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MASTER'S THESIS

DETERMINATION OF SUSTAINABILITY FACTORS FOR ASSESMENT OF CRITICAL RAW MATERIAL

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ABSTRACT

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Currently, the securement of critical raw materials denotes a high-priority matter for most companies and governments given the colossal effect these minerals have on the nation’s economy. However, the sector is impacted by challenges ranging from long-term depletion concerns to the supply disruption threat that translates to scarcity and subsequent hikes in prices. Firstly, the study sought to determine the indicators of supply risk and the economic dimension of sustainability for the assessment of the criticality of raw materials. Secondly, the thesis sought to determine the indicators of the environmental and social dimension of sustainability for the determination of criticality of raw materials. This study aimed to determine the most preferred indicators for the evaluation of sustainability factors related to criticality of raw materials. To meet this objective, the research reviewed literature select the indicators and employed rough set theory to derive the sets of indicators important for criticality assessment. On the results, the study found the set for supply risk indicators to include country concentration, country risk, depletion time, by-product dependency, company concentration, and demand growth. Set for vulnerability indicator included substitutability, value of affected product, future demand, strategic importance, value of material utilized and

spread of utilization. The set for social dimension indicator included local community, society and worker dimension. Environmental indicator included two areas of protection (AoPs), human health, and ecosystem equality.

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Kiriti Saha

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SYMBOLS AND ABBREVIATIONS

AHP – Analytic hierarchy process

AOP – Areas of protection

CES - Conference of European Statisticians

CRM - Critical Raw Material

DOE - Depertment of Energy

EC - European Commission

EI – Economic Importance

EPI - Environmental performance index

EU – European Eunion

HHI - Herfindahl–Hirschman index

IMF - International Monetary Fund

LCIA - Life cycle impact assessment

OECD - Organisation for Economic Co-operation and Development

PGM - Platinum Group Metal

SLCA - Social life cycle assessment

UNECE - United Nations Economic Commission for Europe

1 INTODUCTION & BACKGROUND

1.1 Significance of raw materials

Raw materials are crucial for manufacturing of wide range of goods as well as services that are essential for everyday life and in the development of innovations in Europe that are evidently needed in the development of globally competitive and more eco-efficient technologies (European Commission, 2017) . Europe depends highly on imports for a lot of raw materials considered critical which are increasingly impacted by the rapidly increasing demand pressure from measures of national policies and emerging economies that disrupt the normal global operational markets (European Commission, 2010). Further, the extraction of many critical raw materials (CRM) concentrated in a few countries. For instance, 70% of tungsten and germanium and 90% of antimony and rare earths are produced in China. Similarly, 77% of platinum comes from South Africa while 90% of niobium originates from Brazil. Also, high tech raw materials are frequently produced from by-products of processing primary materials such as aluminum, zinc and copper. Meaning that the availability of high-tech raw materials is dependent on primary products. Also, these primary products have low elasticity thereby making it difficult for mine production to adapt so as to meet the demand pattern. A good example is the rapid upsurge of mobile phones in 2000 that caused a huge demand for tantalum (European Commission, 2010). Also, the rapid growth of economies in Europe and the accelerating cycles of technological innovations have contributed to the augmented global demand for a number of highly sought minerals and metals. Furthermore, the securement of the access to a sustainable supply of these highly sought raw materials remains a major challenge for many economies in Europe because of the limited production that translates to dependence on imports of many metals and minerals including a number of CRMs that are required by industries. For instance, (Mayer and Gleich, 2015) argued that the supply of raw resources in the commodity market is inflexible because of technological changes, population growth, protectionist governance and new lifestyles. That these developments keep the CRMs availability under increased pressure. Also, the manufacturers in the mining sector are struggling to achieve the rapidly soaring demand of the raw materials because of the continued mining under-capacity and the scarce recycled metals sources as the principal raw materials are locked up in products. These factors develop a context around a demand surge from emerging economies which is compounded further by other factors circumstantial issues including climatic problems, supply chain and limited access to the materials deposits. Fewer and fewer raw materials deposits are being extracted, and this translates to heightened prices. Nevertheless, the CRMs are indispensable for virtually all major industry sectors such as health care, engineering, new energy, chemical, automotive and aeronautics. The importance is underscored by the fact that the aforementioned sectors employ at least thirty million individuals which translates to over one trillion Euros of value added (EU Commission, 2016). Therefore, the provision of a reliable and sustainable supply of CRM at competitive prices has become vital since a lot of the manufacturing companies are met with challenges regarding the developments in various sectors. The companies have to fight with increasing uncertainty in breaks in production, material planning or the economical strain brought about by increased volatility in producing countries. In summary, the likelihood of addressing the raw materials as a priority can be founded on the sustainability dimension that includes social, economic and environmental concepts.

1.2 Concept of sustainability of raw materials

Sustainability and sustainable development concepts have gradually received increased attention globally due to the socioeconomic inequity and the growing concern about the environmental issues both emerging because of the prevailing international model of the economy that prioritizes profits (Segura-Salazar and Tavares, 2018) . Brundtland report of 1987 underscored the need for urgent progress in the development of the economy which could be sustained without asserting detrimental effects on the environment and depletion of natural reserve (Barkemeyer *et al.*, 2014). The report transformed the sustainable development viewpoint from the physical concept a perspective based on environmental, social and economic issues. The sustainable development of critical raw materials concepts currently remains significant in industrial and public sectors and constitutes a fundamental objective as world economies are energy and material intensive (KOLTUN, 2012). For instance, the US, one of the advanced economies and close EU ally produces approximately ten tonnes of active raw minerals and metals per person annually, yet, majority of these materials relatively turns to waste quickly. Penn (2001) argued that only six per cent of the extracted active materials are embodied in goods whereas the remaining ninety-four per cent is turned into waste (Penn and Arbor, 2001). Also, the manner in which the goods and services are currently produced is unsustainable and translates to the current environmental problems. The significance of sustainability for critical raw materials is to balance, environmental, social and economic needs thus providing for the contemporary and the future generations (Srebotnjak, 2018). Also, sustainable development encompasses an integrated, long-term approach by developing a healthy society through jointly addressing the social, economic and environmental issues while at the same time circumventing over-utilization of raw materials. In summary, the concept of sustainability development in regards to CRM is therefore significant as it motivates the enhancement and conservation of the metals and minerals through gradually altering technologies developments and use. However, the question drawn from the aforementioned perspective remains what really does the concept of CRM entail. What are the elements in the EU CRM list?

1.3 Critical raw materials (CRMs)

The concept of critical raw materials has been defined differently by different assessments. The variability and vagueness in definitions prompted some researchers to assert that the concept lacks a precise definition (Frenzel *et al.*, 2017). Graedel and Nassar (2013) defined critical material as those having the state, degree or the quality of being of uppermost importance (Graedel, Harper and Nassar, 2013). While a study by (Gleich *et al.*, 2013) described criticality as the extent of both the future and present risks related to as specified metal. However, the associated economic importance and the supply risk denotes the most reviewed and the most considered effective aspect (Jin, Kim and Guillaume, 2016). The perspective was echoed by Hatayama and Tahara (2017) who argued that the widely acknowledged definition of the mineral's criticality is determined by the vulnerability and the risk to supply restrictions (Hatayama and Tahara, 2018). Moreover, each of the aforementioned aspects encompasses many components. For instance, vulnerability looks at the economic impact of sustainability and supply restrictions while supply risk considers the political, economic, and technical aspects (Achzet and Helbig, 2013a). The CRMs regarded by the EU as critical are displayed in the table 1 below.

Table 1 The EU 2017 Critical Raw Material List. (EU, 2017)

Critical Raw Materials (27)				
Antimony	Coking coal	Indium	PGMs	Tungsten
Baryte	Fluorspar	LREEs	Phosphate rock	Vanadium
Berylium	Germanium	Magnesium	Phosphorus	Gallium
Bismuth	Hafnium	Natural graphite	Scandium	
Borate	Helium	Natural rubber	Silicon metal	
Cobalt	HREEs	Niobium	Tantalum	

1.4 Problem Statement

Critical raw materials are valuable for the economy of Europe (European Commission, 2017). For instance, the manufacturers in the mining sector in Europe are struggling to meet the rapidly soaring demand of the raw materials because of the continued mining under-capacity and the scarce recycled metals sources as the principal raw materials are locked up in products (Dewulf *et al.*, 2017a). These factors develop a context around a demand surge from emerging economies which is compounded further by other circumstantial issues including climatic problems, supply chain and limited access to the materials deposits. Fewer and fewer raw materials deposits are being extracted, and this translates to heightened prices.

The EU is facing a great challenge of unhindered and reliable access to most of the CRMs hence the growing concern. The massive contemporary and future technology heavily rely on the supply and availability of critical raw materials (Harper *et al.*, 2015). These minerals are applied in a wide range of sectors including telecommunication, transportation, green technology, defence, microelectronics, aviation, aerial imaging, space exploration and other high-technology services and products (Alliance, 2019). However, the available raw materials are scarce; thus, they cannot meet the demand for new technologies. For example, (Kavlak *et al.*, 2015) found that a limited valuable resource could develop a massive problem for emerging technologies, including photovoltaic solar system, rollout as the sector is impacted by challenges ranging from long-term depletion concerns to the supply disruption threat that translates to scarcity and subsequent hikes in prices (Frenzel *et al.*, 2017; Hatayama and Tahara, 2018). For instance, the rapid increase in demand for indium for flat-panel displays and the scarcity of cobalt due to internal conflict in DRC Congo, all resulted in price hike (Hatayama and Tahara, 2018). In addition, due to the scarcity of the CRM and environmental effects associated with the extraction of the manufacturers are key players in promoting sustainable development, increasing efficiency of the available resources. Although studies have been conducted on concepts of sustainable development in CRM supply chain management, few studies have focused on presenting the challenges regarding the sustainability and criticality of the raw materials.

1.5 Objectives

This study comprehensively explores two objectives. Firstly, the study sought to determine the indicators of supply risk and the economic dimension of sustainability for the assessment of the criticality of raw materials. Secondly, this thesis sought to determine the indicators of the environmental and social dimension of sustainability in regard to criticality of raw materials.

To achieve the above-mentioned objectives, this thesis addresses the following question

1. What are the indicators for supply risk and economic importance used in the determination of criticality of raw materials?
2. What are the indicators for social and environmental dimensions of sustainable development for the assessments for criticality of CRM?

1.6 Significance of the study

A transition into a sustainable economy is essential and overwhelmingly challenging. Indeed, change is required in nearly all aspects of the society, human culture and economy in relation to engagement with biosphere and in particular the raw materials reserve. There are three dimensions to the aforementioned change, Firstly, is decarbonization of the EU economy challenge. The second challenge is one related to social equity and justice while the third lies in conservation of the scarce resource. Perhaps the questions that beg the answer is how these challenges can be addressed to help achieve sustainability of critical raw materials. Adams &

Jeanrenaud (2008) indicated that the challenges require restructuring the existing global consumption of raw materials through reduction of consumption to sustainable levels, redirecting consumption into less harmful forms and redistribution of consumption to the community (Jeanrenaud and Adams, 2010). For instance, mineral-mining has a dark history marked with a framework designed to maximize profits in natural resource extraction without the environmental rehabilitation plan (Segura-Salazar and Tavares, 2018). Identification of sustainability indicators contributes to the protection of the environment and biodiversity. Therefore, this research aims to provide data to the existing knowledge for promoting the adoption of an accurate critical assessment methodology. Similarly, the study seeks to advocate the CRM’s importance that will translate to the establishment of a strong CRM policy for Europe. Furthermore, the study adds to the call for the execution of sustainable practices. This is because the well-being of a society is related to the protection of the ecosystem where the mining process occurs (Segura-Salazar and Tavares, 2018). Since social sustainability touches on the human dimension (Sachs 1999), determination of social indicates may help advocate for mining companies to contribute to the economic development of the areas where the minerals are extracted through the improvement of infrastructure and creation of job opportunity for the locals.

1.7 Operational Definition

Critical raw materials denote goods for economic development activities such as industrial production which have shown to be important in civilized community development (Kim *et al.*, 2019). The EU defined CRM as material that is vulnerable to supply interruptions and of high importance in economic dimension (European Commission, 2017). The term sustainability depicts the process to attain sustainable development (Sartori, Latrônico Da Silva and De Souza Campos, 2011) asserted that the Brundtland report described the concept of sustainability as the contemporary development that satisfies the current society requirements without putting the future generation needs in jeopardy (Gunilla, 2013).

1.8 Summary of chapter

The introduction chapter puts insight into the study regarding Summary the determination of sustainability factor for assessment of CRM. This chapter provides the introduction section which encompasses the background information of the thesis, the problem statement, the objective of the study, the research questions and the relevance of the study and the organization of the thesis. The next section explores the literature review of the existing works of other researchers related to the extant study.

1.9 Organization of the thesis

The thesis will be organized in sections from chapter one to seven. The first chapter is the introduction section which encompasses the background information of the paper, the problem statement, the objective of the study, the research questions and the relevance of the study? The second chapter provides the literature review that explores other authors perspectives on the criticality of raw materials, an overview of selected minerals and the economic importance, supply risk and sustainability indicators of CRMs. The third chapter is the methodology section which shows the approach the paper employs to achieve the aims of the study. The fourth chapter displays the study's findings as guided by the papers research questions. The discussion provides a broader perspective of the findings as well as compare the study's results to the previous studies findings. The conclusion chapter follows the Discussion. It discusses the depth and breadth of the paper's results as well as the study's new perspectives.

2 LITERATURE REVIEW

2.1 Challenges of criticality and sustainability of Raw Materials

Three main parameters are known to impact the criticality of a material, sustainable factors, the supply risk and the economic importance of the minerals (European Commission, 2014). Perhaps the question that arises from the concept of criticality is how vital the CRMs are to modern society. The contemporary societies are increasingly relying on the CRMs to maintain the technologies that sustain and underline the modern living standards (Langkau and Tercero Espinoza, 2018). For instance, electronic gadgets including smartphones and computers contain many varieties of CRM metals all of which contribute to their functionality (Hofmann *et al.*, 2018). For example, Platinum Group Metal (PGM) and Hafnium are used in optics, machinery parts, general electronics, base metals and nuclear reactor industries (European Commission, 2017). These CRMs minerals are essential to the concept of clean technologies. For example, these minerals are essential in energy-efficient lighting, wind turbines and solar panels (Rabe, Kostka and Smith Stegen, 2017). Hatayama and Tahara noted that development in science and technology in the past decade had seen the utilization of a wide array of minerals than in the previous decades (Hatayama and Tahara, 2018). This increased technological development and other related sectors demand has drastically heightened the importance of the mineral resources criticality (Kim *et al.*, 2019). In addition, the development of criticality assessment methodology of decision makers including the corporations, institutions and government groups has contributed to the increased criticality of the raw materials. Bartl et al. (2018) added to the perspective by asserting that it is widely acknowledged that several industries including metallurgy, aerospace automotive, chemicals and constructions heavily depend on CRM (Tkaczyk *et al.*, 2018). For instance, antimony used in plastic production , flame-retardant formulation, lead-acid batteries, , lead alloys and manufacture of ceramics and glass, bismuth is used in the manufacture of metallurgical and fusible alloys, tungsten is in cutting tools, lamps, X-Ray tubes, and radiation shielding, scandium is used in solid oxide fuel cell and Sc-Al alloy in the aerospace sector while niobium is used to make ferroniobium which is important in production of high strength low alloy (HSLA) steels to make car bodies, gas pipelines, ship hulls and so on (European Commission, 2017). Therefore, the need to accord the priority to CRMs was as based on scientific, technological, economic, industrial and strategic importance. Furthermore, the increasing consumptions of mineral resources in sectors such as information technology, energy production and electromobility is posing new challenges to both regional and global economy. For instance, as the consumption of these materials increases, the risk related to the supply chains disruptions and constraints of the CRM increases as well (Langkau and Tercero Espinoza, 2018). In addition, Langkau & Tercero stated that the extraction of these valuable metals has an impact on the ecosystem (Langkau and Tercero Espinoza, 2018). Therefore, the active players such as companies and nations are attempting to reconcile obligations for preserving the ecosystem and economic development (Shaker, 2015). Since raw materials are extracted from the environment, the challenge remains to maintain the state of water, climate and air are of crucial concern (IISD, 2012). The challenges related to critical raw materials are determined using indicators specific for the assessment of CRMs.

2.2 Indicators for Criticality Assessments

Frenzel et al. (2017) supposed that the most commonly employed methodology to asses criticality of raw materials encompasses compelling sets of various identified indicators to form aggregate scores for vulnerable and supply risk indicators, and plotting the dimension against each other to determine the field of CRMs (Frenzel *et al.*, 2017). Glöser et al. asserted that the approach was a construct from the classical risk matrix methodology (Glöser *et al.*, 2015). As aforementioned in the previous section, some scholars have adopted a single dimension approach while others have incorporated the environmental aspect in the method (Graedel *et al.*, 2012). Frenzel et al. (2017) noted that there are two commonly used indicators for criticality assessment; economic importance & supply risk. Indicators of economic importance and supply risk adopted in several assessments are discussed below.

2.2.1 Vulnerability indicators/Economic impact

Helbig described economic impact as the extra cost which arises from an imbalance in supply or demand (Helbig *et al.*, 2016). In addition, scholars have significantly differed on the scope of vulnerability evaluation. (G. A. Blengini *et al.*, 2017) supposed that Economic Importance (EI) assess the significance of raw materials to the EU economy. Also, the economic indicator relates to the probable consequences in an inadequate supply of critical raw material situations. The indicators widely adopted in many studies are discussed below. Similarly, other indicators of economic importance employed in few assessments are also discussed. Further Table 2 displays indicators weighting, the formula for calculation and the selected assessments. The tables show that various assessments have employed different methodologies in weighting the indicators. For instance, Table 4 displays results of indicators weighted using fuzzy analytic hierarchy model.

2.2.2 Substitutability

For a number of critical raw material, currently, substitution is difficult to realize without deterioration in economic viability, performance or quality of a product (Joint Research Centre, European Commission and Knowledge Service, 2017). Substitutability denotes the most applied indicator with (Achzet and Helbig, 2013a) indicating that it is the most commonly adopted indicator for both vulnerability impact and supply indicators. For instance, interpretation of supply risk, a shortage in supply is less likely, if manufacturers can employ substitutes thereby reducing the materials overall demand (Duclos, Otto and Konitzer, 2018). For vulnerability dimension, substitution feasible options show a decreased relevance as equated to a mineral without a suitable substitute (Graedel *et al.*, 2012). Helbig et al. (2016) wrote that substitutability of materials could be interpreted on multiple levels of the development of a product such as technological substitution, functional substitution, material substitution, non-material substitution, and quality substitution (Helbig *et al.*, 2016). Frenzel et al. (2017) noted that substitutability is inversely related to the Economic importance indicator. Meaning that the easier the substitution of minerals, the lower the economic impact of the supply restrictions (Frenzel *et al.*, 2017). Blengini et al. (2017) supposed that for the vulnerability related dimension Substitution covers substitute cost-performance (G. A. Blengini *et al.*, 2017). That the rationale for including replacement in the vulnerability indicators is its economic and technical performance of raw materials substitutes indefinite applications affecting the market uptake readiness and its use in the market. In summary, the market decision for applying material substitute is adopted on the grounds of its functionality/technical performance, also cost.

2.2.3 Value of Product

The value of the product also referred to as the spread of utilization represents the second most commonly used indicator for Economic importance (Frenzel *et al.*, 2017). In addition, product value depicts an example of indicators that have a direct association with the economic impact. For instance, Graedel et al. (2012) ranked metals as very critical whenever he found the revenue to be dependent on the raw material by more than 5 %. Also, the product value indicator evaluates the possible damage to the resource supply disruption (Graedel *et al.*, 2012). Beylot & Villeneuve (2015) supposed that this indicator measures the possible damage of a raw material supply disruption by considering the occurrence of each resource rather than the quantity (Beylot and Villeneuve, 2015). In summary, the study found that the value of the affected product is the second most adopted indicator for assessing economic importance besides as it was used in six studies.

2.2.4 Future Demand

Helbig et al. (2016) noted that out of sixteen studies reviewed, five had employed the ration between the recent supply with the future demand for the raw material with all the identified studies having the assessments done at either technological or national levels (Helbig *et al.*, 2016). This indicator differs from the others in the sense that it does not have value based on historical or present data but rather future based. The general perspective regarding the indicator is that “ramp-up” raw materials are of specific significance whether for a technology meant to be applied on a wide scale or for a regional or national economy, such as resource-efficient technologies or low-carbon energy. Kavlak et al. (2015) asserted that scarcity of essential critical raw materials may turn out to be a huge challenge for the development of evolving technologies including Photovoltaic solar cells (Kavlak *et al.*, 2015). That for strategy and a national economy, the aforementioned issue might be regarded as more significant as compared to handling supply interruptions of utilized materials and existing technologies. Also, future demand has been applied in quantification of supply risk indicators where it is inversely related in the sense that too much dependence on the future technology resources proves to be a threat to the same technology, while the emerging technologies that have a fast-growing demand rate can impact the continuous resource supply negatively, meaning that increased future demand reliance adversely effects on the products.

2.2.5 Strategic importance

Strategic importance is another indicator that affects vulnerability. Strategic importance is interpreted as either assesses the future requirements of a resource to secure the economic status of a nation or the needs that arise as a result of future strategic technologies (Helbig *et al.*, 2016). A study by Roelich et al. (2014) regarded the demand for clean energy as having strategic importance (Roelich *et al.*, 2014). Parthemore investigated the risk associated with the US government reliance on the mineral resource which the study referred to as raw materials of vital importance (Parthemore, 2011). Graedel et al. (2012) linked the indicator to the future revenue that faces a possible raw material scarcity (Graedel *et al.*, 2012).

2.2.6 Material value

Material value has been regarded as an indicator of resource vulnerability in many studies. For instance, Helbig et al. (2016) indicated that the mineral resource value is easier to quantify as compared to other previously used indicators as information can be extracted directly from economic and corporate statistics (Helbig *et al.*, 2016). In addition, this indicator is inversely related to vulnerability as the shortage in supply prompts an increase in the price of resources instead of disruption in supply. Meaning that through supply restriction, the risk considered increases the raw material cost rather than decrease the revenue. A study by Duclos et al. used the material value as a bottleneck for prioritizing the raw material of interest instead of using it as an indicator for evaluating the vulnerability of the resources (Duclos, Otto and Konitzer, 2018).

2.2.7 Spread of utilization

This one has been adopted as an indicator in a number of assessments (Erdmann and Behrendt, 2011; Graedel *et al.*, 2012; Nassar, Graedel and Harper, 2015). This indicator considers that raw materials can be of a higher value in some country's nation compared with others (Graedel *et al.*, 2012), which means that resources may not have similar importance in all societies. Erdmann et al. (2011) termed the indicator 'value chain sensitivity' and evaluated the degree of the raw material crisis to the economy of Germany (Erdmann and Behrendt, 2011).

Other indicators of vulnerability that have not been widely used. Other vulnerable indicators have been used occasionally in a maximum of two assessments of criticality. However, Helbig et al. (2016) asserted that the rare use of an indicator never imply less quality because it is likely that the indicator was added recently or has a narrow focus (Helbig *et al.*, 2016). The indicators found to have been applied in more than one study include, demand share of the target group, change in demand share, capability to pass-through increase in cost and import dependence. Duclos et al. (2010) and Graedel et al. (2012) adopted the ability to pass-through increase in cost. The indicator assesses the possibility of corporates to pass the increase in resources costs to their clients. Demand share change indicator was adopted by (Erdmann and Behrendt, 2011) and (Hatayama and Tahara, 2018) to assess the change in demand for raw material in relation to demand in global resource over a period of time. The study by (Parthemore, 2011) and (Graedel *et al.*, 2012) used reliance on import indicator to evaluate economic impact in nations. The study estimated the net reliance on import through accounting the county's resources flow in comparison to the rate of consumption. Target group's share demand indicator was applied in (Erdmann and Behrendt, 2011; Duclos, Otto and Konitzer, 2018) studies which supposed that certain resources high share demand compared with demand in the global level, indicated the raw material importance to the nation. Other indicators affecting vulnerability include the capability to innovate which was used by Graedel et al. (2012) to estimate the nations and companies economic vulnerability (Graedel *et al.*, 2012). (Parthemore, 2011) used company and country concentration indicators to evaluate the reliance of the U.S on raw materials from foreign suppliers. Achzet and Helbig (2013) supposed that company concentration indicator could be used similarly in estimation supply risk (Achzet and Helbig, 2013a). AEA Technology & Defra (2010) used the consumption volume indicator to evaluate the resource the UK raw material economic impact. (Hatayama and Tahara, 2018) adopted mining production change as an indicator for assessing the international resources demand change. Other indicators of economic impact used by scholars include recyclability, price sensitivity and the primary resource prices (Parthemore, 2011).

Table 2 Indicators; weighting, formula/calculation as adopted by in valuation of economic importance in selected assessments.

Indicators	**Weight**	**formula /calculation**	**Study**
Substitute available	25.0%	$SI_{EI} = \sum_i \sum_a SCP_{i,a} * Sub - share_{i,a} * Share_a$	(Duclos, Otto and Konitzer, 2018)
Price ratio	8.3%	Price Ratio= 50× (Price substitute) divided by (raw material)	(Graedel *et al.*, 2012)
Reliance Import ratio	8.3%	IRR=50× IR (substitute) divided by Import Ratio (raw material	(Graedel *et al.*, 2012)
Products value	100%	($\sum_s$ consumption share) × (Value added)/GDP	(European Commission, 2014)
Future demand	20%	(2030 demand from future technologies)/ (2006 supply)	(Erdmann and Behrendt, 2011)
Strategic importance	11.1%	Expert opinion, Qualitative assessment	(Simon, Ziemann and Weil, 2014)
Demand for clean energy	75.%	market share× Deployment× material intensity	(Bauer *et al.*, 2010)
Material value	Bottleneck	metal price × metal use	(Duclos, Otto and Konitzer, 2018)
Material assets	16.7%	$\log_{10}$ × [(national per capita stock in use) ÷ (global in use stock + reserves)] ×40	(Nassar, Graedel and Harper, 2015; Helbig *et al.*, 2016)

Spread of utilization	25.0%	4-point rating scale, expert opinion	(Erdmann and Behrendt, 2011)
Ability to pass-through cost	25%	Qualitative expert opinion	(Duclos, Otto and Konitzer, 2018)

2.3 Supply Risk Indicators

Supply risk indicators provide evaluation for the likelihood of supply restrictions occurrence (Frenzel *et al.*, 2017). Also, just as in Economic impact dimension, indicators of supply risk differ between individual research. Blengini et al. (2015) noted that supply risk indicator asses the risk of raw materials inadequate supply to meet technological industries demand (G. A. A. Blengini *et al.*, 2017). Table 3 display a number of indicators adopted in selected assessments. The table shows the indicators, the weightings, calculation formulas, measurements and the selected studies. The indicators of supply risk presented in the table are discussed below.

2.3.1 Country concentration

As brought out by (Achzet and Helbig, 2013a), the most widely adopted indicator is the country and company concentration. Also, this indicator is directly correlated to critical raw materials supply risk. For instance, the indicator assumes that the more concentrated the extraction of a given resource in few countries especially those marred with political instability, the higher the likelihood of disruptions in supplies (Graedel, Harper and Nassar, 2013). Further, the monopoly enjoyed by China heavily disrupts the supply of CRMs. For instance, (USGS, 2011) indicated that tungsten, molybdenum, and rare earths are examples of CRMs with increased production concentration . The aforementioned CRMs are mined in China which has a share of 97% for rare earths and 46% for molybdenum. Thus, price development history is impacted by political decisions regarding taxes and export restrictions.

2.3.2 Country risk

Country risk combines each producing country's political risk and its distribution (Kaufmann, D., Kraay, A., Matruzzi, 2012). The EU (2010) stated that country risk of the producing countries is measured by the use of widely recognized world Bank index which quantifies components of governance such as corruption control, lack of violence, political stability, regulatory quality, government accountability, government effectiveness and rule of law (European Commission, 2010). Other indices employed in measuring country risk include the policy potential index (PPI) designed by Fraser Institute, human development index (HDI) developed by UNDP and global political risk index (GPRI) designed by Eurasia group (Achzet and Helbig, 2013).

2.3.3 Depletion time

Depletion time indicator provides another example that assumes an inverse association with supply risk. Meaning that the higher the depletion time frame of the contemporary raw materials, the less likely the occurrence of supply disruption in a given period (Graedel, Harper and Nassar, 2013). Also, the depletion time denotes a dynamic reach, that includes the demand trends, reserve and recycling rates in its assessments. For instance, increasing raw material prices due to increase in demand can help in changing in-profitable deposits into extractions that are that are economically rational within a short period which will in turn raise the extractable reserves to share.

2.3.4 By-product dependency

By-product dependency indicator is closely related to companion production. A lot of the raw material are that are particularly valuable of the contemporary modern technology are mined as by-products of the metal extraction process. Nassar et al. (2015) argued that some metals are valuable for the development of technology but are affected by supply disruptions and also demonstrated that this is because the host metal annual extraction limits the by-product supply which might fail to adjust to the rapid demand increase that translates to shortages (Nassar, Graedel and Harper, 2015). Import dependence and demand growth are another set of indicators that impact supply. Frenzel et al. (2017) argued that greater import reliance leads to an increased likelihood of supply disruption due to conflicts in other regions of the world (Frenzel *et al.*, 2017).

2.3.5 Recyclability

Recyclability demands of products are another indicator. Just like vulnerability substitutability similarly affects supply risk. The supply of CRMs is not only dependent on the primary availability but also the raw materials secondary availability. Therefore, the recyclability rate of raw material is similarly a crucial indicator. The EU Commission (2016) report indicated that it is acknowledged that although the recyclability rate of most CRM appears to be nil or low, many of the resources are indirectly recovered. Felspar, for example, cannot be recycled in its elemental state; however, many glasses being recycled contain feldspar.

2.3.6 Other supply risk indicators

Achzet and Helbig described substitutability as the potential to replace a resource with another raw material (Achzet and Helbig, 2013a) . Therefore, a raw material supply risk will only affect a nation's economy if the resource lacks a substitute mineral. The (EU Commission, 2016) report for ad-hoc group supposed that the substitutability index for a given resource is the combined indices for its application. Other indicators for the supply that have not been discussed because of the relatively rare use in previous studies include Resource abundance, climate change, mining investment, refinery capacity, market balance, stock keeping, and exploration degree (Frenzel *et al.*, 2017).

Table 3 Indicator assessment in selected studies

Indicator	***Weight***	***Calculation***	***Measurement***	***Study***
Country concentration production	16.7%	$HHI(a) = \sum_{i=1}^{N} {a_i}^2$	HHI	(Graedel *et al.*, 2012; Achzet and Helbig, 2013b)
Country risk	16.7%	$Country\ riskN(a) = \sum_{i=1}^{N}(ai*\text{ai})$	Qualitative, country concentration measurement	(Duclos, Otto and Konitzer, 2018)
Depletion time	50% for "long term", 16.7% for "short term"	$DT = t_F - t_0 = R_{t_0} - \sum_i (\int_{t_0}^{t_F} \psi(t_i) + r(t))$	% Years	(Graedel *et al.*, 2012) (Achzet and Helbig, 2013b)
By-product dependency	10%	By-product = By-production÷ Total production	By-production divided by the total production	(Duclos, Otto and Konitzer, 2018)
Recycling rate	Algorithm	Old scrap ÷ demand	Old scrap/demand	(NRC, 2011)
Import dependency	Algorithm	Net import reliance÷ apparent consumption r ate	Net import reliance divided by Apparent consumption	(NRC, 2011) (Dewulf *et al.*, 2017b)

Table 4 Supply risk, vulnerability and economic risk indicators weighting using fuzzy AHP model (Source: (Kim et al., 2019))

Supply indicator	**Weighting**	**Vulnerability**	**Weighting**	**Economic Risk**	**Weighting**
Country concentration	37.58%	Recyclability	14.11%	Economic importance	43.88%

Country risk	37.40%	Substitutability	32.65%	Future demand	32.21%
Depletion time	13.03%	Stock keeping	15.18%	Volatility of mineral prices	23.91%
By-product dependency	11.99%	Self-sufficiency rate	38.06%		
Total sum of weight	100%	**Total**	100%		100%

2.4 Sustainability indicators

Bedřich argued that sustainability concept development definition has evolved to encompass three pillars, environmental, social and social sustainability (Moldan, Janoušková and Hák, 2012). Also, environmental sustainability focusses on improving the welfare of humans through the protection of raw material sources and ensuring that the mineral reserves are not depleted. Sustainability dimension denotes a vital framework that aims to address environmental, social and economic impacts of raw CRMs and thereby guide decisions in policy making towards sustainable Raw materials supplies (NRC, 2011). For instance, Table 4 displays results of quantitative assessment of sustainability of CRMs in three dimension including economic environmental and social dimensions. To incorporate sustainability comprehensively in various sectors associated with CRM, there are some important indicators that are employed in quantifying the sustainability factors (NRC, 2011). It also provided some principles that guide the use of indicators for quantifying sustainability. For instance, the report indicated that the suite of indicators applied should be able to provide a quantitative evaluation of the effects. In addition, the report noted that no single indicator is comprehensive, hence a suite of different indicators should be considered. Another study (UNECE, 2014) published a report on the measure of sustainable development and adopted a so-called capital-based approach that evaluates the measures of social capital, human, natural, economic flows and stocks. Another study, (UN *et al.*, 2003) demonstrated that in actual practice, the most effective sustainable development indicators were suites of policy-based. That policy-based indicators are flexible enough to change over a short period sufficiently to associate the change to the measure policies. Examples of the policy-based indicators include the mortality rate related to critical illness, the energy application per GDP and the greenhouse gas emissions. Yale Center for Environmental Law and Policy (2008) describes the environmental performance index (EPI) as a methodology for numerically marking and quantifying the environmental performance for the nation's policies . The EPI was developed to supplement the UN MDGs environmental target (Yale Center for Environmental Law and Policy, 2008). The EPI employs the outcome-oriented indicators and works as a benchmark index for advocates, policy-makers and environmental scientist. This index was designed to classify nations based on the changes in environmental performance for the past decade Yale (2008). The EPI provided a list of 21 indicators which measured five components by Yale Center for Environmental Law & Policy (2008). The components include environmental systems, institutional and social capacity, and global, reducing stress, reducing human vulnerability, stewardship. The environmental systems had five indicators including air quality, water quality, land, biodiversity, and water quantity. Reducing stress component had indicators such as decreasing air pollution, water stress, Ecosystem stress, and waste and consumption pressure. Reduction of human vulnerability had indicators such as human sustenance and environmental health. Institutional and social capacity had indicators such as science and technology, capacity for debate, environmental governance, private-sector responsiveness, and ecoefficiency (Architecture, 2013). Global stewardship has indicators including greenhouse gas emissions, international cooperative participation efforts, and reduction of transboundary ecological pressures (Yale Center for Environmental Law & Policy 2008). Another leading global indices, GGEI, provides the measure of social economic and environmental of countries' economies . It stated that nations economic development contributes to environmental improvement, even though developments are similarly linked to ecological hazards prevalence (GGEI, 2016).That water and air indicators exhibit these signals. In addition, the GGEI finding noted that in Asia countries, the wealthier the nation gets, the more investment the government puts on water and sanitation. However, in developing countries, as the nation develops, increased shipping, industrial production, and transport sector foul the air thus exposing the population to diseases. The GGEI index finding brings out an example of using an indicator to measure sustainability factors. For instance, water and air quality indicators association brings out an example of how various indicators interact (GGEI, 2016).

*Table 5 Quantitative assessment of raw materials in sustainability dimensions using AHP model (*Source: (Kolotzek *et al.*, 2018) *(Yale Center for Environmental Law & Policy 2008)*)

Supply Risk Dimension	Weighting	Environmental Risk	Weighting	Social Risk	Weighing
Concentration • company concentration • country concentration risk	35.8%	Ecosystem Quality • Agriculture land occupation • Climate change • Fresh water ecotoxicity • Marine ecotoxicity	Single values added up	Local community • Access to immaterial resource • Community engagement • Cultural heritage • Delocalization • Local employment	30.08
Demand Risk • Companion metal fraction • Substitutability • future technology	30.20				
Political risk 18.30 • Policy potential • political stability • regulation	18.30%	Human Health • Human toxicity • Ionizing radiation • Ozone depletion • Particular matter formation • Photochemical oxidant	Single values added up	Society • corruption • Prevention & mitigation of armed conflicts	32.42
Supply Risk • Recycling rate • Static reach reserves • Static reach resource	15.70%			Worker • Child labor • Equal opportunity • Fair salary • Forced labor • Freedom of association and & Bargaining • Health and safety	37.50

2.5 Gap

On the concept of sustainability of raw materials, the question remains on how to develop environmentally sustainable techniques to address the increasing demand for these raw materials. The gap there lies in the recycling of the raw materials, material reduction and system and material substitution. Industries should find ways to recycle the materials considered waste so as to reduce the pressure on the materials reserve as well as reduce Europe dependency on the imports. Also, these industries should carry out research on ways to ensure technologies function satisfactorily with fewer materials. Further, industries should focus on investing in systems or raw materials that produce the same performance without scarce materials.

2.6 Selecting Rough set Theory

Proposed in 1982 by professor Pawlak, the rough set theory is a valuable mathematical tool designed to deal with incomplete, inconsistent, imprecise knowledge and information (Pawlak, 1982). Also, the basic principle concept of rough set theory includes two parts. First part comprises, the formation of rules using the relational database classification, whereas the second part includes the knowledge discovery through the equivalence relation classification for target set approximation. Zhang (2016) defined rough set theory approach as a certain mathematical model employed in dealing with uncertain problems. Also, other methodologies for data analysis and processing including analytical hierarchy process, fuzzy set theory, probability theory, and evidence theory are different from rough set theory in the sense that, they are uncertain mathematical models used to solve uncertain problems. Further, research on rough set theory has been carried out over thirty years with successful application in many fields including databases knowledge discovery, decision analysis, pattern recognition, expert system, knowledge acquisition, medical diagnostics, conflict resolution, inductive inference, decision support and so on. Moreover, there is a consensus among scholars that the rough set theory model has achieved positive results in both applied research and theoretical research (Rissino and Lambert-Torres, 2012; Ciucci *et al.*, 2015; Zhang, Xue and Wang, 2016).

Researchers have employed different methodologies for indicator selection and their weights aggregation. For instance, Kim et al (2018) selected indicators using expert opinion and aggregated the indicator weights using fuzzy analytical hierarchy process. Gleich et al. (2013) selected the indicators through review from literature and aggregated the weights of the indicators through the use of regression analysis. Kolotzek et al. (2018) and Helbig et al. (2018) similarly selected the indicators from literature and weighted the indicators using the analytical hierarchy process (AHP) whose principle is founded on the crisp judgment. However, the above-mentioned methodologies are likely to present biased result since human preferences and choices are prone to the likelihood of uncertainty. Unlike the aforementioned methodologies, rough set approach analysis does not require additional information, models, external parameters, subjective interpretations, functions or grades to the target set. Instead, the rough set only utilizes the information provided within the available data (Zhang 2016).

2.7 Summary

The existing section has provided an analysis of literature regarding the determination of sustainability factor for assessment of CRM. The chapter provides an overview of the concept regarding the current study as brought out by other scholars. In addition, the section connects the insights of other researchers to create a comprehensive perspective of the studies concepts and counter-arguments related to the paper. Firstly, this section puts insight into the cchallenges posed by critical raw materials on both the economy, social and environmental dimensions. Moreover, the study provides a review of the indicators of CRM and sustainability development factors as brought out by other scholars. The next section provides a methodology the study employs for data collection and analysis in the examination of the studies objectives.

3 METHODOLOGY & ASSESMENT:

The study adopted study review design to identify assessments that employed indicators for sustainability and criticality analysis. The identified indicators were analyzed using the rough set theory to determine the target set preferred for the criticality and sustainability analysis.

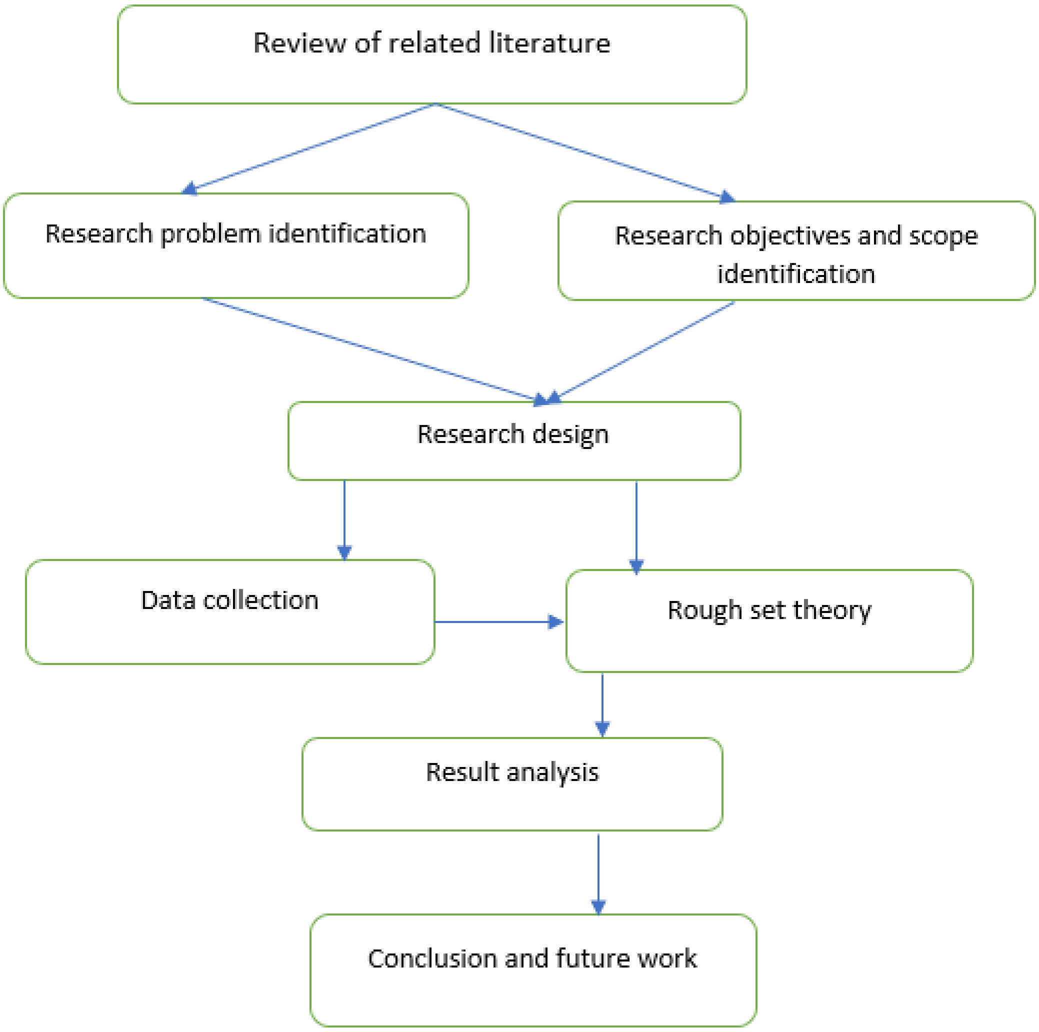

Figure 3 Flow chart of research methodology

3.1 Rough set theory

The rough set theory describes a non-statistical methodology that analyses and classifies incomplete imprecise and uncertain knowledge and information (Pawlak, 1982). The fundamental principle of the rough set theory lies in the approximation of the upper and lower boundaries of a set. The subset created by the upper approximation is defined by objects which may possibly constitute part of the subset of interest whereas the subsets created through lower boundary approximation are categorized by objects in the sets that will definitely constitute part of the subset of interest. All the subset defined through the lower and upper approximations is referred to as rough set (Rissino and Lambert-Torres, 2012). Also, this methodology has evolved to become a significant tool in resolving a number of problems including knowledge analysis, representation of imprecise and uncertain knowledge, reasoning based on redacting and an uncertain information data, and evaluation and identification of date dependency. The starting point of the aforementioned methodology is the indiscernibility relation which a central aspect of rough set theory and is regarded as the relationship between objects that have similar values in with the subset for the attributes of interest (Pawlak, 1998). Thus, indiscernibility relation describes a similarity relation, where every similar object in a set is regarded as elementary. Also, the aim of indiscernibility relation is to put into perspective the fact that lack of information makes it difficult to distinguish some objects adopting the available information. Further, another aspect of rough set theory is the decision table. The decision table incorporates, decision attribute and condition attribute and decision rule which specifies the action to be carried out when condition attributes are satisfied.

The ultimate goal for rough set theory is data reduction (Rissino and Lambert-Torres 2009). Thus, the form in which the information related to the existing study is presented in the table of information system essentially has to guarantee the avoidance of data redundancy since it implicates the limitation of complexly computational regarding setting up rules to help in decision making. Therefore, a reduct describes the set of information that remains after conducting a process of reducing the information system such that the remaining set of the reduced information is independent where further elimination of attributed results in loss of some data.

3.2 Rough set theory process

As shown in figure 2 the study, aimed to eliminate the redundant indicators for sustainability including supply risk, economic importance, social implications and environmental impacts indicators found in the selected literature to determine the sustainability indicators of criticality assessment. The second procedure involves the development of conditional attributes to be used for indicator selection. The conditional attributes used in this study included; the frequency of indicator use in other assessments and the average weight of indicators in the identified assessments. The third step is the determination of the indiscernible relations where the study will attempt to determine whether there is a relation between two or more indicators in relation to the considered set attributes. The fourth step is the approximation of the upper and lower sets. Lower set includes indicators that definitely will be weighted highly and used more frequently hence will be selected. The upper set comprises indicators that possibly will not be adopted as they will have low frequency and weight. The last step incorporates the development of the decision table to display the results.

Rough set theory process scheme

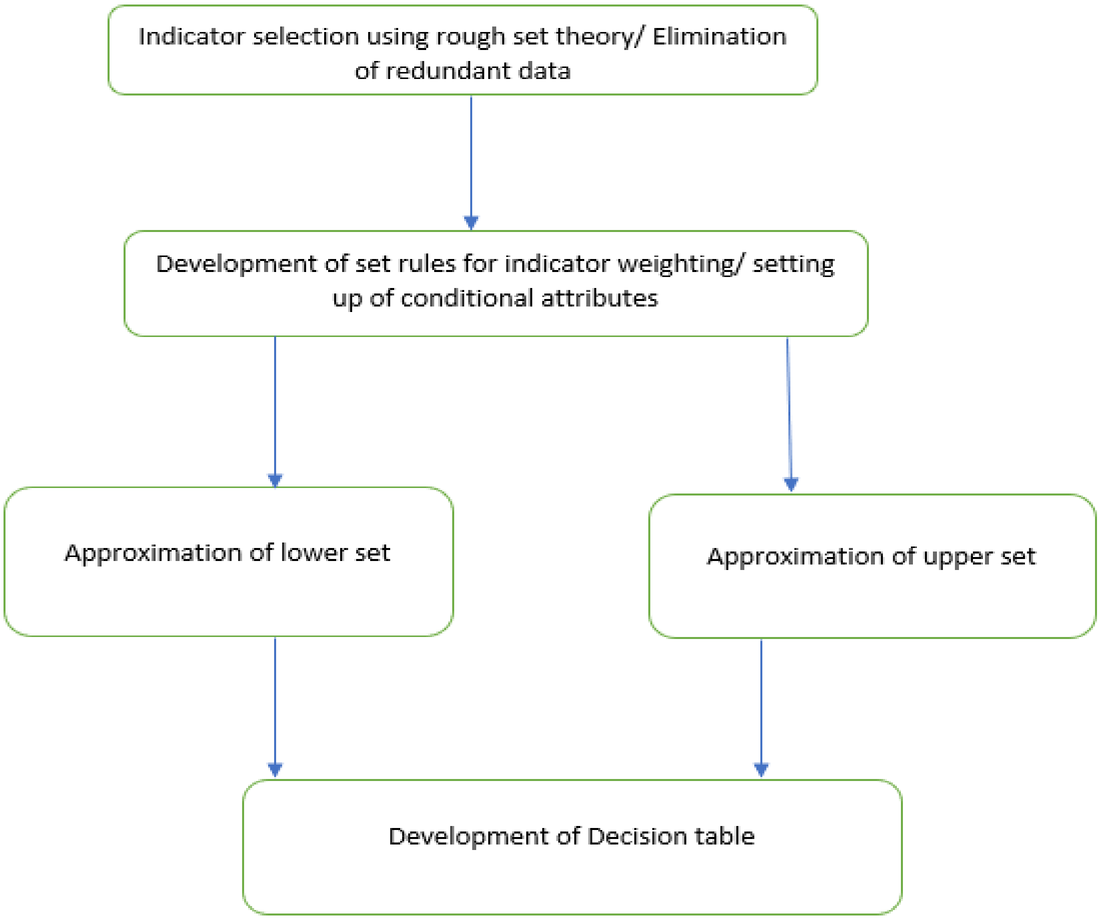

Figure 4 Rough set theory process

3.3 Steps for rough set

The rough set approach is employed as a mathematical instrument to treat the imprecise and the vague. The imprecision and uncertainty in the rough set model are expressed by a set's boundary region (Pawlak 1982). Also, the concept of this approach can be defined generally by means of closure and interior topological operations called approximations. Further, this approach which is based on data analysis begins with a data table known as an information table/information system which contains information regarding the objects of interest that are described in terms of attributes. The second step is the determination of indiscernibility relation followed by the approximations. The lower boundary is considered as the target set.

3.3.1 Information table / information system

An information table or information system is regarded as a table comprising of the objects arranged in the rows and the attributes arranged in the columns (Pawlak 1982). This table describes the conditions that need to be satisfied for the specified decision to be carried out. Further, every information system contains sets of decision algorithm which are the decision rules used in drawing conclusions. Lin (1997) noted that the Information table is used in the illustration of data that is used by rough set, where each included objective is provided with some attributes. Also, In the information table format, the rows are regarded as objects for analysis while the columns are considered for attributes.

For instance, let (I) = (U, A, C, D) represent the information system for the indicator determination, Where;

U denotes a non-empty, finite indicator set known as the universe. A denotes a non-empty finite indicator set of the selected attributes. C and D represent subsets of A where C denotes the conditional attributes whereas D denotes the decision attributes. The elements contained in set U are the indicators for evaluating the sustainability and criticality of raw materials (supply risk, economic importance, social impact). The attributes are the target characteristics conditions, features used in the rough set determination. For instance, in the determination of rough set for supply risk, economic importance, social impact indicators, B represents non-empty finite set for all the supply risk indicators obtained from different assessments. V represents a non-empty finite set for vulnerability indicators while Set S represents the set for social impact indicators. The independent variable used in the study comprise indicators for supply risk, economic importance, and social impact while the dependent variable includes the conditional and decision attributes used for determination of rough set.

3.3.2 Indiscernibility relation

Indiscernibility relation denotes an essential concept of rough set approach that describes the relation between objects (two or more) having identical values in relation to the considered attributes subsets (Rissino and Lambert-Torres 2009). Also, the rough set determination begins with indiscernibility relation determination which is determined using the data regarding the objects of interest. Pawlak (1998) indicated that indiscernibility relation describes equivalence relation in which all the sets identical objects are regarded as elementary. For instance, the indiscernibility relation information tables in this thesis contain sets consisting of attributes required for indicators of sustainability and criticality of raw materials evaluation. The indiscernibility relation of the attributes set (A), IND (P), is described partitions in the universe set U of all equivalence sets such as the equivalence sets for the conditional attributes and equivalence classes in decision attributes.

3.3.3 Approximations

Approximation of lower and upper sets is another central concept of rough set approach (Wu et al. 2004). The upper and lower sets are determined using the indiscernibility relation (Rissino and Lambert-Torres 2009). The lower approximation describes the set of domain objects that positively belongs to the subset of indicators of interest while the upper approximation depicts the set of indicators that are possibly classified as belonging to a subset of indicators of interest.

3.4 Data Collection

The thesis adopted a secondary data collection of qualitative data because the method provides the basis of acquiring broad information regarding the research problem. The study critically reviewed fifteen sources including issued papers and published journals form the EU sites. The research explored relevant electronic databases such as general databases including Google Scholar, JSTOR, Science direct, sage publications, ResearchGate, Elsevier and SpringerLink. The electronic databases search was reinforced with hand searches of materials from the library such as conference proceedings, abstracts, and books. The keywords used for electronic database searches include; Critical raw materials, CRM Indicators, Sustainability, Sustainability Indicators, supply risk indicators, vulnerability/economic importance indicators, economic impact indicators and social implication indicator.

For supply risk indicators, the assessments found to have weighted and adopted indicators for supply risk included Graedel et al. (2012), Angerer et al. (2009), Moss et al. (2011), Rosenau-Tornow et al. (2009), European Commission (2010), Erdmann et al. (2011), Frondel et al. (2006), Buchert et al. (2009), Oakdene Hollins (2008), IW Consult (2009), Department of energy (2011) and Duclos et al. (2008). For economic importance, the assessments identified included Simon et al. (2014), Roelich et al. (2014), Graedel et al. (2012), Goe and Gaustad (2014), Duclos et al. (2008), Department of Energy (2011), Angerer et al. (2009), Angerer et al. (2009), Beylot and Villeneuve (2015), Erdmann et al. (2011), Parthemore (2011), Gandenberger et al. (2012), Simo, Ziemann, and Weil (2014), to Graedel et al. (2012) European Commission (2015) and Hatayama and Tahara (2015). For social dimension the study obtained the study derived the indicator for social sustainability assessment dimension from the field social life cycle assessment (UNEP/SETAC 2009), due to the fact that quantitative assessments of raw material for the social sustainability dimension in the research area of criticality assessments are rarely available. For environmental impact, the study identified publication such as Hsu et al. (2014), Roelich et al. (2014), Goedkoop et al. (2013) and European Commission (2011).

3.5 Inclusion criteria and exclusion criteria.

The study considered the term criticality of raw material, sustainability, supply risk, social implications, and environmental impact while searching for the publications. The study included studies conducted from 2008 to 2019 while publications issued before the year 2008 were excluded. Also, publications issued between 2009 to 2019 with scope outside Europe were subsequently eliminated. further, assessment with qualitative data was eliminated.

3.6 Limitation of Study

The major limitation of this thesis was the overall shortage of grey literature related to the use of social implication and environmental impact indicators in the criticality of raw material assessment. Also, the study observed had limited information on the individual indicator weights aggregation for the environmental dimension. The study found a fair amount of grey literature on the individual indicators for the assessment of environmental impact and social implication; however, these publications did not illustrate the weights and units of measurement or the methodology for aggregating the weights of the indicators. The study acknowledges that relying on the literature review may pose threat to the study findings validity as it may fail to present the true picture of the concept of criticality in EU countries as most literature presents academic perspective even though there are other stakeholders involved. Since the scope of the study is the EU, relying on materials published only in English may exclude other important information related to the extant study. Further, the study acknowledges that rare use of some indicators may not necessarily indicate that it is of low quality since it is possible that the excluded indicator may have just been included to the list of possible indicators for supply risk or vulnerability risk. It is also likely that these indicators were excluded due to their narrowed focus. However, the data extracted from a large amount of literature reviewed provided the required information for the determination of the indicator sets.

3.7 Section summary

This chapter has provided the methodology adopted by the study for exploring the objectives of the thesis. The section incorporates an overview of the rough set theory, the procedure for conducting the analysis, the rough set theory process scheme, data collection, the mathematical steps for rough set approach, the inclusion and exclusion criteria and the limitation of the study. The next section provides the findings and results of the study.

4 FINDINGS & RESULTS

This section presents the results of the determination of indicators using rough set theory approach. Also, the section presents the selected supply risk and economic importance indicators weights as aggregated in the identified assessments. The aggregated weights are included in the findings to show how the identified assessments aggregated the weights of the indicators determined by the rough set. Further, the section displays the results of the determined environmental impact indicators obtained for the reviewed literature.

4.1 Rough set determination for Supply risk indicators

In this section, all the identified indicators for sustainability and critical raw material evaluation obtained from publications are presented in the information system tables from which the rough set approach is employed to determine the target indicators. The rough set is used to eliminate the redundant indicators using the conditional and decision attributes. Table 6 below shows the information system of supply risk indicators displaying all the supply risk indicators obtained from literature and the conditional and decision attributes used in the determination of the target set.

Table 6 Conditional and decision attributes information system table for supply risk indicators

Code	**Supply Risk Indicator**	**Conditional Attributes**		**Decision attribute (included or excluded)**
		Frequency_in_assessments	**Type_of_data**	
S1	Country concentration	9	Quantitative percentage form	yes
S2	Country risk	5	Quantitative, %	yes
S3	Depletion time	4	Quantitative, %	yes
S4	By-product dependency	5	Quantitative, %	yes
S5	Company concentration	4	Quantitative, %	yes

S6	Demand growth	4	Quantitative, %	yes
S7	Recycling/recycling potential	3	Quantitative, %	yes
S8	Substitutability	3	Quantitative, %	yes
S9	Import dependence	3	Quantitative, %	yes
S10	Commodity prices	2	Quantitative, %	yes
S11	Exploration degree	1	qualitative	no
S12	Extraction cost	1	Quantitative	no
S13	Stock keeping	1	quantitative	no
S14	Market balance	1	quantitative	no
S15	Mine/refinery capacity	1	Quantitative, %	no
S16	Extreme nature events	1	Qualitative	no
S17	Future market capacity	1	quantitative	no
S18	Mining investment	1	Quantitative,	no
S19	Climate change	1	Qualitative	no
S20	Temporary scarcity	1	qualitative	no
S21	Risk of strategic use	1	Quantitative, %	no
S22	Raw material earth's crust Abundance	1	Qualitative	no

Table 6 present the information system for conditional and decision attribute for supply risk indicator rough set assessment. The “Frequency_in_assessments” attribute shows the frequency of indicator utilization in the identified assessments while “Type_of_data” attribute shows the type of data presented. For instance, whether the weights were presented in quantitative form or qualitative form. Where A represents a set of all the supply risk indicators selected from fifteen different assessments, available for determination for criticality raw material assessments. The set of supply risk indicator is represented by B= (S1, S2, S3, S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, S14, S15, S16, S17, S18, S19, S20, S21, S22), while the set for conditional attribute for supply risk indicator is represented by C=[Frequency_in_assessments, Type_of_data] whereas set D depicts the decision attribute (indicator selection).

Table 7 below shows the nominal value of the attributes considered for the selection of indicators. Indiscernibility relation presents relations between objects where the individual indicator values are similar in relation to the considered subset attribute. As presented in Table 1, the indiscernibility relation for conditional attributes of supply risk is presented as:

o INDA (Frequency_in_more_than_3_assesments) generates two sets= [(S1, S2, S3, S4, S5, S6, S7, S8, S9), (S10, S11, S12, S13, S14, S15, S16, S17, S18, S19, S20, S21, S22)]. The first set denotes set with indicator utilized in more than three assessments where data was presented in quantitative and percentage for, while the second set represents the indicator used in less than three assessments.

o INDA (Type_of_data) = [(S1, S2, S3, S4, S5, S6, S7, S8, S9), (S10, S12, S13, S14, S15, S17, S18, S21) (S11, S16, S19, S20, S21, S22)]. The first set represents a set consisting of indicators with the frequency of use in less than three assessments and had data quantitative data presented in percentage form. The second set presents indicators used in less than three assessments with quantitative weights presented in percentage form. The third set denotes indicators used in less than three assessments and qualitative data presented. The upper and lower approximation of indicators of the set is closure and interior operations in a topology constructed by indiscernible relations.

Table 7 Nominal values of the conditional and decision attributes

	Attributes	Nominal Values
Conditional attributes	The frequency of data use in different assessments	Yes, no
	Type of Data use	Yes, no
Decision Attributes	Indicator selection	Yes, no

o For data in table 6; Lower Approximation set (A”) of indicators that definitely have attributes for selection are identified as A”=[S1, S2, S3, S4, S5, S6, S7, S8, S9] while upper approximation set (A)” of indicator that possibly will not be selected is presented as A*=[S10, S11, S12, S13, S14, S15, S16, S17, S18, S19, S20, S21, S22].

o the decision rule used to generate the decision attribute Is as follows:

Rule-1

- o If the indicator is used in more than four times assessments= yes
- o if quantitative data used and presented in percentage form =yes

Therefore, the indicators selected for supply risk include country concentration, country risk, depletion time, demand growth, company concentration and by-product dependency.

4.1.1 Country concentration

For country concentration, the study found out that ten out of twelve of the examined studies adopted this indicator. Seven out of nine of the assessments had weighted the indicators as 16.7%, two of the publications weighted the indicator as 25% while only one assessment weighted the country concentration at only 10%. Similarly, six of the publication employed Herfindahl–Hirschman index (HHI) as the unit of measurement. Two out of all the examined publications adopted the Top-3 producing concentration as the unit of measurement while one of the publications used qualitative data. The highest weight, 25%, for country concentration was given in a study by Buchert et al. (2009) while the lowest weight for country concentration was given in (Erdmann and Behrendt, 2011) .

Table 8 present the studies that had employed country concentration indicator for evaluation of supply risk indicator as well as their units of measurements.

Table 8 weights and unit of measurement of country concentration indicator as presented in identified assessments

(Source: Graedel et al. 2012; Erdmann et al. 2011; Behrendt et al. 2007; Frondel et al., 2006; Moss et al. 2011; Buchert et al. 2009; Oakdene Hollins 2008; Duclos et al. 2008; Angerer et al. 2009)

Assessments	**Conditional Attributes**	
	Weight	Measurement
(Graedel *et al.*, 2012)	16.7%	Herfindahl–Hirschman index
(Erdmann and Behrendt, 2011)	10%	Top 3

(Behrendt *et al*., 2007)	16.7%	Herfindahl–Hirschman index
(Frondel, Horbach and Rennings, 2007)	16.7%	Herfindahl–Hirschman index
(Moss et al. 2011)	16.7%	Herfindahl–Hirschman index
(Buchert et al. 2009)	25%	Top 3
(Rosenau-Tornow et al. 2009)	16.7%	Herfindahl–Hirschman index
(Oakdene Hollins 2008)	25%	Top 1
(Duclos et al. 2008)	16.7%	Qualitative, together with country risk
(Angerer et al. 2009)	16.7%	Herfindahl–Hirschman index

4.1.2 Country risk

For Country risk, two out of five assessments weighted the country risk indicator as 16.7% while the other assessments weighted country risk indicator as 25%, 20%, and 16.7%. Three out of five indicators used Country risk$_N$ as the measurement unit. One assessment employed Country risk$_{HH}$ as the as the unit of measurement while the remaining assessment had. The study found that country concentration had a weight range of between 12.5% and 25%. The highest weight for country risk was given in a study by Oakdene Hollins (2008) which employed Country risk$_N$ as the unit for measurement while the lowest weight was provided in IW Consult (2009) study that similarly employed Country risk$_N$ as the unit for measurement (Hollins, 2008) . The above aforementioned findings are illustrated in table 4 below.

Table 9 weights and unit of measurement of country risk indicator (Source: Oakdene Hollins 2008; Department of Energy, 2010; Rosenau-Tornow et al., 200; IW Consult 2009)

Assessments	Conditional Attributes	
	weight	Measurement
(Hollins, 2008)	25%	Country risk$_N$
(Graedel *et al.*, 2012)	16.7%	Country risk$_{HH}$
(Department of Energy, 2010)	20%	Qualitative
(Rosenau-Tornow *et al.*, 2009)	16.7%	Country risk$_N$
(IW Consult, 2009)	12.5%	Country risk$_N$

Table 9 illustrates the aggregated weights and units of measurements as presented in the assessments found to have used country risk in supply risk evaluation.

4.1.3 By-product dependency

For by-product dependency, the indicator weights were aggregated differently across all the five assessments identified. Graedel et al. (2012) weighted the indicator at 50% for long term and 16.7% for short term, Duclos et al. (2008) weighted the indicator at 16.7%, Duclos et al. (2008) at 10%, Buchert et al. (2009) at 25% while Department of Energy (2010) weighted by-product dependency at 10%. The highest weight for by-product dependency (50%) was provided by Graedel et al. (2012) while the lowest 10% was provided by Erdmann et al. (2011).

Table 10 Assessments and their subsequent aggregated weighs and units of measurement for by-product dependency indicator (Source: Graedel et al. 2012; Erdmann et al. 2011; Buchert et al. 2009; Duclos et al. 2008; Department of Energy 2010)

Assessments	Weight	Measurements
(Graedel *et al.*, 2012)	50% for "long term" and 16.7% for "short term"	By-production ÷Total production
(Duclos, Otto and Konitzer, 2018)	16.7%	Qualitative
(Erdmann and Behrendt, 2011)	10%	By-production ÷Total production
(Buchert et al. 2009)	25%	By-production ÷Total production
(Bauer *et al.*, 2010)	10%	By-production ÷Total production

Table 10 show the assessments that adopted by-product dependency indicator and how the aforementioned indicator was subsequently weighted.

4.1.4 Depletion time

For depletion time indicator, the weight aggregation differed in different assessments. For instance, Graedel et al. (2012) weighted depletion time at 16.7% for short term and 50% for long term. Frondel et al. (2006) weighted depletion time at 25%, Department of energy (2010) at 40% while Duclos et al. (2008) weighted the depletion time at 16.7%. The highest weight (40%) was given by the Department of energy (2010) while the lowest was 16.7 % given by Duclos et al. (2008). Table 11 displays the assessments that adopted the depletion time indicator and their aggregated weights.

Table 11 Assessments and their subsequent aggregated weighs and units of measurement for depletion time indicator

(Source: Graedel et al. 2012; Frondel et al. 2006; Duclos et al. 2008; Department of Energy 2010)

Assessments	Weight	Measurements
(Graedel *et al.*, 2012)	16.7% for short term and 50% for long term	Years, %
(Frondel, Manuel; Grösche, Peter; Huchtemann, Dirk; Oberheitmann, Andreas; Peters, 2006)	25%	%
Department of Energy (Bauer *et al.*, 2010)	40%	%
(Duclos et al. 2008)	16.7%	Qualitative, %

Table 11 illustrates how depletion time was weighted in the identified assessments. The table displays all the four assessments that were identified to have adopted depletion time indicator in the evaluation of supply risk indicator with the units of measurements alongside their aggregated weights. As aforementioned in the introduction of the section, the displayed weights are derived directly from the displayed assessments in the table above.

4.1.5 Demand growth

For demand growth indicator, four publications examined employed demand growth indicator in the supply risk evaluation. The highest weight, 100%, was given by Angerer et al. (2009) as it was the only indicator used and the lowest weight was 10% given by Department of Energy (2011). IW Consult 2009, weighted demand growth at 20% while Duclos et al. (2008) weighted the indicator at 16.7%. the average weight for demand growth indicator of the examined studies is at 36.7% (Duclos, Otto and Konitzer, 2018). Table 12 displays the abovementioned findings

Table 12 Assessments and their subsequent aggregated weighs and units of measurement for demand growth indicator

(Source: IW Consult 2009; Angerer et al. 2009; Duclos et al. 2008; Department of Energy 2010)

Assessments	Weight	Measure
(Department of Energy 2011)	10%	%
(Angerer et al. 2009)	100%	%
(Duclos et al. 2008)	16.7%	%, qualitative
(IW Consult 2009)	20%	%

Table 12 shows publications all the four publications identified to have employed demand growth indicator for the evaluation of supply risk. Also, the table illustrates how the indicators were aggregated in the subsequent assessments as well as their units of measurements. The weights were included in this study to illustrate the fact that assessments weight the same indicators differently according to the scope of the study and the methodology used for the weighting.

4.1.6 Company concentration

Company concentration was adopted in four assessments with an average weight of 17.7%. (Erdmann and Behrendt, 2011) weighted company concentration indicator at 25%, IW Consult (2009) weighted the indicator at 10%, Department of Energy gave 20% while Behrendt et al. (2007) provided a weight of 16.7% (Bauer *et al.*, 2010) (Behrendt *et al.*, 2007). All the four assessments identified are displayed in table 13 below.

Table 13 Assessments and their subsequent aggregated weighs and units of measurement for company concentration

(Source: Erdmann et al. 2011; IW Consult 2009; Department of Energy 2010; Behrendt et al. 2007*)*

Assessments	Weight	Measure
(Erdmann and Behrendt, 2011)	25%	Top 3
(IW Consult 2009)	10%	Top 3

(Bauer *et al.*, 2010)	20%	HHI
(Behrendt et al. 2007)	16.7%	n/a

Table 13 displays the assessments that employed company concentration and their aggregated weights. Also, the table displays the units of measurements utilized in the identified publications.

4.2 Rough set determination for vulnerability Indicators

In this subsection, several indicators for vulnerability evaluation are analysed using rough set theory, to determine the target set for vulnerability evaluation. Firstly, all the indicators identified in the publications are displayed in the information system with the conditional and decision attributes. Secondly, indiscernibility relation is determined followed by the target set determination. Table 14 below illustrates the information system table used in the elimination of redundant indicators by rough set approach.

Table 14 Conditional and decision attributes information system table for vulnerability indicators

code	Vulnerability indicator	Conditional Attributes		Decision Attribute (included or excluded)
		Frequency in of use in assessments	Average rating by panelist in assessments	
V1	Substitutability	8	More than 4	Yes
V2	Value of affected product	4	More than 4	Yes
V3	Future demand	5	More than 4	Yes
V4	Strategic importance	4	More than 4	yes
V5	Value of material utilized	4	More than 4	yes
V6	Spread of utilization	3	More than 4	yes
V7	Ability to pass-through	2	Less than 4	No
V8	cost increases	1	More than 4	No
V9	Change in demand share	1	Less than 4	No

V10	Import dependency	1	More than 4	No
V11	Target group's demand share	1	Less than 4	No
V12	Ability to innovate	1	More than 4	No
V13	Change in imports	1	More than 4	No
V14	Company concentration	1	Less than 4	No
V15	Consumption volume	1	More than 4	No
V16	Mine production changes	1	More than 4	No
V17	Price sensitivity	1	Less than 4	No
V18	Primary material price	1	More than 4	No
V19	Climate change	1	Less than 4	No
V20	Depletion potential	1	Less than 4	No
V21	Recyclability	1	More than 4	No
V22	Exploration budget	1	Less than 4	No
V23	Material Abundance	1	Less than 4	No

Table 14 presents information system showing the conditional and decision attributes of vulnerability indicators. The table displays all the indicators in set V, set C for conditional attributes and set D for the decision on whether to include or exclude. Where, V represents the set for all the indicators identified in the publication from which indicators for economic importance evaluation are selected from. Set V = [V1, V2, V3, V4, V5, V6, V7, V8, V9, V10, V11, V12, V13, V14, V15, 16, V17, V18, V19, V20, V21, V22, V23], the set for indicators conditional attributes are denoted by C= [frequency_in-assesments, Average_rating] and set D denotes= (Inclusion for criticality assessments). The indiscernible relation for indicators in set V represents all indicators with similar characteristics in relation to the conditional attributes. The indiscernible relation is represented by;

o INDA (Frequency_of_use_in_more_than_3_assessmnents) = [(V1, V2, V3, V4, V5, V6,), (V7, V8, V9, V10, V11, V12, V13, V14, V15, V16, V17, V18, V19, V20, V21, V22, V23)].

o the indiscernible relation for average rating in assessments similarly generated two sets: INDA (Average_rating) [(V1, V2, V3, V4, V5, V6, V8, V10, V12, V13, V15, V16, V18, V21), (V7, V9, V11, V14, V17, V19, V20, V22, V23)].

o The lower approximation set of indicators that are definitely included are defined as V" = [V1, V2, V3, V4, V5, V6] while lower set approximation (V') for indicators that are definitely excluded are identified as V" = [(V7, V8, V9, V10, V11, V12, V13, V14, V15, V16, V17, V18, V19, V20, V21, V22, V23)].

o Similarly, the upper indicator approximation set that possibly will be included are identified as V*= [(V1, V2, V3, V4, V5, V6, V8, V10, V12, V13, V15, V16, V18, V21)]

o the upper indicator approximation set that will not be possibly included are defined as V*= [(V7, V8, V9, V10, V11, V12, V13, V14, V15, V16, V17, V18, V19, V20, V21, V22, V23)].

Decision Rule

If the indicator is used in more than three assessments= yes (included)

If the indicator has an average rating of more than 4= yes (included)

Therefore, the indicators selected for vulnerability assessments included Substitutability, Value of affected product, Future demand, Strategic importance, Value of material utilized and Spread of utilization.

4.2.1 Substitutability indicator

Substitutability is the most utilized indicator of vulnerability with eight of the observed studies utilizing substitutability. However, as displayed in the table 10, only four out of eight had weight aggregation of substitutability which had an average weight of 23%. Graedel et al weighted substitutability at 33.3%, although the assessment divided the indicator into four substitutability sub-indicators and weighed them equally at 8.33%. the indicators included the import reliance, price ratio, environmental impact, substitute available and substitute performance. Duclos et al. (2008) and the Department of Energy (2011) weighted the indicator at 25% while (Erdmann and Behrendt, 2011) gave the lowest weight at 10% (Duclos, Otto and Konitzer, 2018). The remaining four studies that employed substitutability had no weight aggregation.

Table 15 displays the assessments observed to have used substitutability indicator. The table presents the aggregated weights and the unit of measurement of substitutability as provided in the assessments.

Table 15 weights and units of measurement of substitutability indicator in identified publication

(Source: Graedel et al. 2012; Duclos et al. 2008; Department of Energy 2011; Erdmann et al. 2011)

Assessment	**weight**	**measurement**
(Graedel *et al.*, 2012)	33.3%	Expert opinion
(Duclos, Otto and Konitzer, 2018)	25%	Expert opinion
(Bauer *et al.*, 2010) DOE 2010	25%	Expert opinion
(Erdmann and Behrendt, 2011)	10%	Expert opinion

4.2.2 Value of the product affected

Value of the product affected indicator, four publication employed product value to measure the vulnerability of raw materials . The European Commission (2014) used the product value as the only indicator thus provided a weight of 100%. Duclos et al. (2008) (Duclos, Otto and Konitzer, 2018) weighted product value at 25%, while (Graedel *et al.*, 2012) gave product value indicator the lowest weight, 11.1%. Table 16 presents publications, the aggregated weights and the units of measurements of the indicator as provided in the outlined assessments.

Table 16 Weight and unit of measurement for product value in identified publications

Assessment	**weight**	**measurement**
EU 2014 (G. A. Blengini *et al.*, 2017)	100%	($\sum_s$ consumption share) × (Value added)/GDP
(Duclos, Otto and Konitzer, 2018)	25%	Total revenue
(Glöser *et al.*, 2015)	Not aggerated	n/a
(Graedel *et al.*, 2012)	11.1%	Total revenue

Table 16 illustrates the assessment observed to utilize product value indicator. The table presents publications, the aggregated weights and the units of measurements of the indicator as provided in the outlined assessments. As shown in table 16, four publication employed product value to measure the vulnerability of raw materials.

4.2.3 Future demand

For future demand indicator, four studies employed future demand indicator in assessment of economic importance of critical raw material. Out of four publication observed to have utilized future demand, only two had aggregate weights. Study by Angerer et al. (2009) had the highest weight, 100% while Erdmann et al. (2011) weighted the indicator at 20%. Thus, the aggregate weight of the future demand is 40%. Table 12 illustrates the publication that adopted future demand indicator for economic importance evaluation.

Table 17 Weight and unit of measurement for future demand indicator in identified publications (Source: Angerer et al. 2009; Moss et al. 2013; Parthemore 2011; Erdmann et al. 2011)

Assessment	**weight**	**measurement**
(Erdmann *et al.*, 2009)	100%	(2030 demand from future technologies)/ (2006 supply)

Moss et al. (2013) (Achzet and Helbig, 2013b)	Not aggregated	n/a
(Parthemore, 2011)	Not aggerated	n/a
(Erdmann and Behrendt, 2011)	20%	(2030 demand from future technologies)/ (2006 supply)

4.2.4 Strategic importance

For strategic importance three out of the four studies observed to have adopted strategic importance had aggregate weights. (Simon, Ziemann and Weil, 2014) gave the highest weight, 100%, (Roelich *et al.*, 2014) weighted strategic importance at 50% while (Graedel *et al.*, 2012) weighted the same at 11.1%. Table 18 displays the publications identified to have employed strategic importance indicator for the evaluation of the vulnerability risk of critical raw material.

Table 18 Weight and unit of measurement for strategic importance indicator in identified publications

Assessment	**weight**	**measurement**
(Simon, Ziemann and Weil, 2014)	100%	Expert opinion
(Roelich *et al.*, 2014)	50%	Expert opinion
(Parthemore, 2011)	Not aggerated	n/a
(Graedel *et al.*, 2012)	11.1%	Expert opinion

4.2.5 Value of material utilized

Among all the four studies observed to have employed the value of material utilized, only one assessment had an aggregated weight. (Graedel *et al.*, 2012) weighted value of material utilized at 16.7%. The other studies had no aggregation.

Table 19 illustrates the assessments that adopted value of material utilized indicator for evaluation of economic importance of raw materials.

Table 19 Weight and unit of measurement for value of material utilized indicators in identified Assessments

(Source: Department of Energy 2011; Goe and Gaustad 2014; Duclos et al. 2008; Graedel et al. 2012)

Assessment	**weight**	**measurement**
Department of Energy (2011)	Not aggregated	Consumption rate
Goe and Gaustad (2014)	n/a	Expert opinion
(Duclos, Otto and Konitzer, 2018)	Bottleneck	metal price × metal use
(Graedel *et al.*, 2012) (Achzet and Helbig, 2013b)	16.7%	(metal price × metal use)/ GDP

4.3 Social sustainability dimension.

The study derived the indicator for social sustainability assessment dimension from the field social life cycle assessment (SLCA) (UNEP/SETAC 2009), due to the fact that quantitative assessments of raw material for the social sustainability dimension in the research area of criticality assessments are rarely available. Due to the issue of data availability, the Rough set assessment did not consider the frequency of the indicator used in in the selected assessments for conditional attributes. Therefore, the condition attributes included the quantifiability of the indicator, data gaps in relation to data non-availability in the field of criticality assessment and relevance of the indicator concerning the extraction process of the raw material. For instance, Ekener-Petersen & Finnveden (2013) most of the social assessment models developed focus on supply chain and the raw material extraction, therefore social indicators related to consumer category are excluded (Ekener-Petersen and Finnveden, 2013) .

4.3.1 Rough set determination for social impact

For the social impact, the indicators derived from social life cycle assessment (SLCA) field were presented in the information system table and rough set determined using data gap and relation to consumer category as the conditional attribute. From the information system table, the indiscernibility relation sets were determined from which the approximations were evaluated.

Table 20 below displays the social dimension information system for rough set evaluation. The table displays all the identified social dimension indicators the conditional attributes used for elimination of redundant indicators as well as decision attributes.

Table 20 presents the information analysis table for social dimension indicators. On conditional attributes the cells marked X on data gap attribute denotes indicators that don not have data gap while the cells checked denote indicators with data gap. On “Related_to_consumer_category” attribute, the cells marked X indicate indicators that are not related to consumer indicator category whereas the checked category denote indicators that are related to the consumer category.

Table 20 Table displaying information system for analysis of social dimension indicator conditional and decision attribute

Code	Social dimension indicator	Conditional Attributes		Decision attribute
		Data_gap	Related_to_consumer_category	
S1	Transparency	X	✓	no
S2	Health and safety of consumers	X	✓	no

S3	Feedback mechanism	X	✓	no
S4	Consumer privacy	X	✓	no
S5	End of product life responsibility	X	X	yes
S6	Child labor	X	X	yes
S7	Equal opportunities	X	X	yes
S8	Fair salary	X	X	yes
S9	Forced labor	X	X	yes
S10	Freedom of collective bargaining and association	X	X	yes
S11	Health and safety of workers	X	X	yes
S12	Social benefits	✓	X	no
S13	Working Hour	X	X	yes
S14	Fair competition	✓	X	no
S15	social responsibility promotion	✓	X	no
S16	intellectual property protection	✓	X	no
S17	Supplier relationships	✓	X	no
S18	immaterial resources access	X	X	yes
S19	material resources access	X	X	yes
S20	Community engagement	X	X	yes
S21	Cultural heritage	X	X	yes
S22	Migration and delocalization	X	X	yes
S23	Local employment	X	X	yes
S24	Respect of indigenous rights	X	X	yes
S25	Safe and Healthy living conditions	X	X	yes
S26	Secure living conditions	X	X	yes
S27	Contribution to economic development	✓	X	no
S28	Corruption	X	X	yes
S29	Prevention and mitigation of conflicts	X	X	yes

As displayed in table 20, the set for indicators selected for evaluation of social indicator is identified as;

- Set S= [S1, S2, S3, S4, S5, S6, S6, S8, S9, S10, S11, S12, S13, S14, S15, S16, S17, S18, S19, S20, S21, S22, S23, S24, S25, S26, S27, S28, S29]
- The set conditional attribute for social dimension is identified as C= [Data_gap, Related_to_consumer_category]
- The set for decision attribute is identified as D= (included)

The indiscernible relation of the social dimension indicators as derived from table 10 is presented as

- INDA ({Data_gap}) = {(S1, S2, S3, S4, S5, S6, S6, S8, S9, S10, S11, S13, S18, S19, S20, S21, S22, S23, S24, S25, S26, S28, S29), (S12, S14, S15, S16, S17, S27)}.
- INDA ({Related_to_consumer_category}) = [(S1, S2, S3, S4), (S5, S6, S6, S8, S9, S10, S11, S12, S13, S14, S15, S16, S17, S18, S19, S20, S21, S22, S23, S24, S25, S26, S27, S28, S29)]

Lower Approximation for social dimension set (S”) of indicators that will definitely be selected are identified as;

- S” = {S5, S6, S6, S8, S9, S10, S11, S13, S18, S19, S20, S21, S22, S23, S24, S25, S26, S28, S9}

Lower Approximation social dimension set (s”) of indicators that will definitely not be selected is identified as;

- S” = {S1, S2, S3, S4, S12, S12, S14, S15, S16, S17, S27}

Decision rules

Rule-1

R1: indicator

If Data_gap marked X = yes (means there is no data gap)

If Related_to_consumer_category marked √= no (means the indicator is related to consumer category)

Therefore the set of indicators for social dimension include immaterial resource access, material, resources access, community engagement, cultural heritage, migration and delocalization, local employment, safety and healthy living conditions, secure living conditions, corruptions, prevention and mitigation of conflicts, child labour, equal opportunity, fair salary, forced labour, health and safety , and working hours.

4.3.2 Environmental impact

The identified indicators for environmental impact included the ecosystem equality subcategories such as agriculture land occupation, climate change, freshwater ecotoxicity and eutrophication, marine ecotoxicity, natural land transformation, terrestrial acidification, terrestrial ecotoxicity, and urban land occupation. Human health subcategories include climate change human health, human toxicity, ionization radiation, ozone depletion, particulate matter formation, and photochemical oxidant. For instance, Hsu et al., (2014) utilized the Environmental Performance Index (EPI) to assess the two AoPs, human health, and ecosystem equality. Similarly,” (Roelich *et al.*, 2014) and (Group, 2010) European Commission (2010) utilized LCIA methods to assess the two areas of protections (AoP). Also, the study determined that Goedkoop et al., (2013) and European Commission (2011) used the LCIA ‘ReCiPe’ methodology to assess human health and environmental equality aspects of environmental impact (Goedkoop *et al.*, 2013,). The study noted that the overall weight of the LCIA method is additive. Therefore, the environmental impact of a given product can be determined by adding up the identified contents of the weights of the raw materials in relation to their masses. The ecosystem equality subcategories include agriculture land occupation, climate change, freshwater ecotoxicity and eutrophication, marine ecotoxicity, natural land transformation, terrestrial acidification, terrestrial ecotoxicity, and urban land occupation. Human health subcategories include climate change human health, human toxicity, ionization radiation, ozone depletion, particulate matter formation, and photochemical oxidant (Bach, 2017).

4.4 Section summary

This section has provided results and findings displayed in tables. The tables display results of rough set assessments and the review of the available literature related to the extant study. The next chapter provides the discussion section that presents a broader perspective of the finding.

5 DISCUSSION

The indicator determination model presented in this thesis fulfils several requirements for application in government, corporate, and research contest as it reviews all publications. The sets of indicators determined in all the sustainability dimensions are readily applicable for research, companies, and governments functions. Compared to other assessment's, the existing study considers all the three-sustainability, including economic (supply and vulnerability risk), social and economic importance. Also, the study employed a rough set theory for determination of sustainability indicators for criticality assessment. The indicators determined from the review of literature touching on all dimensions of sustainability are readily applicable and relevant in research, industry and government assessments since they were obtained from different publications with different targets and scope using different methodologies.

The determined most preferred indicators for the evaluation of sustainability factors related to criticality of raw materials for supply risk indicators include country concentration, country risk, depletion time, demand growth, company concentration, and by-product dependency. The determined set of most preferred indicator for vulnerability supply includes substitutability, the value of the affected product, future demand, strategic importance, the value of material utilized, and the spread of utilization. The set for social dimension had indicators such as immaterial resource access, material resources access, community engagement, cultural heritage, migration and delocalization, local employment, safety and healthy living conditions, secure living conditions, corruptions, prevention and mitigation of conflicts, child labour, equal opportunity, fair salary, forced labour, health and safety , and working hours. Lastly, the most preferred indicators for environmental impact include two subcategories, such as the ecosystem equality and human health subcategories. The ecosystem equality included agriculture land occupation, climate change, freshwater ecotoxicity and eutrophication, marine ecotoxicity, natural land transformation, terrestrial acidification, terrestrial ecotoxicity, and urban land occupation. Human health subcategories include climate change, human health, human toxicity, ionization radiation, ozone depletion, particulate matter formation, and photochemical oxidant.

The target indicators set determined by rough set for supply risk, are the indicators with the highest frequency of utilization in the assessments with weights of the indicators presented in quantitative form as percentages. It is evident from the results that country concentration is the most utilized indicator for supply risk evaluation followed by, depletion time, by-product dependency, company concentration, and demand growth.

On comparisons of the results of this thesis with other studies, there are several notable similarities in relation to the set of indicators used for supply risk evaluation. For instance, Kolotzek et al. (2018) reviewed a number of publications and determined that country concentration, depletion time, company concentration, by-product dependency, and demand growth, were the most preferred indicators for the supply risk evaluation. However, the study by Achzet and Helbig (2013) differed with the findings of this study in relation to the preferred target set for supply risk indicator in the sense that recycling/recycling potential, substitutability, and Import dependence were included in the target set. For the target set of indicators for economic importance determined by rough set theory, substitutability was the most utilized indicator followed by future demand, strategic importance, the value of material utilized and the spread of utilization. In comparison to other publications, there was some degree of similarities with the study by Helbig et al. (2016) which analyzed sixteen publications targeting indicators for vulnerability assessments and found that sustainability was the most employed indicator with eight out of sixteen studies reviewed, followed by product value which was used in six evaluations. Also, future demand and strategic importance were used in five out of sixteen studies, while material value was used in four studies. Due to the issue of data availability, the rough set assessment did not consider the frequency of the indicator used in in the selected assessments for conditional attributes. Therefore, the condition attributes included the quantifiability of the indicator, data gaps in relation to data non-availability in the field of criticality assessment and relevance of the indicator concerning the extraction process of the raw material. For instance, according to Ekener-Petersen and Finnveden (2013), most of the social assessment models developed to focus on supply chain and the raw material extraction, therefore social indicators related to consumer category are excluded. On the determination of environmental impact, all the studies identified considered two areas of protection (AoPs) including human health and ecosystem quality. Despite employing different methods for evaluation of environmental effects, these assessments have utilized the two AoPs. These findings are consistent with assessment by Hofstetter (2002), which applied eco-indicator 99 models adopted human health, ecosystem quality, and resource depletion. The results are consistent with the current study in the sense the present study derived human health and ecosystem equality as indicators for environmental impact.

5.1 Chapter Summary

This chapter has provided a broader perspective on the findings of the thesis as guided by the objectives. Also, the section compares the findings of the study to findings of other assessments related to weighting and aggregation of indicators of sustainability for critical raw materials assessments. The section attempts to link works of other scholars to the findings to support the thesis concept and create a general perspective about sustainability factors. The next chapter provides the conclusion which provides an overview of the thesis.

6 CONCLUSION

The concept of raw material criticality and its assessment has gradually become more significant in the recent EU raw materials strategies. It is also acknowledged that further studies are required to help in the determination of risk indicators as well as the aggregation of the subsequent risk indicators since they are largely reliant on the subjective viewpoint of the evaluator. This thesis introduced the rough set theory to determine the sets of indicators for the evaluation of sustainability and raw material criticality. Further, the objective of this study opens up a new direction towards assessing the criticality of raw material using sustainability indicators. Sustainable consumption and production of raw materials can be achieved if the actors involved in the market take responsibility. The ultimate objective is putting the environment into consideration in all decision-making process by the stakeholders such as consumers, retailers, the government and the industry. This is a gradual development process that has to be nurtured by sufficient motivations from both sides of materials demand and supply. The scope of this thesis includes analysing driving factors that determine the criticality of raw materials from social, ecological and economic perspectives.

This thesis comprehensively aimed to determine the indicators of supply risk, economic, social and environmental dimensions of sustainability for the raw materials criticality evaluation. Also, the study quantitatively evaluated the existing difference in weight of the indicators as perceived by a panellist from research and industry. The study was conducted because, although, different assessment has used indicator-based models to assess criticality, few had explored the whole sustainability concept that incorporates, environmental, social and economic dimensions.

The thesis has broadly determined the most preferred indicators for the evaluation of sustainability factors related to criticality of raw materials. The thesis has highlighted the significant sets of indicators valuable for the assessments of supply risk, social implication, economic importance, and environmental impact. The study found the set for supply risk indicators to include country concentration, depletion time, country risk by-product dependency, company concentration, and demand growth. Set for vulnerability indicator included substitutability, future demand, value of affected product, strategic importance, value of material utilized and spread of utilization. The set for social dimension indicator the study found to include immaterial resource access, material resources access, cultural heritage, community engagement, migration and delocalization, local employment, safety and healthy living conditions, secure living conditions, corruptions, prevention and mitigation of conflicts, child labour, equal opportunity, fair salary, forced labour, health and safety , and working hours. For environmental indicator the set include the two AoPs, human health, and ecosystem equality and all the associated subcategories. The present overview of the sustainability indicator can help future assessments to select indicators for the sustainability of the corresponding threshold and subsequently weight the best fitted for harmonizing criticality evaluation methods and the corresponding focus for the criticality assessment. The comprehensive approach to selection and aggregation of sustainable indicators can be view as the starting point for improved understanding of the sustainability concept of critical raw materials.

6.1 Implications

The current overview of sustainability can help future assessments related to criticality to select indicators, weight the indicators and their corresponding threshold related to all the dimensions of sustainability of raw materials that are best fitted for the focus that corresponds with the studies objectives and to harmonize the CRM evaluation methods. Furth more, communities in the EU as a whole will be better off if the explored sustainability factors in relation to environmental and social dimension are considered when determining the criticality of the raw materials as social needs of the public and harmonious environments can be established. Social equity will be sustained which will translate to improved quality of life of the EU residents. The results of this thesis can provide a platform for researchers interested in sustainability aspect of CRM, to conduct research that will address the existing gap on the use of social and environmental indicators for the assessment of the criticality of raw materials. Following this perspective, the general sustainability associated with CRM can be enhanced thereby ensuring the interests of the contemporary society, as well as the future generations, are safeguarded. Further studies should focus on developing models for assessing the criticality of raw materials using all the determined sustainability indicators dimensions. Further, since there is very limited data regarding the evaluation of indicator scores for the environmental dimension, researchers should, therefore, focus on the area. Also, the individual sustainability indicators determined in this study must be validated further, possibly with real cases of a raw material supply shortage.

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