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Department of Environment, Land and Infrastructure Engineering

M.Sc. Thesis

Economic assessment for the criticality of essential raw materials employed in the drilling sector of the Oil & Gas industry using company oriented method

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This modest work is dedicated to my dear father.

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Abstract

The issue of raw material criticality existed historically in various context and was tackled in different ways; remerging again in the last decade, triggering a wave of studies to confront this matter, which coverage was limited to an orbit of repeated topics such as renewable technologies ; thus within our knowledge this is the first time a work was done in an attempt to bring the spotlight of this topic into a classical sector, in our case the drilling sector of the oil and gas industry; displaying the concept of methods used mostly; using a company oriented method that evaluates the relative risk of the Supply dimension of materials, indispensable to conduct the drilling operations, used in the manufacturing of drill pipes, casings and drill bits or used in the mixture of drilling fluids for fracking, that was found to be of Mid-high level for the majority of them, highlighting the potential importance of an underestimated indicator and some suggestion for further development.

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List of Abbreviations

CMF .... *Companion Metal Fraction*
CompC .... *Company Concentration indicator*
CountC .... *Country concentration index*
CRM .... *Critical Raw Material*
DOC.. *Department of the Commerce*

DOD .... *Department of the defense*
DOE..*Department of Energy*
DOI..Department Of the Interior
DOJ .... *US- Department Of Justice*
E.O. ....*Executive Order*
EC..*European Comission*
EOL-RR .... *End of life- recycling rate*
GDP.. *Gross Domestic Product*
HD.. *Human Development*
HHI..*Herfindahl-Hirschman Index*
NRC..*National Reaserch Council*
PP.. *Policy Potential indicator*
PPI.. *Policy Perception Index*
PS..*Political Stability indicator*
REE..*Rear earth Elements*
Reg.. *Regulation indicator*
RM ....*Raw Material*
RR .... *Recycling Rate*
SR..*Supply Risk*
SRRC.. *Static Reach Resource indicator*
SRRV ....*Static Reach Reserve indicator*, *Static Reach Reserve indicator*
Subs ....*Substitutability indicator*
TCMF..*Transformed Value of Companion Metal Fraction indicator*
Tcompc ....*Transformed value of company concentration indicaotr*
Tcountc .... *Transformed value of country concentration indicator*
THHI..*Transformed value for a concentration indicator*
TPP........................ *transformed value of Policy Potential indicator*, *transformed value of Policy Potential*
TPS.. *Transformed Value of Political Stability indicator*
TRR..*Transformed value of Recyclin Rate indicator*
TSRRC..*Transformed Value of Static Reach Resource indicator*
TSRRV.. *Transformed value of Static Reach Reserve indicator*
TSUB ....*Transformed value of Substitutability indicator*
UNDP .... *United Nation Development Programme*
WGI-PV ....*World Governance Index - Political Stability and abscence of violance*

Introduction

Our modern societies rely on wide range of periodic table elements, in many sectors, not just in technology advancement but also in creating new types of energy sources competing with traditional ones, has increased the demand for these materials, coupled with the needs of rising economies, created a conversion from traditional fossil fuel chains (i.e. cuffs) to that of minerals.

In the past decade or so, some apparent innocent actions taken by the Chinese government to guaranty the feed for its own industrialized economy, to create a higher value through extending beyond the extraction phase, has led to a sever shock for other mouths (i.e. other manufacturers);as a result triggered price hike and reactive measurement to counter the effects on different levels from replacing these materials (or at least optimizing it content in different ways from redesign to substitution), stocking, exploration incentives, etc… it seems all well, however this urging need of everlasting hungry industries (the veins of their own nations, at least at some point when it is still beneficial), leads to a normal historical conflicts each for his own interests, that usually triggers unfortunate events of wars, the final tool of politicians when diplomacy and other means fails, which holds within life or destruction of different sides on different levels.

Our story will take form in the era of post ww1, when the term criticality of materials emerged in recent history with different names and actions, and changed with the course of time (Buijs et al., 2012).

The issue here is in fact a normal manifestation imbedded in our human nature and also in our nations, as time moves on, people start from a baby and grow to reach its climax at a certain age with a brief plateau of relaxation then followed by a steep decline towards oldness and concluded by death; as such nations follow the same pattern, in cyclic form, one nation rise on the remains of the other (Ibn khaldoun, 13th century).

The traditional matured industrial countries reaching climax will suffer a transition phase from manufacturing to service system.

With dominance of criticality studies covering materials employed in new technologies, electronics and other,… there is a lack of coverage of other sectors, which spurred the trial here to assess a set of materials used in the drilling sector of the Oil and Gas Industry, displaying for the first time, within our knowledge, the effect of the raw material criticality phenomena on a traditional energy sector form the supply risk perspective.

First we start with fast track of history followed by a brief overview of main ways used in criticality calculation, we show the method used by us here and display the indicator performance for the considered materials, conducting a comparison with other methods at national level, concluded by our conclusion and some suggestion for improvement.

Historical approach to criticality

The criticality of raw materials (RM) is a concept created by governments agencies as a reaction to supply shortage and price spikes, sounding the alarm as a dump reaction without proactive plans (Diemer et al., 2018), stretch back in time with different names.

The fear over availability is seen in the past through windows of awakening that emerged during a period of tension(s) (on different levels global politics, economic crisis, war escalation), then hibernate again (example related to Soviet Union fall and its corresponding effects on the global trade and abolishment of fierce armed conflicts (Buijs et al., 2011)) until the next "fiesta", Which is linked with the natural cyclic crisis of economic systems.

The awakening of the "yellow genie" through economic reform, with the fading of soviet union, led with time to the booming of its economy; thus becoming the largest producer and consumer of minerals in the world, that triggered (with some action taken) the sensation of "inadequate" supply, shaking eventually the international market (Buijs & Seiver2011a, 2011b).

Reemerging back with economic crisis 2008-2009 with Gov. reports (NRC2008 & EC2010), followed by a period of explosion in studies conduct on this problematic (Rosenau2009; Massari & Ruberti , 2013) and the pattern of publication in the later phase reflect the substantial importance of CRM issue (Gloser et al., 2015; Graedel & Reck, 2015; Helbig et al., 2016; NSTC 2016; Frenzel et al., 2017), noting that some studies could backfire through a market panic wave (Buijs et al., 2012).

Definition

Shockingly, there is no universal definition of criticality, *stretchy in some cases*, this being hard to achieve with the distinct evaluations used that changes with the perspective (national, company, global) (Diemer et al., 2018; Erdman & Graedel et al., 2011; Gloser et al., 2015; Frenzel et al., 2017), example of this stretch, "criticality denotes the current and future risk associated with "certain metals" (Gleich et al., 2013).

It should be pointed out here, that criticality is not related to the toxic characteristics of a materials nor the possible misfortune of explosion and its effects under certain conditions.

Example of the national level, in USA, based on the **definition by the presidential order in E.O. number 13817,** for the criticality of a material as, non-funeral mineral crucial for the economy and national defense of USA, characterized by a susceptible supply chain interruption, that plays a fundamental role in the creation of a product whose omission would have huge consequence on the mentioned vital sectors (Fortier et al., 2018; USGS, 2018); other governments and corporations have their own concepts and strategies of categorization of minerals or materials (US-CRM2018).

For instance, in a cluster of national economies, such as the EU, defines it critical when a RM must experience strong challenges with respect to access to it (i.e. elevated supply risk) or environmental risk and be of large monetary significance with the probability that Hurdles the access is large and effect on the entire EU economy would be comparatively notable (EC, 2010 & 2014).

And it's important to note that the EC regularly apply their assessment, with an ever expanding list of materials, and has applied a revision to its method used in 2017, with some modification, withholding as much as possible connection with earlier versions for comparison purposes, to include different **stages**

of the weak point in the supply chain (not remaining in the extraction phase); also observed by others, for instance in (Deetman et al., 2017), indicating that the CRM problematic cross the raw form of minerals into the ingrained materials in semi & finished products.

In fact, it is important to signal the possible range of disruption causes (natural disasters, workforce upheaval, trade contention, resource nationalization, war, infrastructure deficiency, etc…

For a company is that done by (Duclos et al., 2010), that displayed the method used by General electrics, to be noted here that the Supply risk approach tends to be global scope, however the impact is tailored on the specifics of the company.

Based on the remarks in (Frenzel et al., 2017), that define the criticality of a material as a judgment of the monetary danger resulting from its use (spanning from manufacturing to end-of-life) for a particular entity over a certain interval of time.

Importantly, the supply risk is proportional, that is the level changes by material, company, nation (influence of geography, for e.g. EU and Japan), industry, technology (whose rivalry over feed creates a negative impact) and time (Eggert et al., 2011; Erdman & Graedel et al., 2011; Graedel & Reck et al., 2015; Drive, 2018), to illustrate some points we list the following:

Clean technologies such as tellurium for cadmium-telluride consumed in the production of photovoltaic thin films, Indium flat panel screens (TV, Computers,...) and samarium & cobalt in permanent magnets (wind turbines), electrical cars (DOE, 2011; (Eggert, 2011) et al., 2011); continuing in this sense the U.S. DOI, DOD and DOC, each would impose a personal touch on the list based on their own targets.

The time, has the potential to decrease the criticality, design break through (when appropriate intensive “force” themselves on the later), e.g. In some high-strength metal alloys, engineering developments incorporating extra thermal treatments meant less molybdenum in a batch (Eggert et al., 2011); though it can worsen the situation via other aspects.

Additionally, by virtue of the complicated world, each study (representing a particular faction) has its own context, which prevent the existence of an utter strategy satisfying all distinct issues, henceforth the creation of wide spectrum of methods with different list of criticality.

Moreover, the criticality is of dynamic nature with time, but the method used is static “snapshot” of the situation (US-CRM, 2018 and others).

For this reason, criticality is not a permanent stigma for a material, which varies over time even within the same reference of interest; hence it isn’t an attribute (i.e. characteristic) of a mineral (Frenzel et al., 2017);

Generally speaking, exist a common ground for all these methods with 2 facets essential for RM classification:

1) Probability (i.e. “likelihood”) : possibility of supply hiccup (i.e. shortfall)
2) “Vulnerability”: susceptibility of certain user to the latter event, reflecting its significance to the former and repercussion of such incidence.
   (NRC 2008; Erdman & Graedel et al., 2011; Graedel & Reck et al., 2015; Frenzel et al., 2017).

Then, how an element would be considered critical is to be viewed in the next section.

> Distinction btw studies start from the desired system to be protected against the Supply disruption ranging from company (Duclos et al., 2010), nation (BGS, 2015; NRC, 2008; NSTC, 2016; Graedel et al., 2015), multi-national (EC 2010, 2014, 2017; Deetmann et al., 2017), government agencies (U.S. DOE for energy, DOI using USGS, DOD) , interestingly this varieties urged a desire of both house and senate to create an unified list representing the national interest of whole U.S.(Diemer et al., 2018), sector or technology (Eggert et al., 2018; Deweulf et al., 2016; king et al., 2013).

The number of material covered, wither individual or group of materials, and varies from just one up to a big set with different studies (Dewulf et al., 2016; EC 2010, 2014, 2017; NSCT 2016; Graedel et al., 2015b; Harper et al., 2015a, 2015b; Nassar et al., 2012; Nassar et al.,2015; Nuss et al., 2014; Panousi et al., 2016).

A way to classify a material is by scoring hugely on both aspects, mentioned earlier, and would be considered critical (EC, 2010);

METHODS

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Criticality matrix

ALL ROADS LEADS TO NRC

The most common way of evaluating criticality is employing "criticality matrix" (Erdman & Graedel et al., 2011); this work is derived directly and indirectly from the method developed by (NRC, 2008), e.g. (Duclos et al., 2010) indicated the usage of a modified version in suitable fashion with the internal industrial structure of General Electrics.

Which operates on 2 "wings" basis, the supply risk (SR) and the "Vulnerability" dimensions.

On one side, exist general agreement on the operational purpose of SR dimension, manifested in different indicators and different calculations; on the other side, the vulnerability lack this characteristic, nonetheless maintain its core, of assessing the burden of Supply disruption on the targeted system; this reflect the effect of the scope of each study (Dewulf et al., 2016); also noting that this doesn't necessary represent complete physical exhaustion of materials (Eggert et al., 2011).

As marked before, the distinction btw studies start from the objective established, to shield the system to be protected against the supply disruption ranging, from company (Duclos et al., 2010), nation (BGS et al., 2015; NRC et al., 2008; NSTC et al., 2016; Graedel et al., 2015), multi-national (EC 2010, 2014, 2017; Deetmann et al., 2017), sector or technology (US-DOE 2010; Eggert et al., 2018).

It is for sure rooted in the basic "Risk Analysis" domain, where each material is represented as a dot in the Cartesian coordinate system of 2 axes/dimensions

i) "Supply Risk": Probability of supply interruption
ii) "Vulnerability": Effect of the latter event, named also "Economic impact" by EC, reflects the economic burden, supplementary cost due to Supply & Demand equilibrium loss after a shock for a certain user (Helbig et al., 2016; Habib & Wegel et al., 2016).

In a summarized way, this prevailing method consist of gathering a group of indicators into an amount (i.e. “aggregated score”) for each dimension (NRC 2008), after the charting the criticality area is marked.

And here, in a glance the display of the NRC’s work inspiration in classical risk theory;

Risk= likelihood * consequence (Cox et al., 2009)

Shows the analogy from which NRC used in the following way, Criticality= SR*Vulnerability; this is not limited to the economy perspective but can be extended to other features (Frenzel et al., 2017; Gloeser et al., 2015)

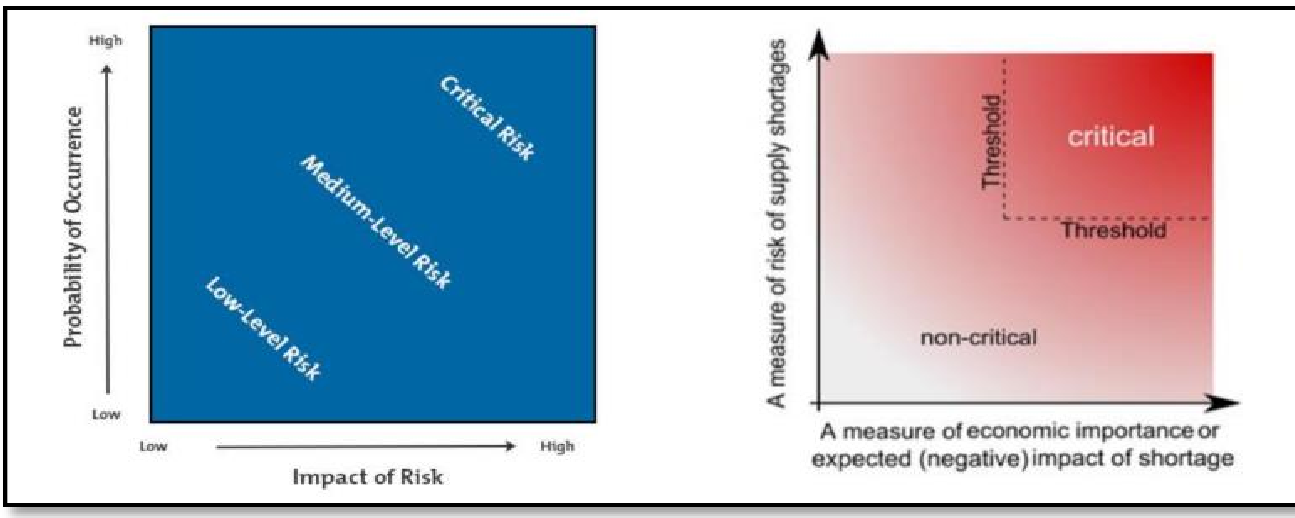

Figure 1: graphical schematization of classical risk matrix and the criticality matrix (EC, 2017)

Some consider that the true values are those resulting from methods binding from classical risk, where the final value of risk (in our case criticality) is the product of the 2 axes, that creates curved contours (shape hyperbolic) used to observe the shades of criticality degree btw different materials (Gloser-chalid et al., 2016; Frenzel et al., 2017) in classic risk theory.

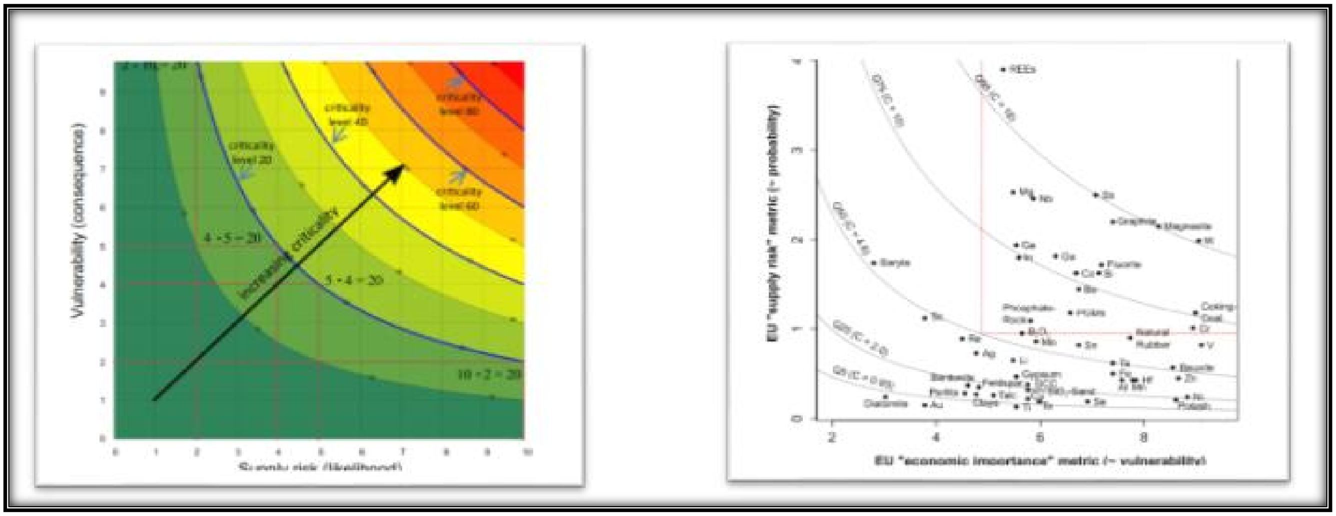

Figure 2 criticality contours inspired by classical risk theory on the left and on the right the over plotting of (EC, 2014) results and the criticality curves of different quantiles (Gloeser et al., 2015; Frenzel et al., 2017)

Not to forget, the existence of other means too, either by reducing the dimension just to one (ex: BGS2015, NSTC 2016), or extending it by another feature such as Environmental &/or social (ex: Graedel et al., 2012; Kolotzek et al., 2018).

The frequency of indicator displayed in the fig below, reflect the availability of data and the level of their quality, which can heavily effect the usage of important indicators.

Indicator	Dimension	Data type
Geopolitical concentration	SR	●
Static reserve range	SR	●
Mine production	SR	●
Economic relevance	VU	O
Supply & demand trends	SR	●
Strategic relevance	VU	O
Recycling rates	SR	●
Substitutability	VU / SR	O
Production as by-product	SR	O
Political conditions	VU	O
Company concentration	SR	●
Emerging technologies	VU / SR	O
Production costs	SR	●
Functionality & Technology	VU	O
Ability to drive through price	VU	O
Damage potential	ER	O
Impact on climate change	SR / ER	O
Exploration budget & investment	SR	●

Frequency of criteria in criticality studies

O : Qualitative data ● : Quantitative data VU: Vulnerability SR: Supply Risk ER: Environmental risk

Figure 3: frequency of indicator usage in studies (EC, 2017)

Aggregation method and final score

How aggregation of the dimensions is done, well many ways exist, that can be summarized in 3 types: summation of indicator with weight (Graedel et al., 2012; Panousi et al., 2016), Multiplication of indicators (e.g.: Vulnerability in EC, 2014) or combination of sum & product for a specific indicator, like the case of WGI-HHI (EC, 2014) or directly the final global criticality of a material (NSTC, 2016).

Obliviously, each way will get different result although having same start (i.e. indicator values) (Frenzel et al., 2017; Erdman & Graedel et al., 2011), who consider along with (Gloeser et al., 2015) that the true results emerge from sticking as much as possible with the classical risk theory, and criticize other available method on the market on the basis of their drift from the ultimate one.

Which leads, to the question of the criticality classification (i.e. the criticality area) that varies also with the beliefs; for the EC any candidate surpassing the pre-agreed cut-off value on both dimensions would fall into the danger area (e.g. EC2014) (which falls within their established definition),Noting that a change of threshold values affects the results which was observe in the 2017 version along with some modifications (EC, 2017); others use the principle of “overall criticality”, by merging the dimensions into one final value, termed by some as “overall score”, thus the classification takes a relative stance, this blend is by: summation of considered indicators (Moss et al., 2013; BGS, 2015); Euclidean distance, considered from the origin of criticality reference to the point (representing the candidate) in the space (by the inclusion of the 3rd dimension)(e.g. Graedel et al., 2012) and Geometric mean of the facets of the study (e.g. NSTC, 2016).

Given the mix of criticality classification, it is important to remember that this designation isn’t something strictly fix (weight or black) but is a relative magnitude, some are more critical while other are more important than others (Graedel & Reck, 2016; Dewulf et al., 2016).

Likewise, going up or down? Direction arise, in “Bottom-up” technics, measuring the quantity used in a product, yet misses to describe the importance of their suspect in economy (e.g. loss or recycling in the product the latter is a of great help; for the other side “top-Down” path (suffering from sensitivity to calculation method and data quality) and gives additional insight for the substation effort; On the other side, the “top-down” guys regard the total CRM apparent need by industrial scale (mind free for the choice and amount in specific product) (Deetman et al., 2017).

Some authors criticize certain features of current methods of not giving theoretical reasoning behind their structure and a range of doubts of the results (Buijs & severs 2011a, 2011b; Graedel & Reck et al., 2015; Reuter et el., 2015 & Reuter 2015; Gloser et al., 2015; Frenzel et al., 2017).

The concept of false criticality should be mentioned, as an example in the (EC, 2014), based on the constant values used on both dimensions, that condemned borate as critical material and left the rubber out of this stigma, by falling out the critical area, as well as other, mentioned by (Frenzel et al., 2017).

Highlighting, the overwhelming importance of criticality methods, some sectors (renewable energy, electrical car and common electronics) steals the spot light from other classical fields (e.g. petrochemicals, glass, etc.) of equal importance, susceptible to the criticality of RM too (Deetman et al., 2017).

Overall, the majority of studies follow the 2D system, while other may: Add another dimension as the environment (Graedel et al., 2012), by implicating the important cost aspect of the later, which is included inside SR in other studies (EC 2010); being an important asset for the sustainability exist hesitation about it to enter the criticality world from the SR door or that of Vulnerability in the 2D (Dewulf et al., 2016), instead of environment a new 3rd feature is introduced as social burden (Bach et al., 2016); while others reduce to 1D (usually SR remain) as a "risk list" (e.g. BGS, 2015; JRC report; Moss et al., 2013).

In brief, the option of indicator and weighting is not objective and represent the author's point of view in many studies (Erdman & Graedel, 2011; Graeddel & Reck, 2015; Frenzel et al., 2017; Kolotzek et al., 2018); some discourage to transfer indicators from upper scale (national) to lower one (company) being meaningless for the latter in some cases (Achzet & Helbig, 2013; Kolotzek et al., 2018); adding that treating all materials with identical weighting is big underestimation of the real situation (Gleich et al., 2013), clarified by the distortion effect to the real situation when applying the HHI relation identically for all materials.

SR of drilling sector

Method's indicators

From company point of view, grasping the supply potential, political risks and competition is important for the manufacturing process of the company (Graedel et al., 2012)In order to justify not just the choice of indicator but their relative importance, using semi-quantitative path seen as better for decision making, deployed questionnaire to academia and field experts, importantly the latter made their estimation based broadly on work experience with care and then through AHP formulated their choices and weights (kolotzek et al., 2018).

It is important to mark, that indicator presented to field's expert is independent from frequency, and still the popularity of indicators is affected extensively by the presence of data (kolotzek et al., 2018)

Each indicator after calculation is transformed to the same scale based on the principles in (Graedel et al., 2012)

We list in the following the indicators included in our work:

1) **Company or Country concentration:** Concentration of the annual raw material production at company or country level, measured by the Herfindahl-Hirschman Index (HHI)

$$X_i^{RD} = \sum_j \left(100 * a_j\right)^2$$

$$X_i^{T} = 17.50 * \ln\left(X_i^{RD}\right) - 61.18$$

Where a is the share of a company or country in the global production of the material (i) under consideration (Buchholz et al., 2014; USGS 2016, 2017, 2018)

2) **Companion Metal Fraction (CMF)**: Annual share of the raw material being mined as a co-product; metals can exist within other ore metals, when sharing comparable Chemical and physical characteristic.
Thus in case of extraction the main metal in the ore is termed "Host metal", otherwise it would be called "Companion metal". (Graedel et al., 2012); thus CMF represent the global share of this material as by-product, ranging from 0-100; simply the higher CMF the chance of disruption of this material is materialized, when the Host metal production.

$$X_i^{RD} = \frac{p_i^x(as\ byproduct)}{p_i^x(total)}$$

$$X_i^T = 100 * X_i^{RD}$$

Where P is the production for the year under consideration of material (i)
(Graedel et al., 2015b; Harper et al., 2015a; Harper et al., 2015b; Nassar et al., 2012; Nassar et al., 2015; Nuss et al., 2014)

3) **Substitutability:** Assessment of the efficiency of another possible material in a similar operation, which is based on replacing the percentage of global usage of a material in a certain field of application with the average of the performance of possible substitutes only in the relative application to the study:

$$Subs_i^{RD} = Average\ (x_j) = Subs_i^T$$

Where x is the substitute j performance (0 to 100) of a material I, following (Graedel et al., 2015a).

4) **Policy Potential:**
State strategies such as tariffs or land ownership procedures will have a significant impact on the extent and mode of investment made by mining and exploration firms. (Graedel et al., 2012) Governments with flexible mining rules are expected to attract more exploration and mining activities, hence improving the prospects of mineral access, translated as a decrease the impact on SR; thus this indicator is quantified by the Policy Potential Index, being the capacity of mining countries to obtain further mining projects developed, (kolotzek et al., 2018).

$$PP_i^{RD} = \sum_j x_j * y_j$$

$$PP_i^T = 100 - PP_i^{RD}$$

Where y is policy perception index (from 0 to 100) for a country j, and x is the global production share of the latter (Fraiser institute 2015 & 2016; USGS, 2016 & 2017)

5) **Political Stability:**

The nations that are politically strong have low impact on the supply constraints; the WGI methodology, has 6 different normalized indexes, estimates the latter danger, these index involves domestic social, economic, and political variables linked to inherent weakness and financial difficulties. (Graeedel et al., 2012; Kaufmann et al., 2010); our interest is limited in the Political stability and absence of violence & terrorism (WGI-PV), that estimate the Producing countries' political unrest, weighted by the annual contribution to global output of the considered material for a certain year. (kolotzek et al., 2018)

$$PS_i^{RD} = \sum_j x_j * y_j$$

$$PS_i^T = 20 * \left(2.5 - PS_i^{RD}\right)$$

Where y is the worldwide governance indicator for political stability & absence of violence (WGI-PV) rating (from -2.5 to +2.5) (Daniel Kaufmann, 2007) for a country j, having a share x in the global production of the considered material (i) (USGS, 2016 & 2017)

6) Regulation:

HDI is an evaluation of Human Development, based on the examination of following essential indicators: health through life expectancy, education that reflect the capability of knowledge gaining and living standards via (GDP), done by the United Nations Development Program (UNDP); offer grounds for assessing a country's stage of social progress under the principle that an elevated value of social progress tends to overlap with a desire for high standard of lives over unwanted industrial activity, where these two characteristics appear to clash, here measure the Capability of the producing countries to uphold constraints on the trade of the considered material, due to their level of development, estimated via the Human Development Index (HDI) (Kolotzek et al., 2018; Graedel et al., 2012).

Hence fore, the higher the HDI, the lower the tendency for the production of materials (mining, smelting or refining), which increase the risk of disruption.

$$Reg_i^{RD} = \sum_j x_j * y_j$$

$$Reg_i^T = 100 * Reg_i^{RD}$$

Where y is HDI estimated in the corresponding year for country j, whose global share in the production is x (USGS, 2016 & 2017; UNDP, 2016 visited 2019)

7) **Recycling Rate:** determined by current end-of-life recycling rate of the material under consideration

$$RR_i^{RD} = \text{EOL-recycling rate of } i$$

$$RR_i^T = 100 - RR_i^{RD}$$

Where end of life- recycling rate, EOL (in %), is based on the average of EOL values presented in (Graedel et al., 2011; EC, 2017)

8) **Static Reach Reserves & Static Reach Resources:**
Static estimation of how many years required to consume the current reserve (or resource) based on the material's annual production for the considered year (Kolotzek et al., 2018);
The transformation formula, intends to make rapidly consumed reserves (or resources) more vulnerable to SR, thus bigger values contributing to the overall value of the later; ranging 0-100, such that the huge quantitative abundance of materials lasting for many decades or virtual inexhaustibility within the reasonable time frame contributing nothing to SR.

$$B_i^{RD} = \frac{A_i}{p_i^x}$$

$$B_i^T = max\left(0; 100 - 0.2 * B_i^{RD} - 0.008 * \left(B_i^{RD}\right)^2\right)$$

Where B is the static reach reserve or resource, and A is either reserve or resource, respectively, of material i estimated for the year under consideration, p being the global production. (USGS, 2016, 2017)

Definition of Reserve and resources:
Reserves: the portion of resources that was completely assessed geologically and is economically mineable under the law; the evaluation of amounts varies with time, in function of a bunch of factors minning technologies, metallurgy sectors, market forces, social acceptance and jurisdiction powers. (USGS, 2010) (BGS, 2015)
Resources: Volume of rock that could become feasible for extraction, has sufficient quantity with certain chemical and physical characteristics that would become economically attractive for exploitation; it include/engulf the "Reserves" and the "reserve base" (USGS, 2010) (BGS, 2015).

Weighting

The original work included the Future demand technology indicator which was eliminated in this work, due to the unpredictable nature of the Oil industry activities that evidently affect directly our sector under consideration and thus the usage.

Therefore its corresponding weight was readjusted for the other indicator within the same category first, then the complete percentage was reallocated solely to the Subs indicator, considered as the added value of this method; adding that significant effect can arise for variations in indictors weighting but still not that crucial for management (kolotzek et al., 2018).

The indicators are distributed on 4 criterias (based on Manson et al., 2011):

Criteria	weight of ind criteria	indicator	Adjusted weight	Biased weight in favor of Subs indicator
Concentration risk	35.8	Company Concentration (CompC)	15.1	15.1
		Country Concentration (CountC)	20.7	20.7
Demand increase risk	30.2	Companion Metal Fraction (CMF)	9.4	6.1
		Substitutibality (subs)	20.8	24.1
Political risk	18.3	PolicyPotential (PP)	4.4	4.4
		Political stability (PS)	8.8	8.8
		Regulation (Reg)	5.1	5.1
Supply reduction risk	15.7	Recycling rate (RR)	6.1	6.1
		Static Reach reserves (SRRV)	6.2	6.2
		Static Reach Resources (SRRC)	3.4	3.4

Table 1: the modified weight of indicators of (Kolotzek et al., 2018) used in calculation

Calculation

List Choice

The supply chain of petroleum industry is highly complex and highly rigid to any disturbance; while the drilling sector itself lies as first tier for a huge supply chain ahead of it, itself fall as a nth tier, this would manifest in this case usually through the service companies that realize these projects on behalf of the oil companies, through drilling contracts.

These projects to be materialized require the usage of a wide range of machines and equipments that need a big span of materials in their manufacturing; however a lot of these are rental, so we seek the materials used in the creation of the most dissipative equipment: the casings, the drill bits, the proppants in drilling fluids (mainly for fracking) and the drilling pipes.

Henceforth, our list consist of: Aluminum, barite, bauxite, betonite, Chromium, Iron, Manganese, Molybdenum, Nickel, Niobium, Potash, Silicon metal, ferrosilicon, silica (frac sand), Titanium, Tungsten and Vanadium.

On one hand the importance of the elements adapted for the harsh workload and conditions faced during the drilling operations, especially in the unconventional wells, dominating the future scene of this industry; on the other side the low cost of some materials is favored.

Hence, in some cases the change of delicate compositions by substitution could alter heavily the performance that might increase the possibility of failure in some cases, translated in more down-time, thus losing money in daily rates; the latter could be faced also as delay in procurement of the materials (usually a good supply management can counter these effects for an ongoing operation); in other cases the substitution (even better) could have no effect on performance but has higher cost in procurement, so in the end it is a matter of compromise btw cost saving and finishing the job.

The problem exhibit itself in the possible overall additional cost arising from such events, that can hinder the development of future projects, depending on the final return of the projects varying from region to another and even from a field to the next, not forgetting of course affected by hydrocarbon prices (through the margin of profitability).

Indicator result

REG

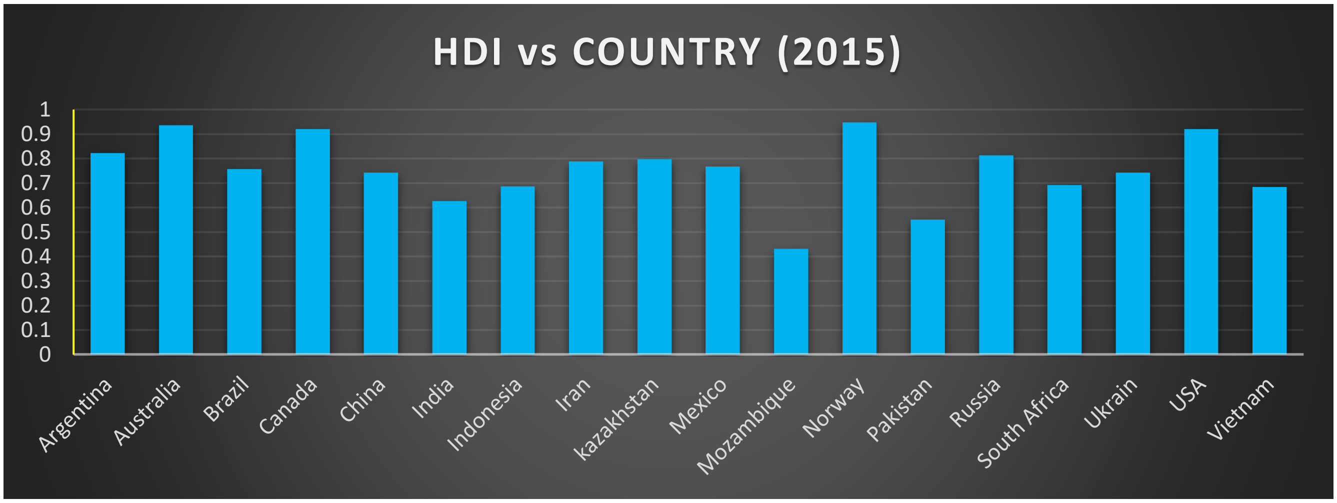

Figure 4 the Variation of HDI for some chosen countries

The values of HDI, before transformation, for the year 2015 are displayed in the figure for the most common countries of production for the considered materials in this study (the list doesn't represent all the contributing countries, but on the major repeated, independently form the quantity of production); the UNDP classify the countries into 4 classes very high Human Development (values above 0.8), High Human development (start from 0.701 until 0.799), Medium Human development (from 0.555 to 0.699) and low (below 0.555); scoring on average 0.892, 0.746, 0.631, 0.497, respectively (UNDP, 2016).

Here, it is noted that the values ranges from as low as 0.432 (Mozambique) (some of the countries in the complete list scored even lower) to as high as 0.948 (Norway) with an average of 0.757 for this sample (slightly above the global average for the same year being 0.717);

6 countries scored in the very high HD, other 6 in the high HD (including most importantly China, Brazil), the other fall in the medium HD, except for Pakistan and Mozambique (in decreasing performance).

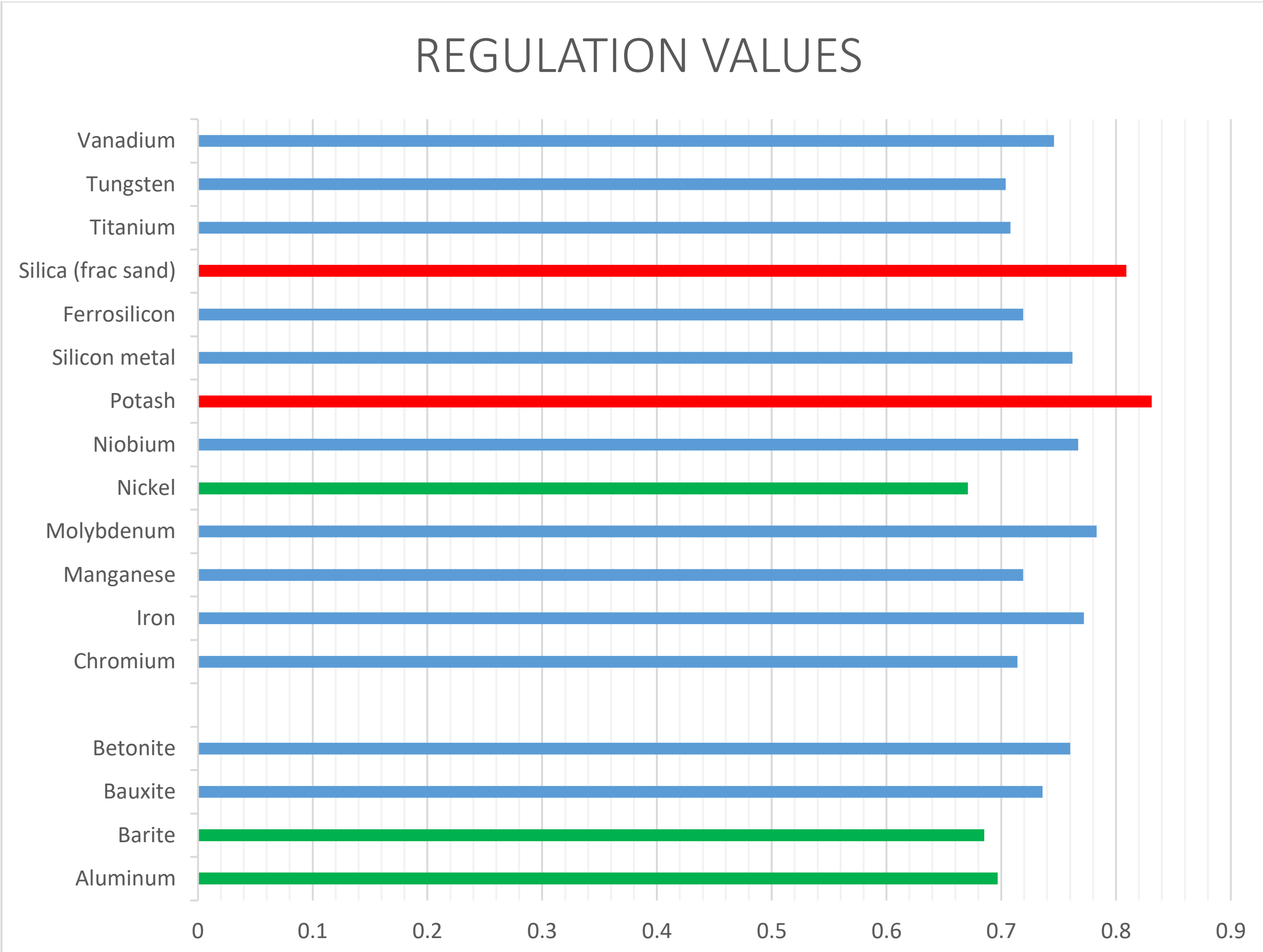

Figure 5 the values of regulation indicator for the materials.

The Regulation index scored an average of 0.740 for the list of materials under our study, with a minimum of 0.671 for Nickel and a maximum of 0.831 for potash.

We sieve the materials into 3, based on the values of Regulation index, inspired from the UNDP classification, as follows:

a) Above 0.800: Potash and Silica (frac sand) (11.8 %)
b) Below 0.699: Nickel, Barite and Aluminum. (17.6 %)
c) Btw 0.700 and 0.799: all the rest (70.6 %)

In the case of Potash, 81 % of the global production is contributed by countries considered in the very high HD, with major producer being Canada with 0.92 HDI.

For Silica (frac sand), the biggest effect can be attributed for the USA, whose HDI is equal to 0.918 with a share of half of the world production.

For Nickel, the major producer was Philippines, having 21 % of the global production with 0.693 HDI; adding that no less than 40 % of global production used in the calculation of REG, had HDI below 0.7.

While in the case of Barite although, the major producer is china (HDI =0.743, above 0.7) with a cut of 39 % of global production and the existence of US (5.2 % of production) with 0.92 HDI, but this was counter balanced by the contribution of 24.24 % to global production by other countries, in decreasing order of production: Morocco, India and Pakistan; having each an HDI value of 0.655, 0.627 and 0.551, respectively.

Now for Aluminum is falls slightly below the 0.7 cut considered, this is due to the low contribution of S. Africa (0.692) and India (0.627) both to just 5.25 % of global production, who were the only countries having HDI below 0.699.

Finally, for the third category comprising 71 % of the list under study, the REG's values vary btw 0.704 for Tungsten and 0.783 for Molybdenum.

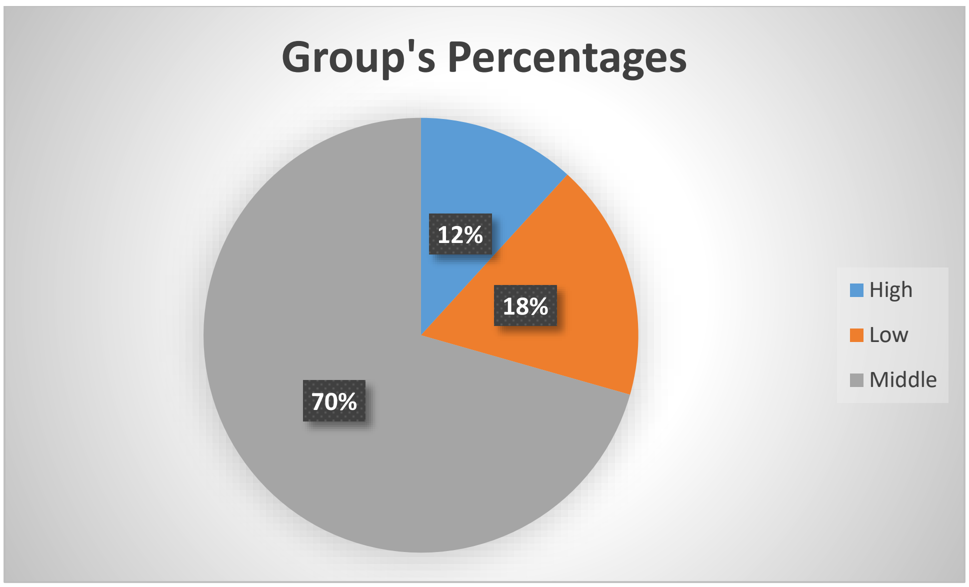

Figure 6: pie chart for distribution of list materials on the 3 defined groups

Political Stability

The values of WGI-PV indicator ranges from -2.5 to 2.5, using the weighted- average based on the individual producing countries portion of the global scale, to achieve the "political stability "(PS) indicator, with greater results suggesting improved achievement, indicating lower impact on SR; thus it is transformed into a compatible value, will range from 0 to 100 using the indicated formula, with a mindset that makes direct relation btw Transformed value and SR, i.e. light impact on SR comes from low transformed value of PS. (Graedel et al., 2012)

Table 2 the values of PS indicator in the [-2.5; +2.5] scale for some chosen countries.

Country	WGI-PV	Country	WGI-PV
Australia	0.88	**Mexico**	-0.8
Brazil	-0.33	**Mozambique**	-0.51
Canada	1.27	**Norway**	1.16
Chile	0.43	**Russia**	-1.03
China (mainland)	-0.55	**South Africa**	-0.21
India	-0.95	**Sweden**	0.95
Iran	-0.93	**Turkey**	-1.49
Japan	1.07	**Ukraine**	-1.96
Kazakhstan	-0.04	**USA**	0.68

PS value	Percentile
-2.5	100
-2	90
-1.5	80
-1	70
-0.5	60
0	50
0.5	40
1	30
1.5	20
2	10
2.5	0

Table 3 the corresponding values of Political Stability indicator in 2 scales (on the left).

These countries represent a sample of the countries contributing to the production of the material considered in this study, which were split into 2 states:

a) WGI-PV above zero: ranging from the least stable Chile (0.43) to the most Canada (1.27), within this category and represented sample, with an average of 0.92 and standard deviation of 0.268
b) WGI-PV below zero: ranging from the least unstable Kazakhstan (-0.04) to the most unstable Ukraine (-1.96), within this category and represented sample, with an average of -0.8 and standard deviation of 0.54

This summarized in the table below:

Category	Percentage of country	Average	std-dev
Above zero	39	0.92	0.268
below zero	61	-0.8	0.54

Table 4 Distribution of countries and averages based on PS performance

In our list, the transformed political Stability (TPS), varied from the least impact on its corresponding SR, 42.35 for Silica (frac sand) up to 61.08 for vanadium with an average of 54.20

That is subdivided into 3 groups based on the values ranges of TPS as follows: category A, B and C with the values of TPS: below 50, from 50 to 60 and above 60, respectively. These categories represent, in order, an increase of the political instability for individual material that could jeopardies their supply.

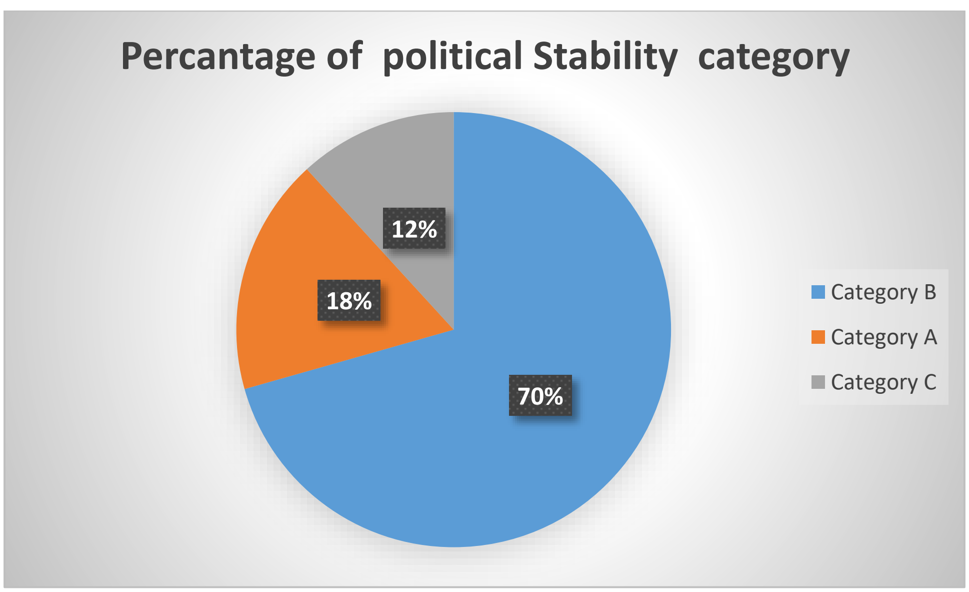

Figure 6 the distribution of countries based on the PS categories

With the majority (70%) of materials falling in the set of category B, meaning medium risk rising from political instability, next (18 %) in the slightly below medium risk (category A) and the rest fall into category C, of slightly higher than medium level of risk contributed by the covered factor.

The average value of these category (A, B and C) is of 46.31, 55.08 and 60.74, respectively

Category	Range of TPS	material	TPS value	Average
A	below 50	Iron	49.6	46.3
		Potash	47.0	
		Silica (frac sand)	42.4	
B	50-60	Aluminum	54.8	55.1 (2.56 std deviation)
		Bauxite	50.4	
		Betonite	57.0	
		Chromium	55.5	
		Manganese	52.3	
		Molybdenum	53.0	
		Nickel	54.2	
		Niobium	53.9	
		Silicon metal	56.9	
		Ferrosilicon	59.3	
		Titanium	54.5	
		Tungsten	59.2	
C	above 60	Barite	60.4	60.7
		Vanadium	61.08262	

Table 5 transformed values of PS indicator for the materials, classified by categories and with average.

The low value of TPS in the case of frac sand, is attributed to USA, the dominant producer globally having WGI-PV equal to 0.68 (weighted by its share becomes, 0.342 that is transformed into 19.1), contributing majorly in low supply risk rising from this factor.

Now within the same group, Iron almost maintained its position in this category, due to the tight balance created by the good stability (WGI-PV =0.88) of the dominant producer Australia (35 %) vs. the other major producers Brazil (19.2 %) and china (16.3 %), with -0.55 and -0.33, respectively.

As for vanadium, its results are the image of slight political instability existing in all its producers, which are limited in 4 countries; in decreasing order of production China (53.2 %), S. Africa (21 %), Russia (18.9 %) and Brazil (6.9 %), all having WGI-PV negative score: -0.55, -0.21, -1.03 and -0.33, respectively; evidently, the dominant effect of china on the final result.

Also, for the Barite, it's evident that the Chinese share has imposed itself on the final results by controlling 39.3 %, followed by Morocco (14.5 %) and India (8.3 %) with -0.34 and -0.95, WGI-PV respectively.

Policy Potential

Frasier institute investigate the impact of public practices on prospective mine development (Graedel et al., 2012, Fraiser institute), in other words the attractiveness of the current system under consideration for future expenditure in the mining industry; expressed through the Policy Perception Index (PPI), values range is from 0 (biggest obstacles hindering investment) to 100 (greatest system encouraging investment in mining), which is the final standardized value of 15 policy characteristics, covering an extensive array of relevant aspects for the administration under consideration, relying mainly on the feedback of the high management within their field of experience in the corresponding region (Graedel et al., 2012; Stedman & Green, 2015).

Adding, that the PPI has nearly 40 % of influence on the decision of management to dive into a new project within a certain country (Stedman & Green, 2018)

The number of countries/regions reported varies by year based on the feedback of the survey; therefore during the calculation some countries contributing to the production of a material weren't represented, hence their contribution was overlooked meaning that calculation was restricted with the available data, to avoid any random value designation even if some countries would have similar tendency based on their close structure. So, the actual production percentage utilized varied from 69.65 (Barite) to 100 (Vanadium) with an average of 86.6 % and standard deviation of 8.5, which can be considered as adequately representative of the real situation.

On the other hand, some countries were not estimated on the entire federal or national level, rather on more local (i.e. subscale) level as regions or state, etc. (depending on the considered country); as a result the relative index of the latter was evaluated based on the average of the former.

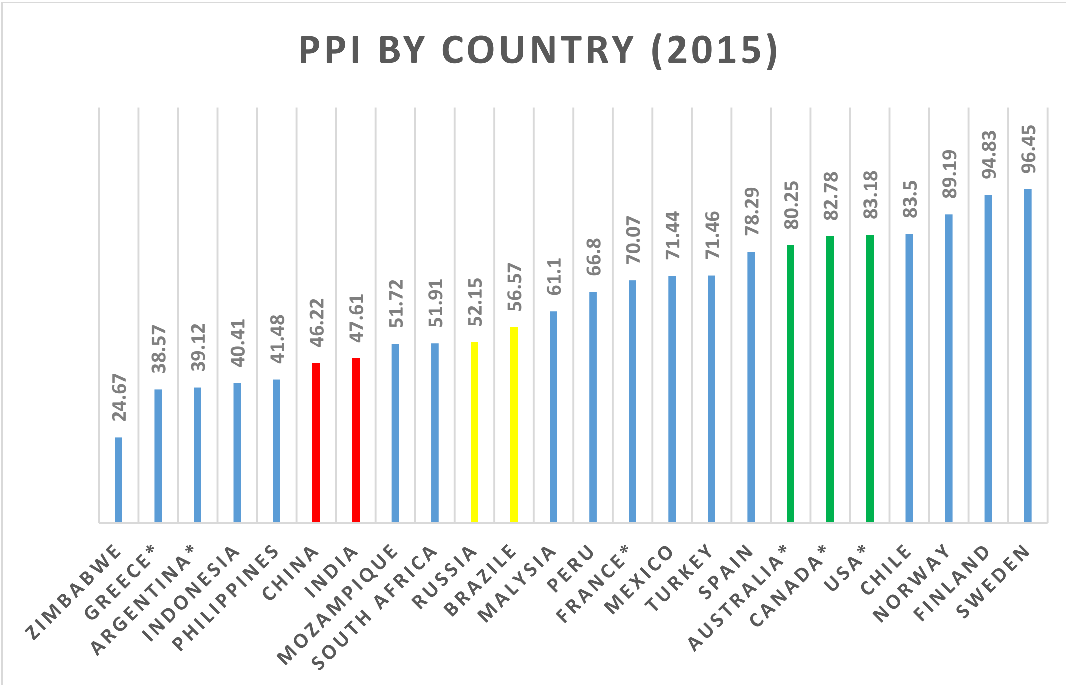

Figure 7 policy perception index by country (Fraser institute, 2016)

The low score was considered below 50, notably including major mining countries in volume (China and India), also Greece and Argentina fell into this group.

On the bright side for investment lies most importantly Australia, Canada, USA, Chile, Norway, Finland and Sweden, in ascending order of investment encouragement by policy effect.

The PP indicator is calculated, using the indicated formula and transformed to reflect a direct relation btw the Transformed value of Policy potential (TPP) and the SR, i.e. lower the TPP the effect on SR is lighter.

The result for the materials considered in this study is shown below:

With the lowest being Molybdenum (40.8), knowing that China (46%) is the dominant producer with low PPI which was countered by the effect of mainly 2 other producer Chile (18.3 %) and USA (16.5 %) with higher PPI 83.5 and 83.18, respectively; up to Barite (62.2), not shocking due to China and India contributing jointly to 48 % of total production; it should be noted that the actual contribution for china in case of Barite for an extreme example, in the calculation of TPP because China has 39.3 apparent contribution but actually 56.4 %, due to lack of data for some countries; adding that the barite had the lowest percentage of global production share in its PPI calculation (rounding 69.6 %); while others have better contribution; as a result a certain degree of caution should be taken with the PPI indicator for the possible error, due to the initial decision in its estimation in this work; that can propagate on a limited level into the overall score of SR, i.e. light effect due to low weight of this indicator of just 4.4 % for the latter.

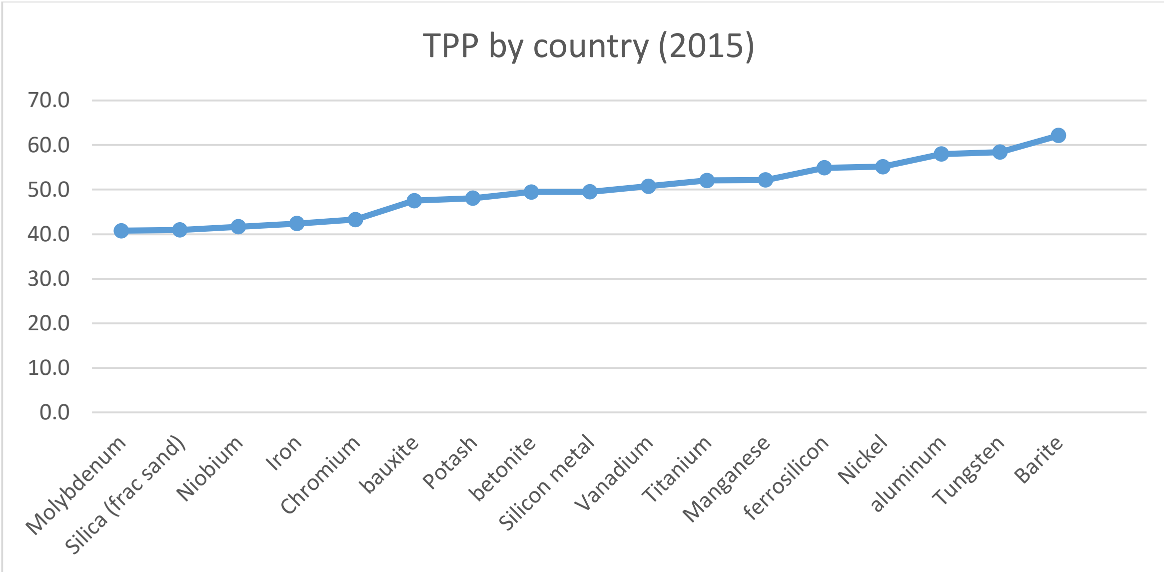

Figure 8 Variation of Transformed values of Policy Potential indicator with materials

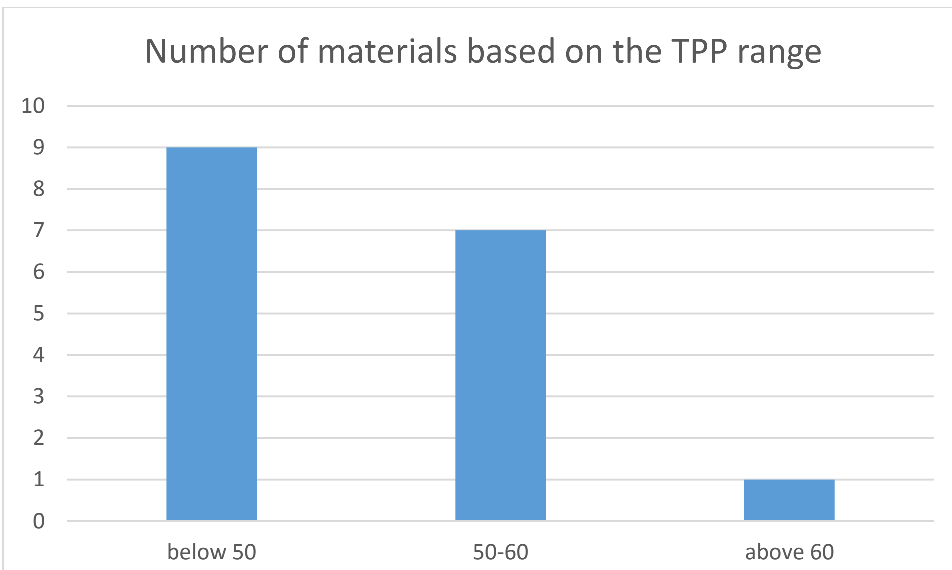

Figure 9 Distribution of materials on categories based on TPP

The average of TPP is 49.85 (std dev =6.4), with 52.9 % of them are below the latter and 41.2 %, have scored btw 50 & 60 and the just one above 60; hence it can be observed the TPP has, in general, moderate values.

Country and company concentration

"Country concentration", examine material concentration on the country scale, is calculated for all the considered materials, favored in many assessment models over "reserve concentration" , as the later have data for all materials, updated routinely and the former effects are in the future not in the present. (Achzet & Helbig, 2013; Kolotzek et al., 2018).

The Herfindahl-Hirschman Index (HHI) is a, frequently used, gauge of market concentration (DOJ, 2006); employed here to estimate the production concentration on the country scale, whose value range from 0 (mathematically) to 10,000 (absolute monopoly, where the complete production is restricted by only and strictly one country); which classify the markets into 3 levels of restricting conditions 0-1500 (healthy and competitive market), 1501 to 2500 (moderate concentration)and above 2501 (immensely concentrated) (investopedia, 2019) (DOJ); the transformation formula, will convert HHI values of (10,000), the threshold of a concentrated market (1800), and virtually very low HHI (below 33) into Tcountc values of 100, 70 and 0, respectively. Thus 70 would represent the start of relative (Graedel et al., 2012)

Table 6 Transformed values of key HHI values

HHI	Tcountc or Tcompc
10,000	100
2500 (threshold of highly monopolist conditions)	75.74(high impact on SR)
1800 (threshold concentrated condition)	70 (relative high impact on SR)
Below 33	0

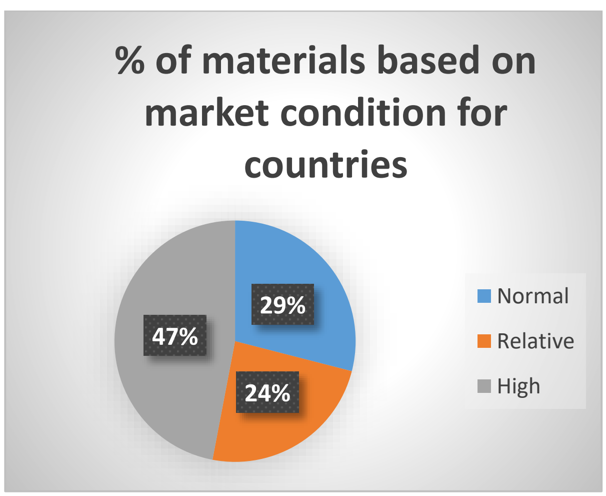

Figure 10 Distribution of materials based on the country concentration classification

Table 7 the transformed values for the country concentration indicator of materials with classification

Market situation	Material	THHI count
Normal	Nickel	60.24
	Titanium	64.11
	Betonite	67.83
	Bauxite	68.27
	Potash	68.34
Relative	Manganese	70.70
	Iron	71.41
	Barite	71.61
	Chromium	75.35
High	Silica (frac sand)	76.89
	Molybdenum	78.20
	Aluminum	79.24
	Vanadium	82.49
	Ferrosilicon	85.59
	Silicon metal	90.84
	Tungsten	92.95
	Niobium	96.70

The values range from 60.24 for Nickel in normal market up to 96.7 for Niobium, with an average of 76.52 (std dev =10), reflecting on overall that the list of materials covered are in concentrated conditions

As illustrated in the chart, the dominant portion (47 %) of considered materials are in highly concentrated conditions, followed by Normal and relative with 29 % and 24 % respectively.

Similarly for the Company concentration, we apply the same principle, however HHI is based on the major 3 companies in their production

Table 8 transformed values of company concentration by material, with classification based on concentration condition.

Market condition	Material	THHI company
Normal	Potash	49.28
	Chromium	51.45
	Nickel	55.15
	Manganese	56.59
	Molybdenum	62.88
	Silicon metal	64.56
	Iron	65.05
	Bauxite	67.83
Relative	Barite	73.37
	Betonite	73.49
Highly	Ferrosilicon	76.89
	Niobium	80.45
	Titanium	81.23
	Vanadium	85.59
	Aluminum	90.84
	Silica (frac sand)	92.30
	Tungsten	93.56

The values shift where potash (49.28) score the least concentrated market based on company production, while the Tungsten (93.56) is on the other extreme side of the scale with super concentration conditions, with an average value 71.8 (std dev =13.9) (slightly above the specified threshold), indicating overall a concentration level below that of countries.

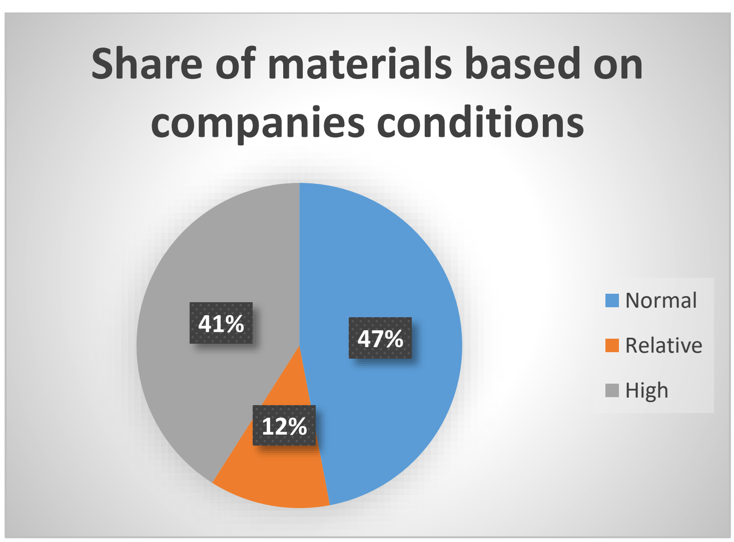

Figure 11 material distribution by company concentration category

However, as shown by the chart above an almost strict segregation btw either normal condition (dominating in this case, 47 %) or highly concentrated condition (41%) and relative has eroded to just 12 %.

Companion Metal fraction

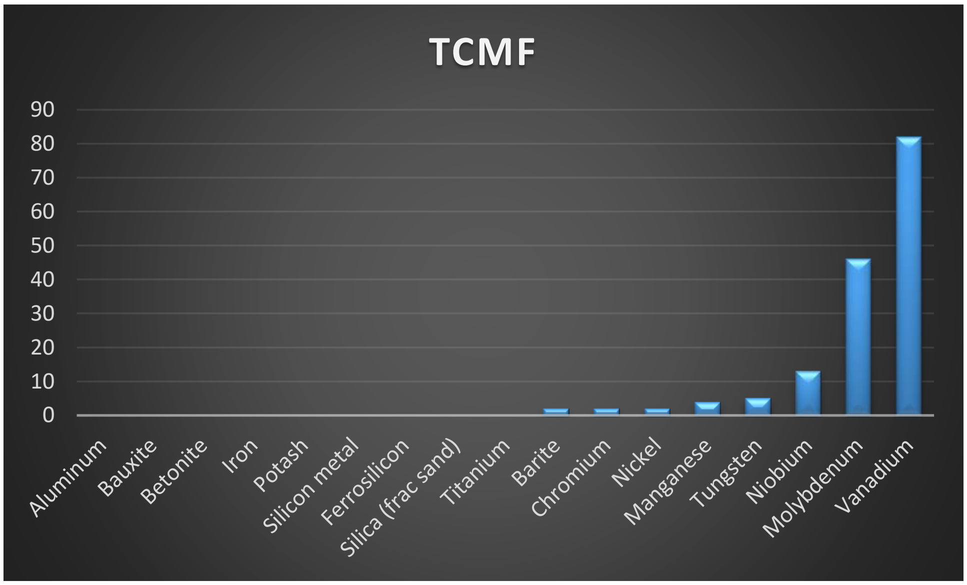

Figure 12 the transformed values of Companion metal fraction indicator

With the exception of Vanadium, almost completely produced as by-product; next is the Molybdenum with significantly high (46%), both are important in the alloying domain; while the other all score below 20%, for alloying and drilling fluid that reflect that the materials in our list are safe from the shortage produced as companion material.

Substitutability

This is built on 4 characteristics, Substitute: efficiency (in complete the operation), easy access (by the user), environmental and cost burden (Graedel et al., 2012), to keep in mind when a replacement is needed and the compromise required; usually the assessment is done for primary, currently established, substitutes (Graedel et al., 2012; EC 2017)

Each element is evaluated from 0-100, averaged to get the substitutability for a specific application, next the latter are weight-aggregated based on the application's share on the global scale consumption resulting in the overall substitutability of the considered material (Graedel et al., 2012);

Substitute adequacy /performance/ cost burden	Subs
Exemplary	12.5
good	37.5
adequate	62.5
poor	87.5
not applicable	100

Table 9 the corresponding values of indicator based on adequacy, performance or cost situation of substitue (from Graedel et al, 2012; Graedel et al., 2015a)

For an individual candidate, its suitability is founded on the functional efficiency ("performance") and cost burden, each is given values based on the above table (reflecting the context of lower suitability is seen as higher risk).

In case of multiple applications, only the relevant percentage for the drilling sector are considered and readjusted to 100% by their corresponding weight; in case of lack of information in the latter approach arithmetic average was used to assess the final value of "Subs".

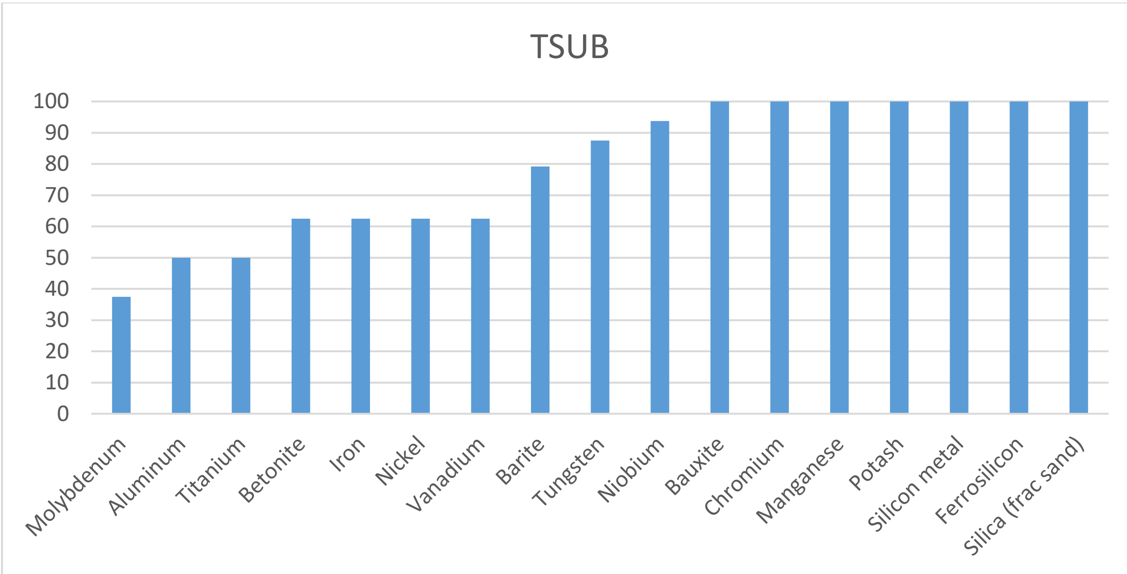

Figure 13 the transformed values of Substitutability indicator by material.

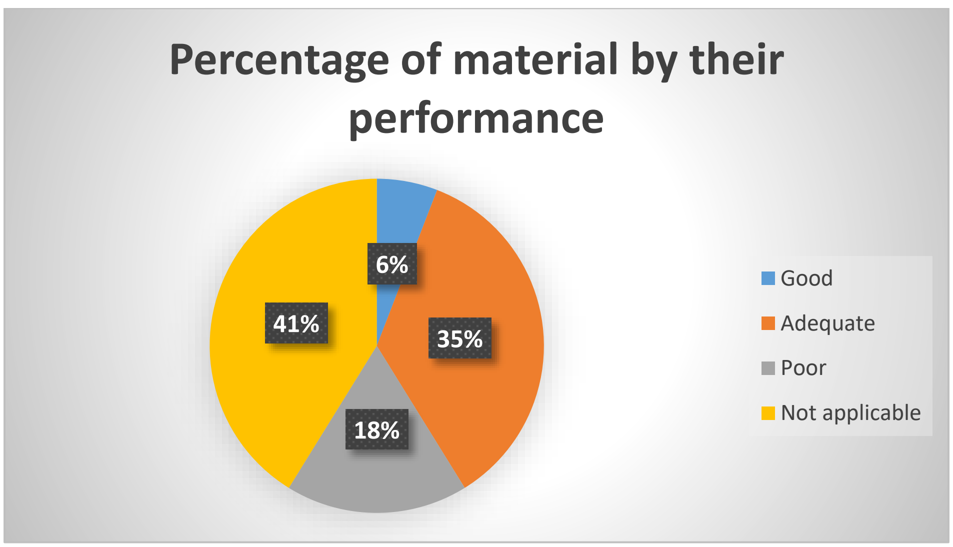

Figure 14 the distribution of materials based on the performance of Sub indicator

The majority (7 out of 17) of the materials in our list are not substitutable, with poor substitutes for Barite (mostly due to extra cost of other substitutes), Tungsten and Niobium; around one third can be adequately substituted and jut the Molybdenum scored the best as good level, finally there is absence of an exemplary performance in our list.

This indicator imposes the added value, mostly distinguishing the sector under consideration compared to others, based on the nature of application involving the materials; which empower the SR, whose has a general characteristic approach in the criticality domain.

SRRV and SRRC

Effect	Material	TSRRV
Nothing	betonite	0
	Silicon metal	0
	Ferrosilicon	0
	Silica (frac sand)	0
	Titanium	0
	Vanadium	0
Low	Bauxite	7.072
	Potash	15.552
	Tungsten	35.67007
Medium	Iron	59.89312
	Barite	74.52328
High	Molybdenum	80.68608
	Manganese	82.042
	Nickel	82.27648
	Chromium	95.02272
	Niobium	98.30088
	Aluminum	99.7419

Effect	Material	TSRRC
Nothing	Bauxite	0
	betonite	0
	Chromium	0
	Iron	0
	Manganese	0
	Niobium	0
	Potash	0
	Silicon metal	0
	Ferrosilicon	0
	Silica (frac sand)	0
	Titanium	0
	Tungsten	0
	Vanadium	0
Low	Barite	20.12608
Medium	Nickel	59.66272
	Molybdenum	71.38432
High	Aluminum	99.7419

Table 10 the material's transformed values of static reach reserve (TSRRV) on left and source (TSRRC) on right.

For the transformed Static Reach reserve values, equal number of materials with high risk and no risk (6:6), 3 with low effect and only 2 Iron and barite have medium effect.

On the other side, with TSRRC, the pocs change in a sense that complete dominance of no risk on the materials (13), low risk decrease to one (barite), medium remain 2 and high only one always Aluminum;

To be noted that, barite has decreased about 40 points, changing the level, which apply also for nickel and Molybdenum changing risk level with reduction of 22 and 9 points respectively but in this situation molybdenum has a higher score (the annual consumption from the latter's resource is 7.5 times less than that of the former which is balanced with an order of magnitude more in favor of the Ni resource); hence the dilution of TSRRC indicator is provided by bigger amounts of resource compared to reserves.

Finally, Aluminum remain with highest score, which is due to the fact of using the smelting capacity (extremely low values) on the global scale instead of the actual reserve and resources, intentionally to represent the transition of the gridlock phase from extraction phase to another (smelting or refining); also the resource has in general, at least for majority in our list, a light impact on SR.

EOL-RR

The contribution of recycling on the global scale from different products, to introduce a secondary feed to the consumption market thus this amount would trim the demand for primary material, which reduce the risk, so higher EOL-RR the lower the risk, hence we use the formula to make the transformed indicator directly correlated to SR.

Impact	Material	TRR
LOW	Chromium	33
	Iron	37.8
	Silica (frac sand)	43.7
	Titanium	45
	Nickel	48.7
	Betonite	50
	Aluminum	54
Medium	Tungsten	64.25
	Niobium	64.6
	Manganese	67.5
	Molybdenum	70
	Vanadium	77.5
High	Barite	100
	Bauxite	100
	Potash	100
	Silicon metal	100
	Ferrosilicon	100

Table 11 the transformed values of recycle rate by materials.

First, the distribution is almost equal btw the 3 levels of impact; with Low (41%) ranging from 33 (Chromium) to slightly medium impact of 54 (Aluminum); also in the medium impact (29 %) values spanning from 64.3 for tungsten reaching 77.5 with Vanadium; as well as high impact (29%) where all have equal values of 100.

The extent of recycling contribution will be affected by the dissipative nature (partial or complete) in some usage of certain materials or during processing or unprofitable recycling process below a threshold price per Kg, echoing into the transformed values.

Final score

We introduce here, a subdivision of the SR into 4 classification for this dimensions, of low, mid-low, mid-high and high risk area as indicated in the table below, in order to represent the relativeness of the SR and avoiding a strict cut of criticality with a single value.

Table 12 Supply risk for each material

Rank (least critical)	Material	SR
1	Titanium	46.9
2	Betonite	51.4
3	Iron	52.5
4	Nickel	54.1
5	Aluminum	58.9
6	Silica (frac sand)	60.6
7	Molybdenum	61.5
8	Potash	62.0
9	Chromium	62.4
10	Bauxite	62.8
11	Manganese	65.4
12	Vanadium	66.1
13	Barite	66.7
14	Ferrosilicon	68.8
15	Tungsten	69.5
16	Silicon metal	70.5
17	Niobium	75.2

Table 13 Classification of Supply risk based on SR score range

Risk Degree	Range of SR values
Low	0-25
Mid-Low	25-50
Mid-High	50-75
High	75-100

Thus almost all the materials in our list (15 out of 17) falls between 50-75 , except for Titanium (46.9) in Mid-Low degree and Niobium (75.2) is slightly in the high degree region; the average is 62.1 (std deviation =7.3); therefore we can say that the majority of considered materials have relatively mid-high degree of supply risk.

A biased shift in the weights for the “Subs” indicator, has been done by allocating the complete weight of the eliminated indicator to the “Sub” indicator and that of “CMF” is reassigned the original lower value; as result, the SR values increased at least 2.8% (Aluminum) and at most of 5.4% (frac sand), with an average of 3.7 % increase (std deviation = 1.8); except for the reduction in SR in case of Molybdenum (-0.5 %) and Vanadium (-1 %); knowing that the “Sub” indicator is 37.5 and 62.5, respectively; which going to increase significantly the contribution in the overall score however this effect is not observed as a result of decrease of “CMF”, especially that both have the highest values in our list 46 and 82, respectively. Thus the effect of biased weighting in general can be expected to follow a certain pattern, however this can be generalized due to the specificity of each material.

Comparison with other studies

BGS

UK, as other industrialized countries relying extensively on import to maintain daily life comfort & health economy, plan to acquire the necessary metal for the latter; which comes in line with the issue of the share of global input of minerals, specifically technological minerals, to the market is from developing countries (Africa and East Asia) with the dominance of production of many raw materials in China; such the case of REE (having good abundance in crust) but the matter is the exclusive production in China and difficulty to confront in other regions, creating panic for dependent industries.(BGS, Mineralsuk)

Thus the first list published by British Geological survey (BGS), 8 years ago, coincide with the general wakefulness over this problem, that was showed during the British Science festival Metals, mines and mobiles (covering the life cycle of technology metal), which covers chemical elements that have monetary importance (for the British economy), centering its work, on detecting critical material, from the supply risk aspect and advancing their perception of the natural geological processes creating the deposits of the latter; having its share of contribution on different levels, regional With EC (in the raw material initiative) and for local perspective (Ministry of defense, DEFRA, consultancy for FCO and Cabinet office) parliament(BGS, Mineral mines mobiles)

Also being granted by the Natural Environment Research council, the “Critical Metals-Science for secure Supply”, to publicize reliable and transparent data on all areas of the lifecycle of critical metals (BGS, 2011).

Table 14 comparison btw BGS and our supply risk results for common materials in both studies

BGS 2015		SR our values	% of variation	original weighting
Vanadium	8.6	66.1	-23.1	
Tungsten	8.1	69.5	-14.2	
Molybdenum	8.1	61.5	-24.1	
Barium	7.6	66.7	-12.2	
Niobium	6.7	75.2	12.2	56
chromium	6.2	62.4	0.6	
manganese	5.7	65.4	14.7	
Nickel	5.7	54.1	-5.1	
Iron	5.2	52.5	1.0	
Titanium	4.8	46.9	-2.3	
Aluminum	4.8	58.9	22.7	47
Aluminum*	48	49.4	2.9	

First, the Iron and Chromium values are consistent with negligible difference, as for Nickel and Titanium can be considered also consistent with negligible decrease.

On one side there is an increase in the SR for 3 materials Aluminum, manganese and Niobium of 22.7 %, 14.7 % and 12.2%, respectively; On the other side, there is a significant decrease in SR score for the rest of covered materials, from -12.2 % to -24 %; noticing a close values of decrease for barium- Tungsten pair and Molybdenum-Vanadium pair, all of which are in mid-low class with close values for SR, which leads us to make a comparison in their indicator to find a normal manifestation of the indicators values reflecting the normal variation in each material characteristics; however just a grouping for the indicated pairs (i.e. not because the similarity in % changes of the values) we compare the relative change in criticality

Table 15 relativity of supply risk of each study comparison

		BGS	our calculation		BGS	our calculation
pair of material	Vanadium	86	66.1	nickel	57	54.1
	Molybdenum	81	61.5	Titanium	48	46.9
% of SR (criticality) change material wise		5.81	6.96		15.79	13.31
Delta (%)		19.7			-15.7	
		BGS	our calculation		BGS	our calculation
pair of material	Niobium	67	75.2	Tungsten	81	69.5
	Manganese	57	65.4	barium	76	66.7
% of SR (criticality) change material wise		14.93	13.03		6.17	4.03
Delta (%)		-12.7			-34.7	

The most important observation is the decrease in SR values for all the materials compared pair-wise in our calculation with that of BGS, hence follow the same relative criticality flow; second the order of change material pair-wise is similar btw the 2 methods, adding that when comparing method pair-wise for the percentage of decrease (delta rows), we can see that in 3 out 4 of the comparisons made our method a lower decrease in risk for material-wise and it is more than 10 % for all cases, the last observation doesn't rise concern due to the original values difference arising from the method itself.

As for SR values, have mostly decreased, a couple increased and another couple are similar; although exist similarities btw the 2 methods in calculating the final score, as the aggregation of indicator is done by addition, but not weighted in BGS, sharing a number of indicator (5 out of 7 in BGS) ("production concentration, recycling rate, Substitutability, Governance (by production) and Companion metal fraction") but the values of each indicator are assessed is distinct, based on assigning values of 1 (high), 2 and 3 (low) for a certain distribution describing the situation for the relative indictor.

To be noticed that in the original weighting and method applied in (Kolotzek et al., 2018), the values of Aluminum and Niobium were consistent with a negligible decrease in the values compared to that of (BGS 2015) in case of aluminum and relatively significant decrease of 16.4 % in case Niobium ; here we point out that for Aluminum in our calculation substitution indicator slightly increased by 6 points and a complete increase of 99.7 points (intentionally using the smelting capacity) where its zero for both reserves and resource indicators originally, which is the main reason for the 23 % increase in the final score of SR in comparison to both (BGS 2015) and (Kolotzek, 2018) values, that justify the concern of (EC 2017) and (Graedel 2012) to surpass the extraction phase criticality limiting mindset.

We recalculated SR of Aluminum, sticking with extraction values, i.e. zero of SRRV and SRRC, which drop 16.1 % to 49.4, which is 2.9% and 5.1 % higher than BGS and kolotzek 2018 methods; and our value of Nb is 34.3 % more than that calculated in the original work of (Kolotzek, 2018)

Hence, the method we used conserve the risk relativity of materials as with BGS, the amount of change is similar in order, but still different due to the root contrast in methods used.

Additionally, SR has a more generalist view, the indicators used are common btw methods, mostly due to data availability, that why a more guided method for our considered sector is realized by deleting FDT, which not suitable in general when applied for a certain sector employing different techs and in our case the future activity of this sector is hard to predict , adjusting the weight and also the calculation approach of the SUBS, to be more suitable for the application in our sector; thus reshaping this method to be more representative for this sector, while maintaining its key essence of indicator weighting

EC

Table 16 comparison btw EC and our study

	EC 2017			
Material	stage of criticality	SR value	Criticality	our calculation
Niobium	P	3.1	1	75.2
Bauxite	E	2	0	62.8
Tungsten	E	1.8	1	69.5
Barite	E	1.6	1	66.7
Vanadium	P	1.6	1	66.1
Silicon metal	P	1	1	70.5
Chromium	P	0.9		62.4
Manganese	E	0.9		65.4
Molybdenum	E	0.9		61.5
Iron	E	0.8		52.5
Potash	E	0.6		62
Aluminum	P	0.5		58.9
Nickel	P	0.3		54.1
Silica (frac sand)	E	0.3		60.6
Titanium	E	0.3		46.9
Betonite	E	0.2		51.4

The EC method does not adopt a relative ranking system, simply when the candidate's SR and EI, surpass the pre-agreed on threshold, is considered as critical.

In our list 6 materials, have their SR's value above 1, the threshold value for this dimension (EC, 2017), Niobium, bauxite, Tungsten, barite, Vanadium and Silicon metal; only one (Bauxite) is not deemed critical in the study.

By observation of the results no correlation between most of the materials and the corresponding EC – SR, as some would have higher value of EC-SR than other materials while in our calculation it has opposite direction, e.g. bauxite, Tungsten and barite having computed 62.8, 69.5 and 66.7 while in the EC-SR it decrease from 2, 1.8 to 1.6.

Hence, the comparison btw these 2 methods is not applicable; this conclusion can be extended for the (NSTC, 2016) method.

Suggestion

Important indicator

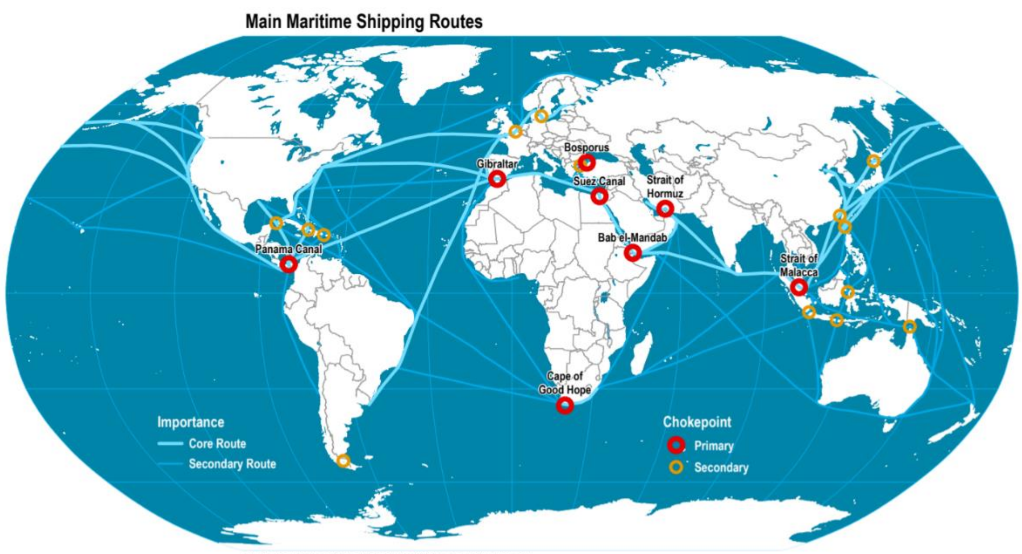

Figure 15 primary and secondary maritime routes and hot spots (transport geography)

The fig shows the main and secondary maritime routes, the cheapest mean of transport, pointing out to the critical points;

In time of peace these routes are safe under the maritime navigation regulations, nonetheless the global economic tensions go hand with hand with escalation of different types and levels, in different zones; thus these straights could be jammed either intentionally (directly or by proxy) or as unintentional side effect even in with international peace still standing.

Distinguishing btw the main production and the sourcing of materials, which mean that even the cut of a route doesn't limit the physical flow of materials to a considered system however this event would spike the prices.

Now even the geographic position of the system under consideration change the relative criticality of some maritime straights for the physical feed but can't escape the effect of price.

For example the Middle East and North Africa, striving under long instability, could in some cases impose an issue for the maritime shipments, due to the geopolitical position, as Bab el-Mandeb and Suez canal create restriction for south Europe ports, adding on the latter that of Gibraltar for UK and North European ports, these latter doesn't impose a direct physical risk for the North American ports.

Now in case of a cut of primary routes, have limiting effect over the feed delivery, so some solution would be to use secondary routes, that will increase the time of delivery and the cost of voyage, especially if insurance companies stop their coverage for certain routes and withholding these types of physical and monetary risk is not favored by anyone.

This indicator to be incorporated would require the extensive analysis of the amount of a certain material being shipped through a route to formulate the impact of such events, considering the quantitative magnitude of shock to markets of case and prices reaction to the cut, the shipping increment cost by companies and the cost of time delay on the downstream industries.

It came to our attention the complete lack of this consideration, from the part of criticality assessments, although the evident unbalanced distribution of mineral production and consumer on the geographical scene; where the main matter was the physical concentration in the producing countries or companies and their characteristics of political stability and mining regulation, but overlooking the characteristic of the countries on the road, specifically those on the hotspots, that could face certain events that escalate in different ways, by assuming a general political stability on the global theater and mistakenly decoupling the linked nature btw economic issues and political escalations.

Conclusion

In the usual context of criticality, comes up to our mind the materials required by new technologies either for common consumer or renewable energy or electrical cars (depending on specific sector), however this over focus on the latter, establish a blind spot on the traditional ones, that are completely neglected; so within our knowledge this is the first time an attempt to introduce the oil industry into the sphere of critical materials using a method adapted to companies.

The work done here shows that most essential materials (most notably: Tungsten, metallurgic silicon, barite, Chromium, Frac sand, Iron and Aluminum), are characterized of having Mid-high level of possible threat for its supply constrictions, as for Titanium was in Mid-Low level of SR and Niobium has scored slightly in the High level SR; evidently as indicated the SR here is not absolute, even within the same class.

Importantly, to remember that these results represent the situation of a specific point in the timeline with low predictive capability.

On one side, these results are consistent with that of BGS, due to similar nature of methods, in sense of relative level of criticality are reliable (i.e. doesn't follow guilty or not guilty approach); however the structure particulates of each one, yield different values. On the other side, due the different nature of NSTC and EC methods make the comparison irrelevant.

Now the overall criticality of materials can't be achieved yet, because the monetary impact dimension still need to be developed; which isn't an easy task by virtue of the complexity of oil industry's supply chain, the necessity of intense collaboration of multi- disciplinary staff with crucial dynamic and active contribution of field and management experts.

Signaling that the data availability and quality remain the most critical key in any assessment development and/or employment, restricting significant advancement.

One of the most effective way to accomplish this matter would be to hold the old carrot and stick approach, through tax incentive for collaboration between academia and industry personnel.

This study covered only an economic aspect of the criticality that need additional advancement by including the social and environmental aspects, as auxiliary, in sense to be segregated from the criticality rising from pure economic perspective.

Finally, this work pointed out to an important indicator untouched in all previous studies, related to the safety of maritime routes that represent a threat on price equilibrium or physical availability, which can be assessed qualitatively as well as quantitatively, when appropriate data are available.

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