. (15) claim that improved recycling can in principle supply the majority of global material needs. However, recycling has limitations and can never be 100% efficient due to the economic and technological restrictions (58, 65). Recycling as a mitigation strategy is shown to have poor short-term results for technology metals (22, 27) due to the long lifetime of key end-uses like wind turbines, and non-availability of commercial-scale recycling technologies.

In the recent scientific literature, the discussion is especially active on the recovery of REEs. On one hand this is due to the fact that REEs are considered as critical materials for major economies such as the European Union (56) and United States (84), mainly because of China’s monopoly in terms of supply (85) and because REEs are associated with products that are important for the decarbonisation of the energy sector (58). On the other hand, there is a tremendous opportunity for improving recycling rates (58, 86) since only 1% of all used REEs are recycled (87). The results of studies (87–89) show that secondary supply from fluorescent lamps, permanent magnet waste flows and hard disk drives has the potential to contribute to the supply of REEs, especially in the long term.

Increasing attention is also paid to phosphorus (30, 60). Phosphorus is consumed by 100% of the global populations since it is an essential nutrient for both plants and animals and cannot be substituted. The supply of phosphorus is predicted to become dependent on one country in the medium term. Recovering phosphorus from waste activated sludge is one of the investigated possibilities to ensure the supply (90).

Reducing dissipative losses

High dissipative losses along the life cycle are one of the causes of low recycling rates. These losses occur in raw material extraction, processing, manufacturing and disposal of a product or in its use phase, and makes recycling technically or economically unfeasible (49, 81). Quantitative estimation of dissipative losses is a challenging task due to the lack of data on material and substance flows. Some materials, such as fluorspar, gallium, germanium, indium and REEs are estimated to have over 90% dissipation. The dissipative losses can be reduced by prioritizing these losses and focusing on optimal measures for a specific material, like separation and recycling of the corresponding products and production waste, improving collection of end of life products (49).

Substitution of material

In the majority of criticality studies, substitution is specified as an adequate response to mitigate resource criticality as long as it is substituted for less critical material (27, 33, 52). The research in this field focuses on finding substitutes for the high-tech metals, identified as critical for the EU. Halme, et al. (91) concluded that with the present technology substitution of these materials is difficult without loss of performance or resource efficiency. Therefore, looking for substitutes is one of the important directions in this field of research. For example, according to Morley and Eatherley (52) nanotechnology could facilitate substitution of rare materials. Wigger, et al. (92) investigate a possibility to substitute neodymium, gadolinium and REEs for nano materials in permanent magnets, magnetic resonance imaging and photovoltaics, but underlines a high degree of uncertainty especially in terms of toxicological and eco-toxicological repercussions as well as recyclability.

The challenge is to find substitutes that are more preferable not only from the technological point of view but also from economic and environmental aspects. Also, having in mind that criticality is dynamic, the evolution of technology and substitution decisions, especially by large international companies might have a significant effect on criticality itself. With the aim to better understand the effects of substitution decisions Knoeri, Wäger, et al. (50) proposed the conceptual model, which aims to introduce dynamic assessment of criticality by integrating dynamic material flow and agent-based behaviour models. The proposed conceptual framework is designated to assess the availability of scarce metals over time by explicitly modelling industrial decisions and their interaction on the stocks and flows of materials.

In contrast to material substitution, system substitution could be a more balanced approach, including the creation of new value chains and systems that satisfy the needs of society, but are less dependent on the supply of critical materials (79, 91).

1.3. Approaches and strategies to improve resource efficiency

It can be stated that there exist adequate policies and general strategies for material criticality mitigation at the regional level. Moreover, after performing the review of relevant literature, it can be stated that criticality is related to the more efficient use of resources from one hand because environmental conditions have effect on criticality, on the other hand, resource efficiency improvement provides an adequate response to mitigate criticality. Thus, the improved product and process efficiency is an adequate measure to mitigate resource criticality (40).

Resource efficiency means “using the Earth’s limited resources in a sustainable manner while minimizing impacts on the environment” (93). The resource efficiency measures to support resource criticality mitigation listed in Chapter 1.2.2 can be implemented by applying principles provided by various approaches and strategies, such as Resource Efficient and Cleaner Production, Pollution prevention, Industrial Ecology and Sustainable manufacturing (82). The European Union promotes the implementation of these strategies by adopting programmes of action such as the Circular Economy Package, which aims to contribute to the move towards a more circular economy where resources are used in a more sustainable way (10).

The United Nations Environmental Programme in 1990 defined Cleaner Production (CP) as the “continuous application of an integrated preventative environmental strategy to processes products, and services to increase efficiency and reduce risks to humans and the environment”. In 2008, the confluence of global economic and environmental crisis had led to the broadening of the definition of CP and the term of Resource Efficient and Cleaner Production (RECP) was introduced. However, CP still continues to be a valid and widely used definition (94). RECP addresses the three sustainability dimensions by synergistically promoting production efficiency, environmental management and human development (95). Thus, RECP is an area of basic and applied research, which embraces concepts and methodologies from different disciplines (96). It has become the most widely adopted of the various environmental management practices (97) and has proven itself as an effective way of obtaining improved resource utilisation (98), meanwhile, providing an opportunity for reducing costs. Cleaner production management strategies endeavour to increase the productivity of materials, improve energy efficiency, improve material flow management, apply preventive environmental protection approaches, strive for sustainable use of natural capital and achieve accordance with legal compliance (99). In North America, the term Pollution Prevention (P2) is used, which is similar to CP but tends to be applied almost exclusively to manufacturing processes (100). P2 is defined as “the use of materials, processes, or practices that reduce or eliminate the creation of pollutants or waste at the source. It includes practices that reduce the use of hazardous materials, energy, water, or other resources and practices that protect natural resources through conservation or more efficient use” (101).

Industrial Ecology (IE) is defined as the study of interactions and interrelationships both within industrial systems and between industrial and natural systems (102–104). Applied industrial ecology is an integrated management and technical program including: creation of industrial ecosystem (biological analogy), balancing industrial input and output to natural ecosystem capacity, dematerialization of industrial output, improving the metabolic pathways of industrial processes and materials use and policy alignment with a long-term perspective of industrial ecosystem (100). The core elements of IE can be applied at a variety of levels: at the firm (104) or units process level (micro level), at the inter-firm, district or sector level and at the regional, national or global level (100, 105).

Depending on selected system boundaries, CP and IE can be overlapping approaches (104). Nevertheless, in practice, CP is mostly focused at the firm-level, while IE typically takes a system view that draws the boundary for analysis more broadly (100, 105). Some approaches to IE at micro levels promote the inclusion of CP (100).

1.3.1. Decision-making support for the implementation of RECP and IE strategies in industry

Computational and mathematical models are used extensively to support decision-making in the field of sustainable resource management (106, 107). Several of the numerous examples of recent studies include:

- substance flow analyses and materials flow analyses (MFAs) (108);
- life cycle assessments (LCAs) (109–111),
- agent-based models (ABMs) (112);
- environmentally extended input-output (EEIO) models (113);
- system dynamics models (114, 115);
- integral models (50, 116).

Despite an abundant number of studies, (106) it should be emphasized that many models, especially in the field of IE, are constructed to address a particular problem within a particular context, and thus the universal and integrated approach is actually still lacking. Cleaner production is acknowledged as the most widely implemented environmental management practice in companies, but mostly lacks the wider perspective of long-term sustainability (97).

To facilitate an informed implementation of RECP and IE strategies, the decision-making involves the application of assessment and decision-making methods.

1.3.2. State of the art in assessment methods of RECP and IE strategies to support decision-making in industry

Various methodologies and methods for every domain of sustainability assessment are available (117–119). In the context of sustainability assessment (117) the following terminology is proposed. The method is “a set of models, tools and indicators that enable the calculation of indicators’ values” (e.g. ReCiPe). The methodology is “a collection of individual characterisation methods, which together address the different sustainability issues and the associated effect/impact” (e.g. LCA). However, it must be emphasized that terminology differs from study to study and in some cases (118, 119) methods and methodologies are denominated as “tools”.

Ness et al. (119), Finnveden and Moberg (118), Sala et al. (117), Angelakoglou and Gaidajis (120) and others provided comprehensive reviews of existing methodologies for sustainability assessment. The methodologies can be categorized in many different ways. Finnveden and Moberg (118) differentiate between procedural and analytic methodologies for business and policy decision making. Procedural methodologies (e.g. Environmental Impact Assessment) focus on the connections to its societal and decision context whereas analytical methodologies (e.g. Cost-Benefit Analysis) focus on technical aspects of analysis. However, analytical tools can be used within the framework of procedural tools. Ness, et al. (119) proposed to distinguish between indicators/indices, product-related assessment, and integrated assessment methodologies.

The recent review of Angelakoglou and Gaidajis (120) aimed to identify the methods that can be explicitly applied to industries and classified them into categories corresponding to two domains: environmental assessment and sustainability assessment. In accordance with the scope of this thesis, only environmental assessment methods are listed in Table 1.4, although the Environmental accounting methods also integrate the economic assessment. Methods are listed according to the scope of the evaluation, which is relevant to industrial decision-makers: product, process, industrial facility or corporation.

Table 1.4 Classification of methods contributing to the environmental assessment from the perspective of the industrial decision-makers. Adapted from Angelakoglou and Gaidajis (120)

Category	**Scope of assessment**			
	Product	**Process**	**Industrial facility**	**Corporation**
Material and Energy Flow Analysis	EF MIPS CED/CExD EE EA EXA WF	EF CED/CExD EE EA EXA SPI	SFA WF	SFA
Life Cycle Analysis	CF LCSD USE-LCA CML 2001 EI99 EDIP 2003 EPS 2000 IMPACT2002+ LIME ReCiPe TRACI	CF LCSD USE-LCA CML 2001 EI99 EDIP 2003 EPS 2000 IMPACT2002+ LIME ReCiPe TRACI	CF EDP	BRIDGES CF

Table 1.4 (continued)

Environmental accounting	CBA CVM TCA	CBA CVM MFCA TCA	CBA CVM EMA MFCA TCA	EMA MFCA

EF=Ecological Footprint; MIPS=Material Inputs per Service and Ecological Rucksack, SFA=Substance Flow Analysis, SPI=Sustainable Process Index; WF=Water Footprint; CED/CExD=Cumulative Energy/Exergy Demand; EE=Embodied Energy; EA=Energy Analysis; EXA=Exergy Analysis; CBA=Cost-Benefit Analysis; CVM=Contingent Valuation Method; EMA=Environmental Management Accounting; MFCA=Material Flow Cost Accounting; TCA=Total Cost Assessment; BRIDGES=Bridges to Sustainability; CF=Carbon Footprint; EDP=Ecosystem Damage Potential; LCSD=Life Cycle Sustainability Dashboard; USES-LCA=Uniform System for the Evaluation of Substance, EI99=Eco-Indicator 99

As presented in Table 1.2 in terms of environmental assessment there exist well-known and appropriate methods to perform analysis within every scope. In terms of the broader assessment, that covers several sustainability domains Angelakoglou and Gaidajis (120) categorise methods to individual/set of indicators, composite indices, and socially responsible investment indices.

Well established and documented methodologies (119) such as Life cycle assessment, Environmental impact assessment, cleaner production feasibility analysis and others provide the possibility to combine several methods of environmental assessment or assessment of other sustainability domains. To perform holistic assessments of RECP and IE strategies, the methodologies can be combined into frameworks. The comprehensive overviews of environmental and sustainability assessment methods and methodologies, including their advantages and disadvantages are provided by Angelakoglou and Gaidajis (120), Ness, et al. (119), Sala, et al. (121), Singh, et al. (122) and other authors. It is essential to use the proper evaluation methodologies to support decision-making (96), the proposals of detailed procedures on how to select methods are provided in (121, 123).

Decision-making in sustainability is a multi-objective optimization problem. Multi-criteria analysis allows problems involving multiple criteria to be structured and resolved. The most widely used multi-criteria decision-making methods are: multi-attribute utility theory (MAUT), analytic hierarchy process (AHP), fuzzy set theory, case-based reasoning, data envelopment analysis, simple multi-attribute rating technique, goal programing, ELECTRE, PROMETHEE, simple additive weighting (SAW) and the technique for the order of preference by similarity to the ideal solution (124). Most of the multi-criteria decision support methods were not developed explicitly for resolving sustainability problems. However, thanks to the ability to cover cross-disciplinary issues, these methods are extensively applied to assess RECP and IE strategies from the point of view of industrial decision makers.

Numerous examples of the application of multi-criteria decision-making support methods include: CP feasibility analysis (125), AHP for CP planning (126), composite indexes for decision-making in SMEs (127), AHP and fuzzy membership degree analysis for quantitative evaluation of CP effectiveness in the stone processing industry (128), AHP for evaluating sustainable manufacturing practices in electrical panel industries (129).

1.3.3. Overview of the studies that consider the integration of criticality assessment into decision-making support models for improving environmental performance in industry

The growth of an enterprise can be threatened by an increase in the price of material or the unavailability of material (74). Authors like Bench et al. (33), Graedel et al. (17), Knoeri et al. (50), Duclos et al. (63), Mayer and Gleich (32) and Rosenau-Tornaw et al. (16) acknowledge that consideration of the criticality can help limit the risk of supply of resources from the point of view of the industrial companies. Moreover, new technologies and products have often been developed with little attention to possible constraints on the availability of critical materials. Although it is acknowledged that designers and engineers have a great influence in the planning phase where the major decisions on the used quantities of resources and decisions on how long the materials will be kept in the loop are made (7, 80), technology developers seem to be relatively unaware of material scarcity and enterprises are usually not well-prepared to tackle the issue (80). In this chapter, the current attempts to integrate criticality assessment into existing models for industrial environmental performance are discussed.

The studies with the regional focus, or assessing only specific cases such as specific materials (e.g. (130) resource efficiency scenarios for indium), specific strategy (e.g. system dynamics model for adopting product multiple life cycles by Asif, et al. (74)) or general technology development (e.g. transition to low-carbon infrastructure (24)) are not included in this review, as well as contributions that provide only general suggestions (131, 132).

In terms of the state of the art assessment methodologies, technical, environmental, and economic aspects are most often evaluated for feasibility analysis of RECP and IE alternatives (133–135). In some studies, the social criterion is also taken into account (136). From the life cycle assessment perspective, currently, the impact assessment in LCA of resources is limited to the depletion potential of abiotic resources and delivers no conclusion about actual resource availability at the site of production. Thus, it cannot capture criticality aspects such as supply risk (42, 137) and economic aspects influencing the security of supply (11).

Currently available studies can be categorized into those based on LCA, and those based on other approaches (Table 1.5).

Table 1.5 Overview of the recent research proposals to integrate criticality assessment into decision-making support models for sustainability improvement in industry

Author	Model, methodology or method	Criteria	Criticality dimensions covered	Scope of assessment
Knoeri, Wäger, et al. (2013)	Agent-based behaviour model and dynamic material flow model	No eventual recommendation	No eventual recommendation	Industries and companies
Schneider, et al. (2014)	LCSA	Economic scarcity potential ESP, as economic dimension in LCSA	Supply risk, environmental risk (under LCA)	Global economy/mining
Mancini, Sala, et al. (2015)	LCSA	no eventual recommendation	no eventual recommendation	Micro and macro level, European context
Dewulf, et al. (2015)	Integrated sustainability assessment framework (ISAF)	Lack of alternatives as technical dimension, market stability and geopolitical issues as economic dimension/EC approach	Supply risk and economic importance, environmental risk (under LCA)	European context/production and supply
Gemechu, et al. (2015), Sonnemann, et al. (2015)	LCSA	Geopolitical supply risk, vulnerability to supply risk as economic dimension, social availability and geopolitical availability as social dimension /Graedel (17) approach	Supply risk and vulnerability to supply risk, environmental risk (under LCA)	Country based/global production and import
Bensch, et al. (2015)	Environmental management information system (EMIS)	Production concentration risk, political risk, supply reduction risk, demand increase risk under economic dimension	Supply risk, ecological dimension	Global economy/global production

Integration to the LCA

Currently, the LCA community is taking the first steps toward resource criticality assessment by acknowledging its importance (42). All analysed studies that address this issue, advocate that criticality should be integrated into LCSA in order to contribute to the holistic sustainability assessment of resources by integrating socioeconomic and geopolitical issues (such as supply risk).

The research conducted by Schneider, et al. (11) was the first attempt found in the scientific literature to integrate criticality into LCSA. Authors proposed a new indicator of Economic scarcity potential ESP, which is indented to capture supply risk, identified as an economic aspect in LCSA. It comprises eight equally weighted indicators: reserve-to-annual production ratio, new material content, HHI of mine production, WGI, human development indicator (HDI), an increase in demand, the share of mine production under trade barriers and the percentage of production as a companion metal. The vulnerability dimension is not considered. The system under study is the “global economy”, thus, supply risk is determined as the average global risk. The authors suggest that future studies should evaluate the whole life cycle and differentiate between primary and secondary resources.

In two complementary articles, Mancini et al. (38, 42) discuss the potential to integrate criticality assessment into LCA for the identification of hot spots and improvement opportunities at both the micro and macro scale. Using only approaches based on physical flows (such as MFA) is not sufficient because critical materials might be neglected due to the criteria based on quantity. The study does not propose a concrete implementation but suggests that at impact assessment level the standard list of critical materials could be used, or otherwise the information about the origin of material for a specific application would be required. However, the authors underline that before discussing concrete implementation, several open issues should be addressed, such as relative ranking, subjectivity of assessment (subjective thresholds), absence of absolute validity (critical materials are assessed relatively to a certain country or region), and the differentiation of the geographic origin in the life cycle inventory analysis.

Dewulf, et al. (46) proposed a new concept of integrated sustainability assessment framework ISAF, which would cover all the sustainability pillars by combining different quantitative frameworks: LCA, social LCA, ecosystem services, resource criticality assessment and conflict minerals assessment. The indicators of criticality assessment are integrated as criteria for technical and economic assessment. The selection of indicators is based on the EU (56) approach and thus, cover European (in some cases global) data.

Complimentary publications by Gemechu, et al. (138) and Sonnemann, et al. (12) rely on the Graedel, et al. (17) approach and propose to integrate criticality into the LCSA framework as economic and social dimensions. The study by Gemechu, et al. (138) is the first attempt to suggest that geopolitical risk should be addressed not only by considering the concentration of global production but also by considering the import countries. The authors advocate that criticality should not be linked only with minerals, but also with other resources such as water and land use.

However, the authors acknowledge that there would be significant difficulties to operationalize the integration of criticality assessment into the LCSA framework.

Other approaches

Knoeri, Wäger, et al. (50) aim to tackle important aspects of criticality assessment, such as the possibility for dynamic assessment, feedback between possible demand and supply chain developments. The authors develop a conceptual model, which is designated to investigate how far criticality will be affected by industrial substitution decisions if dynamic interrelations are considered. The proposed model is designated to industries or single companies to evaluate specific substitution decisions. However, it is not clear how specifically this conceptual framework could be applied by the companies.

Bensch, et al. (33) put forward the idea to integrate criticality into the decision support system for procurement and product design provisions to allow decision making in the three dimensions of sustainability: economic, ecological and societal. The decision-making system is designated for SMEs. In contrast to the previous approaches that aim to integrate criticality dimensions into the existing LCA framework, this study considers criticality as a separate framework. Two dimensions of criticality are proposed: economic and environmental. The economic dimension consists of 11 indicators that are selected based on various previous studies, the environmental dimension is covered by Human health and ecosystem quality categories based on ReCiPe. The method provides the generic assessment at the global level without differentiating the actual availability in the specific geographic location. Thus it could be defined as a database (33).

1.4. Conclusions from the literature review

In addition to the physical resource scarcity, there are enough other concerns that should encourage a more sustainable use of resources, such as increasing consumption, environmental impacts associated with the use of natural resources, ever-decreasing ore grades, volatile prices and the geopolitical situation. The issues related to the secure supply of resources are analysed by the recently emerged research field that studies resource criticality.

Despite the currently increased interest, this field of research is still heterogeneous, and there is no common definition or methodology on how to evaluate resource criticality, and therefore there is no agreed list of critical resources. Even so, it is clear that there is no such thing as absolute criticality. There are resources that are more critical than others under some conditions, some users, and for some time scales (37). Thus, despite the variety of methodologies that can be found in the scientific literature, researchers agree that resource criticality is relative, and criticality assessment involves the holistic evaluation of multidimensional criteria. Criticality is often defined as supply risks for resources whose shortage may endanger the functioning of technology, infrastructure, or the functioning of a productive society, and thus supply risk and vulnerability to the supply risk are the most common dimensions in the criticality assessments. The inclusion of the environmental dimension seems to be balanced quite evenly between supporters and non-supporters. Nevertheless, the analysis of the recent scientific literature showed that there is enough evidence to claim that environmental implications are relevant in the context of resource criticality. Two different assumptions were identified: the suggestion that environmental implications have an influence on the supply risk of resources and the suggestion that negative environmental impact related to the use of resources should be considered as a separate dimension in the criticality assessments.

In terms of the scope of the assessment, it can be concluded that criticality assessments tend to focus on geographical regions and on the specific technologies. Until recently there was relatively little attention paid to the assessments from an entrepreneurial perspective.

Although there is no consensus on how environmental implications should be included in the criticality assessments, in terms of mitigation strategies, most of the authors agree that resource efficiency improvement is a key strategy to mitigate resource criticality. Increasing resource efficiency can be achieved by implementing concepts such as Resource efficient and cleaner production (RECP) and Industrial ecology (IE). Thanks to the evidence of the positive correlation between cleaner production and improved business performance, cleaner production is the most widely adopted of the various environmental management practices (97).

Although, the role of industrial decision makers is acknowledged to be crucial for moving toward a more sustainable use of natural resources and it is evident that any successful industrial activity is dependent on the secure supply of resources, the extensive analysis of the scientific literature in this field of research showed that very few attempts have been made to integrate resource criticality assessment into decision-making models for sustainability improvement in industry. The most promising of them is the integration into the LCSA framework. However, in terms of supply risk assessment this would only provide the database based on the global or regional scope of assessment. Otherwise, in order to provide country-specific data the integration would encounter significant difficulties of operationalization due to the required up-to-date on-site specific data. This issue does not seem to be addressed in the scientific literature to the extent necessary to facilitate decision-making from the industrial perspective. Thus, it can be concluded that the integration of criticality assessment into other methodological frameworks that would enable decision-making support for industrial decision-makers is needed.

To the best of the knowledge of the author of this thesis, there is no such decision support system that would support decision-making from the point of view of a production company for improving environmental performance, and that would integrate resource criticality assessment as the measure to identify risks related to resource supply and as a measure to evaluate resource efficiency improvement strategies.

Based on this conclusion the *aim* of this doctoral thesis was defined: to develop a decision support system model for resource efficiency improvement in companies that integrate the assessment of resource criticality.

2. METHODOLOGY

2.1. Methodological framework

Methodological framework (Fig. 2.1) represents the main stages of the doctoral thesis.

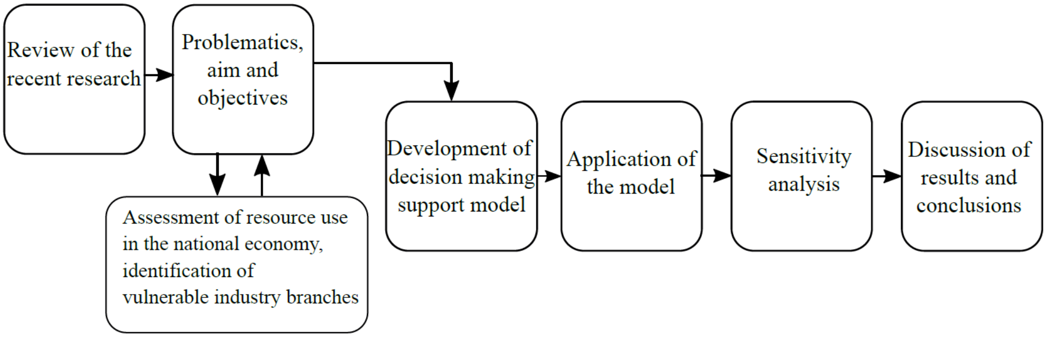

Fig. 2.1 Methodological framework of the doctoral dissertation

The literature review includes the overview of the recent research addressing two concepts integrated into this doctoral thesis: resource criticality and decision-making support for improving resource efficiency in industrial companies. The review of the literature related to resource criticality includes in-depth analysis of the definitions and methodologies applied in the recent studies with a particular focus on the environmental implications related to resource criticality. Whereas resource efficiency improvement is acknowledged as a key strategy to mitigate criticality, the literature review continues to elaborate on the state of the art in decision-making to support the implementation of resource efficiency strategies in the industry. The in-depth analysis of the studies that consider resource criticality as criteria for decision-making support for improving environmental performance in the industry is provided. The main conclusion of the literature review is that even if any successful industrial activity is dependent on the secure supply of resources, and meanwhile resource efficiency can be seen as one of the strategies to manage resource criticality, to the best of the knowledge of the author of this thesis, there is no decision-support system, which would allow industrial decision makers to integrate resource criticality assessment into the decision-making for resource efficiency improvement.

The assessment of resource use in the Lithuanian economy includes the assessment of geostrategic supply risk and economic importance of the main imported resources. The methodology of the assessment is described in detail in Chapter 2.2. The analysis allowed the most important resources and the industry branches to be identified, which are the most vulnerable to the uninterrupted supply of these resources.

Based on the findings of the literature review and the results of the assessment of resource use, the need to develop an integrated decision-support system model was identified. The developed model was tested by applying it to the companies corresponding to the vulnerable industry branches, and sensitivity analysis was performed. The results were discussed, and conclusions were drawn.

2.2. Methodology for the assessment of resource use in the national economy in terms of geostrategic supply risk, economic importance, and resource productivity

2.2.1. Screening of resources

The resources for the evaluation were selected considering several aspects, such as:

a) Material origin in nature;
b) Purpose of material;
c) Data availability;
d) Dependence on import.

Material origin in nature

Natural resources can be classified in several ways. Dividing them into biotic and abiotic resources is often used in the scientific literature (46). Biotic resources are materials which are derived from renewable biological resources that are of organic origin but not of fossil origin. Whereas, abiotic resources are metals (or metallic ores) and industrial minerals derived from static reserves (75). Abiotic resources are non-renewable and thus are associated with resource depletion. In this assessment, only the resources and materials of abiotic origin are evaluated.

Purpose of material

Resources can be also classified in terms of the use of their purpose: raw materials and energy carriers. In this assessment, only resources and materials used for manufacturing purposes are evaluated.

Data availability

As revealed in the literature review (see chapter 1.1.5) data availability is the limiting factor for most criticality studies. The materials assessed in this study were pre-selected according to the selection of the “most important” materials by Statistics Lithuania. These materials were considered to be the most important from the quantitative perspective. The material balances, including production, consumption, import, export and the end-uses according to the industry branches, were provided by Statistics Lithuania until 2009. The investigated materials include manufactured materials, rather than basic materials. In addition, based on the expert judgement, crude oil and natural gas were included in the assessment.

This assessment does not include the so-called “Critical materials for the EU”. Firstly, because in terms of the supply sources, the risks in the context of the Lithuanian economy are considered to be similar to the context of the European

Union and thus can be a priori considered as insecure. Secondly, there is no data about the end-uses of these materials in Lithuanian industry. Therefore, the economic assessment would include the same assumptions about the end-uses in the European or even global context as in the latest study provided by the European Commission (56). Thus, the evaluation in the Lithuanian context would come up with similar results. It should be also mentioned that the estimation of end-uses is also acknowledged as a subject to be improved in terms of available data in the EC study.

Dependence on imports

As the first step to identify possibly critical raw material the dependence on imports is evaluated. The dependence on imports of certain material (IMPD, %) in this thesis is defined as follows:

$$IMPD_i = \frac{Net\ IMP_i}{DMC_i} \cdot 100\%; \tag{2.1}$$

where Net IMP_i- net import (t),

DMC_i- domestic material consumption (t).

Net import is defined as the difference between physical imports and physical exports. Material consumption DMC is defined as the annual quantity of raw material extracted from (produced in) the domestic territory plus all physical imports minus all physical exports.

Only non-renewable raw materials with IMPD>50% are further investigated.

2.2.2. Estimation of supply risk

This assessment aims to identify the origin of imported materials with particular reference to imports from non-EU (third) countries. Therefore, when investigating the import data (Eurostat 2013), primary and secondary import countries were considered. The net import from EU-27 countries was analysed, assuming that positive export value (export<import) indicates that the analysed EU country is the country of origin of the investigated material. In the case of positive net import, the data of import into the particular EU country was considered.

The supply risk is evaluated based on the methodology used for the evaluation of critical materials for the EU (56). Within this methodology, it is assumed that concentrated primary supply from countries exhibiting poor governance has a large influence on the supply risk, since the supply may be interrupted e.g. through political unrest (56). The import related risk for the resource *i* is expressed as follows:

$$HHI_{WGIi} = \sum_c (S_{ic})^2 \cdot WGI_c; \tag{2.2}$$

where S_{ic}- share of material production in the particular country (the share of primary or secondary import country is considered in this case), %;

WGI_c- Worldwide Governance Indicator of the World Bank for each country c.

Worldwide Governance Indicators provided by the World Bank (139) are used to estimate stability/instability levels of producing countries. They include six indicators: voice and accountability index, political stability, government effectiveness, regulatory quality, rule of law and control of corruption. The values of WGI lie in the range of -2.5 to 2.5. In order to obtain a representative result, the values are scaled to the range from 0 to 10. The higher score corresponds to higher risk.

In order to compare the possible outcomes, the geostrategic supply risk was evaluated by considering both import countries and origin countries.

It is assumed that the geostrategic supply risk can be reduced if a secondary supply from end-of-life products is available and/or options for full substitution exist (considering price and performance). Thus, the supply for material i is expressed as follows:

$$SR_i = \sigma_i(1-\rho_i)HHI_{WGI}; \tag{2.3}$$

where: σ_i - substitutability of material (overall substitutability by considering substitutability in the main end-use sectors); possible values: 0-easily and completely substitutable at no additional cost, 0.3-substitutable at low cost. 0.7-substitutable at high cost and/or loss of performance, 1-not substitutable.

ρ_i - recycling rate from old scrap.

The maximum values of supply risk indicator lie in the range of 0-100 000 (the maximum value would be obtained if 100% of the material would be imported from a single country with the scaled WGI value equal to 10, the material could not be substituted and could not be recycled). In order to obtain more representative results, the values are scaled to fit in the range of 0-10.

2.2.3. Estimation of economic importance

Economic importance is evaluated based on the methodology used for the evaluation of critical materials for the EU (56). The relative economic importance of material *i* is expressed as follows:

$$EI_i = \frac{1}{GDP}\sum_s A_s Q_s; \tag{2.4}$$

where: A_s - share of demand of a raw material *i* in a sector *s*;

Q_s - value-added of the sector s that requires material i, million EUR;

GDP - national gross domestic product of the analysed year, million EUR.

2.2.4. Aggregation of results

Different ways of representation can be observed in the literature: graphical aggregation, matrices, and indexes as well as future market situation analysis (32). In this assessment, the results of the evaluation of supply risk and economic importance are represented in the so-called criticality matrix (Fig. 2.2). The concept of criticality matrix derives from the field of risk analysis. The concept of criticality determination within a criticality matrix is a powerful tool to identify and communicate economic vulnerabilities due to insecure raw material supply (41).

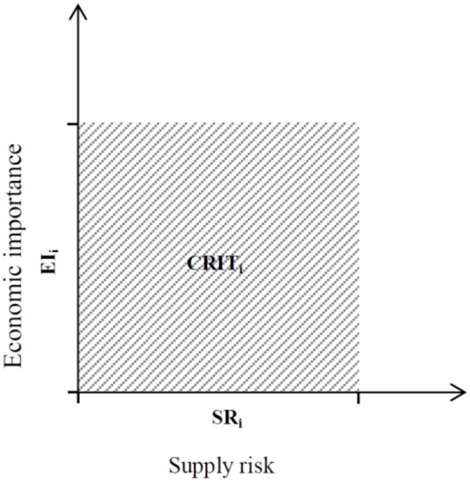

Fig. 2.2 Schematic view of criticality matrix and aggregation of results

In order to have the possibility to rank materials and to compare rankings of several years, the supply risk, and economic indicators are aggregated by multiplying the values:

$$CRIT_i = EI_i \cdot SR_i; \tag{2.5}$$

where EI_i - economic importance of material i (derived from eq. 2.4);

SR_i - supply risk of material i (derived from eq. 2.3).

Due to the high degree of subjectivity, the threshold for the "critical" material is not considered. Instead, the ranking of material is provided. The assessment intends to prioritize materials rather than separate them into critical and non-critical.

To facilitate the assessment, the Excel database was created. The database includes all the required data and calculations.

2.2.5. Estimation of resource productivity

Resource Productivity (GDP divided by Domestic Material Consumption) is a headline resource efficiency indicator proposed by the European Commission in the Roadmap to a Resource Efficient Europe COM (2011) 571 (9). Domestic Material Consumption (DMC) measures the annual quantity of raw materials extracted from the domestic territory (DE) plus all imports minus all exports. DMC is a recommended indicator for the evaluation of material use for the assessment of domestic resource efficiency (140).

In this assessment, the productivity of separate raw materials is investigated. Instead of using GDP of the entire economy, this study uses the industrial value added of the economy branches in which selected non-renewable raw materials are used. Resource Productivity (GDP/DMC) is expressed in euro/tonne.

2.2.6. Identification of the vulnerable industry branches

Based on the results of the criticality evaluation, the industry branches that are vulnerable to the availability of identified critical resources are identified. The industry branch is assumed to be relatively vulnerable if the percentage share of consumption of the critical material is greater than 10%.

Data

The Combined Nomenclature (CN) codes of investigated materials are provided in Annex 1.

The statistical data on the quantities of import, export, domestic material extraction (production) was obtained from Statistic Lithuania indicator database and is provided in Annex 2.

The detailed statistical data on partner countries for the import of investigated materials was obtained from the Market Access Database (141). In the context of foreign trade, partner country stands for the origin country for third (non-EU) countries and sending country for EU countries. The breakdown of import by partner countries is provided in Annex 3. The source of WGI values is the World bank database (139). The average values for the investigated years are scaled to 0-10 and are provided in Annex 4.

The end-uses according to the industry branches are obtained from the Statistics Lithuania report “Materials 2009”. From 1991 to 2009 Statistics Lithuania use to form mass balances for selected raw materials which are important for the Lithuanian economy. These included import, consumption, production, stock exchange and export data of metals, chemical materials, paper and paperboard, wood products and building materials. The data on end-uses is provided in Annex 5. The data on GDP and added value by industry branches is obtained from Statistics Lithuania indicator database.

2.3 Method for an integrated decision-making support system model development

The model is a description of a certain system. The decision-making model should describe, represent or mimic the phenomena or process that takes place in the real world, establishing the relationships between the variables and the objectives, in a satisfactory level, respecting the limitations of cost and time (142). The modelling procedure typically consists of problem identification, model conceptualization, model formulation and model validation.

The decision-making support model was developed based on the method of rational decision making. Rational decision making is a multi-step process for making choices between alternatives that is based on reason and facts. It requires the:

a) Identification of possible alternatives,
b) Choice of relevant criteria on which to assess their performances,
c) Option of weighting the criteria in terms of their relative importance,

d) Assessment of the various alternatives with respect to the criteria,
e) Option of translating the assessment into a partial utility value,
f) Ranking of the alternatives with respect to their overall utility,
g) Choice of the best option or, alternatively, re-start the process from the beginning (143).

The description of certain system consists of:

a) The transformation process or activities of the system;
b) The boundaries of the system (what is inside the system and what makes up its environment);
c) The components and sub-systems, and the dynamic relationships and stable relationships or the structure;
d) The uncontrollable inputs from the environment, the control inputs or decisions, and decision rules,
e) The outputs (performance measures).

The developed decision-support model can be mathematically described as a multi-objective optimization problem. Multi-objective, multi-criteria or vector optimization is a process in which a number of objective functions are optimized. The problem of multi-objective optimization can be mathematically formulated as follows (116):

$$\text{Maximize } F(\vec{x}) = [f_1(\vec{x}), f_2(\vec{x}), \dots, f_k(\vec{x})\ ] \tag{2.6}$$

Subject to:

$\vec{g}(\vec{x}) \leq 0$

$\vec{h}(\vec{x}) = 0$

$\vec{x} \in R^n, \vec{F}(\vec{x}) \in R^k, \vec{g}(\vec{x}) \in R^m, \vec{h}(\vec{x}) \in R^p$

where the integer k≥2 is the number of objectives,

m - number of inequality constrains;

p - number of equality constrains;

$\vec{x} \in R^n$ - vector of decision variables where n is the number of independent variables;

$\vec{F}(\vec{x}) \in R^k$ - vector of objective functions in which $f_i(\vec{x})$: $R^n \to R^1$.

The feasible decision space X and feasible criterion space S are defined as: $X = \left\{\vec{x} | g_m(\vec{x}) \leq 0, m = 1,2, \dots m \text{ } and \text{ } h_p(\vec{x}) = 0, p = 1,2, \dots, p\right\}$ and $X = \{F(\vec{x})\ | \vec{x} \in X\}$, respectively.

The multi-objective problem is solved by transferring it into a single objective optimization problem. The Simple Additive Weighting (SAW) method is used.

3. RESULTS OF ASSESSMENT OF RESOURCE USE IN THE LITHUANIAN INDUSTRY

The assessment of materials criticality is especially relevant for the economies that are considerably dependent on resource import. For example, the European Union imports three times more goods by weight than it exports. The amount of imports into the EU are dominated by fossil fuels and other raw products (144). Physical trade data by stage of manufacturing shows that the EU imports of finished products is more or less balanced with exports, the same balance holds for semi-finished products, however, the EU imports 10-12 times more raw products than it exports (144). Mining and production of metals have been moved to locations that are economically more attractive and have lighter regulatory standards; therefore, mining activities in the European Union and in other developed countries, such as the United States, have declined (145).

In this section, the results of the assessment of resource availability for the Lithuanian economy for the year 2008-2009 are presented. The main findings of the evaluation are in line with the study[1] initiated by the Ministry of Economy of the Republic of Lithuania in 2011. The main results were published in the scientific publication[2]. The assessment was updated by replacing the environmental risk evaluation by the evaluation of resource productivity.

3.1. Lithuanian economy dependence on imported resources

In terms of mineral resources, only six resources are domestically extracted in Lithuania, namely sand and gravel, clay, dolomite, limestone, peat and an insignificant amount of crude oil.

Import dependence for the year 2005-2009 of the following non-renewable resources was analysed: metals (cast iron, copper, aluminium, lead, zinc, tin, iron and steel) and chemical materials (sulphur, caustic soda, calcined soda, polyethylene, polypropylene, polystyrene and copolymers of styrene, polymers of vinyl chloride), natural gas and crude oil. Since the import dependence of aluminium, iron and steel, sulphur, polyethylene, polypropylene, polystyrene, vinyl chloride, and crude oil was also over 50%, all the selected resources were further investigated. The detailed data is provided in Annex 2. In addition, the import dependence on third (non-EU) countries for the year 2008 and 2009 was estimated (Table 3.1).

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[1] Kliopova, I., Knašytė, M., Staniškis, J.K. Lietuvos ūkio apsirūpinimo svarbiausiomis žaliavomis esamos ir prognozuojamos ateityje situacijos ir šios situacijos poveikio Lietuvos konkurencingumui analizės studija. 2011.

[2] Knašytė, M., Kliopova, I., Staniškis, J.K. Economic importance, environmental and supply risks on imported resources in Lithuanian industry // Environmental research, engineering and management = Aplinkos tyrimai, inžinerija ir vadyba. Kaunas: KTU. ISSN 1392-1649. 2012, nr. 2(60), p. 40-47.

Table 3.1 Import dependence on third (non-EU) countries

Resource	Import dependence on third countries, %			
	2008		2009	
	Considering import country	Considering country of origin	Considering import country	Considering country of origin
Cast iron	95	98	98	98
Aluminium	14	42	13	38
Lead	28	84	15	81
Tin	0	100	0	100
Zinc	1	95	1	96
Copper	3	43	56	80
Iron and steel	43	42	46	47
Sulphur	100	100	94	94
Caustic soda	36	41	27	36
Calcined soda	79	87	39	41
Polyethylene	35	39	24	30
Polypropylene	13	21	15	18
Polystyrene and copolymers of styrene	38	44	40	43
Polymers of vinyl chloride	2	6	2	5
Crude oil	100	100	100	100
Natural gas	100	100	100	100

The evaluation of statistical data (141, 146) showed that 95% of cast iron was imported from Russia in 2008 and 98% in 2009. When considering the country of origin 98% in 2008 and 2009 was from Russia. 86% of aluminium was imported from EU countries in 2008 and 87% in 2009. The main country of origin of imported aluminium was China (35% in 2008 and 32% in 2009). 72% of lead was imported from EU countries in 2008 and 85% in 2009. The main country of origin of imported lead was China (28% in 2008 and 33% in 2009). 100% of tin was imported from EU countries in 2008 and in 2009. The main country of origin of imported tin was China (44% in 2008 and 2009). 99% of zinc was imported from EU countries in 2008 and in 2009. The main country of origin of imported zinc was China (about 30% in 2008 and in 2009). 97% of copper was imported from EU countries in 2008 and 44% in 2009. The main country of origin of imported zinc was Russia (53% in 2009). 57% of iron and steel was imported from EU countries in 2008 and 54% in 2009. The main country of origin of imported iron and steel was Russia (20% in 2008 and 24% in 2009). According to the statistics in 2008 and 2009 sulphur was imported from the countries of origin (51% in 2008 and 58% in 2009 from Russia, 49% in 2008 and 35% in 2009 from Kazakhstan). 64% of caustic soda was imported from EU countries in 2008 and 73% in 2009. The main countries of origin of imported caustic soda were EU countries (59% in 2008 and 64% in 2009) and Russia (28% in 2008 and 30% in 2009). 58% of cast calcined soda was imported from Russia in 2008 and 12% in 2009. When considering the country of origin 65% in 2008 and 13% in 2009 was from Russia. 65% of PE was imported from EU countries in 2008 and 76% in 2009. The main countries of origin of imported PE were EU countries (61% in 2008 and 70% in 2009) and Belarus (14% in 2008 and 16% in 2009). 87% of PP was imported from EU countries in 2008 and 85% in 2009. The main countries of origin of imported PP were EU countries (79% in 2008 and 82% in 2009) and Russia (7% in 2008 and 13% in 2009). 62% of PS was imported from EU countries in 2008 and 60% in 2009. The main countries of origin of imported PS were EU countries (54% in 2008 and 57% in 2009) and Russia (34% in 2008 and 37% in 2009). 98% of PVC was imported from EU countries in 2008 and in 2009. The origin of PVC was the EU (94% in 2008 and 95% in 2009). 100% of natural and crude oil gas was imported from Russia.

The analysis of primary and secondary import countries in 2008 and 2009 allows several important countries of raw materials origin to be distinguished. The top four countries are: Russia (cast iron, crude oil, sulphur, polystyrene and copolymers of styrene, caustic soda, iron and steel, polypropylene, natural gas, calcined soda, copper, lead, polyethylene, building glass), China (tin, lead, aluminium, building glass), Belarus (polyethylene, iron and steel, building glass) and Ukraine (iron and steel, calcined soda, caustic soda).

3.2. Results of supply risk evaluation

The results of evaluating supply risk (based on eq. 2.2 and eq. 2.3) of the selected resources are provided in Table 3.2 and Fig. 3.1. In order to illustrate how results change depending on the selected approach for each year, three different values are provided: geostrategic supply risk (eq. 2.3) calculated considering both import countries and origin countries, and supply risk (eq. 2.4).

Table 3.2 Results of supply risk evaluation

Resource	Supply risk [1]					
	2008			2009		
	Considering import country	Considering country of origin		Considering import country	Considering country of origin	
	Geostrategic supply risk		Supply risk	Geostrategic supply risk		Supply risk
Cast iron	5.86	6.22	1.87	6.20	6.20	1.86
Aluminium	0.34	1.09	0.50	0.26	0.90	0.41
Lead	0.52	0.87	0.28	1.13	1.02	0.33
Tin	0.97	1.74	1.39	1.35	1.70	1.36
Zinc	1.66	0.96	0.50	1.10	1.01	0.53
Copper	1.42	1.28	0.57	1.85	2.01	0.90
Iron and steel	0.51	0.64	0.35	0.57	0.79	0.43
Sulphur	3.09	3.09	3.09	2.90	2.90	2.90
Caustic soda	1.79	1.76	1.12	1.56	1.60	1.02

Table 3.2 (continued)

Calcined soda	2.51	3.04	2.77	1.46	1.49	1.36
Polyethylene	0.47	0.47	0.17	0.40	0.39	0.14
Polypropylene	0.52	0.41	0.19	0.49	0.47	0.22
Polystyrene and copolymers of styrene	0.89	0.90	0.13	1.04	1.07	0.15
Polymers of vinyl chloride	1.25	1.38	0.71	0.89	0.83	0.42
Crude oil	6.45	6.45	6.26	6.49	6.49	6.30
Natural gas	6.45	6.45	4.78	6.49	6.49	4.81

In the majority of cases, consideration of resource origin country increases the value of geostrategic supply risk indicator or does not change it compared to the assessment of import countries only. The increase can be explained by the fact that the importing of resources often takes place through the intermediate countries in the EU, that are often associated with the lower geopolitical risk compared to the origin countries. After the evaluation of estimated origin countries, the lower import related risk was determined only for four resources (zinc, copper, caustic soda, and polypropylene) in 2008 and five resources (lead, zinc, polypropylene, polyethylene and polymers of vinyl chloride) in 2009. On the other hand, the inclusion of substitutability and recycling aspects, decrease the supply risk in the vast majority of cases, except sulphur. Thus, these indicators should be treated reservedly as it was also concluded in the criticality assessment performed by the European Commission (56).

In order to contribute to the dynamic assessment, the supply risk indicator was evaluated for two years. Since substitutability and recycling rates were kept the same, it mainly reflects the change of the import-related risk index. Fig. 3.1 shows the change of values in 2008-2009, as well as the minimum and maximum values, including values of import related risk.

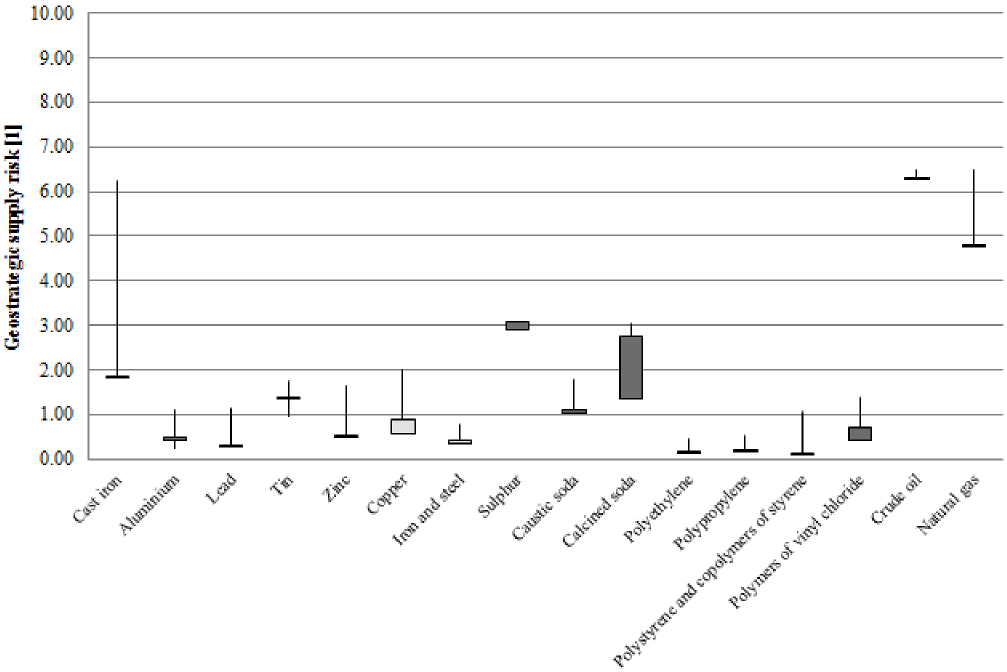

Fig. 3.1 Change of supply risk values in 2008-2009 (dark grey = decrease, light grey = increase), and min-max value amplitude

It can be stated that the supply risk of most resources did not change significantly in 2009 compared to 2008, except copper (increased by 1.6 times), calcined soda (decreased by around 2 times) and polymers of vinyl chloride (decreased by 2.1 times). In total, compared to 2008, the supply risk of nine out of sixteen resources increased.

3.3. Results of economic importance evaluation

The results of evaluating economic importance (based on eq. 2.4) are provided in Table 3.3 and Fig. 3.2. In order to illustrate that economic importance indicators do not directly reflect the quantitative use, the amounts of consumed resources are also provided.

Table 3.3 Results of economic importance evaluation

Resource	**2008**		**2009**	
	Amount (tonnes/year)	**Economic importance**	**Amount (tonnes/year)**	**Economic importance**
Cast iron	495	0.07	139	0.08
Aluminium	10 874	0.13	6 193	0.12
Lead	223	0.11	153	0.09
Tin	9	0.09	8	0.09

Table 3.3 (continued)

Zinc	781	0.07	664	0.07
Copper	6015	0.08	2 926	0.09
Iron and steel	490 688	0.22	307 255	0.10
Sulphur	334 938	0.19	380 693	0.14
Caustic soda	7 518	0.24	6 496	0.26
Calcined soda	8 995	0.09	6 883	0.07
Polyethylene	44 632	0.08	45 495	0.07
Polypropylene	10 170	0.10	10 646	0.09
Polystyrene and copolymers of styrene	204 633	0.08	14 704	0.07
Polymers of vinyl chloride	28 859	0.14	13 579	0.08
Crude oil	9 241	0.19	8 407	0.14
Natural gas	1172 million nm^3 (non-energy)	0.21	721 million nm^3 (non-energy)	0.24

In terms of amounts, the use of resources sharply decreased in 2009 compared to 2008 (with the exception of a minor increase of Sulphur, polyethylene and polypropylene). This can be explained by the economic crisis, which peaked in 2009. In order to contribute to the dynamic assessment, the changes of economic importance values are provided in Fig. 3.2.

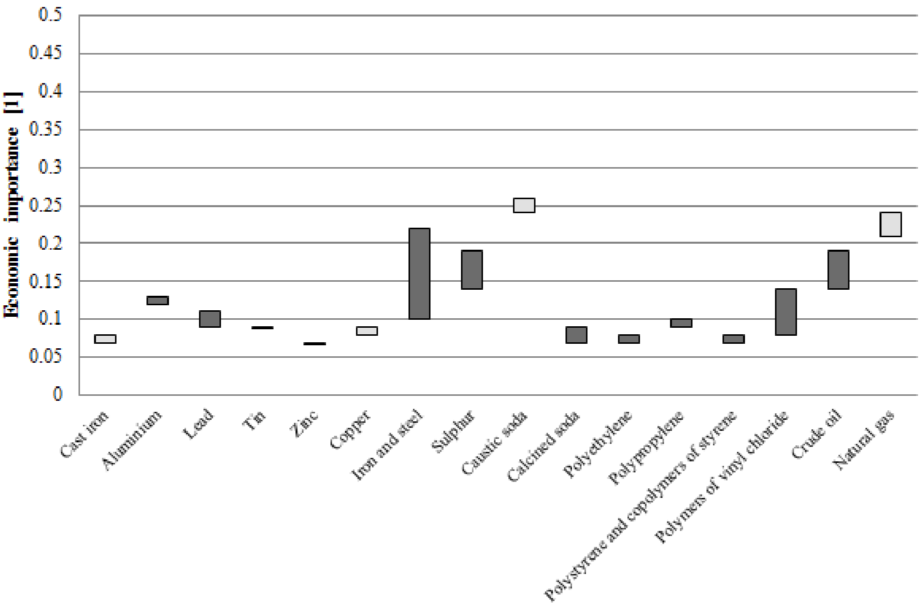

Fig. 3.2 Change of economic importance values in 2008-2009 (dark grey = decrease, light grey = increase)

Since economic importance depends on value added weighted by the share of the amount attributed to the specific industry branch, estimated values of indicators do correlate with the quantitative amount of resource. Thus, the economic importance of six out of sixteen resources increased or did not change during the analysed year. However, compared to supply risk, the significant change of economic importance can be attributed to more resources. The economic importance of iron decreased by 2.2 times, sulphur decreased by 1.4 times, polymers of vinyl chloride decreased by 1.75 times, crude oil decreased by 1.4 times, natural gas increased by 1.1 times.

3.4. Estimation of critical resources for the Lithuanian economy

The results of supply risk and economic evaluation of 16 resources for the year 2008 are provided in Fig. 3.3.

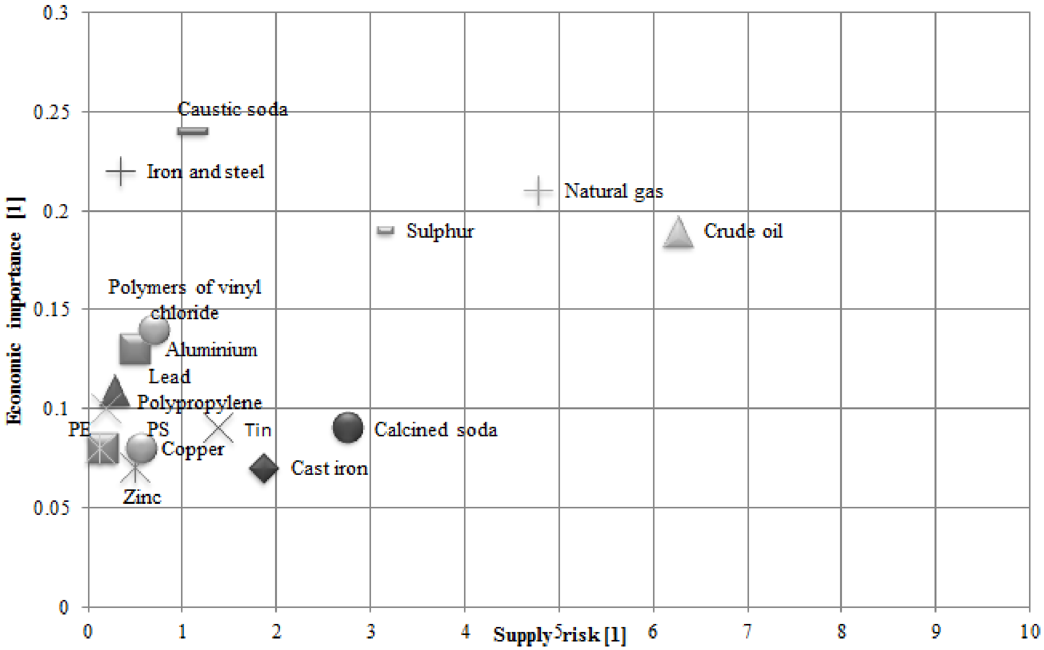

Fig. 3.3 Supply risk and economic importance of resources for the Lithuanian economy in 2008

In terms of supply risk, the top five resources are crude oil (SR = 6.26), natural gas (SR = 4.78), Sulphur (SR = 3.09) and calcined soda (SR = 2.77). In terms of economic importance, the top five resources are caustic soda (EI = 0.24), iron and steel (EI = 0.22), natural gas (EI = 0.21), Sulphur (0.19) and crude oil (0.19).

The results of supply risk and economic evaluation for the year 2009 are provided in Fig. 3.4.

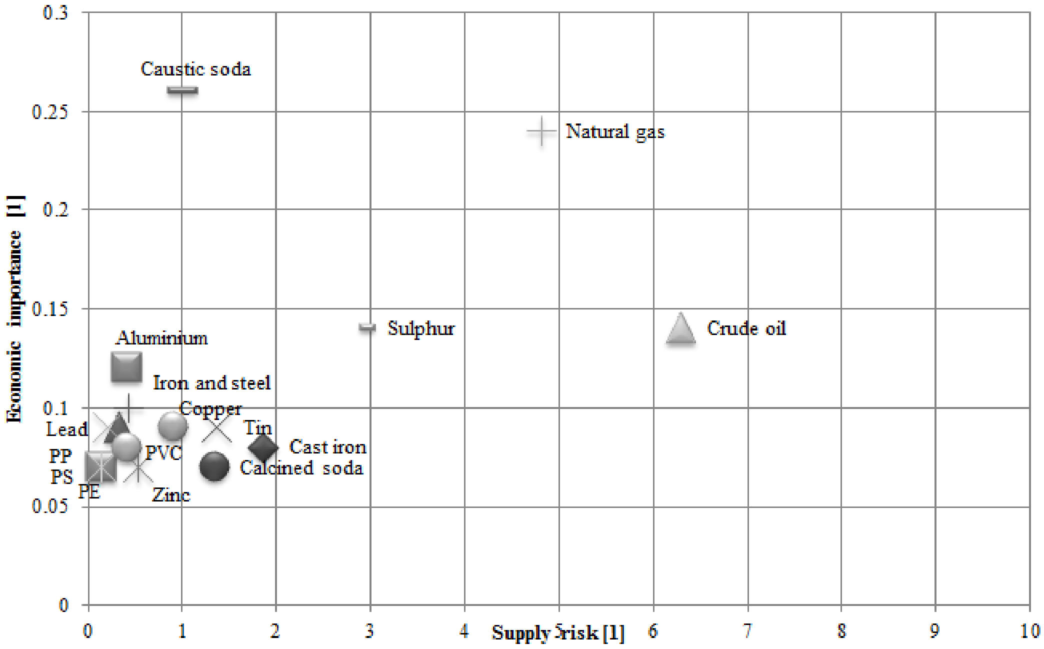

Fig. 3.4 Supply risk and economic importance of resources for the Lithuanian economy in 2009

In terms of supply risk, the top five resources are crude oil (SR = 6.30), natural gas (SR = 4.81), Sulphur (SR = 2.90) and cast iron (SR = 1.86). In terms of economic importance, the top five resources are caustic soda (EI = 0.26), natural gas (EI = 0.24), crude oil (0.14), Sulphur (0.14) and aluminium (EI = 0.12).

Aggregated values of supply risk and economic importance indicators for 2008 and 2009 are provided in Table 3.4. Resources are ranked starting with the most critical one. In addition, the percentage changes of criticality index are provided, and resources are ranked accordingly.

Table 3.4 Aggregated values and ranking of resources

	2008			**2009**			**Change compared to 2008, %**	
	Resource	**Value**		**Resource**	**Value**		**Resource**	**Value**
1	Crude oil	1.19	1	Natural gas	1.15	1	Copper	76.7
2	Natural gas	1.00	2	Crude oil	0.88	2	Natural gas	15.0
3	Sulphur	0.59	3	Sulphur	0.41	3	Cast iron	13.9
4	Caustic soda	0.27	4	Caustic soda	0.26	4	Zinc	5.2
5	Calcined soda	0.25	5	Cast iron	0.15	5	Polystyrene and copolymers of styrene	4.0
6	Cast iron	0.13	6	Tin	0.12	6	Polypropylene	3.2

Table 3.4 (continued)

7	Tin	0.13	7	Calcined soda	0.09	7	Caustic soda	-1.5
8	Polymers of vinyl chloride	0.10	8	Copper	0.08	8	Tin	-2.3
9	Iron and steel	0.08	9	Aluminium	0.05	9	Lead	-4.1
10	Aluminium	0.06	10	Iron and steel	0.04	10	Aluminium	-23.8
11	Copper	0.05	11	Zinc	0.04	11	Crude oil	-25.9
12	Zinc	0.04	12	Polymers of vinyl chloride	0.03	12	Polyethylene	-27.4
13	Lead	0.03	13	Lead	0.03	13	Sulphur	-30.8
14	Polypropylene	0.02	14	Polypropylene	0.02	14	Iron and steel	-43.9
15	Polyethylene	0.01	15	Polystyrene and copolymers of styrene	0.01	15	Calcined soda	-61.9
16	Polystyrene and copolymers of styrene	0.01	16	Polyethylene	0.01	16	Polymers of vinyl chloride	-65.6

With regard to aggregated values, natural gas, crude oil, sulphur and caustic soda were the most critical resources for the Lithuanian economy in 2008 as well in 2009. The order of ranking has changed slightly, but the list of top 10 resources remained nearly the same, except for copper, which replaced polymers of vinyl chloride. In addition, Table 3.3 provides the percentage changes of criticality values. The criticality of copper, natural gas, cast iron, zinc, polystyrene and copolymers of styrene, and polypropylene has increased compared to the year 2008, while it has decreased for the remaining evaluated resources.

3.5. Results of resource productivity evaluation

The resource productivity for each evaluated resource was estimated, taking into account domestic material consumption and the value added of the industry branches in which the resource is consumed. The results are provided in Fig. 3.5. in comparison with the percentage change of domestic material consumption of each resource.

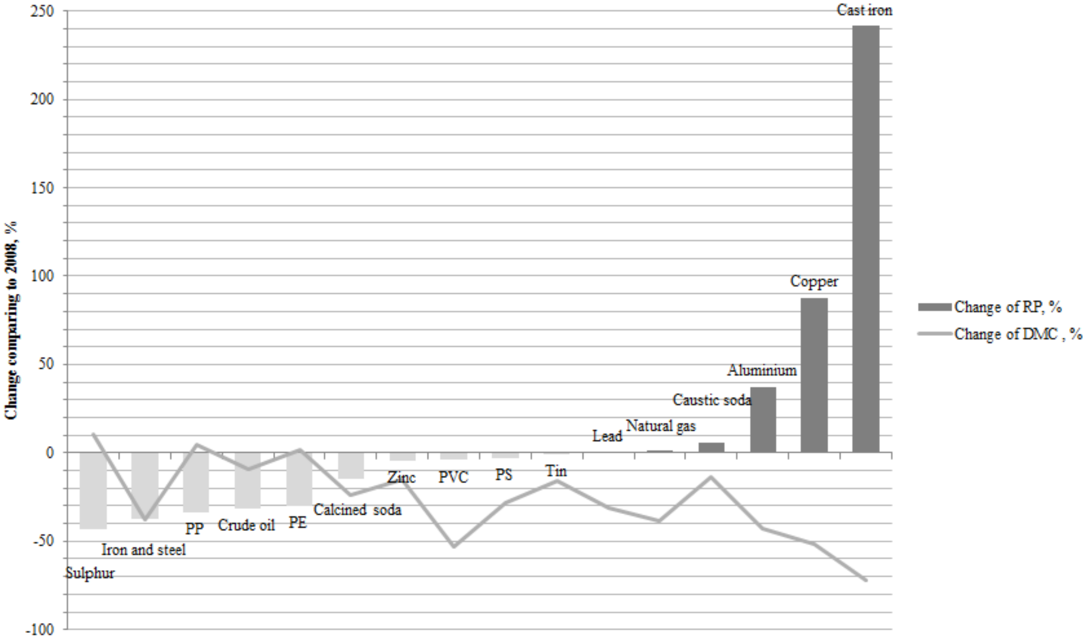

Fig. 3.5 Change of resource productivity in comparison with change of domestic material consumption during 2008-2009

The significant decrease of resource productivity was identified for Sulphur (43%), iron and steel (37%), polypropylene (33%), crude oil (31%), polyethylene (30%) and calcined soda (14%). The decrease of resource productivity of Sulphur, polypropylene, and polyethylene is also associated with the slight increase in material consumption. The resource productivity of zinc, polymers of vinyl chloride, polystyrene, and tin decreased insignificantly (0.8-4.6%), while the productivity of other resources increased. The material consumption of most of the evaluated resources has declined in line with the overall domestic material consumption (Fig. 3.6).

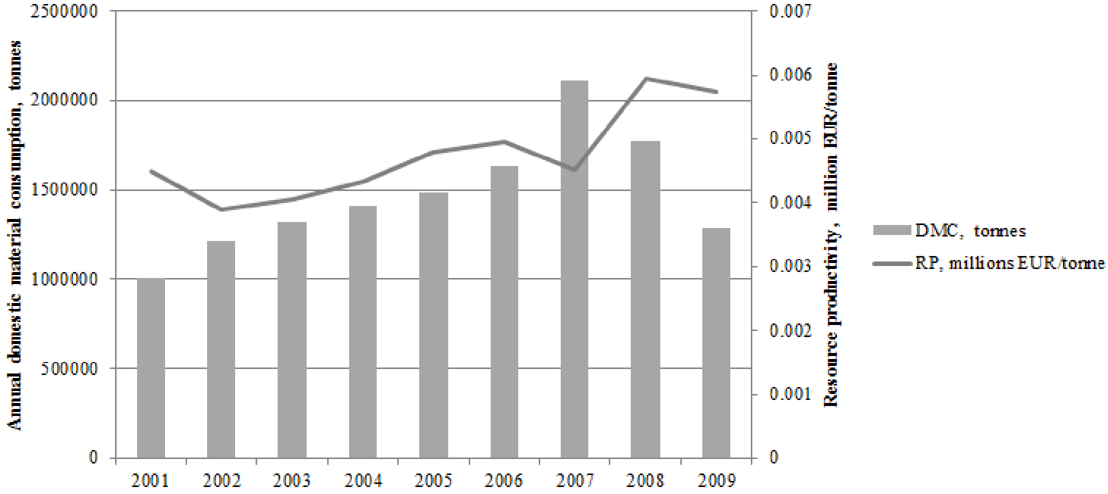

Fig. 3.6 Overall domestic material consumption and resource productivity of evaluated resources

The increase in domestic material consumption in 2007 can be associated with an economic upturn, while the decrease in 2008 with the beginning of the economic crisis, which peaked in 2009. In contrast, the resource productivity, which has been constantly increasing since 2002, has decreased in 2007. It increased significantly in 2008, but despite the sharp decrease in material consumption in 2009, it did not change drastically.

Fig. 3.7 shows the estimated resource criticality for the year 2009 in comparison to the change of resource productivity during 2008-2009.

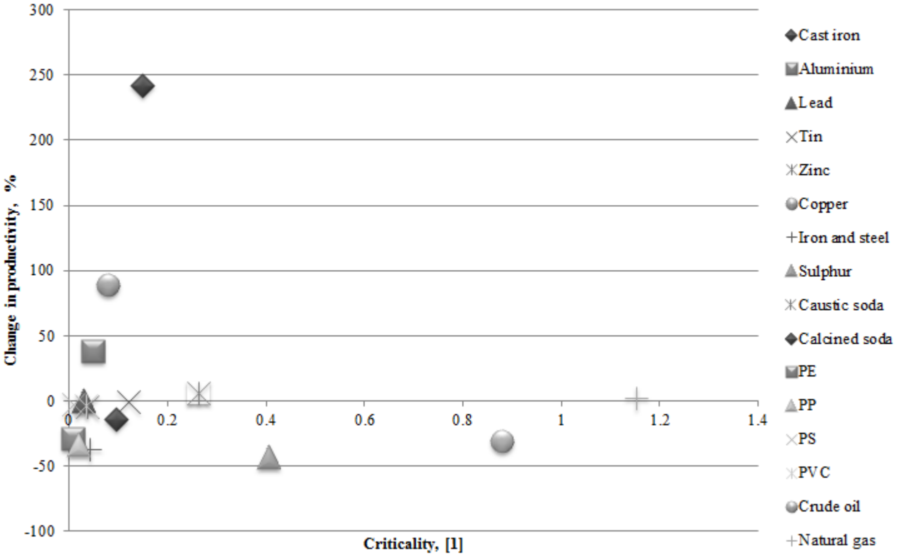

Fig. 3.7 Resource criticality in 2009 versus the change in resource productivity

In terms of the productivity of resources that were identified as the most critical to the Lithuanian economy, crude oil and Sulphur are the resources of concern. These resources are associated with the high supply risk, high economic importance, and decreased resource productivity during the analysed year.

3.6. Main industrial end uses of evaluated resources, identified vulnerable industry branches

With regard to identifying the most sensitive industry branches, the end uses (more than 10% of total consumption in the manufacturing industry) of top 10 critical resources for the year 2009, were identified (Table 3.5).

Table 3.5 Main end uses of most important resources in 2009

Resource	Industry branch	Share, %
Natural gas (non-energy)	Manufacture of refined petroleum products, chemicals, and chemical products	100.00
Crude oil	Manufacture of refined petroleum products, chemicals, and chemical products	99.99
Sulphur	Manufacture of refined petroleum products, chemicals, and chemical products	99.98
Caustic soda	Manufacture of food products, beverages, and tobacco products	47.51
	Manufacture of refined petroleum products, chemicals, and chemical products	46.85
Cast iron	Repair and installation of machinery and equipment	49.50
	Manufacture of machinery and equipment	33.89
	Manufacture of fabricated metal products, except machinery and equipment	12.58
Tin	Repair and installation of machinery and equipment	42.86
	Manufacture of computer, electronic and optical products	28.57
	Manufacture of machinery and equipment not elsewhere classified	21.43
Calcined soda	Manufacture of other non-metallic mineral products	88.09
Copper	Manufacture of electrical equipment	55.65
	Manufacture of fabricated metal products, except machinery and equipment	29.74
Aluminium	Manufacture of food products, beverages, and tobacco products	33.23
	Manufacture of textiles	22.44
Iron and steel	Manufacture of fabricated metal products, except machinery and equipment	31.00
	Manufacture of basic metals	29.00
	Manufacture of other transport equipment	17.00

It appears that the three most critical resources are used exclusively for the manufacture of refined petroleum (crude oil and sulphur) and for the manufacture of chemicals and chemical products (natural gas, caustic soda). The following evaluated resources are mainly metals (except calcined soda), thus the second branch of the manufacturing industry, which can be identified as sensitive, covers the manufacture, repair and installation of various metal products, including machinery, electrical and other equipment.

3.7. Discussion of results

The screening of resources in terms of import dependency revealed that the Lithuanian economy is dependent on the import of all the initially selected resources. In addition, after the evaluation of the share of imports from third countries, it was identified that the secure supply of most of the evaluated resources heavily depends on the imports from non-EU countries. Thus, all of the pre-selected resources were further investigated.

The evaluation of the supply risk disclosed that the results may differ quite considerably depending on the selected evaluation method. For most of the evaluated resources, the supply risk is higher when the origin countries of resources are evaluated in comparison to the evaluation of import countries only. On the other hand, the substitutability and recycling potential can significantly decrease the value of estimated supply risk. Measuring substitutability includes a degree of subjectivity. Thus, these parameters should be interpreted with caution.

With the aim of contributing to the dynamic assessment of criticality and determine how the evaluated measures change, the evaluation for the year 2008 and 2009 was performed, and the changes in results were compared. All in all, it was identified that the most critical resources for the Lithuanian economy were natural gas, crude oil, sulphur and caustic soda. Moreover, even if the order of ranking changed, the top 10 resources remained the same for both years (with the exception of polymers of vinyl chloride, which was replaced by copper). Thus, it can be concluded that the results of criticality evaluation should not be treated in terms of definite values, but rather it should be interpreted as an indication of the tendencies in the security of supply and economic importance. Furthermore, even if in terms of the overall performance of the economy, the evaluated years were quite different, it did not result in the significant changes in the criticality assessment. Based on this finding, but meanwhile acknowledging the dynamic character of the criticality, it can be proposed that the criticality assessments should be performed for the longer periods of time.

With the aim of investigating the relationship between criticality and efficient use of resources, the change of resource productivity in 2009 compared to 2008 for each selected resource was evaluated. The results revealed that two out of five most critical resources were also associated with the significant decrease in resource productivity. As a result, the evaluation of resource productivity could supplement the methodology for the evaluation of resource criticality and thus provide directions for the resource efficiency improvement.

Finally, the evaluation of the end-uses of most critical resources disclosed that the most vulnerable industries are related to the production of refined petroleum products, chemical products and manufacturing of various metal products. Based on this finding, it can be recommended that efforts to mitigate resource criticality should consider the most sensitive industries first.

4. DEVELOPMENT OF DECISION SUPPORT SYSTEM MODEL: INTEGRATION OF RESOURCE CRITICALITY ASSESSMENT INTO EVALUATION OF RESOURCE EFFICIENCY IMPROVEMENT ALTERNATIVES

4.1. Integrated decision support system model for resource efficiency improvement in the manufacturing companies

This thesis aims to support the management of material flows in industrial companies and introduce resource criticality as an additional relevant resource management aspect by integrating the resource criticality assessment into the common procedures for the implementation of cleaner production innovations. The decision-making support system model (Fig. 4.1) allows for the identification of significant aspects of resource use, and assessing resource efficiency improvement strategies in terms of environmental performance, economic feasibility, and resource criticality for production companies. To be applicable, a prerequisite was that the proposed methodology to assess the resource criticality should only require freely available data and the developed procedure could be integrated into widely applied sustainable resources management practices.

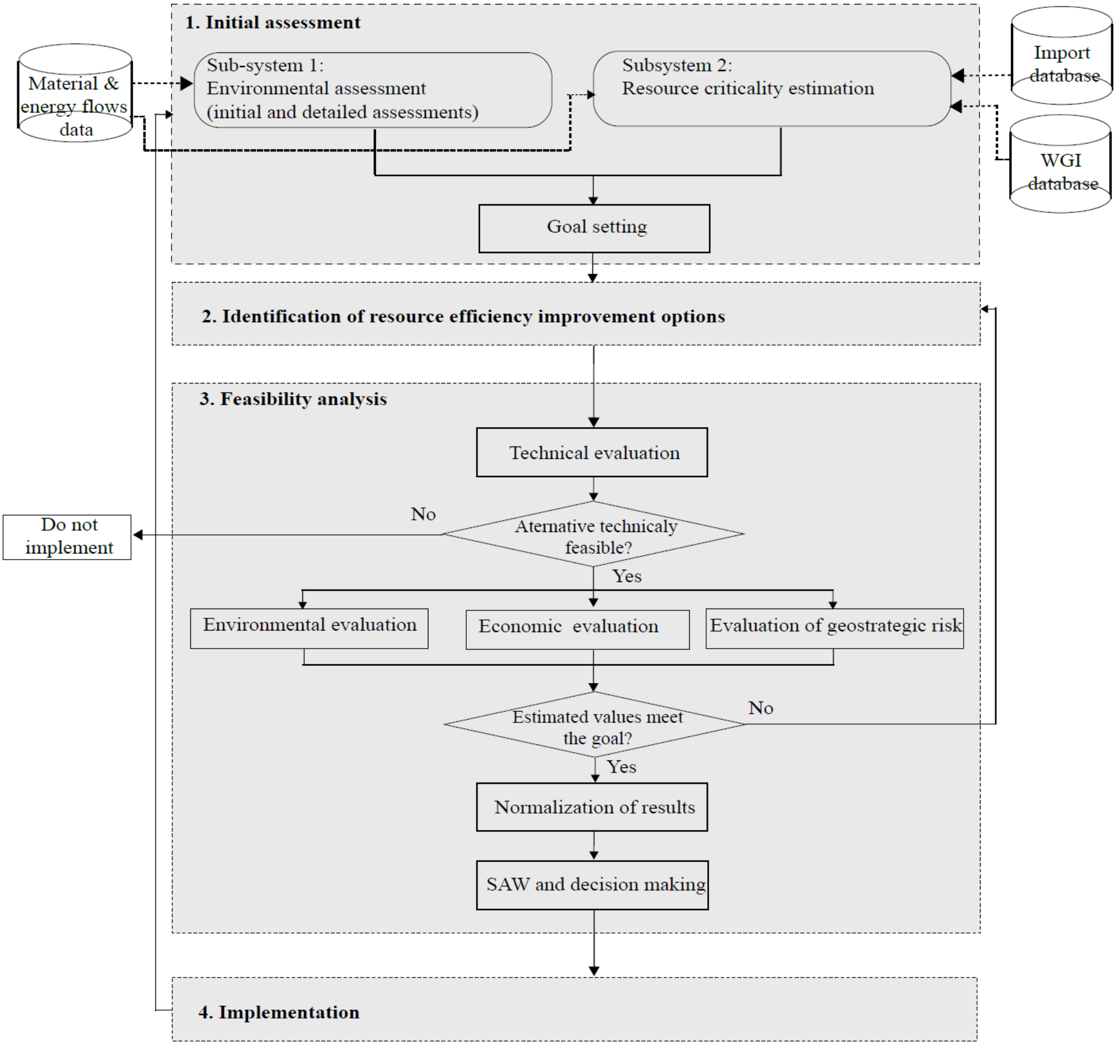

Fig 4.1 Integrated decision support system model for resource efficiency improvement in manufacturing companies

The *aim of the model* is to find a technically feasible, and most preferable resource efficiency improvement alternative in terms of environmental performance, economic feasibility, and resource criticality from the point of view of an industrial company.

The conceptual structure of the model is based on the procedures for the implementation of cleaner production innovations (125). Resource criticality assessment is integrated as an additional measure to identify significant aspects of resource use and evaluate resource efficiency improvement options. The proposed decision-making support procedure consists of three main steps:

1. Initial assessment at a company level for a business-as-usual (BAU) situation, including an environmental assessment at the company and at the process levels (sub-system 1), and the estimation of resource criticality from the point of view of an industrial company (sub-system 2);
2. Identification of resource efficiency improvement options;
3. Feasibility analysis, including a multi-criteria decision-making support process for the evaluation of technically feasible, environmentally and economically beneficial alternatives, which meanwhile reduce resource criticality from the point of view of an industrial company.

Choosing the most suitable alternative is a multi-objective optimization problem, therefore, the multi-objective model can be described as follows:

$max f_1(\vec{x})$: maximize the environmental performance
$max f_2(\vec{x})$: maximize the economic feasibility
$max f_3(\vec{x})$: maximize the decrease of geostrategic supply risk

The multi-objective optimization functions are described in Chapter 4.4. The classic approach to solving a multi-objective optimization problem by assigning weights to each normalized objective function is used and described in Chapter 4.4.

4.2. Description of the sub-system 1: environmental assessment

In order to identify the reasons for inefficient use of resources and develop suggestions for improvement possibilities, the environmental assessment is performed at the company level as well as at process level.

Initial assessment at company level

The goal of the initial environmental assessment is to evaluate the current environmental performance for the business-as-usual (BAU) situation at the level of the entire production company.

The main steps of the initial environmental assessment are:

- Material and energy flow analysis (MFA);
- Formation of material and energy balance (evaluation of flows in absolute terms, units/year);
- Evaluation of environmental efficiency (evaluation of flows in relative terms and comparison with benchmarks). Relative environmental indicators (EIm_i) are estimated (147):

$$EIm_i = \frac{X_i(t)}{P_i(t)}; \tag{4.1}$$

where: *i* - input or output flow;

$X_i(t)$ - amount of consumed raw materials, energy, water or amount of generated waste, pollution per year (t/year, m^3/year, MWh/year);

$P(t)$ - production volume (t/year).

Detailed assessment on process or flow level

After analysing the results of the initial environmental assessment, the particular process or resource flow is selected for a more detailed investigation. The material and energy balance for the selected process is formed, and the *EIm* are estimated in order to identify the reasons for environmental problems and improvement options. Cleaner production and industrial ecology measures (hereafter RE alternatives) can be identified as options for resource efficiency improvement: input substitution, process optimization, equipment modification, technology change, on-site recovery/reuse, production of useful by-products, product modification (95), and the creation of symbiotic links.

4.3. Description of the sub-system 2: resource criticality estimation

In parallel to the environmental assessment, the criticality of the main resources is evaluated. The causal diagram (Fig 4.2) qualitatively represents the conceptual approach of the resource criticality from a point of view of an industrial company, which was developed based on the findings of the literature review.

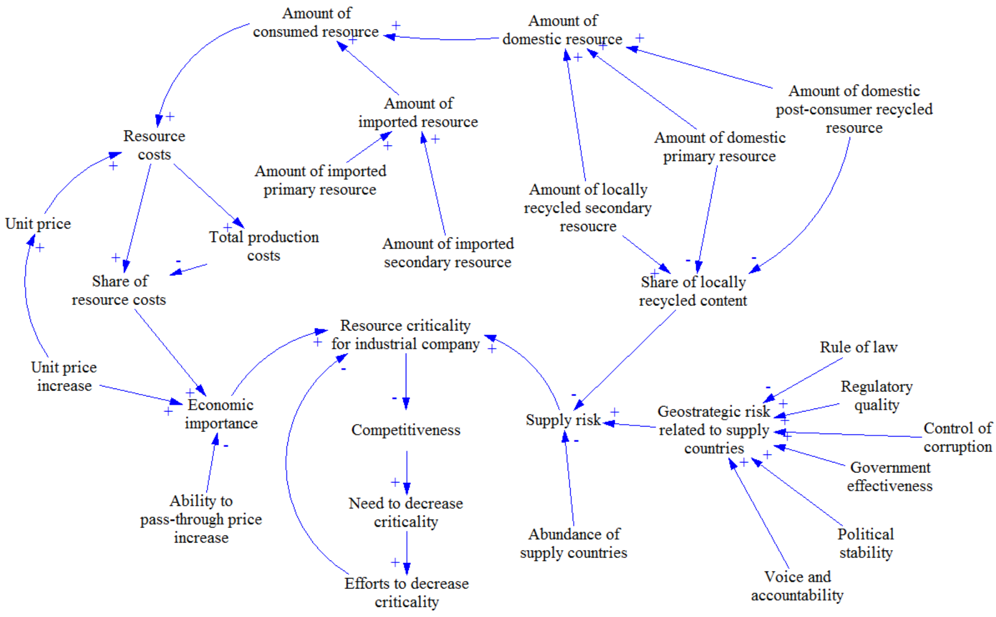

Fig. 4.2 Causal diagram of resource criticality from a point of view of an industrial company

A stable and secure supply of resources is the key condition for successful industrial activity. Thus, increased resource criticality decreases the competitiveness of an industrial company. The decreasing competitiveness triggers the need to decrease criticality and calls for increased efforts. The successful efforts decrease resource criticality. On the other hand, the increase of economic importance (*EI*) and geostrategic supply risk (*SR*) increases resource criticality.

Based on the approach presented in Fig. 4.2. the estimation of *EI* and *SR* is adapted to evaluate the aspects that are relevant from a point of view of an industrial company.

Economic importance of resource i for an industrial company

Estimation of the *EI* of resources for an industrial company allows the assessment of the relative importance of raw materials that are exposed to the geostrategic supply risk. Not only price changes, be they increase, decrease or are volatile, are metrics by which a material can be determined as critical (7), but from a point of view of a producing company the total annual expenses for a resource i in relation to the total production costs is an important metric to define how significant certain resources are for a financially successful industrial activity. Therefore, in order to assess the economic importance (*EI*) for industrial companies the share of annual expenses for a resource i compared to the total annual production costs was chosen as an indicator. With the goal to reflect the importance of price change the ratio was modified by a measure of price change, and qualitative measure of the ability to pass-through cost increases (in line with the approach introduced by (63) and later used by (17)):

$$EI_i = \left[\left(1 + (d_i \cdot PT_i)\right)\frac{p_i}{TC}\right] \cdot 100; \tag{4.2}$$

where: d_i - unit price change comparing analysed year (t) to the reference year (t-1):

$d_i = (\text{price}_t - \text{price}_{t-1})/\text{price}_{t-1}$;

PT_i - ability to pass-through cost increases to customers; possible values (adapted from (17, 63)): 0- relatively easy (there is no material price increase/sale prices can be adjusted to changes in material costs); 0.3- possible; 0.7- difficult; 1.0- practically impossible (competition is very high, sale prices are essentially fixed, and the company will have to absorb cost increase); if $d_i>0$, when $PT_i = [0;1]$, if $d_i \leq 0$, when $PT_i = 0$;

p_i - annual expenses for resource i, EUR/year;

TC - total annual costs of production for the company, EUR/year.

Geostrategic supply risk of resource i for an industrial company

Geostrategic Supply Risk is the second dimension chosen to determine the resource criticality from a point of view of an industrial company. Unplanned and unanticipated events that disrupt the normal flow of goods and materials within the upstream supply chain (148) can occur in any segment of a supply chain. Although the underlying complexity of supply risk is hard to define and even harder to assess (149), the increased frequency disruptive events that can result in cascading disruptions across regions or industries (150) has led to increasing awareness of supply chain risks and how to address these by management.

Given the complexity of modern supply chains (148, 151, 152), broad aspects of supply risks and impacts of disruptions (152, 153) as well as challenges in definition, quantification and modelling of supply chain risk (149) this framework does not aim to provide a precise assessment of all possible supply risks related to all hazards in a supply chain. Instead, this study divides the upstream supply chains to "resource origin" and "distribution" segments and aims to propose a method to assess only the most relevant geostrategic supply risk of the resources' origin.

In order to gain a proxy for the Geostrategic Supply Risk of a resource's origin a modified form of the Herfindahl-Hirschman Index (HHI), often used in material criticality studies as a measure of market concentration (25), was chosen. It is defined as the sum of squares of market shares of market participants (154).

Summing up the square percentage shares of suppliers instead of just adding the percentage shares gives even more power to large suppliers. Therefore sole-sourcing increases supply risk (155) and oligopolistic markets are more vulnerable to fluctuations in demand, leading to market volatility (3), therefore, lower concentration of supply countries means better resilience to changing market conditions and political situations.

Geostrategic supply risk (SR_i) associated with the origin countries of resource *i* is estimated according to the modified Herfindahl-Hirschman Index for the concentration of resource *i* origin countries:

$$SR_i = ((a_{i,1} - \rho_{i,1})^2 \cdot WGI_1 + \sum_{c=2}^{n}((a_{i,c})^2 \cdot WGI_c)/1000; \qquad (4.3)$$

where: WGI_c - rescaled score of the World Governance Indicator of country c. Worldwide Governance Indicators are provided by the World Bank and used to estimate stability/instability levels of producing countries. It includes six indicators: voice and accountability index, political stability, government effectiveness, regulatory quality, rule of law and control of corruption. The values of WGI are linearly rescaled to 0-10 instead of -2.5 to 2.5. A higher score corresponds to higher risk; WGI_1 is the rescaled score of the World Governance Indicator of the home country;

$a_{i,c}$ - percentage share of the supply of resource i from origin country c, including from domestic origin country 1;

$\rho_{i,1}$ -share of pre-consumer recycled material (new scrap), i.e. which is recycled in-house or within links of industrial symbioses of the consumed resource i. non-domestic recycling or post-consumer recycling (old scrap) in this case is accounted for as the primary resource (Fig. 4.3).

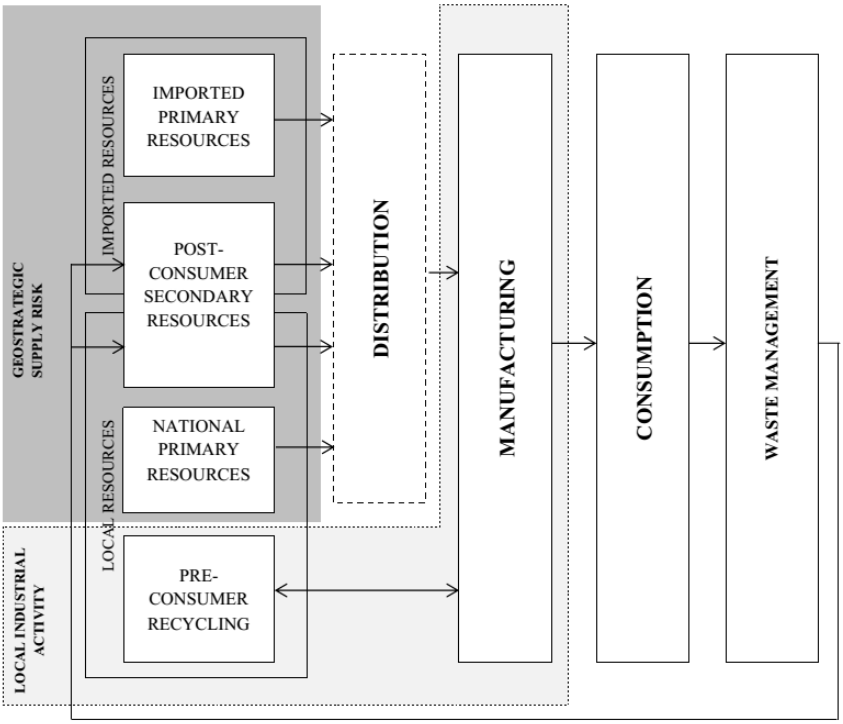

Fig. 4.3 Resource flows through the supply chain and system boundaries of geostrategic supply risk evaluation

Underlying assumptions:

- It was assumed that better institutional efficiency (3) and political stability in the resource origin country, characterized by lower WGI, leads to better resilience to potential internal and external disruption factors, such as political events or natural disasters;
- Since the market of recycled materials is also dynamic and exposes organizations to the risks of price volatility and supply disruptions (156) it was assumed that the origin of post-consumer recycled material (old scrap) is subject to a geostrategic supply risk similar to the primary raw material. However, the positive effect of decreasing the overall criticality might be seen if the cost of recycled material is lower than the cost of primary raw material, or recycling is taking place in the home country, which is characterized by higher political stability;
- It was assumed that utilization of pre-consumer recycled material (new scrap), which is recycled in-house or within links of industrial symbioses, does not contribute to the geostrategic supply risk and can, therefore, be deducted.

Calculated SR and EI values of all evaluated resources can be visualized in a two-dimension graph. Resources are prioritized according to the current values and change over the time of the Geostrategic Supply Risk and Economic Importance for an industrial company. While some authors provide the benchmark values for selected indicators, for example (11, 16), others like Roelich et al. (25) refuse to claim that thresholds would need to be informed by a combination of political and economic factors, as well as technical analysis, and, as a result, rely only on comparison with values for other materials. The study of Critical Raw Materials for the EU (56) provides thresholds but acknowledges that the set thresholds might be too strict, and small changes in a score might lead to the raw material being considered critical or not. Given the heterogeneity of existing interpretations of resource criticality, this methodology did not aim to provide thresholds but rather focused on prioritization of resources in terms of Supply Risk and Economic Importance from a point of view of industrial companies.

4.4. Description of multi-objective optimization functions

The multi-criteria decision-making process is solving the multi-criteria problem and involves the definition of the goal, identification of evaluation criteria, and criteria weights, formulation of a decision matrix, ranking of alternatives and sensitivity analysis.

Optimization objective 1: Maximize environmental performance

The optimization objective can be described as follows:

$$max f_1(\vec{x}) = max\ \overrightarrow{w}_{plan}; \tag{4.4}$$

$$s.t.\ \vec{w}_{plan} = \begin{cases} w_{plan\ 1} \\ w_{plan\ 2} \\ \dots \\ w_{plan\ n} \end{cases}$$

The environmental performance of selected alternatives for the flow i are generally estimated by calculating the relative EIm after implementation of the RE option and compared with the relative EI before implementation (147):

$$W_{plan\ i}(t) = EIm_{before\ RE\ i} - EIm_{after\ RE\ i} = \frac{X_{i(t-1)}}{P_{(t-1)}} - \frac{X_{i(t)}}{P_{(t)}}; \tag{4.5}$$

$$\text{when } EIm_{after\ RE\ i} \leq EIm_{max};$$

where $\text{EIm}_{\text{before RE}}$ and $\text{EIm}_{\text{after RE}}$ - relative environmental indicators before and after implementation of RE option (t/t, m^3/t, MWh/t),

EIm_{max} - benchmark indicator for the flow i (e.g. value corresponding to the relevant BAT, if available).

Optimization objective 2: Maximize economic feasibility

The optimization objective can be described as follows:

$$max f_{21}(x) = max\{-P\}; \tag{4.6}$$

$$max f_{22}(\vec{x}) = max\ \overrightarrow{EI}_{plan}; \tag{4.7}$$

$$s.t.\ \overrightarrow{EI}_{plan} = \begin{cases} EI_{plan\ 1} \\ EI_{plan\ 2} \\ \dots \\ EI_{plan\ n} \end{cases}$$

Payback period of CP investment is the main result of economic evaluation of the suggested alternative:

$$P = \frac{I}{S}; \tag{4.8}$$

where I - total project investments (EUR);

S - savings due to decrease of annual direct process costs and incomes after project implementation (EUR/year).

In order to be able to compare the alternatives where investment is not needed, the annual costs and the need for investment are compared as separate sub-criteria.

The change of Economic Importance of material *i* before and after the implementation of the RE alternative is expressed as follows:

$$EI_{plan\ i} = EI_{before\ RE\ i} - EI_{after\ RE\ i}; \tag{4.9}$$

where: $EI_{before\ REi}$ - Economic Importance of resource *i* (EUR/year) before the implementation of the RE alternative;

$EI_{after\ REi}$ - Economic Importance of resource *i* (EUR/year) after the implementation of the RE alternative.

Optimization objective 3: Maximize the decrease of Geostrategic supply risk from the point of view of an industrial company

The optimization objective can be described as follows:

$$max f_3(\vec{x}) = max\ \overrightarrow{SR}_{plan}; \tag{4.10}$$

$$\text{s.t.}\ \overrightarrow{SR}_{plan} = \begin{cases} SR_{plan\ 1} \\ SR_{plan\ 2} \\ \dots \\ SR_{plan\ n} \end{cases}$$

The change of Geostrategic Supply Risk of material i before and after the implementation of the RE alternative is expressed as follows:

$$SR_{plan\ i} = SR_{before\ CP\ i} - SR_{after\ CP\ i}; \tag{4.11}$$

where: $SR_{before\ RE\ i}$ - Geostrategic Supply Risk of resource i before the implementation of the RE alternative;
$SR_{after\ RE\ i}$ - Geostrategic Supply Risk of resource i after the implementation of the RE alternative.

Solving the multi-objective optimization problem

Simple Additive Weighting (SAW) is used to obtain a global score for each alternative. This widely known method was selected because it is intuitive to decision makers, involves simple calculations and has the ability to compensate among criteria (124).

SAW is a value function and is established based on a simple addition of scores that represent the goal achievement under each criterion, multiplied by the particular weights (157):

$$v(a_n) = \sum_{k=1}^{m} w_k \cdot v_k(f_k\,(a_n)); \tag{4.12}$$

when

$$w_k \geq 0$$

$$\sum_{k=1}^{m} w_k = 1$$

where: w_k - weight assigned to criterion k, $v_k(f(a_n))$ is a one-dimensional value function.

One-dimensional value functions are normalized to the interval [0;1], where the better score gets the higher rank. Thus:

$$f_k(a_n) \rightarrow max \tag{4.13}$$

After solving the multi-objective optimization problem, the alternatives can be ranked in order to facilitate the decision-making process.

Sensitivity analysis

Since the weights of the criteria are chosen arbitrarily, sensitivity analysis is conducted. By using sensitivity analysis, it can be determined how the global scores and thus the ranking of alternatives depend on the weights assigned to the criteria. The initial weights are assigned equally for each of the three dimensions. In sensitivity analysis several variants are tested, including the case when only criticality criteria are considered as well as the case when criticality criteria are excluded.

Decision-support system applicability in the industrial companies

The proposed decision-support system is supposed to be applied in the industrial companies in line with the procedures of the implementation of measures for resource efficiency improvement. During the planning and organization phase, the management of the company should establish the working group, designate responsibilities, and ensure the necessary resources for the implementation of tasks. During the evaluation phase one of the key aspects is the update of the information needed for the estimation of resource criticality and evaluation of environmental performance. Comparatively big companies that rely on imported raw materials and have sufficient resources could maintain the databases that contain information about the origin of the raw materials. Ideally, these databases should be updated continually, when the major changes in the supply chains occur. Smaller companies could use the country-specific information, which should be provided by the national authorities. The MADB and WGI databases are updated annually, but based on the findings of Chapter 3, the national criticality assessments could be updated every 3-5 years.

Based on the results of the feasibility analysis the final decision to implement the suggested measures has to be made by the management of the company. The purpose of the model application is to sustain continuous improvement.

5. RESULTS OF MODEL APPLICATION IN MANUFACTURING COMPANIES

5.1. Results of model application in a nitrogen fertilizer production company

The analysed company produces nitrogen fertilizers and chemical products, such as nitrogen and compound fertilizers, ammonia, nitric acid, methanol, formalin, resins, adhesives, carbonic acid gas, oxygen, nitrogen, aluminium sulphate, and other products and intermediates.

The basic component of industrial nitrogen fertilizer production is ammonia, which is formed in a Haber-Bosch process. The hydrogen needed for the process originates from natural gas, and the nitrogen originates from ambient air (158). Additionally, natural gas in the nitrogen fertilizer production is also used as an energy source and to clean the exhaust gas by burning it in industrial flares. This makes nitrogen fertilizer production heavily dependent on fossil fuels. Production of nitrogen fertilizers is very energy-consuming, accounting for 1.2% of global primary energy demand (159). The Ministry of Energy of the Republic of Lithuania states that in 2013 the consumption of natural gas for the production of nitrogen fertilizers has been about 40% of all natural gas consumed in Lithuania. Besides natural gas, the analysed nitrogen fertilizer production company uses about 60 different types of other imported raw materials.

System boundaries: the developed model is applied to the nitrogen fertilizer production company from a “gate-to-gate” perspective.

The results of the evaluation are in line with the feasibility study[3] performed during the research project "Resource efficient and cleaner production of nitrogen fertilisers" implemented by the Institute of Environmental Engineering, Kaunas University of technology. The research results were published in the scientific publication[4].

5.1.1. Results of initial assessment

Results of environmental assessment

During the initial environmental assessment, the Integrated Pollution Prevention and Control (IPPC) proposals and permits of the selected company were analysed. Additionally, the company provided data on the main material flows for 2013. Based on this data, the MFA for 17 facilities was performed. The schematic view of the main material flows is shown in Fig. 5.1.

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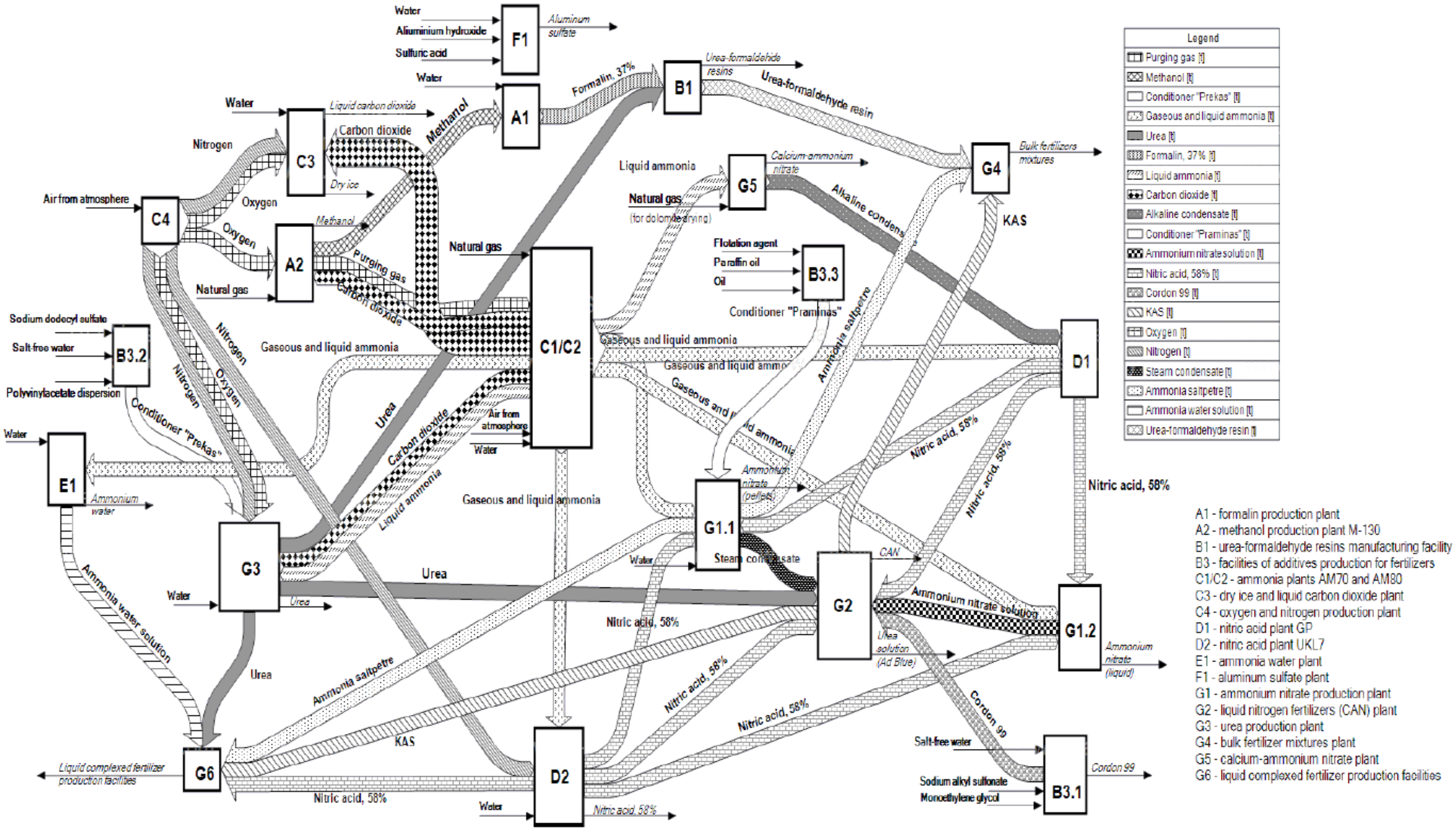
[3] Kliopova, I., Malinauskienė, M., Baranauskaitė I. Išteklius tausojančių švaresnės azoto trąšų gamybos inovacijų įvykdomumo analizės studija. 2014.

[4] Kliopova, I., Baranauskaitė-Fedorova, I., Malinauskienė, M., Staniškis, Jurgis Kazimieras. Possibilities of increasing resource efficiency in nitrogen fertilizer production // Clean technologies and environmental policy. Berlin: Springer. ISSN 1618-954X. 2016, vol. 18, iss. 3, p. 901-914.



A1 - formalin production plant
A2 - methanol production plant M-130
B1 - urea-formaldehyde resins manufacturing facility
B3 - facilities of additives production for fertilizers
C1/C2 - ammonia plants AM70 and AM80
C3 - dry ice and liquid carbon dioxide plant
C4 - oxygen and nitrogen production plant
D1 - nitric acid plant GP
D2 - nitric acid plant UKL7
E1 - ammonia water plant
F1 - aluminum sulfate plant
G1 - ammonium nitrate production plant
G2 - liquid nitrogen fertilizers (CAN) plant
G3 - urea production plant
G4 - bulk fertilizer mixtures plant
G5 - calcium-ammonium nitrate plant
G6 - liquid complexed fertilizer production facilities

Fig. 5.1. Schematic view of material flows in nitrogen fertilizer production company

The production volume of the analysed nitrogen fertilizer production company in 2013 was around 4.4 million tonnes, of which 2 million tonnes were fertilizers. All the facilities share the common infrastructure, and most of them are related in terms of output-input flows. As mentioned before, ammonia is a primary element for the production of nitrogen fertilizer and is produced in two facilities: C1 and C2. Prior to the processing, natural gas undergoes the treatment process that includes desulfurization, two reforming stages, shift adjustment, CO_2 removal, methanation, and compression. Liquid and gaseous ammonia are the raw materials for the production of urea or carbamide (G3), ammonium nitrate (G1), nitric acid (D1, D2), ammonium water (E1), and calcium-ammonium nitrate CAN (G5). Urea is used for the production of urea-formaldehyde raisins (B1) and liquid nitrogen fertilizers (G2). Formalin (A1) is used for the production of urea-formaldehyde resins (B1). Cordon99 produced in B3.1 is used for liquid nitrogen fertilizers (G2), which are further used for the production of bulk fertilizer mixtures (G4). The liquid ammonium nitrate from G1.1 and G1.2, as well as nitric acid from D1 and D2 is also used for bulk fertilizer mixtures (G4), etc. Moreover, the heat produced via chemical reaction is used for steam production, by-products of one process become raw material in another process. Thanks to this synergy of processes, the company is capable of producing most of the principal raw materials that are needed for the production of various fertilizers and chemical products. However, natural gas and a number of other materials, including raw materials, additional materials and catalysts have to be purchased from external sources. The relative environmental indicators related to the flows of main input materials (eq. 4.1) are provided in Table 5.1.

Table 5.1 Relative Environmental Indicators for the main input materials in the analysed nitrogen fertilizer production company

INPUT Flow	Codes of facilities	Unit	EIm_i
Natural gas	C1, C2, G5, E1, K1, K2, K3, K4, K5, D2, A1	10^6 $m^3/10^3$ t	2.4636
Melamine	B1	t/10^3 t	0.0036
Natrium hydroxide	B1, B3, C1, C2	t/10^3 t	2.2636
Acetic acid	B1	t/10^3 t	0.0045
Ferrous sulphate	C1, C2, G4, G6	t/10^3 t	0.2409
Monoethylene glycol	B3	t/10^3 t	0.0716
Monoethanolamine	B3	t/10^3 t	0.0068
Methyldiethanolamine	C1, C20	t/10^3 t	0.1557
Lauric acid	B3	t/10^3 t	0.0295
Sodium alkyl sulfonate	B3	t/10^3 t	0.0955

Table 5.1 (continued)

Sodium dodecyl sulphate	B3	t/10^3 t	0.1182
Industrial mineral oil	B3	t/10^3 t	0.4136
Paraffin	B3	t/10^3 t	0.0511
Flotigam	B3	t/10^3 t	0.0500
Brucite	G1	t/10^3 t	6.9136
Dolomite	G5	t/10^3 t	205.5523
Aluminium hydroxide	F1	t/10^3 t	0.4500
Sulphuric acid	F1	t/10^3 t	0.7523
Superphosphate	G4	t/10^3 t	0.0727
Amofos	G4	t/10^3 t	0.2068
Potassium chloride	G4	t/10^3 t	0.2955
Potassium sulphate	G4	t/10^3 t	0.0341
Boric acid	G4, G6	t/10^3 t	0.0046
Copper sulphate	G4, G6	t/10^3 t	0.0159
Manganese sulphate	G4, G6	t/10^3 t	0.0046
Zinc sulphate	G4, G6	t/10^3 t	0.0016
Ammonium molybdate	G4, G6	t/10^3 t	0.0001
Phosphoric acid	G4	t/10^3 t	0.0017
Potassium magnesia	G4	t/10^3 t	0.0341
Ammonium sulphate	G4	t/10^3 t	0.2455
Potash	G6	t/10^3 t	0.0045
Trilon B	G6	t/10^3 t	0.0001
Magnesium sulphate	G6	t/10^3 t	0.0007

Note: production volume for EIm evaluation: P(t) = 440 000 t/year

Additionally, the company uses river water for technological and cooling purposes within the eight water cycles with similar open cooling systems.

Different forms of energy are used in the production. In addition to the production of ammonia, natural gas is also used as a primary energy source and combustion of air emissions (Table 5.2). Steam is produced by using natural gas and waste energy. Electricity is produced in the company's cogeneration plants.

Table 5.2 Energy consumption per unit of manufactured product in the analysed nitrogen fertilizer production company

Code of facility	Manufactured product	Total energy consumption per unit of production GJ/t	Natural gas		
			Raw material	**Energy**	**Industrial flares**
A1	Formalin	2.16	0	0	+
B1	Carbamide-formaldehyde resins	2.09	0	0	0
B3	Fertilizer additives	2.6	0	0	0
C1	Ammonia	36.75	+	+	+
C2	Ammonia	37.27	+	+	+
C3	Liquid carbon dioxide and dry ice	2.45	0	0	0
D1	Nitric acid	-0.004	0	0	0
D2	Nitric acid	1.188	0	0	+
E1	Ammonia water solution	46.32	0	0	+
F1	Aluminium sulphate	0.35	0	0	0
G1	Ammonium nitrate solution and Ammonium nitrate fertilizer	0.89	0	0	0
G2	Liquid nitrogen fertilizer	0.065	0	0	0
	Ad Blue	0.33	0	0	0
G3	Carbamide	4.52	0	0	0
G4	Bulk fertilizer mixtures	0.36	0	0	0
G5	Calcium ammonium nitrate	1.136	0	+	0
G6	Liquid complex fertilizer	0.566	0	0	0

1 084 million nm^3 of natural gas (246 nm^3/t of all products or 36.6–37.3 GJ/t NH^3) is used annually as raw material for the ammonia production (more than 50% of total consumption), for exhaust gas burning in industrial flares (up to 6.6% of total consumption), the rest is used as a primary energy source for steam production. According to the BAT (160) for the Manufacture of Large Volume Inorganic Chemicals, the total energy consumption in ammonium production should be less than 31.8 GJ/t NH$_3$. Both facilities exceed the limit (C1 by 12.5% and C2 by 8.64%). Thus, the energy consumption was identified as the most significant environmental aspect in the analysed nitrogen fertilizer production company and was selected for further analysis.

Despite some already implemented process integration and cleaner production innovations in the selected nitrogen fertilizer production company, there is still potential for resource efficiency improvements.

The main identified reasons for energy inefficiencies are the following:

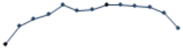
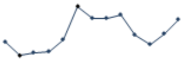
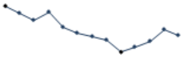
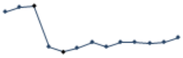
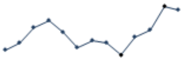
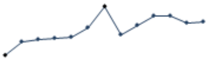
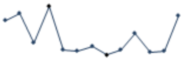
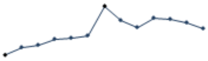
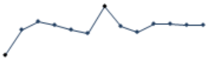
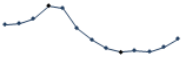
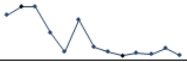
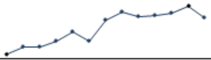
- Heat losses in open water cooling systems and in exhaust gases (its temperature often exceeds 300 °C);
- Inefficient use of waste heat;
- Considerable amounts of natural gas are used for exhaust gas incineration: in ammonia, ammonia water, nitric acid and formalin production;
- Inefficient use of primary energy (natural gas), producing steam in rather old combustion boilers.

Results of resource criticality evaluation

For the identification of geostrategic supply risk and economic importance of imported resources only the main resources used in the nitrogen fertilizer production company were investigated, that is with a projected annual consumption of more than 100 tonnes. The mass flow data for 2007 and 2013 were used to identify values for indicators for natural gas, melamine, sodium hydroxide, potassium hydroxide, acetic acid, monoethylene glycol, monoethanolamine, paraffin, magnesia, aluminium hydroxide, superphosphate, ammonium di-hydro phosphate, potassium chloride, potassium sulphate, phosphoric acid, ammonium sulphate and potash (see Annex 1 for corresponding CN codes). The analysis of import statistics revealed that the main import countries of selected resources in 2002–2014 were the Russian Federation (import of nitrogen hydroxide, acetic acid, monoethylene glycol, monoethanolamine, magnesia, aluminium hydroxide, superphosphate, ammonium di-hydro phosphate, potassium chloride, potassium sulphate, ammonium sulphate and potash), and Ukraine (import of potassium chloride, ammonium sulphate).

Table 5.3 represents the trend of resource origin countries concentration indicator weighted by political stability (SR_i) over the period 2002–2014 and the trend of statistical prices of one tonne (one thousand nm^3 of natural gas) in 2002–2014.

Table 5.3 Trends of geostrategic supply risk (SR) and resource price changes over the period 2002–2014 in the analysed nitrogen fertilizer production company

Resource	SR [1]			Price [1000 EUR/ton] ([1000 EUR/thousand m^3])			
	Trend (2002-2014)	Max	Min	Trend (2002-2014)	Max	Min	Price amplitude
Natural gas		64.85	62.09		0.38	0.062	0.32
Melamine		39.28	5.30		1.78	0.20	1.57
Sodium Hydroxide		35.78	10.69		0.34	0.016	0.33
Potassium Hydroxide		32.70	10.83		1.40	0.038	1.36
Acetic Acid		47.72	12.62		0.56	0.038	0.52
Monoethylene Glycol		52.14	5.25		0.88	0.043	0.84
Monoethanolamine		24.62	5.63		1.38	0.089	1.29
Praffin		59.85	16.28		1.15	0.054	1.10
Magnesia		64.83	20.89		1.16	0.015	1.15
Aluminium Hydroxide		60.15	20.66		0.36	0.017	0.34
Superphosphate		40.83	25.38		0.24	0.12	0.12
Ammonium di-hydrophosphate		64.46	21.46		0.55	0.018	0.53
Potassium chloride		69.60	31.19		0.38	0.0074	0.38
Phosphoric acid		30.62	6.50		1.17	0.066	1.11
Ammonium sulphate		59.17	7.81		0.20	0.0039	0.20
Potash		62.98	6.80		1.13	0.020	1.11

The highest absolute price amplitude during 2002–2014 was identified for melamine, followed by potassium chloride and monoethanolamine.

Results of the geostrategic supply risk and economic importance assessment for the materials are presented in two-dimension graphs in Fig. 5.2 and Fig. 5.3, where geostrategic supply risk is shown on the x-axis and economic importance is shown on the y-axis.

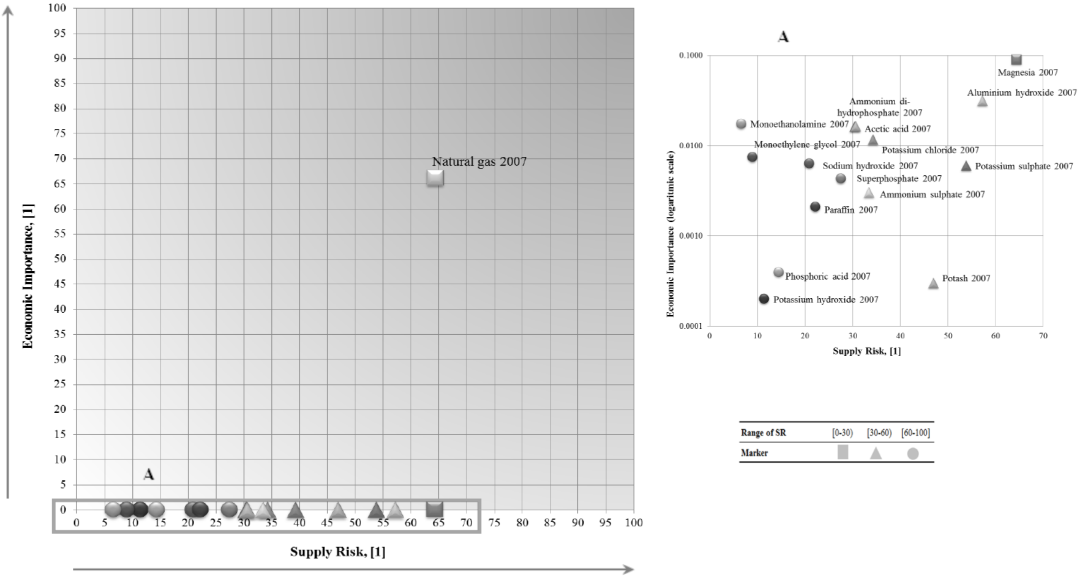


Fig. 5.2 Geostrategic supply risk (SR) and economic importance (EI) of selected resources for nitrogen fertilizer production company in 2007

In 2007 in terms of geostrategic supply risk (Fig. 5.2), the most significant resources for the analysed nitrogen fertilizer production company were natural gas (SR = 64.4), magnesia (SR = 64.4), aluminium hydroxide (SR = 57.2), potassium sulphate (SR = 53.8) and potash (SR = 46.9). In 2013 (Fig. 5.3) the most important resources were natural gas (SR = 64.2), ammonium di-hydro phosphate (SR = 61.8), paraffin (SR = 59.8) and aluminium hydroxide (SR = 35.6). It was assumed that there was no secondary resource content in the total consumption of any of the evaluated materials.

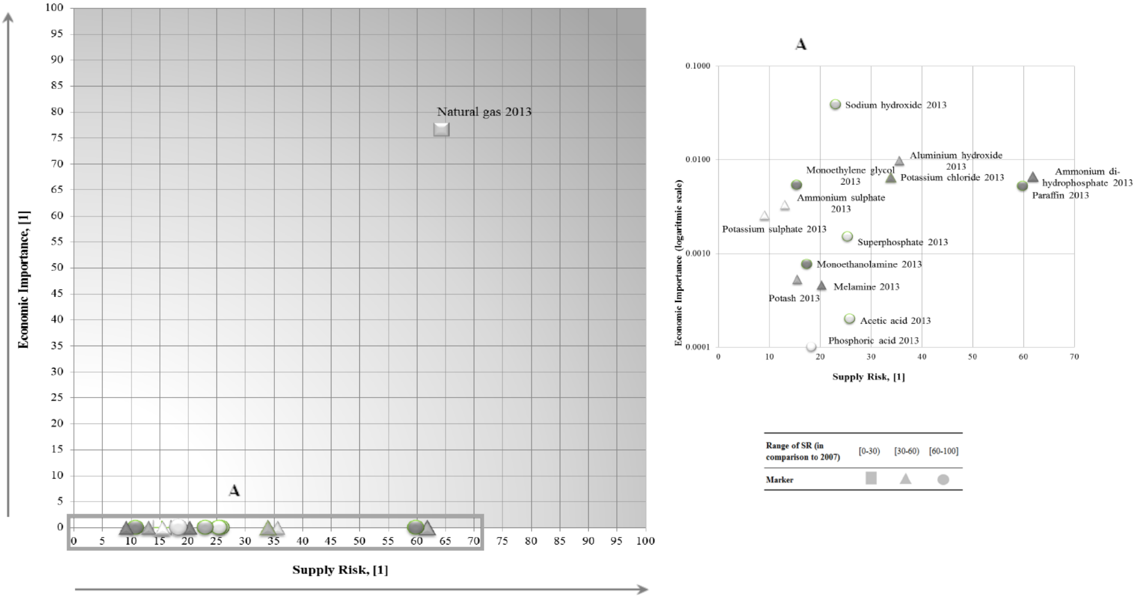


Fig. 5.3 Geostrategic supply risk (SR) and economic importance (EI) of selected resources for nitrogen fertilizer production company in 2013 in comparison to 2007

Natural gas has by far the highest economic importance for the analysed nitrogen fertilizer producing company. The economic importance of all other resources is not significant compared with natural gas. Nevertheless, all resources are necessary in order to ensure the production processes. However, the production costs are clearly dominated by the expenses for gas and variations in other resources prices will not affect the production costs significantly. In 2007 magnesia (EI = 0.0897), aluminium hydroxide (EI = 0.0315), monoethanolamine (EI = 0.0175) and ammonium di-hydro phosphate (EI = 0.0164) had relatively high economic importance compared to other resources, except natural gas. In 2013 magnesia has been substituted by $Mg(OH)_2$ (there is no data on the import of $Mg(OH)_2$), therefore, sodium hydroxide (EI = 0.0388) and aluminium hydroxide (EI = 0.0098) had relatively high economic importance. Other costs were labour costs and other operating costs.

Table 5.4 represents the ranking of resources in terms of absolute values and in terms of change compared to the year 2007.

Table 5.4 Prioritization of resources in terms of absolute values of geostrategic supply risk (SR) and economic importance (EI) indicators in 2013 and in terms of percentage change compared to 2007

Rank	**SR (2013) [1]**		**EI (2013) [1]**		**SR percentage change (compared to 2007), %**		**EI percentage change (compared to 2007), %**	
1	Natural gas	64.2	Natural gas	76.68	Paraffin	169.37	Sodium hydroxide	509.61
2	Ammonium dihydrophosphate	61.8	Sodium hydroxide	0.0388	Monoethanolamine	163.64	Paraffin	149.14
3	Paraffin	59.8	Aluminium hydroxide	0.0098	Ammonium dihydrophosphate	101.96	Potash	76.85
4	Aluminium hydroxide	35.6	Ammonium dihydro phosphate	0.0066	Monoethylene glycol	71.11	Natural gas	15.88
5	Potassium chloride	33.9	Potassium chloride	0.0065	Phosphoric acid	27.08	Ammonium sulphate	9.05
6	Acetic acid	25.8	Monoethylene glycol	0.0054	Sodium hydroxide	10.05	Monoethylene glycol	-27.88
7	Superphosphate	25.4	Paraffin	0.0052	Natural gas	-0.31	Potassium chloride	-44.23
8	Sodium hydroxide	23	Ammonium sulphate	0.0033	Potassium chloride	-0.88	Potassium sulphate	-57.26
9	Melamine	20.3	Lauric acid	0.0032	Superphosphate	-7.64	Ammonium dihydrophosphate	-59.76
10	Phosphoric acid	18.3	Potassium sulphate	0.0026	Acetic acid	-15.13	Superphosphate	-64.85
11	Monoethanolamine	17.4	Superphosphate	0.0015	Aluminium hydroxide	-37.76	Aluminium hydroxide	-68.89
12	Potash	15.5	Monoethanolamine	0.0008	Ammonium sulphate	-60.78	Phosphoric acid	-75.00
13	Monoethylene glycol	15.4	Potash	0.0005	Potash	-66.95	Monoethanolamine	-95.60
14	Ammonium sulphate	13.1	Melamine	0.0005	Potassium sulphate	-83.09	Acetic acid	-98.77
15	Lauric acid	13	Acetic acid	0.0002				
16	Potassium sulphate	9.1	Phosphoric acid	0.0001				

In 2007 as well as 2013 the highest identified geostrategic supply risk combined with the highest economic importance was identified for natural gas (used as raw material, energy source and used for effluent gas treatment in industrial flares). Although the geostrategic risk of natural gas supply decreased marginally by 0.31%, the overall economic importance of natural gas increased by 16%. In 2007 fertilizer prices were increasing steadily, demand was increasing, and supply was insufficient (161). Therefore, the ability to pass-through cost increases can be considered as “possible” (PT = 0.3). On the contrary, in 2013 fertilizer sales were declining (162) and thus for this year the ability to pass-through the cost increases to customers can be considered as “practically impossible” (PT = 1).

Compared to 2007, in 2013 the geostrategic supply risk of paraffin has increased by 169%, monoethanolamine by 164%, ammonium di-hydro phosphate by 102%, Economic importance of sodium hydroxide has increased by 510%, of paraffin by 14%. Magnesia with the high geostrategic supply risk (SR = 64.4) was substituted by brucite in 2013. There is no data about the imports of brucite for the analysed years. In the previous years, brucite was imported from EU countries. However, the main producers are non-EU countries. Prioritization of resources in terms of different dimensions allowed the targeted strategies to be identified for the resource criticality management from the point of view of an industrial company.

Goal setting

Based on the results of the environmental assessment and estimation of economic importance, and geostrategic supply risk, the goal is to choose a technically and economically feasible RE alternative that would increase environmental performance related to the use of natural gas and meanwhile would decrease the geostrategic supply risk.

5.1.2. Identification or resource efficiency improvement possibilities

Given the highest Economic Importance and Geostrategic Supply Risk, as well as the potential for resource efficiency improvement, natural gas was selected for further analysis. After performing material and energy flow analysis, and evaluating environmental performance in terms of environmental indicators, it was determined that the development of symbiotic links would allow the utilization of waste heat from fertilizer production and therefore decreasing energy intensity. Moreover, the possibility to partly substitute natural gas by renewable resources was identified.

Several possible options for resource efficiency improvements were identified, and four scenarios were developed:

1. Partial substitution of natural gas used to burn exhaust gas in industrial flares by biogas from biodegradable waste of surrounding cattle farms and slaughterhouses;
2. Use of waste heat from water cooling system for heating of premises and hot water preparation in the new target industrial zone and in the company’s administrative department;

3. Use of waste heat (low-pressure steam) received from fertilizer production processes for foreseen economic activities in the new industrial zone for technological purposes (for example, solid recovered fuel and wood product production companies);

4. Installation of new steam boiler with condenser economizer.

Partial substitution of natural gas by biogas (scenario 1)

Bearing in mind the considerable environmental impact caused by nitrogen fertilizer production, as well as the high reliance on supply of finite fossil fuels, the possibilities to gradually replace fossil fuels by renewable resources and thereby move from a linear towards a circular economy are investigated in the scientific literature (158, 159, 163). In line with the authors mentioned above, this study aims to apply industrial ecology principles in order to investigate the potential use of biodegradable waste for the production of biogas in order to substitute natural gas in nitrogen fertilizer production.

Most biodegradable waste (BDW) is characterized by good energy potential. This potential can be recovered by different methods and depends on the type of waste. For example, anaerobic fermentation for biogas production is an optimal decision for liquid BDW management. In this case, the remaining biomass is usually supplied to bio-compost production. Currently, in Lithuania, liquid BDW such as sewage sludge, the waste of some dairy and meat production companies, is used for energy purposes. Unfortunately, the biogas potential of BDW of stockbreeding still has not been used or used rarely.

The ratio of methane in biogas is up to 1.4 times lower than in natural gas. Therefore, the use of biogas as a raw material in the analysed company requires a large investment in equipment replacement. Usage of biogas for combustion of air emissions in industrial flares would be a more feasible suggestion. Up to 71.55 million nm^3 of natural gas (around 6.6% of total consumption) was used for this purpose in 2013. The combustion of air emissions takes place in the production units of ammonia, ammonia water, nitric acid and formalin. Three possible options of sourcing the biogas were identified:

1. Biogas potential of BDW of the nearest stockbreeding farm and slaughterhouse (local biogas potential): BDW from the nearby stockbreeding farm and slaughterhouse and the company’s municipal wastewater;
2. Biogas potential of BDW of stockbreeding farms and the nearest slaughterhouse in the Kaunas region (regional biogas potential);
3. Biogas potential of BDW of stockbreeding farms in Lithuania (National biogas potential).

The results of biogas potential evaluation and the associated risks are summarized in Table 5.5.

Table 5.5 Biogas potential and associated risks

Option	Biomass, t/year	Biogas potential, thousand nm^3/year	CH4 potential, thousand nm^3/year	Energy potential, GWh/year	Associated risks
1	21 961	1 810	1 244	12.5	-Dependence on one supplier
2	594 950	23 674	16 314	162.2	-Considerable environmental impact related to transportation of biodegradable waste -Smell during transportation -Considerably large area needed for storage
3	3 956 600	124 166	85 375	849.0	-Very significant environmental impact related to transportation of biodegradable waste -Smell during the transportation -No enough space for storage in the company's premises

Despite the high potential in terms of the biogas amount, the second and third options are related to the considerable risks associated with the negative environmental impact related to the transportation and the need for a storage area. Thus, these options are rejected as technically unfeasible, and only the first alternative is further investigated.

Utilization of waste energy received from ammonia fertilizer production process (scenario 2 and scenario 3)

The large amount of waste heat energy that occurs in various forms, such as hot water, low parameter steam or cooling water, could be used in the planned nearby industrial zone for:

1. heating of premises and hot water preparation in the new target industrial zone and in the company's administrative department (scenario 2);
2. technological purposes in the nearby industrial zone (scenario 3).

In the case of scenario 2, the heat from the water cooling system could be used for heating of premises and hot water preparation in the new planned industrial zone and in the company's administrative department. It was assumed that 50% of the new industrial zone area would have one- or two-storey buildings: up to 500 000 m^2 would be special purpose facilities, and up to 100 000 m^2 would be administrative purpose buildings. Some of the warm water (70°C) after cooling processes would be supplied through 2 heat exchangers, the existing one used for heating the company's administration facilities and a new one for heating the premises of the new industrial zone. Thus, wastewater would be cooled, and waste heat energy could be used for heating purposes. The rest of the water would be supplied to the existing cooler to be cooled to 26°C. Around 24 000 nm^3 of natural gas could be saved annually thanks to the reduced electricity consumption for water cooling (recirculation pumps). Around 234 000 nm^3 of natural gas could be saved annually thanks to the avoided burning of natural gas for heating of premises. In total around 260 000 nm^3 of natural gas could be saved annually.

In the case of scenario 3, the waste heat (in the form of low-pressure steam) could be used for the technological purposes of the foreseen economic activities in the new industrial zone. For example, in processes that require a large amount of heat energy, like the production of biofuel and/or production of solid recovered fuel (SRF) or technological processes of wood production. As an example, it was assumed that these production activities in the planned industrial zone, could require around 300 000 MWh of heat energy. This would correspond to the 16 000 MWh of electricity (or around 1 874 thousand nm^3 per year of natural gas), which could be avoided thanks to the decreased need for waste heat cooling in the analysed company.

Installation of new steam boiler with condenser economizer (scenario 4)

Compression of natural gas and treatment of sulphur compounds are the first technological stages in ammonia production. Heated to 360-400°C, natural gas and a mixture of nitrogen and hydrogen are supplied to the hydrogenation reactor of sulphur compounds. Superheated steam at a pressure of 4 MPa and at a temperature of 440°C is used as heat energy for start-up. It is produced in a large combustion plant (LCP) with a 40 MW capacity. Knowing that the technology requires steam with a temperature of 380°C, the produced steam is cooled by spraying the feeding water. Part of water flow is supplied to the heat exchanger by steam cooling pipelines, the other part is supplied directly to the heat exchanger for heating to 270°C. In the next stage, the overheated steam is produced. About 11.700 MWh/year of heat energy was produced in the analysed LCP in 2013. This required 1.5 million m^3 of natural gas to be burnt. The identified main heat energy losses in the analysed LCP were up to 1.180 MWh/year (17%) due to the air emissions (the temperature of exhaust gas being over 200°C), natural depreciation of LCP, water de-aeration (about 0.2%) and during blow-off (about 0.7%). The heat losses occur as well during cooling of steam from 440°C to 380°C (although most of the waste heat energy is used for heating the feeding water). It was therefore suggested to install a new steam boiler of lower capacity with a condenser economizer and higher efficiency.

5.1.3. Feasibility analysis

Environmental evaluation

The proposed alternatives would involve the changes of different input and output flows, including the material and energy flows in new production activities. However, since natural gas was identified as the most critical resource and the consumption of it was identified as the most significant environmental aspect, the further analysis involves only the evaluation of natural gas. The summary of results of the potential to decrease natural gas consumption for all developed scenarios is presented in Table 5.6.

Table 5.6 Potential to decrease natural gas consumption after implementation of identified cleaner production and industrial symbiosis measures (E = energy, GC = gas cleaning)

Scenario	**Natural gas E**		**Natural gas GC**		**Total**	
	Decrease of natural gas consumption (1 000 m^3/yr)	**Decrease of natural gas consumption (%)**	**Decrease of natural gas consumption (1 000 m^3/yr)**	**Decrease of natural gas consumption (%)**	**Decrease of natural gas consumption (1 000 m^3/yr)**	**Decrease of natural gas consumption (%)**
1	-	-	1 181	1.65	1 181	0.11
2	260	0.06	-	-	260	0.02
3	1 874	0.43	-	-	1 874	0.17
4	237	0.05	-	-	237	0.02

The identified cleaner production and industrial symbiosis measures would allow the reduction in the consumption of natural gas used as an energy source and natural gas used for exhaust gas burning in industrial flares. If all the alternatives were implemented, the total annual consumption of natural gas would decrease by around 3 552 thousand nm^3, that would correspond to around 0.33% of the total consumption. The EIm associated to natural gas would decrease by the same ratios.

Economic feasibility

The main results of economic feasibility assessment are presented in Table 5.7

Table 5.7 Results of economic analysis of resource efficiency increasing alternatives for a nitrogen fertilizer production company

	Unit	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Investment	thousand EUR	2 800	-	-	600
Savings	thousand EUR/year	614	80	576	100
Pay-back period	years	4.6	-	-	3.6

The investment needed for scenario 1 would be about 2.80 million EUR, including 52.6% - for the implementation of anaerobic treatment equipment, 45.5% - for intensive composting equipment and loader, other – for designing, start-up, adjustment works. The implementation of this alternative will allow savings of 614 000 EUR/year (including income from produced bio-compost). Payback period is assumed to be 4.6 years. It is assumed that in the case of scenario 2, there would be no significant investments from the perspective of the analysed company. For the heating of the administrative building the existing heat exchanger would be used, and for the heating of the new industrial zone the investments would have to be made by other companies. The implementation of this scenario would allow savings of around 80 000 EUR per year thanks to the decreased consumption of natural gas. Similarly, in the case of scenario 3, it was assumed that the required investments should be covered by the companies in the new industrial zone. The savings would be around 576 000 EUR per year thanks to the avoided electricity for the cooling of waste heat. In the case of scenario 4, the investment would be around 600 000 EUR, the annual savings around 100 000 EUR. With 40% of the funding provided by the EU structural funds, the payback period could be reduced to around 3.6 years.

Criticality evaluation

The first scenario suggests that natural gas used for exhaust gas cleaning in industrial flares could be partially substituted by biogas, produced from biodegradable waste generated in the companies within the same industrial area. Therefore, in this case biogas was considered to be a locally produced secondary resource and this has the potential to decrease the value of Geostrategic Supply Risk indicator compared to the value for 2013 (Table 5.8). Cleaner production alternatives proposed in scenario No. 2, scenario No. 3 and scenario No. 4 do not affect the actual value of the Supply Risk indicator.

Table 5.8 The potential impact of cleaner production and industrial symbiosis alternatives for Geostrategic Supply Risk and Economic Importance of resources used in a nitrogen fertilizer production company

Resource		**Annual consumption (1 000 nm^3/year)**	**Share of secondary resource, %**	**Supply Risk SR (normalized to 0-100)**	**Economic Importance**
Natural and bio-gas	BAU	1 084 265	0	64.24	76.68
	1 a.	1 084 265	0.11	64.10	76.85
	2 a.	1 084 005	0	64.24	76.67
	3 a.	1 082 391	0	64.24	76.59
	4 a.	1 084 028	0	64.24	76.61

The implementation of the first scenario would not have any impact on the total annual consumption of gas, because of the higher costs of production of biogas from biodegradable waste the total annual expenses would increase (Table 5.8). Scenario No.2, scenario No. 3 and scenario No. 4 allow the volume of annual natural gas consumption to decrease, therefore, the annual expenses for natural gas would decrease.

Results of SAW comparison and sensitivity analysis

The specification of criteria that were selected for the multi-criteria evaluation of the RE alternatives in a nitrogen fertilizer production company is provided in Table 5.9.

Table 5.9 Selected criteria for assessment of RE alternatives in a nitrogen fertilizer production company

Evaluated dimension	Criterion	Explanation	Unit
1. Environmental performance	C11: Change in natural gas consumption	Change in natural gas consumption per thousand tonnes of product	10^6 nm^3/10^3 tonnes
2. Economic feasibility	C21: Savings	Annual savings	10^3 EUR/ year
	C22: Investment	Investment	10^3 EUR
	C23: Economic importance of natural gas	Relative economic importance of natural gas	-
3. Geostrategic supply risk	C31: Geostrategic supply risk	Relative supply risk of natural gas	-

The decision matrix of the normalized criteria values and results of SAW comparison are presented in Table 5.10.

Table 5.10 Normalized criteria values, criteria weights and results of comparison of RE alternatives in a nitrogen fertilizer production company

Alternatives	Criteria					Results	
	C11	C21	C22	C23	C31	SAW	Rank
1	0.630	1	0.333	0.996	1	0.802	2
2	0.139	0.130	1	0.999	0.998	0.615	3
3	1	0.938	1	1	0.998	0.992	1
4	0.126	0.163	0.500	0.999	0.998	0.559	4
Weights	1/3	1/9	1/9	1/9	1/3		

Equal initial weights were assigned for all three evaluated dimensions (1/3 for each). The weights for criteria were assigned equally within each evaluated dimension (1/3 for each criterion in the environmental dimension, 1/9 for each criterion in the economic dimension, 1/3 for each criterion in the supply risk dimension). Alternative 3 was ranked as the most preferred. This alternative corresponds to the highest decrease in natural gas consumption and would not require investment from the analysed company. The second most preferable would be Alternative 1 corresponding to the second highest decrease of natural gas consumption but meanwhile requires the largest investment.

The assignment of criteria weight involves a high degree of subjectivity, thus, the final results are assumed to be sensible to this assumption. Sensitivity to the weight of criteria was performed, and the results were compared (Table 5.11).

Table 5.11 Weights of criteria for sensitivity analysis of RE alternatives

	Weights				
Criteria	**C11**	**C21**	**C22**	**C23**	**C31**
Initial	1/3	1/9	1/9	1/9	1/3
Variant 1	1/2	1/12	1/12	1/12	1/4
Variant 2	9/20	3/20	3/20	3/20	1/10
Variant 3	1/4	1/6	1/6	1/6	1/4
Variant 4	1/2	1/4	1/4	-	-
Variant 5	-	-	-	1/2	1/2

For Variants 1 and 3 the weight assigned to the supply risk was decreased to 1/4, for Variant 2– decreased to 1/10. For Variant 2 the rest weights of variants were assigned equally to the environmental and economic dimensions. For Variant 1 the weight of environmental dimension was increased to 1/2, for Variant 3 the economic dimension was assigned with the increased weight equal to 1/2. Variant 4 eliminates the consideration of criticality dimension, Variant 5 considers solely criticality dimension. The estimation of the impact on the final results is provided in Table 5.12.

Table 5.12 Results of sensitivity analysis of RE alternatives

Results	**SAW**						**Rank**					
Weights (variants)	**Initial**	**1**	**2**	**3**	**4**	**5**	**Initial**	**1**	**2**	**3**	**4**	**5**
Alt. 1	0.802	0.759	0.733	0.796	0.648	0.998	2	2	2	2	2	3-4
Alt. 2	0.615	0.496	0.482	0.639	0.352	0.998	3	3	3	3	3	3-4
Alt. 3	0.992	0.994	0.990	0.989	0.985	0.999	1	1	1	1	1	1-2
Alt. 4	0.559	0.451	0.406	0.558	0.229	0.999	4	4	4	4	4	1-2

The results of sensitivity analysis (Table 5.12) show that change of weights did not have an influence on the final ranking of alternatives. If criticality evaluation is eliminated the ranking would not change either. However, if only criticality dimension is considered Alternatives 3 and 4 would be ranked as equally preferable.

5.2. Results of model application in a metal processing company

The analysed metal processing company produces ovens for laboratories and industry, solid fuel boilers, agricultural machinery, low-pressure compressors, metal constructions for furniture and other metal products. The main manufacturing processes are: metal moulding in an induction furnace; thermal pre-treatment of metal parts to protect them from corrosion, such as heating to a certain temperature, hardening in a saline solution and oil; metal mechanical treatment such as polishing, turning, milling, clipping, stamping, welding, laser cutting, bending; pre-treatment of metal parts with solvents; dyeing; electroplating of metal or metal parts; galvanic waste water treatment. The company produces around 12.7 million units of metal products per year, which is equivalent to about 1 909 tonnes.

System boundaries: the developed model is applied to a metal processing company from “gate-to-gate” perspective.

The research results were published in the scientific publication[5].

5.2.1. Results of initial assessment

Results of initial environmental assessment

Around 2 727 tonnes of different metals, such as carbon steel, aluminium, and stainless steel, are used annually as raw materials. Electricity is used for the production processes and lighting. Heat energy is used to heat the premises and to provide hot water. Natural gas is used in dyeing processes, other gases – in welding and laser cutting. Water and most of the chemicals are used for electroplating processes; some of the water is also used for domestic needs. The annual material and energy balance and relevant EIms were evaluated. The results are presented in Table 5.13.

Table 5.13 Relative Environmental Indicators of the analysed metal processing company

INPUTS	**Unit**	**EIm$_i$**	**OUTPUTS**	**Unit**	**EIm$_i$**
Raw materials (metals)	t/t	1.429	Production	t/t	1.000
Lubricants	t/t	0.007	Steel waste	t/t	0.423
Chemicals	t/t	0.012	Non-ferrous metals waste	t/t	0.005
Oil	l/t	1.006	Metal slag	t/t	0.004
			Air emissions, inc.		
Electricity	MWh/t	1.982	CO	kg/t	1.382
Heat energy	MWh/t	2.515	NOx	kg/t	1.202
Natural gas	nm3/t	35.626	PM,	kg/t	0.866
Liquefied gas	t/t	0.005	Fe compounds	kg/t	0.090
Other gases (nitrogen, oxygen, argon, etc.)	nm3/t	17.998	Al oxides	kg/t	0.002
			VOC	kg/t	2.683
Water	m3/t	3.144	Waste water after treatment	m3/t	~ 3.144
			Sludge	kg/t	1.572
Paper and cardboard	kg/t	0.393	Packaging waste	t/t	0.027
Packaging tape	kg /t	2.173	Other hazardous waste	t/t	0.002
PE film	m2/t	2.950	Other non-hazardous waste	t/t	0.014

Note: production volume for EIm evaluation: P(t) = 1 908.7 t/year

The results of the initial environmental assessment have revealed the following significant environmental aspects: emissions to the air related to the mechanical treatment and treatment with solvents (aluminium oxide, ferrum compounds, particular matter); relatively high consumption of heat and electricity;

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[5] Malinauskienė, M., Kliopova, I., Slavickaitė, M., Staniškis, J.K. Integrating resource criticality assessment into evaluation of cleaner production possibilities for increasing resource efficiency // Clean technologies and environmental policy. Berlin: Springer. ISSN 1618-954X. 2016, vol. 00, p. [1-12].

production waste (shavings of cast iron, steel and aluminium, spoilage, slag, dust from cyclones, packaging of chemicals, galvanic slag, mixture of metal, abrasive dust and emulsion).

Results of assessment on process level

One of the most important problems in the analysed production company is the relatively high amount of metal waste, since the percentage of production waste and spoilage is as high as 30% (818 tonnes per year), of which 808 tonnes is steel waste. After a detailed assessment of all the production processes, it was identified that the main loss of raw material occurs during the laser cutting process of metal sheets, which is the first stage of metal sheet processing. Around 60% of the raw material is processed at this stage and around 37% of the initial metal mass is wasted.

There is one laser cutting line, which uses the CNC-cutting equipment “Bystronic Bystar 2512”, in the production facility (~3 000 working hours per year). The installed electric capacity of the cutting machine is 3 kW. The size of the processed sheets: 1250 x 2500 mm, thickness: 0.5-20 mm (depends on the metal). The material and energy balance of the laser cutting process and associated EIms are presented in Table 5.14. Helium, nitrogen, and carbon dioxide gases are used to generate the laser beam. Oxygen is also used in the cutting process. Metal cutting is associated with emissions, such as carbon monoxide, nitrogen oxides, iron compounds, and manganese oxide to the air. Iron and manganese compounds are captured in the electrostatic precipitator. Metal waste – up to 0.587 t/t of cutting metal – is a significant environmental aspect of the cutting process. It is four times above the BAT level for metal cutting (164).

Table 5.14 Material and energy balance of laser cutting process and associated Environmental Indicators

Input	**Unit**	**Amount (unit/year)**	**EIm$_i$ (units/t)**	**Output**	**Unit**	**Amount (unit/year)**	**EIm$_i$ (units/t)**
Metal sheets	to	1 636	1.59	Production	t	1031	1.000
Electricity	MWh	21	0.020	Metal waste	t	605	0.587
Heat energy	kWh	450	0.436	Emissions to air	kg	66.5	0.065
Water	m^3	320	0.310	Wastewater	m^3	320	0.310
Various gases (helium, nitrogen, carbon dioxide, oxygen)	nm^3	16 260	15.77				

Note: production – processed metal sheets.

In addition, other waste, such as mixtures of dust and powder, and used grinding wheels are generated (not included in Table 5.14).

Results of resource criticality evaluation

The results of criticality evaluation of main raw materials: steel and aluminium are shown in Fig. 5.4.

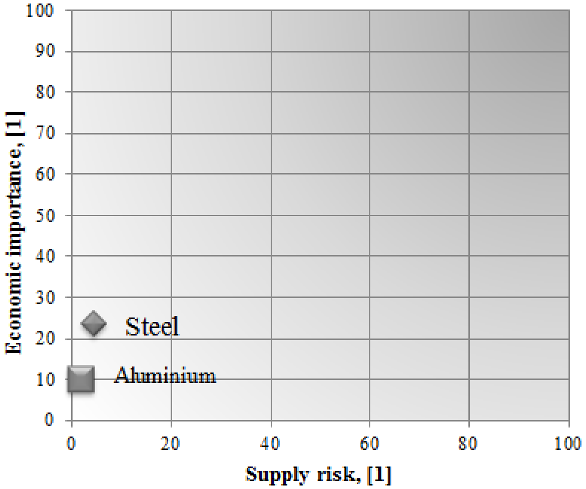

Fig. 5.4 Geostrategic supply risk (SR) and economic importance (EI) of main raw materials for the metal processing company in 2009

The assessment of resource criticality dimensions revealed that relative SR related to the supply of aluminium (SR = 1.98) is less than half the SR related to the supply of steel (SR = 4.45). In terms of Economic Importance, steel (EI = 23.40) has a higher priority compared to aluminium (EI = 9.81) due to the considerably higher amount consumed.

5.2.2. Identification or resource efficiency improvement possibilities

The options for potential improvement were determined in collaboration with the representatives of the analysed metal processing company by analysing BAT technologies for metal processing and other technical and scientific literature. Four metal cutting methods were identified: automated laser cutting, cutting with a high-pressure water jet, plasma cutting and gas cutting. The technical feasibility was assessed based on the criteria provided in Table 5.15.

Table 5.15 Technical criteria for feasibility analysis of metal cutting process

Criterion	Description	Target
Thickness of processed material	Interval of thickness of processed metal sheets	Larger interval
Variety of processed materials	Possibility to process the sheets of different metals	Bigger variety

Table 5.15 (continued)

Quality of cutting	Precision of cutting	More precise cutting, less spoilage
	Generation of slag	Minimal quantity or no slag
	Need for further processing after cutting	No further processing
Cutting speed	Expressed as length of cut per minute	Higher speed

Based on the results of the evaluation of technical feasibility criteria for metal cutting, only automated laser cutting and cutting with high-pressure water jet were identified as technically feasible alternatives and selected for further investigation. In addition, the alternative that involves the use of the recycled material was proposed. Identified alternatives for increasing resource efficiency selected for further feasibility analysis:

1. Automated laser cutting;
2. Cutting with high-pressure water jet;
3. Increasing the content of locally recycled materials.

Automated laser cutting allows precise cuts of complicated geometry to be performed. The precision of positioning is ± 0.1 mm, the speed of cutting is 100 mm/min, which is 2.8 times faster than the existing cutting machine (165). Operating power depends on the thickness of the processed metal and is about 2-5 kW. Another advantage is that consumption of gases can be halved compared to the existing situation. The implementation of automated cutting would allow the amount of raw material to be reduced by around 15% as there would be about 40% less metal waste (spoilage), which occurs because of the inevitable human factor during the cutting process.

Cutting with high-pressure water jet allows even more precise cutting to be performed, because of the smoother edges of the sheet and smaller distortions caused by heat. Heat affected zones are not formed in the cutting zone, and therefore, the structure of the cutting material does not change (166). No smoke or dust is emitted during this cutting process. The precision and thickness of the cut allow the maximum exploitation of the raw material. Moreover, there is a greater variety of sheet thickness, the minimum sheet thickness is 0.762 mm. The water used for cutting is recycled; therefore, the amount of water used is not significant. The introduction of this method would also allow the human factor to be minimized and would allow the amount of raw materials to be reduced by up to 20%, and the amount of metal waste to be reduced by up to 55%.

Increasing the content of locally recycled materials (164). Metals, compared to other materials, have the highest potential for systematic recycling, because of their high economic value, the large scrap volumes enabling economies of scale and their distinctive feature of excellent recyclability (167). The use of recycled metals allows the environmental impact to be reduced compared to the use of primary metals. The recycling of steel allows energy consumption to be reduced by 75%, recycling of aluminium – by 95% compared to producing it from ore. The use of locally recycled material allows the environmental impact related to the transportation of raw materials, and the risks associated with the supply of raw material, to be reduced. According to the statistical data of material flows, the local use of steel scrap in comparison to the total consumption of material was around 7%, and the use of aluminium scrap was 28% in Lithuania in 2009. Having in mind the technical possibilities to use recycled metals, this alternative would suggest that the content of locally recycled materials could be increased to 90%. The regional recycling facilities would be involved in the implementation of this alternative.

5.2.3. Feasibility analysis

Environmental evaluation

The estimated EIms for BAU and all resource efficiency increasing alternatives are represented in the Table 5.16.

Table 5.16 Input and output flows of metal cutting process in the analysed company for estimated business as usual (BAU) and the RE alternatives

	Unit/year	BAU	Alternative 1	Alternative 2	Alternative 3
Input					
Steel (total):	t	1309	1113	1047	1309
Steel (primary)	t	1214	1032	971	131
Steel (secondary)	t	95	81	76	1178
Aluminium (total):	t	327	278	262	327
Aluminium (primary)	t	200	170	160	33
Aluminium (secondary)	t	127	107	101	294
Electricity	MWh	21	18.9	45	21
Heat energy	kWh	450	450	450	450
Water	m^3	320	281	295	320
Helium	nm^3	180	90	0	180
Nitrogen	nm^3	3297	1649	0	3297
Carbon dioxide	nm^3	15	8	0	15
Oxygen	nm^3	12768	6384	0	12768
Output					
Production	t	1031	1031	1031	1031
Steel waste	t	484	288	223	484
Aluminium waste	t	121	72	56	121
Waste water	m^3	320	281	295	320
Emissions to air:					
iron compounds	kg	0.5	0.33	0	0.5
NO_x	t	0.025	0.016	0	0.025
CO	t	0.041	0.027	0	0.041

The results of the evaluation of environmental performance are represented in Table 5.17.

Table 5.17 The estimated environmental performance due to the implementation of the RE alternatives in comparison to BAU

	Unit	Alternative 1		Alternative 2		Alternative 3	
		EIm$_i$	**Wplan**	**EIm$_i$**	**Wplan**	**EIm$_i$**	**Wplan**
Input							
Steel (total):	t/t	1.079	0.191	1.016	0.254	1.270	0
Steel (primary)	t/t	1.001	0.176	0.942	0.235	0.127	1.051
Steel (secondary)	t/t	0.078	0.014	0.074	0.018	1.143	-1.051
Aluminium (total):	t/t	0.270	0.047	0.254	0.063	0.317	0
Aluminium (primary)	t/t	0.165	0.029	0.156	0.038	0.032	0.162
Aluminium (secondary)	t/t	0.105	0.018	0.098	0.025	0.286	-0.162
Electricity	MWh/t	0.018	0.002	0.044	-0.024	0.020	0
Heat energy	kWh/t	0.437	-0.001	0.437	-0.001	0.436	0
Water	m^3/t	0.273	0.037	0.286	0.024	0.310	0
Helium	nm^3/t	0.087	0.088	0	0.175	0.175	0
Nitrogen	nm^3/t	1.599	1.599	0	3.198	3.198	0
Carbon dioxide	nm^3/t	0.007	0.008	0	0.015	0.015	0
Oxygen	nm^3/t	6.192	6.192	0	12.384	12.384	0
Output			0		0		0
Production	t/t	1.000	0	1.000	0	1.000	0
Steel waste	t/t	0.280	0.19	0.216	0.254	0.470	0
Aluminium waste	t/t	0.070	0.047	0.054	0.063	0.117	0
Waste water	m^3/t	0.273	0.037	0.286	0.024	0.310	0
Emissions to air	kg/t	0.042	0.023	0	0.065	0.065	0

The implementation of Alternatives 1 and 2 would allow the direct and indirect environmental impact of the metal cutting process to be reduced. The implementation of Alternative 1 would reduce the yearly amount of electricity by 10%, the amount of cutting and laser gases by 50%, and the amount of water for cooling by 12% in comparison with BAU. The amount of metal waste would be reduced by 40% in comparison with BAU thanks to the improved cutting precision. The implementation of Alternative 2 would eliminate the gas used for cutting and laser beam formation. Emissions to the air would be eliminated since there is no smoke or dust produced during the high-pressure water jet cutting process. The amount of metal waste would be reduced by 54% in comparison with BAU thanks to the narrowness of cut and better cutting precision. However, the implementation of Alternative 2 would increase the consumption of energy due to the high-pressure pump. Alternative 3 would allow the share of recycled metal in the total consumption of metal to be increased and thus, reduce the indirect environmental impact associated with the production of raw materials. However, it would not have any effect on the direct environmental impact of the process.

Economic feasibility

The results of economic analysis are presented in Table 5.18.

Table 5.18 Results of economic analysis of resource efficiency increasing alternatives for metal cutting

	Unit	**Alternative 1**	**Alternative 2**	**Alternative 3**
Annual costs	EUR/year	1 088 355	835 430	1 333 962
Investment	EUR	317 480	450 000	-
Savings	EUR/year	295 942	548 867	44 335
Pay-back period	years	1.1	0.8	-

Note: it is assumed that the price of locally recycled metal is 20% lower compared to the price of imported primary metal

In terms of economic feasibility, Alternative 2 would require the biggest investment, and Alternative 3 would require no additional investments. The annual production costs would be considerably decreased (by 40%) if Alternative 2 were implemented.

Criticality evaluation

The results of relative resource criticality evaluation are presented in Table 5.19.

Table 5.19 Results of relative resource criticality evaluation of RE alternatives for metal cutting

	Value				**Increase (+)/ decrease (-) compared to BAU**		
	BAU	Alt. 1	Alt. 2	Alt. 3	Alt. 1	Alt. 2	Alt. 3
$\mathrm{SR}_{\mathrm{aluminium}}$	1.98	1.98	1.98	0.01	0	0	-1.97
$\mathrm{SR}_{\mathrm{steel/iron}}$	4.45	4.45	4.45	0.04	0	0	-4.41
$\mathrm{EI}_{\mathrm{aluminium}}$	9.81	8.34	7.83	7.85	-1.47	-1.98	-1.96
$\mathrm{EI}_{\mathrm{steel/iron}}$	23.40	19.90	18.72	18.72	-3.50	-4.68	-4.68

The evaluation of relative resource criticality revealed that the implementation of Alternatives 1 and 2 would have zero impact on the supply risk of selected metals, whereas there would be no change in the supply chain of raw materials Meanwhile, in comparison with BAU, the implementation of Alternative 3 would allow the risk associated with the supply of aluminium to be reduced by 99.5%, as well as reducing the risk associated with the supply of steel and iron by 99.1%. The implementation of Alternative 3 would allow the dependency on imported raw materials to be reduced by increasing the use of locally recycled materials. The Economic Importance would decrease if Alternatives 1 and 2 were implemented thanks to the more efficient use of raw materials, the Economic Importance in the case of Alternative 3 would decrease thanks to lower costs of local secondary resources.

Results of SAW comparison and sensitivity analysis

The specification of criteria that were selected for the multi-criteria evaluation of the RE alternatives in a metal processing company is provided in Table 5.20

Table 5.20 Selected criteria for assessment of RE alternatives in a metal processing company

Evaluated dimension	Criterion	Explanation	Unit
1. Environmental performance	C11: Change in raw material consumption	Change in raw material consumption per tonne of product	tonnes/tonne
	C12: Secondary material content	Secondary locally recycled material content (weighted arithmetic mean of values for selected raw materials)	%
	C13: Change in energy consumption	Change in energy consumption per tonne of product	kWh/tonne
	C14: Change in water consumption	Change in water consumption per tonne of product	m3/tonne
	C15: Change in cutting and laser gas consumption	Change in amount of cutting and laser gases per tonne of product	nm3/tonne
	C16: Change in amount of waste	Change in amount of metal waste per tonne of product	tonnes/tonne
	C17: Change in emissions to air	Change in emissions to air per tonne of product	kg/tonne
2. Economic feasibility	C21: Annual costs	Annual costs	EUR/year
	C22: Investment	Investment	EUR
	C23: Change in Economic importance of raw materials	Change in Relative economic importance of resource from the point of view of the industrial company (weighted arithmetic mean of values for selected raw materials)	-
3. Geostrategic supply risk	C31: Change in Geostrategic supply risk	Change in Relative supply risk of resource from the point of view of the company (weighted arithmetic mean of values for selected raw materials)	-

The decision matrix of the normalized criteria values and results of SAW comparison are presented in Table 5.21.

Table 5.21 Normalized criteria values, criteria weights and results of comparison of RE alternatives for metal cutting process

Alt.	**Criteria**											**Results**	
	C11	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C21**	**C22**	**C23**	**C31**	**SAW**	**Rank**
1	0.187	0.122	1	1	0.500	0.748	0.354	0.768	0.500	0.746	0	0.410	3
2	1	0.122	0	0.649	1	1	1	1	0.333	1	0	0.486	2
3	0	1	0.545	0	0	0	0	0.623	1	0.999	1	0.698	1
W.	1/21	1/21	1/21	1/21	1/21	1/21	1/21	1/9	1/9	1/9	1/3		

Equal initial weights were assigned for all three evaluated dimensions (1/3 for each). The weights for criteria were assigned equally within each evaluated dimension (1/21 for each criterion in the environmental dimension, 1/9 for each criterion in the economic dimension, 1/3 for each criterion in the supply risk dimension).

Alternative 3 was ranked as the most preferred. The result complies with an intuitive judgement since the alternative that requires no additional costs for implementation but provides certain benefits, should be implemented in the first place. Alternative 2 was ranked as the second priority. This was because of the higher savings and bigger environmental effect, even if the investment were higher compared to Alternative 1. However, the results are sensible to the assignment of weights. Therefore, sensitivity to the weight of the criteria was performed, and the results were compared (Table 5.22).

Table 5.22 Weights of criteria for sensitivity analysis of RE alternatives

	Criteria										
Weights	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C21**	**C22**	**C23**	**C31**
Initial	1/21	1/21	1/21	1/21	1/21	1/21	1/21	1/9	1/9	1/9	1/3
Var. 1	3/56	3/56	3/56	3/56	3/56	3/56	3/56	1/8	1/8	1/8	1/4
Var. 2	2/35	2/35	2/35	2/35	2/35	2/35	2/35	2/15	2/15	2/15	1/5
Var. 3	9/140	9/140	9/140	9/140	9/140	9/140	9/140	9/60	9/60	9/60	1/10
Var. 4	1/14	1/14	1/14	1/14	1/14	1/14	1/14	1/4	1/4	-	-
Var. 5	-	-	-	-	-	-	-	-	-	1/2	1/2

For Variant 1 the weight assigned to the supply risk was decreased to 1/4, for Variant 2 – decreased to 1/5, for Variant 3 – decreased to 1/10. The rest of the weights in all the variants were assigned equally to the environmental and economic dimensions, and equally to all the criteria within the dimensions. Variant 4 eliminates criticality dimension, while Variant 5 considers only criticality dimension.

Table 5.23 Results of sensitivity analysis of RE alternatives

Results	**SAW**						**Rank**					
Weights (variant)	**Initial**	**1**	**2**	**3**	**4**	**5**	**Initial**	**1**	**2**	**3**	**4**	**5**
Alt. 1	0.410	0.461	0.492	0.554	0.596	0.373	3	3	3	3	2	3
Alt. 2	0.486	0.547	0.584	0.658	0.674	0.500	2	2	2	1	1	2
Alt. 3	0.698	0.661	0.638	0.593	0.516	0.999	1	1	1	2	3	1

The results of sensitivity analysis (Table 5.23) show that the change of weights in Variant 1 and Variant 2 did not have an impact on the ranking of alternatives. However, in Variant 3 the weight of supply risk decreased to 10%, resulting in a change of ranking. Alternative 2 was nominated as the most preferred. If criticality dimension is not considered (Variant 4), then Alternative 2 is nominated as the most preferable. If only criticality dimension is evaluated, then Alternative 3 is nominated as the most preferable.

Discussion of results

The results of the developed decision-support system model application in two manufacturing companies revealed that criticality evaluation contributes to the identification of significant aspects of resource use by providing a more holistic approach for the assessment of resource availability in the particular industrial object. Moreover, the two case studies showed that criticality assessment can be successfully integrated into the common procedures for the cleaner production implementation. Based on the results of sensitivity analysis it can be stated that the priorities of resource efficiency measures implementation differ if environmental and economic criteria are evaluated compared to the evaluation of criticality criteria only. The combination of these criteria provides the base for the informed decision-making in terms of environmental, economic and criticality aspects. Thus, it can be stated that the set key thesis was confirmed.

CONCLUSIONS

1. The analysis of the relevant research in the field of resource criticality assessment and mitigation revealed that the heterogeneity of existing definitions, evaluation methodologies and their results, as well as a lack of focus on the analysis from the entrepreneurial perspective, lead to confusion on how the decision-makers in industry should address the issue of resource criticality. Thus, producing companies miss the opportunity to mitigate the risk related to the supply of resources by implementing relevant strategies.
2. The analysis of relevant research revealed that environmental aspects in the field of criticality assessment and mitigation are addressed from two perspectives. On one hand environmental implications can have an influence on the availability of natural resources, on the other hand resource efficiency improvement is acknowledged as an adequate strategy to mitigate resource criticality. Production companies play a major role in the implementation of resource efficiency improvement measures. However, state of the art decision-making support methods and models for resource efficiency improvement do not integrate criticality assessment and recently proposed concepts encounter major difficulties to provide information about the actual resource availability on the specific production site.
3. The assessment of dependence on imported resources revealed that the Lithuanian economy is dependent on the import of the majority of industrial raw materials, and a considerable part of them are imported from non-EU countries. The assessment of resource use disclosed that during the evaluated year natural gas, crude oil, sulphur, and caustic soda were the most important resources for the Lithuanian economy. The assessment of the efficient use of resources revealed that sulphur and crude oil were also associated with the decrease in resource productivity during the evaluated year. The evaluation of the end-uses of most critical resources revealed that the most vulnerable industry branches involve the production of refined petroleum products, chemical products and manufacturing of various metal products.
4. The developed integrated decision support system model enables industrial companies to:
    a. Identify significant aspects related to the use of natural resources in terms of environmental performance and resource criticality. For this purpose, the methodology for resource criticality evaluation from a perspective of a production company was proposed;
    b. Assess and prioritize identified resource efficiency improvement alternatives in terms of environmental performance, economic feasibility and resource criticality. The created model extends the scope of the cleaner production assessment methodology by supplementing it with the criticality evaluation and thus allows industrial decision-makers to holistically address the issue of resource availability.

5. The developed decision-making support system model was applied in two companies corresponding to identified vulnerable industry branches:
    a. A nitrogen fertilizer production company, where the use of natural gas was identified as the most significant aspect in terms of environmental performance (EIm = $2.46 \cdot 10^6$ $m^3/10^3$ t) and resource criticality (SR = 64.2; EI = 76.68). The alternative that suggests to use waste heat for technological purposes in the surrounding industrial zone and thus enables the consumption of natural gas to be decreased by around 1874 nm^3 per year was identified as the most preferable.
    b. A metal processing company, where metal waste from production processes was identified as the significant environmental aspect (EIm = 0.428t/t). The alternative that suggests to increase the content of locally recycled materials by 90% was identified as the most preferable. In addition to the decreased environmental impact, the SR would decrease by around 99%, the EI–by around 20%;
    c. Sensitivity analysis showed that the final ranking of alternatives would be different in both cases comparing the variant when only criticality criteria are considered and the variant when criticality criteria are eliminated.

6. The developed decision support system model provides a tool for industrial companies to merge the benefits of resource efficiency innovations and criticality mitigation and thus decrease the environmental impact and increase overall competitiveness. The application of the developed model is especially relevant for the companies that operate in the countries or regions that are dependent on the imported resources. Also, it is a beneficial approach to compare and rank the resource efficiency alternatives, especially to prioritize alternatives that would provide similar results in terms of technical, environmental and economic aspects considered in the classic cleaner production assessments. Moreover, a broader perspective of the evaluation of resource use, provides additional motivation for the implementation of industrial ecology measures such as industrial symbiosis.

RECOMMENDATIONS

1. The disrupted supply of key resources can affect the performance of whole economy or region, but it is none the less relevant to the separate companies. Since resource efficiency improvement is acknowledged as one of the key strategies to mitigate resource criticality, the implementation of relevant strategies should be fostered systematically having a top-down as well as bottom-up approach. The concrete actions arise from the companies, but encouragement from policy makers is crucial to accelerate these actions. At the regional and/or national level the implementation of relevant measures could be encouraged by the promotion and financing of sustainable innovations, development of recycling infrastructure, fostering research and development

activities. The key aspect for the targeted policies is continuous monitoring of the risks associated to the supply of imported resources and identification of vulnerable industry branches. For this purpose, the continuous update of relevant statistical data is needed.

2. It can be recommended that efforts to mitigate resource criticality should be focused on the most sensitive industries in the first place.
3. The implementation of resource efficiency measures that meanwhile decrease resource criticality contributes to the mitigation of risks not only from a perspective of an industrial company, but also from a regional and national perspective. Moreover, the investigation of the resource criticality could be introduced as an additional aspect in the selection for funding CP innovations. Proposals that have a positive impact on resource criticality decrease from the national perspective should be evaluated more positively.

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LIST OF SCIENTIFIC PUBLICATIONS ON THE TOPIC OF THE DISSERTATION

Publications in journals included in the Institute of Science Information (ISI) database:

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2. **Malinauskienė, Milda**; Kliopova, Irina; Slavickaitė, Milda; Staniškis, Jurgis Kazimieras. Integrating resource criticality assessment into evaluation of cleaner production possibilities for increasing resource efficiency // Clean technologies and environmental policy. Berlin: Springer. ISSN 1618-954X. 2016, vol. 00, p. [1-12]. [Science Citation Index Expanded (Web of Science); SpringerLINK; Inspec] [IF (E): 1,934 (2014)]
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Annex 1. Combined Nomenclature codes (source: (168))

Material	**CN code**
Sulphur	2503, 2802
Caustic soda	281511, 281512
Calcined soda	283620
Polyethylene	390110, 390120
Polypropylene	390210
Polystyrene and copolymers of styrene	3903
Polymers of vinyl chloride	3904
Cast iron	7201
Aluminium	7601, 7603, 7604, 7605, 7606, 7607, 7608, 7609
Lead	7801, 7804, 78060030, 78060050
Tin	8001, 8003, 80070010, 80070030, 80070050
Zinc	7901, 7903, 7904, 7905, 7907
Copper	740311, 740312, 740313, 740319, 740610, 740620, 740710, 740811, 740819, 740911, 740919, 741011, 741021, 741110, 771210
Iron and steel	7206, 7207, 7208, 7209, 7210, 7211, 7212, 7213, 7214, 7215, 7216, 7217, 7218, 7219, 7220, 7221, 7222, 7223, 7224, 7225, 7226, 7227, 7228, 7229
Ammonium di-hydrophosphate	31054000
Paraffin	27122090
Aluminium hydroxide	28183000
Potassium chloride	310420
Acetic acid	29152100
Superphosphate	310310
Sodium hydroxide	28151200
Melamine	29336100
Phosphoric acid	28092000
Monoethanolamine	29221100
Potash	28364000
Monoethylene glycol	29053100
Ammonium sulphate	31022100
Lauric acid	29159030
Potassium sulphate	31043000

Annex 2. Flows of selected materials within the Lithuanian economy (source: (146)), calculated DMC, Net IMP, IMPD values

Material		2005	2006	2007	2008	2009
Cast iron	Extraction/ production	0	0	0	0	0
	Import	676200	1007800	1729000	1217500	415100
	Export	234500	474800	812900	921900	280000
	DMC	441700	533000	916100	295600	135100
	Net IMP	441700	533000	916100	295600	135100
	IMPD	1	1	1	1	1
Aluminium	Extraction/ production	3497000	3558900	3717800	3897400	1957000
	Import	10495100	12304400	13814800	11500900	7461200
	Export	5764900	4873300	5243600	5596900	3866100
	DMC	8227200	10990000	12289000	9801400	5552100
	Net IMP	4730200	7431100	8571200	5904000	3595100
	IMPD	0.57	0.68	0.70	0.60	0.65
Lead	Extraction/ production	0	0	0	0	0
	Import	207600	229300	512400	360600	298100
	Export	0	8300	33900	140700	73700
	DMC	207600	221000	478500	219900	224400
	Net IMP	207600	221000	478500	219900	224400
	IMPD	1	1	1	1	1
Tin	Extraction/ production	0	0	0	0	0
	Import	36400	33600	16100	13100	6500
	Export	9200	3500	1000	4300	1000
	DMC	27200	30100	15100	8800	5500
	Net IMP	27200	30100	15100	8800	5500
	IMPD	1	1	1	1	1
Zinc	Extraction/ production	200	0	0	0	0
	Import	1102500	1443000	1486600	1635600	675100
	Export	138100	374700	343000	172700	138900
	DMC	964600	1068300	1143600	1462900	536200
	Net IMP	964400	1068300	1143600	1462900	536200
	IMPD	1	1	1	1	1
Copper	Extraction/ production	0	0	0	0	0
	Import	5164500	5171300	4414100	4064300	847100

Material		2005	2006	2007	2008	2009
	Export	181500	270400	162600	152300	424500
	DMC	4983000	4900900	4251500	3912000	422600
	Net IMP	4983000	4900900	4251500	3912000	422600
	IMPD	1	1	1	1	1
Iron and steel	Extraction/ production	59132000	59716600	64296000	50437100	50062100
	Import	518106940	630646600	733728000	657489700	436124400
	Export	95880600	122373600	165587800	184811300	156742200
	DMC	481358340	567989600	632436200	523115500	329444300
	Net IMP	422226340	508273000	568140200	472678400	279382200
	IMPD	0.88	0.89	0.90	0.90	0.85
Sulphur	Extraction/ production	74276700	6135100	42617800	73869700	69722300
	Import	307190600	321264900	317808500	293769000	319370800
	Export	3850800	1300	7200	1516800	14038500
	DMC	377616500	327398700	360419100	366121900	375054600
	Net IMP	303339800	321263600	317801300	292252200	305332300
	IMPD	0.80	0.98	0.88	0.80	0.81
Caustic soda	Extraction/ production	0	0	0	0	0
	Import	14213800	16102800	17180100	16304300	14844200
	Export	1725100	2770200	2846200	3105900	2827800
	DMC	12488700	13332600	14333900	13198400	12016400
	Net IMP	12488700	13332600	14333900	13198400	12016400
	IMPD	1	1	1	1	1
Calcined soda	Extraction/ production	0	0	0	0	0
	Import	12662600	9794600	9506200	13430000	6073500
	Export	692000	408300	527100	3719800	980500
	DMC	11970600	9386300	8979100	9710200	5093000
	Net IMP	11970600	9386300	8979100	9710200	5093000
	IMPD	1	1	1	1	1
Polyethylene	Extraction/ production	2763000	3409300	2233900	2801900	1618100
	Import	36866100	38259700	42223300	44604600	41619900
	Export	16838000	23638700	19327200	24659600	18920600
	DMC	22791100	18030300	25130000	22746900	24317400
	Net IMP	20028100	14621000	22896100	19945000	22699300
	IMPD	0.88	0.81	0.91	0.88	0.93
Polypropylene	Extraction/ production	169600	243200	279000	269900	11000

Material		2005	2006	2007	2008	2009
	Import	9043300	11873400	14234100	23712100	17956700
	Export	8502100	9541800	9597000	14079900	12539000
	DMC	710800	2574800	4916100	9902100	5428700
	Net IMP	541200	2331600	4637100	9632200	5417700
	IMPD	0.76	0.91	0.94	0.97	1
Polystyrene and copolymers of styrene	Extraction/ production	947000	557700	339500	161000	0
	Import	23157700	23746300	32083200	30553800	20717700
	Export	1791300	2403900	9604700	9886900	8677800
	DMC	22313400	21900100	22818000	20827900	12039900
	Net IMP	21366400	21342400	22478500	20666900	12039900
	IMPD	0.96	0.97	0.99	0.99	1
Polymers of vinyl chloride	Extraction/ production	5036500	8481800	10614000	10621000	3067000
	Import	15850300	18583900	20399700	19371300	10618200
	Export	445300	1075000	1164400	1769400	2036100
	DMC	20441500	25990700	29849300	28222900	11649100
	Net IMP	15405000	17508900	19235300	17601900	8582100
	IMPD	0.75	0.67	0.64	0.62	0.74

Annex 3. Import breakdown of selected materials to Lithuania from partner countries, kg/year (source: (141))

Material	Country	2008	2009
Sulphur	Kazakhstan	144589.3	112323.4
	Norway	0	2136.4
	Russian Federation	148708.6	184733.8
	Ukraine	404.1	0
	Total EXTRA-EU27	**293702**	**299193.6**
	Germany	0	0.4
	Italy	1.3	11384.3
	Latvia	39.8	0
	Poland	25.9	82
	Spain	0	8710.5
	Total INTRA-EU27	**67**	**20177.2**
Sulphur	Total	293769	319370.8
Caustic soda	China, People’s Republic of	241.8	172

Material	**Country**	**2008**	**2009**
	Russian Federation	3408.1	3080
	Ukraine	2229.3	808.2
	Total EXTRA-EU27	**5879.2**	**4060.2**
	Austria	0	72
	Belgium	0.4	0
	Czech Republic	0.7	0.6
	Denmark	0	1
	Estonia	1.2	837.3
	Finland	24.5	31
	France	36.4	22.3
	Germany	3.7	19.6
	Hungary	140.9	800.4
	Latvia	171.9	16.6
	Netherlands	0	0
	Poland	10044.1	8782.3
	Romania	0	22
	Slovakia	0	178.9
	Sweden	1.3	0
	Total INTRA-EU27	**10425.1**	**10784**
Caustic soda	Total	16304.3	14844.2
Calcined soda	Russian Federation	7804.8	699.8
	Ukraine	2741.6	708.5
	United States		956.8
	Total EXTRA-EU27	**10546.4**	**2365.1**
	Estonia	1.6	
	Germany	0.3	0.2
	Latvia	1187.7	133.4
	Poland	1694	3574.8
	Total INTRA-EU27	**2883.6**	**3708.4**
Calcined soda	Total	13430	6073.5
Polyethylene	Azerbaijan	2877.5	406
	Belarus	9513.1	8532.4
	Brazil	2521.3	70.1
	China, People’s Republic of	0.3	0
	Iceland	38.2	0
	Korea, Republic of	247.7	7.6
	Norway	77	93.8

Material	**Country**	**2008**	**2009**
	Qatar	690.3	903.7
	Russian Federation	6331.1	2299.1
	Saudi Arabia	0	2.8
	Switzerland	0	15.5
	Thailand	66.2	235
	Ukraine	240.4	18
	United States	972.7	290.7
	Uzbekistan	0	3
	Total EXTRA-EU27	**23611.9**	**12901.5**
	Austria	592	94.5
	Belgium	3958	4777.6
	Czech Republic	17344.5	9441.2
	Denmark	23.4	0.6
	Estonia	137.8	2
	Finland	32.6	555.5
	France	2227.2	2302.8
	Germany	2318.3	4729.1
	Hungary	5128.5	5860.4
	Italy	72.9	136.6
	Latvia	1684.7	2194
	Netherlands	4328.6	4275.4
	Poland	3964.7	4380.5
	Portugal	0.5	0
	Slovakia	1737.6	1901.2
	Sweden	142	240.4
	United Kingdom	911.3	728.1
	Total INTRA-EU27	**44604.6**	**41619.9**
Polyethylene	TOTAL	68216.5	54521.4
Polypropylene	China, People’s Republic of		4
	Israel	127.5	
	Korea, Republic of	17.5	0.2
	Russian Federation	1631.6	2266.9
	Ukraine	506.2	353.6
	United States	822	
	Total EXTRA-EU27	**3104.8**	**2624.7**
	Austria	46.8	38.4
	Belgium	9099	6258.6

Material	**Country**	**2008**	**2009**
	Czech Republic	2595.2	1994.8
	Denmark	3	36
	Estonia	218	35.1
	Finland	176.8	480.2
	France		37.2
	Germany	215.8	678
	Hungary	330.5	118.1
	Italy	323.3	421.3
	Latvia	168.5	504.9
	Netherlands	4014.8	1531.3
	Poland	1050.5	1214.7
	Romania		23.4
	Slovakia	1147.7	1320.7
	Sweden	527	65.7
	United Kingdom	690.4	573.6
	Total INTRA-EU27	**20607.3**	**15332**
Polypropylene	Total	23712.1	17956.7
Polystyrene and copolymers of styrene	Belarus	32	
	China, People’s Republic of	177.4	18.1
	Croatia	1273.8	608.3
	Korea, Republic of	163.8	12.9
	Russian Federation	10088	7586.2
	Switzerland	6.9	
	Taiwan	2	
	Total EXTRA-EU27	**11743.9**	**8225.5**
	Austria	3	48.9
	Belgium	1019.7	517.7
	Czech Republic	600	1304.7
	Denmark	315.6	1
	Estonia	162.1	119.9
	Finland	3952	1704.9
	France	277.6	466.2
	Germany	5221.7	3413.5
	Hungary	1885	291
	Italy	0.2	1.1
	Latvia	4372.3	2976.8
	Netherlands	74.9	50.5

Material	**Country**	**2008**	**2009**
	Poland	310.3	1086.8
	Slovenia		0.3
	Spain	24	
	Sweden	91.2	188
	United Kingdom	500.3	320.9
	Total INTRA-EU27	**18809.9**	**12492.2**
Polystyrene and copolymers of styrene	Total	30553.8	20717.7
Polymers of vinyl chloride	Japan		141.2
	Russian Federation	386.3	68.1
	United States		0.3
	Total EXTRA-EU27	**386.3**	**209.6**
	Austria	5.2	0
	Belgium	121.6	41.9
	Estonia		22.4
	Finland	0	1.7
	France	0.1	0
	Germany	14603.7	6549.9
	Hungary	45.9	
	Ireland	1478	1569.9
	Italy	275.6	165.2
	Latvia	0.3	1.8
	Netherlands	0.3	0
	Poland	2170.7	787.9
	Spain		52.6
	Sweden	46.8	167
	United Kingdom	236.8	1048.3
	Total INTRA-EU27	**18985**	**10408.6**
Polymers of vinyl chloride	Total	19371.3	10618.2
Cast iron	Russian Federation	1160.2	406
	Total EXTRA-EU27	**1160.2**	**406**
	Czech Republic	52.7	
	Estonia		5.5
	Germany	1.6	3.5
	Latvia	3	
	Poland		0.1
	Total INTRA-EU27	**57.3**	**9.1**
Cast iron	Total	1217.5	415.1

Material	**Country**	**2008**	**2009**
Aluminium	Belarus	117.3	150.2
	Canada	9.5	0
	China, People’s Republic of	867.6	463.4
	Israel	0.2	0.1
	Japan	127.4	20.9
	Kazakhstan	30.2	21
	Korea, Republic of	0	8.4
	Norway	6.8	6
	Malaysia	0.3	0
	Russian Federation	143.2	69.6
	Switzerland	4.4	5.3
	Taiwan	1.3	20.5
	Turkey	144.6	207.4
	Ukraine	160.5	13.6
	United States	1.6	0.2
	Total EXTRA-EU27	**1614.9**	**986.6**
	Austria	80.9	11.9
	Belgium	65.6	25.2
	Bulgaria	14.9	61.6
	Czech Republic	520.7	403
	Denmark	482.7	356.7
	Estonia	213.9	92.4
	Finland	410	159.3
	France	37.8	2.5
	Germany	2227.7	1294
	Greece	0	23
	Hungary	18.6	9.6
	Italy	487.9	271.5
	Latvia	373.9	225
	Luxembourg	86	43.3
	Netherlands	266.1	44.7
	Poland	2660.8	1471.6
	Romania	56.1	111
	Slovakia	68.8	19.4
	Slovenia	0.9	0.4
	Spain	111.3	14.9
	Sweden	73.9	37.4

Material	**Country**	**2008**	**2009**
	United Kingdom	7	105.5
	Total INTRA-EU27	**9886**	**6474.6**
Aluminium	Total	11500.9	7461.2
Lead	Belarus	20	0
	Kazakhstan	60	45
	Russian Federation	21.6	0
	Turkey	1	0
	Total EXTRA-EU27	**102.6**	**45**
	Belgium	97.6	190.1
	Denmark	49.1	24
	Estonia	21.5	2.1
	Germany	75.3	24.5
	Italy	1.6	0
	Latvia	0.6	0.1
	Poland	12.3	12.3
	Total INTRA-EU27	**258**	**253.1**
Lead	Total	360.6	298.1
Tin	Belgium	0	0.1
	Denmark	0.3	0
	Germany	8.4	4.9
	Netherlands	0.3	0
	Poland	1.9	1.3
	Sweden	0.7	0.2
	Estonia	0.6	0
	Italy	0.9	0
	Total INTRA-EU27	**13.1**	**6.5**
Tin	Total	13.1	6.5
Zinc	Belarus	0	20
	China, People’s Republic of	11.9	3.7
	Georgia	0	20
	Kazakhstan	489.4	121.6
	Switzerland	0.5	0
	Taiwan	5	0
	Total EXTRA-EU27	**17.4**	**3.7**
	Austria	0.3	5.1
	Czech Republic	16.1	56.9
	Greece	13	0

Material	Country	2008	2009
	Belgium	118.5	96.9
	Denmark	21.9	4.5
	Estonia	707.7	46.2
	Finland	7	0.8
	Germany	16.5	16.8
	Italy	37.8	20.5
	Latvia	27.6	95.8
	Netherlands	1.1	0
	Poland	637.4	307.6
	Sweden	0.1	6.8
	United Kingdom	13.2	1.4
	Romania	0	0.9
	Spain	0	11.2
	Total INTRA-EU27	**1618.2**	**671.4**
Zinc	Total	1635.6	675.1
Copper	China, People’s Republic of	44.2	2.9
	Kazakhstan	19	0
	Israel	31.3	0
	Russian Federation	2.8	429.4
	San Marino	1.3	0
	Thailand	0	4.1
	Ukraine	26.9	40.1
	Total EXTRA-EU27	**125.5**	**476.5**
	Austria	25.1	9
	Belgium	6.9	7.4
	Bulgaria	0	2.5
	Czech Republic	6.1	0
	Denmark	4.6	0.8
	Estonia	8.4	1.8
	Finland	35.8	7.9
	France	1.7	2.8
	Germany	218.2	115.2
	Ireland	0.3	0
	Italy	96.9	9
	Latvia	1096.9	24.6
	Netherlands	5.2	8.2
	Poland	2252.3	157.2

Material	**Country**	**2008**	**2009**
	Spain	36.5	18.3
	Sweden	143.4	0.7
	United Kingdom	0.5	5.2
	Total INTRA-EU27	**3938.8**	**370.6**
Copper	total	4064.3	847.1
Iron and steel	Armenia	0	120.7
	Belarus	70830.4	65564.7
	Brazil	17.1	22.4
	China, People’s Republic of	4616.4	1393.8
	Hong Kong	15.4	0
	India	437.8	168.9
	Kazakhstan	309	127.8
	Korea, Democratic People’s Republic of	2553.1	2577.9
	Korea, Republic of	1500	641.6
	Malaysia	0	18
	Morocco	46.4	0
	Norway	1080.9	1843.5
	Moldova, Republic of	389.2	0
	Russian Federation	95291.3	81188.9
	Serbia	285.5	0
	Switzerland	11.9	15
	Taiwan	2199.5	776.4
	Thailand	64.1	34.2
	Turkey	759.6	2733.8
	Ukraine	96965.1	38782.4
	United States	2366.1	2747.1
	Total EXTRA-EU27	**280101**	**198757.1**
	Austria	478	214.3
	Belgium	5068.2	1028.9
	Czech Republic	6364.4	5702.1
	Denmark	10938.3	20411.3
	Estonia	37688.2	14911.3
	Finland	20749.2	11750.3
	France	3373.3	930.6
	Germany	49556.4	29307.7
	Greece	64.3	0
	Hungary	630.9	528.4

Material	Country	2008	2009
	Italy	4697	3167.8
	Latvia	100241.6	40725
	Luxembourg	3864	5039.1
	Netherlands	1537.1	1468.3
	Poland	77144.2	66679.5
	Portugal	5.4	24.3
	Romania	411.5	1644.8
	Slovakia	9084.6	3579.2
	Slovenia	102.2	190.7
	Spain	2328.6	1294.7
	Sweden	20373.6	14014.6
	United Kingdom	31556.2	23157.4
	Total INTRA-EU27	**377388.7**	**237367.3**
Iron and steel	total	657489.7	436124.4

Annex 4. WGI values (average, scaled) (source: (World Bank, 2015))

Country		2008	2009	2010	2011	2012	2013	2014
AFGHANISTAN	AFG	8.5	8.6	8.5	8.5	8.2	8.2	8.0
ALBANIA	ALB	5.4	5.3	5.3	5.4	5.5	5.5	5.0
ALGERIA	DZA	6.6	6.7	6.7	6.8	6.8	6.6	6.7
AMERICAN SAMOA	ASM	3.5	3.5	3.5	3.5	3.5	3.5	#N/A
ANDORRA	ADO	2.3	2.3	2.3	2.2	2.2	2.2	2.4
ANGOLA	AGO	7.1	7.1	7.0	7.1	7.0	7.1	7.0
ANGUILLA	AIA	2.3	2.5	2.3	2.3	2.3	2.3	#N/A
ANTIGUA AND BARBUDA	ATG	3.4	3.4	3.4	3.4	3.3	3.4	4.2
ARGENTINA	ARG	5.6	5.8	5.6	5.5	5.7	5.7	5.8
ARMENIA	ARM	5.6	5.5	5.6	5.5	5.4	5.3	5.5
ARUBA	ABW	2.8	2.4	2.5	2.5	2.5	2.4	2.8
AUSTRALIA	AUS	1.8	1.8	1.8	1.7	1.8	1.9	1.8
AUSTRIA	AUT	1.7	1.9	1.9	2.0	2.0	1.9	1.9
AZERBAIJAN	AZE	6.5	6.5	6.6	6.6	6.7	6.4	6.4
BAHAMAS, THE	BHS	2.8	3.1	3.1	3.2	3.2	3.3	3.4
BAHRAIN	BHR	4.7	4.7	4.8	5.1	5.2	5.2	5.1
BANGLADESH	BGD	6.8	6.8	6.7	6.7	6.8	6.8	6.6
BARBADOS	BRB	2.6	2.8	2.8	2.6	2.7	2.7	2.9
BELARUS	BLR	6.7	6.7	6.9	7.0	6.7	6.7	6.3

Country		**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
BELGIUM	BEL	2.5	2.4	2.4	2.3	2.3	2.3	2.4
BELIZE	BLZ	5.3	5.2	5.2	5.3	5.1	5.1	5.5
BENIN	BEN	5.5	5.5	5.6	5.6	5.7	5.7	5.7
BERMUDA	BMU	2.9	2.9	2.7	2.7	2.7	2.7	#N/A
BHUTAN	BTN	4.8	4.8	4.8	4.8	4.7	4.7	4.4
BOLIVIA	BOL	6.2	6.3	6.1	6.1	6.2	6.1	6.2
BOSNIA AND HERZEGOVINA	BIH	5.7	5.7	5.8	5.8	5.6	5.5	5.4
BOTSWANA	BWA	3.6	3.7	3.7	3.6	3.6	3.6	3.7
BRAZIL	BRA	5.1	4.9	4.8	4.8	4.9	5.1	5.1
BRUNEI DARUSSALAM	BRN	4.0	3.5	3.6	3.6	3.7	3.7	3.7
BULGARIA	BGR	4.6	4.5	4.6	4.7	4.7	4.8	4.8
BURKINA FASO	BFA	5.5	5.5	5.6	5.8	5.9	6.0	6.1
BURUNDI	BDI	7.2	7.1	7.3	7.4	7.5	7.2	7.0
CAMBODIA	KHM	6.7	6.7	6.7	6.6	6.4	6.5	6.4
CAMEROON	CMR	6.8	6.7	6.8	6.8	6.9	6.9	6.9
CANADA	CAN	1.8	1.7	1.8	1.8	1.8	1.8	1.7
CAPE VERDE	CPV	4.0	4.0	4.0	3.9	3.9	4.1	4.0
CAYMAN ISLANDS	CYM	2.9	3.0	3.0	2.8	3.0	3.0	3.3
CENTRAL AFRICAN REPUBLIC	CAF	7.6	7.6	7.6	7.5	7.7	8.1	8.4
CHAD	TCD	8.1	7.8	7.7	7.6	7.6	7.5	7.6
CHILE	CHL	2.8	2.7	2.6	2.6	2.6	2.6	2.6
CHINA	CHN	6.0	6.0	6.1	6.1	6.1	6.1	5.9
COLOMBIA	COL	5.8	5.9	5.7	5.5	5.6	5.6	5.5
COMOROS	COM	7.2	7.1	7.0	6.9	6.9	6.7	6.6
CONGO, DEM. REP.	ZAR	8.1	8.2	8.3	8.3	8.3	8.1	8.1
CONGO, REP.	COG	7.2	7.1	7.1	7.1	7.2	7.1	7.0
COOK ISLANDS	COK	#N/A	5.8	5.7	#N/A	#N/A	#N/A	#N/A
COSTA RICA	CRI	4.0	3.8	3.8	3.9	3.7	3.7	3.7
CÔTE D’IVOIRE	CIV	7.6	7.3	7.4	7.3	7.0	6.7	6.3
CROATIA	HRV	4.3	4.3	4.2	4.2	4.2	4.1	4.1
CUBA	CUB	6.2	6.2	6.2	6.2	6.2	6.2	5.9
CYPRUS	CYP	2.6	2.9	2.8	2.9	2.9	3.0	3.0
CZECH REPUBLIC	CZE	3.2	3.2	3.2	3.2	3.3	3.3	3.2
DENMARK	DNK	1.3	1.3	1.4	1.3	1.5	1.4	1.5
DJIBOUTI	DJI	6.1	6.0	6.2	6.3	6.3	6.4	6.7
DOMINICA	DMA	3.5	3.6	3.5	3.5	3.6	3.5	3.8
DOMINICAN REPUBLIC	DOM	5.7	5.7	5.8	5.8	5.6	5.6	5.4

Country		2008	2009	2010	2011	2012	2013	2014
ECUADOR	ECU	6.7	6.7	6.6	6.6	6.4	6.2	6.2
EGYPT, ARAB REP.	EGY	6.0	5.9	6.1	6.5	6.5	6.8	6.8
EL SALVADOR	SLV	5.3	5.2	5.2	5.2	5.3	5.3	5.2
EQUATORIAL GUINEA	GNQ	7.5	7.4	7.5	7.5	7.5	7.6	7.8
ERITREA	ERI	7.6	7.7	7.8	7.8	7.9	8.0	8.0
ESTONIA	EST	2.9	3.0	2.9	2.9	2.9	2.8	2.6
ETHIOPIA	ETH	6.8	6.9	6.9	6.9	6.9	6.8	6.6
FIJI	FJI	6.0	6.5	6.4	6.2	6.2	6.2	5.3
FINLAND	FIN	1.4	1.2	1.3	1.3	1.3	1.3	1.3
FRANCE	FRA	2.5	2.6	2.5	2.6	2.6	2.7	2.7
FRENCH GUIANA	GUF	3.8	3.0	3.0	3.0	3.0	3.0	2.8
GABON	GAB	6.2	6.2	6.1	6.0	5.9	6.0	6.1
GAMBIA, THE	GMB	6.0	5.9	6.0	6.0	6.1	6.2	6.3
GEORGIA	GEO	5.3	5.3	5.1	4.9	4.7	4.6	4.2
GERMANY	DEU	2.1	2.1	2.1	2.1	2.1	2.1	1.8
GHANA	GHA	4.9	4.8	4.8	4.8	4.9	4.9	5.0
GREECE	GRC	3.8	4.1	4.2	4.3	4.5	4.4	4.5
GREENLAND	GRL	#N/A	2.4	2.3	2.2	2.2	2.2	2.2
GRENADA	GRD	4.2	4.3	4.2	4.3	4.2	4.2	4.4
GUAM	GUM	3.6	3.6	3.7	3.6	3.6	3.6	#N/A
GUATEMALA	GTM	6.1	6.2	6.2	6.2	6.2	6.2	6.2
GUINEA	GIN	7.9	7.7	7.5	7.4	7.4	7.3	7.2
GUINEA-BISSAU	GNB	7.1	7.0	7.0	7.1	7.5	7.7	7.5
GUYANA	GUY	5.8	5.8	5.7	5.8	5.8	5.8	5.7
HAITI	HTI	7.2	7.2	7.3	7.4	7.3	7.1	7.3
HONDURAS	HND	6.2	6.2	6.2	6.1	6.3	6.4	6.3
HONG KONG SAR, CHINA	HKG	2.1	2.2	2.2	2.2	2.1	2.2	2.0
HUNGARY	HUN	3.4	3.6	3.6	3.6	3.7	3.7	3.9
ICELAND	ISL	1.6	2.0	2.1	2.0	2.1	2.0	2.0
INDIA	IND	5.4	5.5	5.6	5.6	5.7	5.7	5.6
INDONESIA	IDN	6.0	5.9	6.0	5.9	5.8	5.7	5.4
IRAN, ISLAMIC REP.	IRN	7.1	7.4	7.4	7.3	7.2	7.2	7.0
IRAQ	IRQ	8.2	7.9	7.8	7.7	7.7	7.7	7.9
IRELAND	IRL	1.8	2.0	2.1	2.1	2.2	2.2	1.9
ISRAEL	ISR	3.8	4.0	3.9	3.7	3.8	3.8	3.7
ITALY	ITA	3.8	3.9	4.0	4.0	4.0	4.0	4.1
JAMAICA	JAM	5.0	5.1	5.1	5.0	5.0	5.0	4.9

Country		**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
JAPAN	JPN	2.7	2.6	2.6	2.5	2.5	2.4	2.2
JERSEY, CHANNEL ISLANDS	JEY	#N/A	#N/A	#N/A	2.3	2.3	2.3	2.3
JORDAN	JOR	4.9	5.0	5.2	5.2	5.2	5.3	5.2
KAZAKHSTAN	KAZ	6.0	5.8	6.0	6.2	6.3	6.4	5.9
KENYA	KEN	6.5	6.5	6.3	6.4	6.5	6.3	6.2
KIRIBATI	KIR	4.8	5.0	5.0	4.9	5.0	5.0	4.9
KOREA, DEM. REP.	PRK	8.0	8.0	8.2	8.2	8.1	8.3	8.3
KOREA, REP.	KOR	3.7	3.5	3.5	3.4	3.5	3.5	3.5
KOSOVO	KSV	5.3	5.4	6.1	6.0	6.0	6.0	5.7
KUWAIT	KWT	4.6	4.6	4.6	4.8	5.1	5.1	5.3
KYRGYZ REPUBLIC	KGZ	6.8	6.8	6.8	6.7	6.6	6.6	6.5
LAO PDR	LAO	6.9	7.0	7.0	6.9	6.7	6.6	6.3
LATVIA	LVA	3.8	3.8	3.7	3.8	3.7	3.6	3.4
LEBANON	LBN	6.5	6.3	6.2	6.3	6.4	6.4	6.5
LESOTHO	LSO	5.5	5.3	5.2	5.3	5.3	5.1	5.4
LIBERIA	LBR	7.0	6.8	6.5	6.6	6.5	6.6	6.6
LIBYA	LBY	6.6	6.8	7.1	7.7	7.7	8.0	8.5
LIECHTENSTEIN	LIE	2.1	1.8	1.7	1.7	1.8	1.8	1.7
LITHUANIA	LTU	3.7	3.7	3.6	3.6	3.4	3.3	3.2
LUXEMBOURG	LUX	1.6	1.6	1.6	1.5	1.6	1.6	1.6
MACAO SAR, CHINA	MAC	3.8	3.5	3.3	3.3	3.7	3.6	3.1
MACEDONIA, FYR	MKD	5.2	5.1	5.2	5.2	5.1	5.1	4.7
MADAGASCAR	MDG	5.8	6.3	6.5	6.4	6.5	6.6	6.5
MALAWI	MWI	5.6	5.5	5.6	5.7	5.7	5.8	5.8
MALAYSIA	MYS	4.5	4.6	4.3	4.4	4.3	4.2	4.0
MALDIVES	MDV	5.7	5.7	5.6	5.7	5.7	5.7	5.3
MALI	MLI	5.5	5.7	5.8	5.9	6.8	6.6	6.7
MALTA	MLT	2.5	2.6	2.6	2.7	2.7	2.7	2.8
MARSHALL ISLANDS	MHL	5.0	5.1	5.2	5.1	5.2	5.1	#N/A
MARTINIQUE	MTQ	3.5	3.5	3.5	3.5	3.5	3.5	#N/A
MAURITANIA	MRT	6.7	6.6	6.8	6.7	6.7	6.8	6.7
MAURITIUS	MUS	3.4	3.4	3.5	3.4	3.3	3.4	3.3
MEXICO	MEX	5.4	5.3	5.4	5.3	5.3	5.3	5.5
MICRONESIA, FED. STS.	FSM	4.6	4.7	4.9	4.9	4.8	4.8	4.6
MOLDOVA	MDA	5.8	5.9	5.8	5.6	5.6	5.6	5.5
MONACO	MCO	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
MONGOLIA	MNG	5.4	5.4	5.4	5.4	5.4	5.4	5.1

Country		2008	2009	2010	2011	2012	2013	2014
MONTENEGRO	MNE	4.8	4.7	4.8	4.8	4.7	4.8	4.7
MOROCCO	MAR	5.8	5.6	5.5	5.6	5.6	5.7	5.5
MOZAMBIQUE	MOZ	5.6	5.5	5.5	5.7	5.7	6.0	6.1
MYANMAR	MMR	8.3	8.5	8.5	8.3	7.8	7.7	7.4
NAMIBIA	NAM	4.0	4.3	4.4	4.4	4.3	4.3	4.4
NAURU	NRU	4.7	4.6	4.5	4.7	4.6	4.9	#N/A
NEPAL	NPL	6.7	6.8	6.8	6.7	6.8	6.6	6.3
NETHERLANDS	NLD	1.7	1.7	1.7	1.6	1.6	1.6	1.6
NETHERLANDS ANTILLES (FORMER)	ANT	3.2	3.5	3.4	3.3	3.4	3.5	#N/A
NEW CALEDONIA	NCL	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
NEW ZEALAND	NZL	1.6	1.5	1.4	1.3	1.4	1.4	1.3
NICARAGUA	NIC	6.2	6.2	6.3	6.2	6.2	6.1	6.1
NIGER	NER	6.3	6.4	6.4	6.2	6.4	6.4	6.4
NIGERIA	NGA	7.1	7.3	7.3	7.3	7.3	7.3	7.4
NIUE	NIU	#N/A	5.8	5.7	#N/A	#N/A	#N/A	#N/A
NORWAY	NOR	1.7	1.7	1.6	1.5	1.4	1.4	1.5
OMAN	OMN	4.3	4.4	4.5	4.8	4.7	4.7	4.5
PAKISTAN	PAK	7.2	7.2	7.2	7.4	7.3	7.3	7.1
PALAU	PLW	4.5	4.4	4.6	4.6	4.6	4.7	#N/A
PANAMA	PAN	4.7	4.8	4.8	4.8	4.9	4.9	4.7
PAPUA NEW GUINEA	PNG	6.4	6.5	6.4	6.3	6.3	6.3	6.0
PARAGUAY	PRY	6.4	6.4	6.3	6.2	6.3	6.3	6.1
PERU	PER	5.6	5.7	5.5	5.4	5.5	5.5	5.4
PHILIPPINES	PHL	6.1	6.1	6.1	5.9	5.8	5.6	5.4
POLAND	POL	3.7	3.5	3.4	3.4	3.3	3.3	3.2
PORTUGAL	PRT	2.9	3.0	3.1	3.2	3.1	3.1	3.1
PUERTO RICO	PRI	3.6	3.8	3.8	3.7	3.7	3.9	3.6
QATAR	QAT	3.9	3.4	3.6	3.9	3.5	3.5	3.8
REUNION	REU	3.1	3.2	3.2	3.2	3.2	3.2	#N/A
ROMANIA	ROM	4.7	4.7	4.7	4.8	4.9	4.7	4.6
RUSSIAN FEDERATION	RUS	6.4	6.5	6.5	6.5	6.5	6.4	6.3
RWANDA	RWA	5.9	5.9	5.5	5.5	5.4	5.2	5.0
SAMOA	WSM	4.1	4.3	4.4	4.4	4.3	4.2	4.0
SAN MARINO	SMR	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
SÃO TOMÉ AND PRINCIPE	STP	5.7	5.8	5.9	5.8	5.9	5.8	5.7
SAUDI ARABIA	SAU	5.6	5.7	5.5	5.9	5.6	5.6	5.5
SENEGAL	SEN	5.6	5.7	5.9	5.8	5.5	5.4	5.2

Country		**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
SERBIA	SRB	5.5	5.4	5.3	5.2	5.3	5.2	4.9
SEYCHELLES	SYC	4.8	4.8	4.7	4.6	4.6	4.6	4.7
SIERRA LEONE	SLE	6.5	6.5	6.4	6.3	6.5	6.4	6.5
SINGAPORE	SGP	1.9	2.1	2.0	2.0	1.8	1.9	1.8
SLOVAK REPUBLIC	SVK	3.4	3.5	3.5	3.5	3.5	3.6	3.5
SLOVENIA	SVN	3.0	3.0	3.2	3.1	3.2	3.3	3.3
SOLOMON ISLANDS	SLB	6.1	6.0	5.9	5.8	5.9	5.9	5.8
SOMALIA	SOM	10.0	9.8	9.7	9.6	9.5	9.5	9.4
SOUTH AFRICA	ZAF	4.4	4.5	4.5	4.5	4.6	4.6	4.6
SOUTH SUDAN	SSD	#N/A	#N/A	#N/A	8.0	7.8	8.1	8.7
SPAIN	ESP	3.3	3.4	3.3	3.2	3.3	3.4	3.4
SRI LANKA	LKA	6.0	5.9	5.8	5.6	5.7	5.7	5.5
ST. KITTS AND NEVIS	KNA	3.3	3.2	3.3	3.3	3.3	3.3	4.3
ST. LUCIA	LCA	3.3	3.2	3.2	3.2	3.5	3.2	3.9
ST. VINCENT AND THE GRENADINES	VCT	3.3	3.3	3.3	3.3	3.3	3.3	3.8
SUDAN	SDN	8.2	8.1	8.2	8.2	8.2	8.2	8.2
SURINAME	SUR	5.1	5.2	5.3	5.2	5.2	5.1	5.3
SWAZILAND	SWZ	6.2	6.1	6.0	6.3	6.2	6.1	6.1
SWEDEN	SWE	1.5	1.5	1.5	1.4	1.4	1.4	1.5
SWITZERLAND	CHE	1.5	1.6	1.6	1.6	1.5	1.5	1.3
SYRIAN ARAB REPUBLIC	SYR	6.8	6.7	6.8	7.3	8.2	8.4	8.5
TAIWAN, CHINA	TWN	3.4	3.3	3.1	3.0	3.1	3.1	2.9
TAJIKISTAN	TJK	7.2	7.3	7.2	7.2	7.3	7.4	6.9
TANZANIA	TZA	5.7	5.7	5.7	5.8	5.9	5.9	6.0
THAILAND	THA	5.6	5.6	5.7	5.5	5.5	5.6	5.6
TIMOR-LESTE	TMP	6.7	6.7	6.7	6.6	6.5	6.6	6.3
TOGO	TGO	6.8	6.8	6.8	6.8	6.8	6.9	6.6
TONGA	TON	5.5	5.5	5.0	5.0	4.8	4.8	4.8
TRINIDAD AND TOBAGO	TTO	4.8	4.7	4.8	4.7	4.8	4.8	4.8
TUNISIA	TUN	5.3	5.3	5.4	5.4	5.5	5.6	5.5
TURKEY	TUR	5.1	5.1	5.1	5.1	5.1	5.2	5.2
TURKMENISTAN	TKM	7.6	7.7	7.8	7.8	7.7	7.7	7.5
TUVALU	TUV	4.6	4.5	4.5	5.0	4.9	4.9	4.7
UGANDA	UGA	6.1	6.2	6.2	6.1	6.2	6.2	6.2
UKRAINE	UKR	5.9	6.1	6.1	6.1	6.1	6.4	6.6
UNITED ARAB EMIRATES	ARE	4.0	4.0	4.2	4.0	3.9	3.8	3.6
UNITED KINGDOM	GBR	2.2	2.4	2.2	2.3	2.3	2.2	2.1

Country		2008	2009	2010	2011	2012	2013	2014
UNITED STATES	USA	2.4	2.6	2.5	2.5	2.5	2.6	2.6
URUGUAY	URY	3.5	3.4	3.4	3.4	3.5	3.5	3.3
UZBEKISTAN	UZB	7.5	7.6	7.6	7.6	7.5	7.5	7.2
VANUATU	VUT	4.5	4.5	4.5	4.5	4.5	4.5	4.6
VENEZUELA, RB	VEN	7.4	7.5	7.6	7.5	7.5	7.6	7.7
VIETNAM	VNM	6.1	6.0	6.1	6.1	6.1	6.0	5.9
VIRGIN ISLANDS (U.S.)	VIR	3.3	3.6	3.4	3.2	3.3	3.2	#N/A
WEST BANK AND GAZA	WBG	7.4	6.5	6.1	6.5	6.6	6.4	6.4
YEMEN, REP.	YEM	7.2	7.5	7.5	7.7	7.8	7.7	7.9
ZAMBIA	ZMB	5.6	5.7	5.7	5.6	5.4	5.5	5.5
ZIMBABWE	ZWE	8.1	8.2	8.1	8.0	7.7	7.6	7.6

Annex 5. End-uses of selected materials in 2008-2009 (source: (146))

Material	Industry branch	Share, %	
		2008	2009
Cast iron			
	Other	2.25	2.60
	Manufacturing:		
	Manufacture of food products, beverages and tobacco products	1.01	0,00
	Manufacture of textiles	0.01	0.00
	Manufacture of coke and refined petroleum products	6.41	0.00
	Manufacture of other non-metallic mineral products	0.70	0.46
	Manufacture of basic metals	41.50	21.87
	Manufacture of basic metals and fabricated metal products, except machinery and equipment	6.00	1.42
	Manufacture of machinery and equipment	0.83	1.61
	Manufacture of machinery and equipment n.e.c.	3.04	2.62
	Manufacture of furniture (and other)	0.99	0.01
	Repair and installation of machinery and equipment	0.11	0.43
	Electricity, gas, steam and air conditioning	0.36	1.80
	Water supply; sewerage, waste management and remediation activities	32.74	59.98
	Other industrial activities	1.69	2.66
	Construction	2.02	4.49
Aluminium			
	Other	32.46	20.11

Material	Industry branch	Share, %	
		2008	2009
	Manufacturing:		
	Manufacture of food products, beverages and tobacco products	1.23	1.84
	Manufacture of textiles	1.37	0.47
	Manufacture of wood and of products of wood and cork, except furniture	2.00	2.42
	Manufacture of pulp, paper and paper products	1.21	1.11
	Manufacture of coke and refined petroleum products	0.00	0.01
	Manufacture of rubber and plastic products	2.22	1.24
	Manufacture of other non-metallic mineral products	1.22	2.16
	Manufacture of basic metals	0.17	0.37
	Manufacture of basic metals and fabricated metal products, except machinery and equipment	35.53	37.97
	Manufacture of computer, electronic and optical products	0.40	0.29
	Manufacture of electrical equipment	2.36	1.13
	Manufacture of machinery and equipment	3.23	3.34
	Manufacture of motor vehicles, trailers and semitrailers	3.49	2.31
	Manufacture of machinery and equipment n.e.c.	0.03	0.02
	Manufacture of furniture (and other)	7.60	14.87
	Other manufacturing	0.24	0.69
	Repair and installation of machinery and equipment	0.59	1.90
	Electricity, gas, steam and air conditioning	0.02	0.03
	Water supply; sewerage, waste management and remediation activities	0.01	0.01
	Other industrial activities	0.27	0.55
	Construction	4.34	7.20
Lead			
	Other	26.00	41.20
	Manufacturing:		
	Manufacture of food products, beverages and tobacco products	0.27	0.33
	Manufacture of textiles	26.97	31.96
	Manufacture of coke and refined petroleum products	0.90	0.46
	Manufacture of basic metals	0.04	0.00
	Manufacture of basic metals and fabricated metal products, except machinery and equipment	42.79	22.13
	Manufacture of computer, electronic and optical products	0.13	0.13
	Manufacture of machinery and equipment n.e.c.	0.04	3.34
	Manufacture of furniture (and other)	0.00	0.00

Material	Industry branch	Share, %	
		2008	2009
	Other manufacturing	0.67	0.33
	Repair and installation of machinery and equipment	0.04	0.00
	Electricity, gas, steam and air conditioning	0.85	0.00
	Water supply; sewerage, waste management and remediation activities	0.09	0.13
	Other industrial activities	0.00	0.00
	Construction	1.17	0.00
Tin			
	Other	84.40	80.30
	Manufacturing:		
	Manufacture of basic metals	1.11	0.00
	Manufacture of computer, electronic and optical products	1.11	5.26
	Manufacture of electrical equipment	0.00	1.32
	Manufacture of machinery and equipment	3.33	3.95
	Repair and installation of machinery and equipment	8.89	7.89
	Electricity, gas, steam and air conditioning	0.00	1.32
	Other industrial activities	1.11	0.00
Zinc			
	Other	29.10	61.70
	Manufacturing:		
	Manufacture of textiles	0.09	0.02
	Manufacture of wood and of products of wood and cork, except furniture	0.00	0.03
	Manufacture of coke and refined petroleum products	0.06	0.06
	Manufacture of other non-metallic mineral products	0.04	0.02
	Manufacture of basic metals	0.00	0.17
	Manufacture of basic metals and fabricated metal products, except machinery and equipment	24.64	3.39
	Manufacture of electrical equipment	40.19	28.39
	Manufacture of machinery and equipment	1.45	0.45
	Manufacture of machinery and equipment n.e.c.	3.02	4.93
	Manufacture of furniture (and other)	0.17	0.00
	Other manufacturing	0.08	0.06
	Repair and installation of machinery and equipment	0.06	0.30
	Electricity, gas, steam and air conditioning	0.08	0.03
	Other industrial activities	0.01	0.02

Material	Industry branch	Share, %	
		2008	2009
	Construction	1.00	0.47
Copper			
	Other	48.34	62.36
	Mining and quarrying	0.05	0.02
	Manufacturing:		
	Manufacture of food products, beverages and tobacco products	1.40	1.30
	Manufacture of wood and of products of wood and cork, except furniture	0.01	0.01
	Manufacture of pulp, paper and paper products	0.03	0.04
	Manufacture of coke and refined petroleum products	0.07	0.06
	Manufacture of rubber and plastic products	0.01	0.01
	Manufacture of other non-metallic mineral products	0.08	0.04
	Manufacture of basic metals	0.04	0.02
	Manufacture of basic metals and fabricated metal products, except machinery and equipment	9.58	10.68
	Manufacture of computer, electronic and optical products	0.48	0.75
	Manufacture of electrical equipment	36.54	18.67
	Manufacture of machinery and equipment	0.86	0.94
	Manufacture of motor vehicles, trailers and semitrailers	0.01	0.00
	Manufacture of machinery and equipment n.e.c.	0.19	0.10
	Manufacture of furniture (and other)	0.17	0.23
	Other manufacturing	0.10	0.19
	Repair and installation of machinery and equipment	0.64	1.19
	Electricity, gas, steam and air conditioning	0.11	1.95
	Water supply; sewerage, waste management and remediation activities	0.01	0.03
	Other industrial activities	0.06	0.03
	Construction	1.17	1.38
Iron and steel			
	Forestry and logging	0.02	0.03
	Mining and quarrying	0.07	0.07
	Manufacturing		
	Manufacture of food products, beverages and tobacco products	1.03	0.70
	Manufacture of textiles	0.02	0.01
	Manufacture of wood and of products of wood and cork, except furniture	0.15	0.21
	Manufacture of pulp, paper and paper products	0.04	0.08

Material	Industry branch	Share, %	
		2008	2009
	Manufacture of coke and refined petroleum products	0.46	0.21
	Manufacture of rubber and plastic products	0.80	0.67
	Manufacture of other non-metallic mineral products	5.60	3.03
	Manufacture of basic metals	14.46	21.96
	Manufacture of basic metals and fabricated metal products, except machinery and equipment	26.33	24.07
	Manufacture of computer, electronic and optical products	0.21	0.31
	Manufacture of electrical equipment	2.25	1.67
	Manufacture of machinery and equipment	4.13	4.93
	Manufacture of motor vehicles, trailers and semitrailers	1.54	1.14
	Manufacture of machinery and equipment n.e.c.	11.87	13.02
	Manufacture of furniture (and other)	2.32	2.22
	Other manufacturing	0.04	0.01
	Repair and installation of machinery and equipment	1.36	1.49
	Electricity, gas, steam and air conditioning	0.15	0.39
	Water supply; sewerage, waste management and remediation activities	1.37	3.07
	Other industrial activities	0.15	0.21
	Construction	17.78	10.89
	Other	6.74	9.60
Sulphur			
	Manufacturing:		
	Manufacture of food products, beverages and tobacco products	0.02	0.02
	Manufacture of coke and refined petroleum products	99.98	99.98
Caustic soda		0.00	0.00
	Mining and quarrying	0.00	0.02
	Manufacturing:	0.00	0.00
	Manufacture of food products, beverages and tobacco products	46.29	45.39
	Manufacture of textiles	2.13	1.73
	Manufacture of pulp, paper and paper products	0.41	0.29
	Manufacture of coke and refined petroleum products	41.86	44.76
	Manufacture of other non-metallic mineral products	2.72	2.08
	Manufacture of basic metals and fabricated metal products, except machinery and equipment	0.53	0.52
	Manufacture of computer, electronic and optical products	0.42	0.16

Material	Industry branch	Share, %	
		2008	2009
	Manufacture of electrical equipment	0.05	0.04
	Manufacture of machinery and equipment n.e.c.	0.05	0.15
	Electricity, gas, steam and air conditioning	4.50	3.91
	Other industrial activities	0.80	0.44
	Construction	0.01	0.04
Calcined soda			
	Mining and quarrying	0.00	0.01
	Manufacturing		
	Manufacture of food products, beverages and tobacco products	4.15	5.98
	Manufacture of textiles	2.12	2.05
	Manufacture of leather and related products	0.38	0.80
	Manufacture of coke and refined petroleum products	1.11	1.39
	Manufacture of other non-metallic mineral products	88.63	84.26
	Manufacture of basic metals	0.01	0.01
	Manufacture of basic metals and fabricated metal products, except machinery and equipment	0.07	0.04
	Manufacture of computer, electronic and optical products	0.01	0.00
	Manufacture of machinery and equipment n.e.c.	0.01	0.00
	Electricity, gas, steam and air conditioning	0.01	0.05
	Other industrial activities	1.49	1.15
	Construction	0.01	0.00
Polyethylene			
	Manufacturing:		
	Manufacture of food products, beverages and tobacco products	0.92	0.78
	Manufacture of textiles	0.11	0.78
	Manufacture of coke and refined petroleum products	0.02	0.02
	Manufacture of rubber and plastic products	93.98	90.00
	Manufacture of other non-metallic mineral products	0.01	0.00
	Manufacture of computer, electronic and optical products	0.01	0.01
	Manufacture of electrical equipment	0.12	0.12
	Manufacture of machinery and equipment n.e.c.	0.12	0.08
	Other manufacturing	0.03	0.02
	Water supply; sewerage, waste management and remediation activities	1.99	0.59
	Other industrial activities	0.01	0.00

Material	Industry branch	Share, %	
		2008	2009
	Construction	0.00	0.00
Polypropylene			
	Manufacturing:		
	Manufacture of textiles	9.29	3.11
	Manufacture of coke and refined petroleum products	15.53	14.93
	Manufacture of rubber and plastic products	65.17	73.87
	Manufacture of basic metals and fabricated metal products, except machinery and equipment	0.03	0.03
	Manufacture of computer, electronic and optical products	1.53	0.84
	Manufacture of electrical equipment	0.12	0.15
	Manufacture of machinery and equipment n.e.c.	3.58	4.27
	Other manufacturing	4.41	3.82
	Other industrial activities	0.02	0.04
Polystyrene and copolymers of styrene			
	Activities of households	0.00	13.29
	Manufacturing		
	Manufacture of coke and refined petroleum products	1.04	1.40
	Manufacture of rubber and plastic products	76.12	72.56
	Manufacture of computer, electronic and optical products	3.87	1.61
	Manufacture of electrical equipment	12.06	5.47
	Manufacture of machinery and equipment n.e.c.	0.98	1.33
	Other manufacturing	5.54	4.09
	Repair and installation of machinery and equipment	0.01	0.00
	Other industrial activities	0.02	0.02
	Construction	0.00	0.23
Polymers of vinyl chloride			
	Manufacturing:		
	Manufacture of textiles	0.00	0.01
	Manufacture of leather and related products	1.82	3.65
	Manufacture of coke and refined petroleum products	57.66	0.01
	Manufacture of rubber and plastic products	30.07	71.86
	Manufacture of basic metals and fabricated metal products, except machinery and equipment	0.86	2.22
	Manufacture of computer, electronic and optical products	0.00	0.01

Material	**Industry branch**	**Share, %**	
		2008	**2009**
	Manufacture of electrical equipment	3.59	1.97
	Other manufacturing	5.99	15.53
Natural gas			
	Manufacture of refined petroleum products, chemicals, and chemical products	100.00	100.00
Crude oil			
	Manufacture of refined petroleum, chemicals and chemical products	100.00	100.00

Annex 6. Excerpt from the database

		End-use, t		**Share of total consumption, A_{is}**		**Value added, Q_s, mln. EUR**		**EI**	
		2008	2009	2008	2009	2008	2009	2008	2009
Aluminium	Total	14168700	8592700	1.000	1.000	32461.7	26620.1	0.013	0.012
	Other (G 45; T)	4599702	1727791	0.325	0.201	306.8	250.3		
	Manufacturing:	5655400	3845600			5119.8	4019.2		
	Manufacture of food products, beverages and tobacco products	174700	157800	0.012	0.018	993.1	1074.9		
	Manufacture of textiles	194600	40300	0.014	0.005	393.4	307.0		
	Manufacture of wood and of products of wood and cork, except furniture	282700	208300	0.020	0.024	344.6	271.5		
	Manufacture of pulp, paper and paper products	171400	95000	0.012	0.011	79.6	70.6		
	Manufacture of coke and refined petroleum products	300	1100	0.000	0.000	602.2	375.8		
	Manufacture of rubber and plastic products	315100	106300	0.022	0.012	265.4	194.3		
	Manufacture of other non-metallic mineral products	172500	185600	0.012	0.022	263.2	134.7		
	Manufacture of basic metals	24700	31400	0.002	0.004	27.3	19.0		

		End-use, t		**Share of total consumption, A_{is}**		**Value added, Q_{s}, mln. EUR**		**EI**	
	Manufacture of basic metals and fabricated metal products, except machinery and equipment	5034100	3262800	0.355	0.380	279.8	167.3		
	Manufacture of computer, electronic and optical products	56100	24700	0.004	0.003	113.3	115.9		
	Manufacture of electrical equipment	335000	96900	0.024	0.011	82.4	50.5		
	Manufacture of machinery and equipment	457500	286700	0.032	0.033	145.3	102.6		
	Manufacture of motor vehicles, trailers and semitrailers	494200	198800	0.035	0.023	80.7	25.8		
	Manufacture of machinery and equipment n.e.c.	4300	2000	0.000	0.000	124.8	100.3		
	Manufacture of furniture (and other)	1076200	1277900	0.076	0.149	509.6	414.9		
	Other manufacturing	34400	59500	0.002	0.007	0	0		
	Repair and installation of machinery and equipment	84000	163200	0.006	0.019	161.6	147.1		
	Electricity, gas, steam and air conditioning	2400	2700	0.000	0.000	800.6	822.8		
	Water supply; sewerage, waste management and remediation activities	1200	700	0.000	0.000	205.3	195.7		
	Other industrial activities	38600	47300	0.003	0.006	0	0		
	Construction	614700	618400	0.043	0.072	3261.5	1585.8		

Aluminium		**Import, kg/yr**		**Import, S_{ic}**		**WGI_c**		**$S_{ic}^2 \cdot WGI_c$**	
		2008	2009	2008	2009	2008	2009	2008	2009
	Belarus	117.3	150.2	0.010	0.020	6.7	6.7	6.97	27.02
	Canada	9.5	0	0.001	0.000	1.8	1.7	0.01	0.00
	China, People’s Republic of	867.6	463.4	0.075	0.062	6.0	6.0	341.11	231.94
	Israel	0.2	0.1	0.000	0.000	3.8	4.0	0.00	0.00
	Japan	127.4	20.9	0.011	0.003	2.7	2.6	3.28	0.20
	Kazakhstan	30.2	21	0.003	0.003	6.0	5.8	0.41	0.46
	Korea, Republic of	0	8.4	0.000	0.001	3.7	3.5	0.00	0.04
	Norway	6.8	6	0.001	0.001	1.7	1.7	0.01	0.01
	Malaysia	0.3	0	0.000	0.000	4.5	4.6	0.00	0.00
	Russian Federation	143.2	69.6	0.012	0.009	6.4	6.5	9.99	5.64
	Switzerland	4.4	5.3	0.000	0.001	1.5	1.6	0.00	0.01
	Taiwan	1.3	20.5	0.000	0.003	3.4	3.3	0.00	0.25
	Turkey	144.6	207.4	0.013	0.028	5.1	5.1	8.03	39.55
	Ukraine	160.5	13.6	0.014	0.002	5.9	6.1	11.44	0.20
	United States	1.6	0.2	0.000	0.000	2.4	2.6	0.00	0.00
	Total EXTRA-EU27	**1614.9**	**986.6**	0.140	0.132			0.00	0.00
	Austria	80.9	11.9	0.007	0.002	1.7	1.9	0.83	0.05
	Belgium	65.6	25.2	0.006	0.003	2.5	2.4	0.82	0.27
	Bulgaria	14.9	61.6	0.001	0.008	4.6	4.5	0.08	3.10
	Czech Republic	520.7	403	0.045	0.054	3.2	3.2	65.96	93.57
	Denmark	482.7	356.7	0.042	0.048	1.3	1.3	22.32	29.63
	Estonia	213.9	92.4	0.019	0.012	2.9	3.0	10.11	4.58
	Finland	410	159.3	0.036	0.021	1.4	1.2	17.24	5.67
	France	37.8	2.5	0.003	0.000	2.5	2.6	0.27	0.00
	Germany	2227.7	1294	0.194	0.173	2.1	2.1	782.42	636.13
	Greece	0	23	0.000	0.003	3.8	4.1	0.00	0.39
	Hungary	18.6	9.6	0.002	0.001	3.4	3.6	0.09	0.06
	Ireland	0	0	0.000	0.000	1.8	2.0	0.00	0.00
	Italy	487.9	271.5	0.042	0.036	3.8	3.9	69.19	52.03
	Latvia	373.9	225	0.033	0.030	3.8	3.8	40.55	34.18
	Luxembourg	86	43.3	0.007	0.006	1.6	1.6	0.91	0.54
	Netherlands	266.1	44.7	0.023	0.006	1.7	1.7	9.33	0.62
	Poland	2660.8	1471.6	0.231	0.197	3.7	3.5	1973.52	1379.39

Aluminium		Import, kg/yr		Import, S_{ic}		WGI_c		$S_{ic}^2 \cdot WGI_c$	
		2008	2009	2008	2009	2008	2009	2008	2009
	Romania	56.1	111	0.005	0.015	4.7	4.7	1.13	10.46
	Slovakia	68.8	19.4	0.006	0.003	3.4	3.5	1.21	0.24
	Slovenia	0.9	0.4	0.000	0.000	3.0	3.0	0.00	0.00
	Spain	111.3	14.9	0.010	0.002	3.3	3.4	3.06	0.13
	Sweden	73.9	37.4	0.006	0.005	1.5	1.5	0.64	0.37
	United Kingdom	7	105.5	0.001	0.014	2.2	2.4	0.01	4.77
	Total INTRA-EU27	**9886**	**6474.6**	**0.860**	**0.868**			0.00	0.00
	TOTAL	**11500.9**	**7461.2**	**1**	**1**			**0.34**	**0.26**

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