Tool to Assess Raw Material Social Supply Risks

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

This research considers the use of country-level social indicators of governance, conflict and human rights used by companies to assess social risks in product supply chains. The study developed a computational tool that brings together three areas relevant to companies with global supply chains: life cycle assessment, critical raw materials and responsible sourcing of minerals and metals. This work is particularly valuable given the growing use of the OECD guidance for responsible sourcing of raw materials from high-risk and conflict-affected areas, which describes practices that are being increasingly adopted by businesses. To better understand the short-term supply risk and the associated impacts that social aspects can have on the sourcing of critical raw materials, the research built on the method for the Geopolitical Supply Risk (GPSR), which has been previously used to extend environmental life cycle assessment (LCA) to consider raw material criticality based on the World Bank's Worldwide Governance Indicators. The computational tool developed provides improved access and speed of calculations, making the GPSR more manageable for researchers and available to companies The functionality of the GPSR is also extended by adding eight additional country social indicators of social supply risk to the computational tool, selected based on policy guidance and industry practice in areas of governance, conflict and human rights risk. A case study was used to show operationalization of the tool. The social supply risk was calculated for eight materials associated with lithium ion batteries, assuming production in the EU-27, Japan and USA for 2015-2018. A database was created based on information from the US Geological Survey and United Nations Comtrade. Results demonstrated that social supply risks can provide additional information on raw material impacts for companies to consider in their sourcing decisions. This information is complementary to environmental LCA and there is future potential to integrate GPSR calculations into LCA software. As such, meaningful assessment of multiple social supply risks can be provided as part of understanding and management the life cycle of products.

Keywords: criticality assessment, conflict minerals, geopolitical supply risk, life cycle assessment, life cycle sustainability assessment, responsible sourcing, social supply risk

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List of Abbreviations

ADP: Abiotic Depletion Potential
AoP: Area of Protection
CPI: Corruption Perception Index
CRM: Critical Raw Material
ESP: Economic Scarcity Potential
EV: Electric Vehicle
FSI: Fragile State Index
GeoPolRisk: Probability of supply disruption due to geopolitical factors
GHG: Greenhouse Gas
GPSR: Geopolitical Supply Risk
GWP: Global Warming Potential
HDI: Human Development Index
HFI: Human Freedom Index
HHI: Herfindahl-Hirschman Index
LCA: Life Cycle Assessment
LCC: Life Cycle Cost
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
LCM: Life Cycle Management
LCSA: Life Cycle Sustainability Assessment
LCSM: Life Cycle Sustainability Management
LIB: Lithium Ion Battery
REE: Rare Earth Element
PPI: Policy Perceptions Index
PTS: Political Terror Scale
WGI: Worldwide Governance Indicator
WGI-PV: Worldwide Governance Indicator for Political Stability and Absence of Violence

1.0 Introduction

This chapter provides background information and introduces the context of the problem being addressed in this thesis. The chapter begins by presenting the problem and pressures that companies are facing with regards to responsible sourcing of raw materials with a focus on conflict minerals.

Next, the chapter discusses the significance of this problem to better understand the importance of the research presented in this thesis. In this section, the need for better reporting and risk assessment tools is discussed particularly as companies increase their contribution to extraction of materials which results in negative environmental impacts and socio-economic problems in their supply chains.

The following section presents the research questions being answered by this study and lastly, the contribution of this study is discussed in relation to industry practice. The outcome of the thesis is briefly described as well as the potential of this work to be used in industry.

1.1 Background and Context

Supply chains have become increasingly complex with globalization and new technologies that require the use of more diverse materials in products (Cardoso et al. 2015). The extraction of materials has been constantly increasing as well over the years due to increasing affluence, population, consumption and large-scale manufacturing (UNEP 2011). Due to the increasing complexity of supply chains, there is a growing concern over the security and sustainable supply of raw materials for businesses and governments, particularly in manufacturing intensive countries (Gemechu et al. 2016).

For companies, it is important to assess the availability and accessibility of materials they need, in order to make informed decisions about material selection for their products. In the last ten years, this has led companies doing more systematic analysis of risks associated with raw material usage (Duclos et al. 2010). Companies often make decisions about products and the materials used in products based on stakeholder and consumer concerns and, increasingly, on environmental and social aspects associated with materials. This has given rise to concerns and approaches for responsible sourcing of raw materials (Yawar and Seuring 2017).

As an example, General Electric was one of the first few companies to address the issue of increasing constraints on the availability of raw materials (Duclos et al. 2010). General Electric developed a method to quantitatively understand what materials are at risk and identified steps that can be taken to minimize the risks, particularly for critical raw materials (CRM). Critical raw materials (CRM) have high economic importance and are vulnerable to supply disruption (EC, 2017). Similarly, other companies that are heavily manufacturing focused and rely on the procurement of CRM have developed their own supply and price risk assessment methods. However, these risk assessment methods are mostly developed in house and are not publicly available for other companies.

Similarly, international organizations and associations such as Drive Sustainability – a collection of ten leading automotive manufacturers are pushing for standards and commitments to ensure that their supply chains are socially responsible. The partnership of automotive companies has published several reports and guidelines on supply risk assessment with the Responsible Minerals Initiative (RMI). The report mentions that regulators, investors, consumers and social rights groups are increasingly asking companies to disclose the results of supply chain due diligence (Drive Sustainability, 2018). Due diligence describes the efforts taken to investigate supply partners to discover any corruption risks and to increase transparency in the supply chain to address negative impacts associated with their activities and improve operating practices (Drive Sustainability, 2018).

The Drive Sustainability report provides sixteen criteria that were identified as being areas of concern for the manufacturers. These criteria are divided into two broad categories that deal with the importance to industry and environmental, social and governance issues. The latter category consists of eleven criteria that indicate the extent to which production of a material is associated with adverse environmental, social or governance impacts that affect upstream communities and wider society and present a risk to corporate reputation (Drive Sustainability, 2018). This includes factors such as countries with weak rule of law, countries experiencing corruption and countries experiencing high intensity conflict among many other things.

These reports show that with increasing demand of materials and complexity of supply chains, downstream companies are making efforts to increase the transparency of their supply chains to be able to identify supply risks and to make a strategy for responsible and sustainable sourcing of raw materials.

1.2 Problem Statement

While economic and ecological risks of resources have been studied for quite a time, there is little knowledge of the social risks involved in a material's upstream supply. Recently, a stronger emphasis has been placed on the social impacts and practices such as corporate social responsibility (CSR) and responsible sourcing of materials have grown popularity. Studies on sustainable supply chain management (SSCM) have evolved from a focus on economic and environmental issues to incorporate social issues as corporations and researchers try to study the types of problems or concerns that may arise with respect to sourcing raw materials (Feng et al., 2017). As a result, social aspects are being included in the decisions that companies make in the product design process (Dreyer et al., 2006) as the sourcing of materials (particularly critical materials) has various implications for the company in terms of public image, reputation, product performance and economic gains.

Social LCA (S-LCA) is slowly becoming more popular but it is focused on the inside-out impacts i.e. how the sourcing practices of a company could impact communities around where the material is sourced from. Regarding the supply of materials, companies need to ensure that social factors, including geopolitical and conflict issues do not disrupt the supply of these resources, and there is very little work done to assess those risks. Most academics have looked at resource availability from a criticality purpose, but companies have other important aspects to consider as well such as supply disruption due to conflicts, money laundering, child labor, etc. (EC, 2017; Drive Sustainability, 2018).

1.3 Significance of the Problem

The need for a risk assessment method and tool is highlighted by companies as they report on social issues relevant to their supply chains (GE, Drive Sustainability, LME). Given the lack of proper understanding of social indicators and how they can affect supply risk (Dreyer et al., 2010; Kühnen and Hahn 2017; Popovic et al. 2018), it is important for companies to accurately assess the varying social risks in their supply chain in order to address them (Yawar and Seuring 2017; Hossain et al. 2018). Often, larger manufacturers and downstream companies have their own assessment and due diligence methods that have been recently developed based on the latest guidelines on responsible sourcing. However, these methods or tools are generally not available for public use and are not transparent in defining the methodology or criteria used for assessment (Zorzini et al. 2015; Subramanian et al., 2018). Furthermore, due diligence methods to ensure responsible supply chains are not linked to supply risk of materials as they are focused on establishing guidelines and standards to manage sustainable supply chains.

This presents an opportunity to explore the criteria that companies have already used to establish responsible sourcing practices and to develop an open-sourced calculation tool based on publicly available data that can be used by anyone to assess social supply risks.

The concept of social supply risk is used and elaborated in this research. A social supply risk is defined as: a risk imposed on a company as a result of social factors in activities and processes that are upstream in the supply chain. A social supply risk may result in harms like shortage in physical supply of a material, economic disruption or reputational implications harming the brand of a company. Here the physical risks come in the form of disruption of raw material supply, economic risks come from the cost increase of raw materials, and reputational risks come from damage to a company's reputation due to negative activities in raw material sourcing practices. In the current research, the focus is on social supply risks associated with the upstream production and supply of mineral and metal materials, where the social supply risks are areas of increasing concern, specifically in the mining sector, or electronics and automotive industries (EC, 2017; Drive Sustainability, 2018).

1.4 Research Question and Objectives

Given the need to assess raw material supply risks at a company level, the main research question considered is:

How can raw material social supply risks be efficiently assessed to support company decision-making?

Furthermore, given the diversity available in the selection of social risk indicators; there is a need to better understand how different country indicators can affect supply risk assessments. This provides us with a secondary research question:

How does the choice of country-level social indicator influence the assessment of a company's supply risks?

Given these research questions, the study focused on developing a risk assessment tool. This tool is based on the GeoPolitical Supply Risk (GPSR) methodology developed at Bordeaux University (Sonnemann et al., 2015; Gemechu et al., 2016). The GPSR methodology integrates criticality assessment and Life Cycle Assessment (LCA) to give a more holistic assessment of the various impacts associated with natural resources. The tool was operationalized through a case study, where materials in an electric vehicle lithium ion battery (LIB) were assessed. The social supply risks of the materials in a LIB were evaluated for three regions in the world to validate the tool and provide insights for further development of this tool.

1.5 Contribution of the Study

This research considers the three approaches that have developed to help companies assess the risks and impacts of materials used in products. The focus is on the upstream supply of resources: environmental footprint, criticality assessment and responsible sourcing. These are approaches that have developed as companies, governments and researchers have tried to support best management practices to ensure sustainable supply chains.

This paper presents a tool that was developed to calculate the geopolitical supply risk (GPSR). The GPSR methodology was developed by the Bordeaux group that attempts to integrate criticality assessment to a lifecycle assessment (LCA) approach (Sonnemann et al., 2015; Gemechu et al., 2016; Gemechu et al., 2017). The GPSR method uses the production and trade data to make country-level assessments using the Worldwide Governance Indicators (WGI) for political (in)stability and violence (WGI-PV) that assesses the political stability of countries.

This paper also shows how the proposed framework was developed and how the tool extends the LCA and GPSR methodology to account for social supply risks based on the Organization for Economic Cooperation and Development (OECD) guidelines for responsible sourcing. The tool extends the GPSR methodology by introducing additional social indicators based on responsible sourcing guidelines to assess the social and geopolitical supply risks in their raw material supply chain. This allows users and potentially companies to calculate the raw material supply risks based on social categories of conflict, governance or human rights to assess the various factors affecting supply risks.

Results obtained from the operationalization of the model and tool demonstrate that supply risks for the short term of availability of raw materials can be obtained based on different social aspect indicators. The results and analysis show that the tool can be used by companies to provide a country level risk assessment for the supply risk of materials together with LCA to provide a more comprehensive assessment of impacts with regards to responsible sourcing of materials. This is demonstrated using a case study of a lithium ion battery (LIB) product system for three regions in the world that shows the supply risk of the materials used in a lithium battery calculated for the various selected indicators related to social supply risk. The case study shows that the tool could be used for country level and potentially product level risk assessment, and to get information on the various supply risks associated with conflict and critical materials.

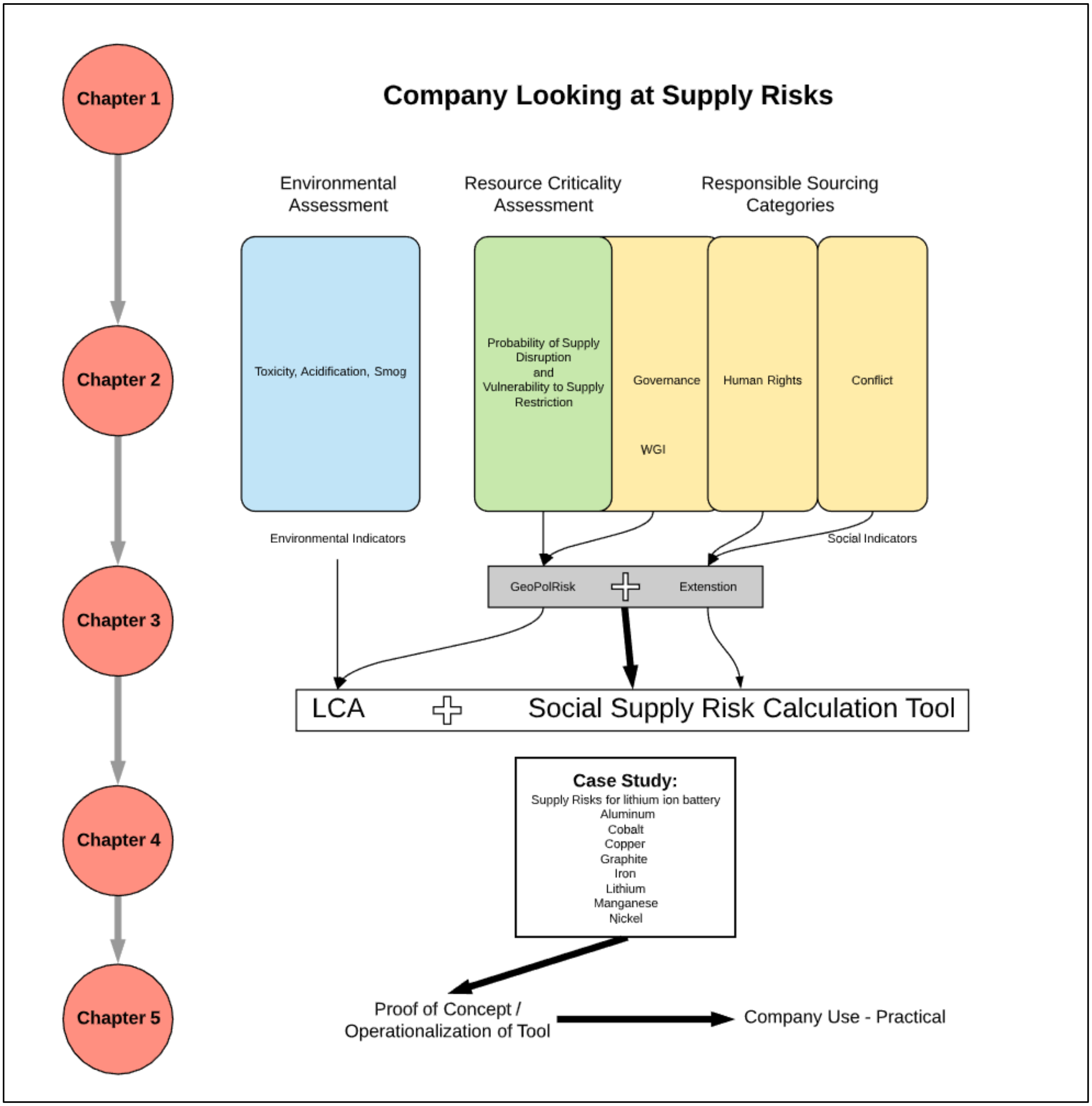


Figure 1. Conceptual figure showing the outline of this research and the connection between three areas of research regarding sustainable supply chain management of raw materials

2.0 Literature Review

Chapter 2 reviews the literature focused on sustainable management of raw material supply chains with a specific focus on lifecycle assessment (LCA), criticality assessments and responsible sourcing. This review is used to propose a framework upon which the GPSR tool is built.

The chapter begins by introducing the three areas of research and then discusses each of those sections in more detail. The environmental impacts section talks about life-cycle assessment as well as social lifecycle assessment and the need to better evaluate the area of natural resources within LCA. This section ends with discussing the limitations and gaps in current LCA methodology with respect to natural resources.

The next section reviews the literature associated with resource criticality assessments with a focus on integration with LCA. Three methods are discussed in more detail that have attempted to calculate raw material supply risks. The limitations and opportunities for further development of these methods is also discussed.

The third area of literature is discussed in the next section: responsible sourcing. This is a relatively recent area that has become more important with increasing competition of raw materials and the role that companies play in sustainably managing their supply chains. The limitations of responsible sourcing are also discussed as they relate to lifecycle thinking methodology and criticality assessments.

The following section presents a review of the comprehensive assessments that have been done in the past to assist companies in assessing the raw material risks in supply chain. These are divided in to 3 categories of sustainable development: environment, economy and society.

Using information from these various areas of literature, and based upon the GPSR methodology, a new framework is presented that combines these three areas and uses responsible sourcing guidelines to provide assessment of raw material supply risks based on the trade flows.

2.1 The Three Areas of Literature in Sustainable Supply Chain Management

Since 2008, three areas of activity have developed that concern the sourcing of raw materials and the factors that go into material selection from a sustainability perspective: environmental footprint, criticality assessment and responsible sourcing as shown in Figure 1. Export constraints put in place by China on export of rare earth elements (REE) gave rise to significant illegal mining and exports that eventually contributed up to 40 percent of total world production (Mancheri A. et al., 2018). This incident along with concerns from stakeholders and consumers helped drive the OECD to publish a guideline for responsible sourcing of raw materials from conflict affected and high-risk areas (CAHRAs). The three areas of literature are introduced below and further elaborated in the following sections:

- The environmental impacts of products and associated materials have been studied for over 3 decades using Life Cycle Assessment (LCA). The LCA methodology is now quite mature and while it has certain limitations (Igos et al. 2019), it is accepted as the most scientific approach to estimate and assess the potential environmental impacts of products and processes using indicators such as global warming potential (GWP), toxicity and smog.
- Resource criticality assessments started gaining popularity after companies and nations realized the possibility of supply disruptions for REE (Mancheri A. et al., 2018). Consequently, the extraction and use of raw materials increased and both organizations as well as governments tried to assess possible supply disruptions and vulnerability to supply of materials. This is becoming more important for companies as the global competition for material resources affects the supply chain and availability of materials which in turn affects economic performance (Graedel et al. 2015).
- The area of responsible sourcing is quite recent and there has been relatively little research on this specifically. It began with a specific focus for the so-called “conflict minerals” that are associated with production in areas with high risk of conflict (OECD 2012). This was also pushed by the approval of the Dodd-Frank Act in 2010. Section 1502 of this Act, also known as the Conflict Minerals Provision was focused on supply chain due diligence with the purpose of identifying the risk of sourcing conflict minerals and to dissuade companies from continuing to engage in trade supporting armed conflict.

Reviewing these three areas and the social aspects that influence these areas will guide the development of a more structured framework for companies to follow where they can eventually choose the social aspects relevant to their sourcing situation and assess potential impacts and risks based on those social aspects.

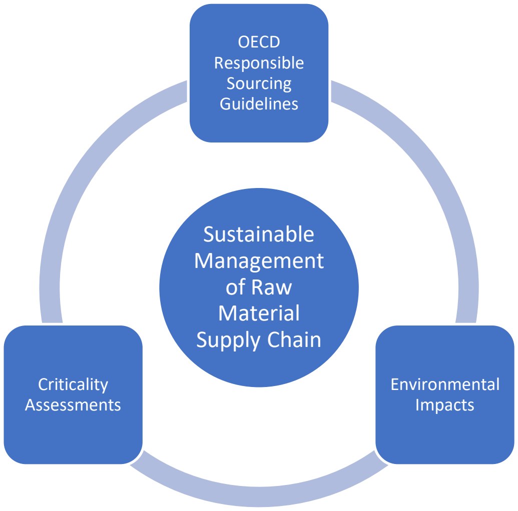


Figure 2. Three areas of literature regarding sustainable management of raw materials

2.2 Environmental Impacts and Life-cycle Assessment

The use of life cycle impact assessment (LCIA) to assess the environmental footprint of materials gained popularity in the 1990s when the first scientific publications emerged (SETAC, 1993; Baumann and Tillman, 2004; ISO, 2006a, 2006b). Since then a strong development and harmonization has occurred resulting in an international standard (ISO, 2006a, ISO, 2006b), which has increased the maturity and methodological robustness of LCA (Finnveden et al. 2009). LCA is the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006).

LCA employs multiple mid-point indicators that relate to end-point impacts providing measures on the three areas of protection (AoP): ecological health, human health and natural resources. The main advantages of the midpoint indicators are their relatively strong scientific robustness, whereas endpoint indicators are less precise but easier to interpret (Bare et al., 2000). As the environmental impacts are evaluated over the entire life cycle, consequently the whole life cycle has to be modelled. For several impact categories e.g. climate change, eutrophication, etc. LCIA models and methods are available, which have been applied in LCA case studies for many years.

With existing LCA methods there are several limitations in terms of using it as a decision-making tool for sustainable supply chain management; and this thesis attempts to address two of those limitations: firstly, it lacks the inclusion of social aspects while assessing the various impacts of a product system. Secondly, it does not evaluate the area of natural resources adequately and cannot be used to assess the short to medium term accessibility of raw materials.

LCA has done a thorough job in assessing environmental impacts but there have been suggestions to make it broader since sustainable development includes additional dimensions such as social and economic impacts (CALCAS 2009). Traditional LCA studies deal only with the environmental footprint and therefore social aspects are not considered in a comprehensive assessment tool (Sonnemann et al., 2015). Thus, the most recent developments in LCA have been focused on the social aspects of a product's life-cycle. A major outcome of this research has been the development of social-LCA and the use of social indicators that are integrated with LCA. While it has been difficult for researchers to agree on a set of indicators and for s-LCA, certain methods have developed like social hotspot database. Social hotspots are unit processes in a product's lifecycle that are within a sector and region with high risks of negative impact or high opportunities for positive impact. (Benoît et al. 2010).

Furthermore, there have also been calls for improving the assessment of the AoP "natural resources" (Dewulf et al. 2015; Drielsma et al., 2016; Stewart and Weidema, 2005). As Dewulf et al. (2015) point out, these AoPs extend beyond the environmental dimension of sustainable development. Human health is not an "environmental" issue per se, and arguably issues pertaining to resources are largely socio-economic in nature. There have been efforts to better evaluate the area of natural resources within LCA by integrating the methodology of criticality assessments in LCA (Sonnemann et al., 2015; Gemechu et al., 2015). This introduces a new socioeconomic dimension to resources and is another step towards a more comprehensive assessment of raw materials.

2.2.1 Social Life-cycle Assessment

A social and socio-economic Life Cycle Assessment (S-LCA) is a social impact (and potential impact) assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle encompassing extraction and processing of raw materials; manufacturing; distribution; use; re-use; maintenance; recycling; and final disposal (Benoît et al., 2013). Social life cycle assessment (S-LCA) uses a method that looks at issues of human right such as child labor, minimum wage, slave trade as well as other aspects including gender equality to assess the social aspects of products.

The emergence of corporate social responsibility (CSR) has spurred the development of various social impact assessment tools that correspond to stakeholder needs (Wang et al., 2016). Addressing the social implications of their products throughout the supply chain is a pressing need that has emerged for brand manufacturers (Hutchins et al. 2013). Thus, the research and development of S-LCA methods have increased. Social LCA was first used by Dreyer and subsequently, a number of publications and research articles followed with varying indicators and frameworks to standardize the method (Dreyer et al., 2006).

The guidelines published by SETAC/UNEP are now seen as the standard. The framework detailed in the S-LCA guidelines is in line with the ISO 14040 and 14044 standards for LCA with adaptations for the consideration of social and socio-economic issues. It proposes a two-fold classification of social impacts: by stakeholder categories and by impact categories (UNEP/SETAC).

A stakeholder category is a cluster of stakeholders that are expected to have shared interests due to their similar relationship to the investigated product systems. The proposed stakeholder categories are deemed to be the main group categories potentially impacted by the life cycle of a product. These include the categories of workers, consumers, local community, society and value chain actors. Each of the stakeholder group is further divided into subcategories to make sure that the S-LCA matches the goal and scope and is assessing the bulk of the situation.

Based on the stakeholder categories, the guidelines propose five impact categories that should be addressed by a S-LCA study.

1. Human rights
2. Working conditions
3. Health and safety
4. Cultural heritage
5. Governance

The purpose of the classification into impact categories is to support the identification of stakeholders, to classify subcategory indicators within groups that have the same impacts, and to support further impact assessment and interpretation. The impact categories should preferably reflect internationally recognized categorizations/standards (like the UN declaration on economic, social and cultural rights - ECOSOC, standards for multinationals) and/or result from a multi-stakeholder process.

Table A1 in the appendix shows the classification of the stakeholder categories and their relation to the impact categories as well as the indicators used to assess each impact category.

Based on the UNEP guidelines, two methods of S-LCA have emerged that follow the same guideline but have different approaches. These are the social hotspots database method (SHDB) (Norris et al., 2013; Benoît et al., 2013) and the product social impact assessment (Goedkoop et al., 2018). The social hotspots database was developed by Norris et al. (2013) and it provides data for several sectors and countries on social conditions that can be used to identify social hotspots of product systems (Benoit-Norris et al., 2012). While SHDB focuses on providing an initial assessment of potential hotspot areas with high social risk, product social impact assessment focuses on the complete life cycle impact of a product on society based on the following methodology:

Stakeholder groups → social topics → Performance Indicators → reference scales to assess impact

From the perspective of supply chain management, work at the product level should be considered, particularly in the upstream part of product chain (Jørgensen et al. 2009). According to Porter and Kramer (2006), the inter-relations between sustainable development and business activities can be examined in two ways (Cimprich et al. 2017). Social LCA currently assesses the “inside-out” relation that describes the impacts of business operations (including products) on the society. There is still a lack of understanding and assessing the “outside-in” relation that describes how firms are impacted by external environmental and socio-economic conditions (Porter and Kramer, 2006). For example, business risks and opportunities are affected by consumer preferences, policy and regulatory regimes, supply constraints, conflicts in areas of mineral production and environmental phenomena such as droughts and other extreme weather events.

2.2.2 Natural Resources “Area of Protection”

The area of natural resources in LCA is more complicated to assess for the various impacts. This is due to the socio-economic qualities of resources and the limited availability and accessibility in the short to medium term that depends not only on environmental impacts but also includes other considerations such as geopolitical and social conditions, material production, and recycled content.

Despite almost 20 years of research, there remains no robust, globally agreed upon method—or even problem statement—for assessing mineral resource inputs in life cycle impact assessment (LCIA) (Drielsma et al. 2016). There are four agreed upon methods for assessing mineral resource in LCA: depletion, future efforts, thermodynamic accounting, and supply risk methods.

The depletion concept is related to the reduction of a certain stock (or a set of stocks). This method uses the characterization models of the ADP (Abiotic Depletion Potential)

Future Efforts methods are based on assumptions to assess the consequences of current resource use on future societal efforts, which may include increased effort to extract a unit of mineral resource in the future or increased economic externalities. Most existing Future Efforts methods are based on the assumption that ore grades mined in the future will be lower and apply various proxy indicators to assess the related assumed increases in costs (Sondregger et al. 2019).

Thermodynamic Accounting methods quantify the cumulative exergy (or energy) used in a product system.

Supply Risk methods are based on criticality assessment concepts and have been developed according to an LCA context. These include the Geopolitical Supply Risk (GPSR) method (Gemechu et al. 2016; Helbig et al. 2016a; Cimprich et al. 2017b), the Economic Scarcity Potential (ESP) method (Schneider et al. 2014), and the Integrated Method to Assess Resource Efficiency (ESSENZ) (Bach et al. 2016), which is an extension and update of the ESP method.

The criticality concept typically includes considerations of potential supply disruption (e.g. due to trade barriers, armed conflicts, economic and technological limitations of exploration and extraction, environmental regulations, and natural disasters) and potential (socioeconomic) impacts of this supply disruption (also referred to as vulnerability. The supply risk is defined as a function of supply disruption probability *and* vulnerability (Cimprich et al. 2018), although parts of the criticality literature refer to *supply risk* only as the *supply disruption probability*.

2.3 Criticality Assessment

The diversity of raw materials used in modern products, compounded by the risks of supply disruptions—due to uneven geological distribution of resources, along with socioeconomic factors like production concentration and political (in)stability of raw material producing countries—has drawn attention to the subject of raw material "criticality" (Cimprich et al. 2019). Criticality assessment has been studied extensively outside of the LCA community and several methods have been proposed to determine the "criticality" of resources and commodities (e.g., European Commission, 2010, 2014, 2017; Graedel et al., 2012; Graedel, Harper, Nassar, Nuss, & Reck, 2015a; National Research Council, 2008). It deals with a wide variety of factors such as geological deposits, geographical concentration of deposits or processing facilities, social issues, regulatory structures, geopolitics, environmental issues, recycling potential, and sustainability (Graedel, Nuss, 2014).

Criticality is typically defined in terms of risk of supply disruption (supply risk) and vulnerability to supply disruption. The model presented by Graedel et al. (2012) is considered as being one of the more robust and comprehensive approaches (Sonneman et al., 2015). This measures criticality in 3 dimensions – environmental impact, supply risk and vulnerability to supply disruption (Graedel et al., 2012). The European Commission defined the term critical raw material (CRM) as a material that is important to the national economy and has a high risk of supply disruption (EC, 2014) whereas the National Research Council (NRC) considers a material to be critical "…only if it performs an essential function for which few or no satisfactory substitutes exist…" and "…only if an assessment also indicates a high probability that its supply may become restricted, leading either to physical unavailability or to significantly higher prices for that mineral in key applications…" (National Research Council, 2008). This shows how the definition of critical materials is context specific. In general, CRMs are both of high economic importance and vulnerable to supply disruption. Vulnerability to supply disruption means that their supply is associated with a high risk of not being adequate to meet EU industry demand. High economic importance means that the raw material is of fundamental importance to industry sectors that create added value and jobs, which could be lost in case of inadequate supply and if adequate substitutes cannot be found. Bearing the above concepts in mind, criticality has two dimensions:

(1) Supply Risk (SR)

(2) Economic Importance (EI)

A raw material is defined as being critical if both dimensions overcome a given threshold (EC, 2014).

While these assessments have been conducted on a national, regional, or global level, raw material criticality is also relevant on a product-level—to inform product design, material selection, and supply-chain management (Cimprich et al. 2019). There is a growing interest in adapting criticality assessment to a product-level analysis as a complement to (environmental) LCA (Bach et al., 2016; Cimprich, Karim, & Young, 2017a; Cimprich et al., 2017b; Gemechu, Helbig, Sonnemann, Thorenz, & Tuma, 2015; Helbig et al., 2016a; Henßler, Bach, Berger, Finkbeiner, & Ruhland, 2016; Schneider et al., 2014; Sonnemann, Gemechu, Adibi, De Bruille, & Bulle, 2015).

Furthermore, the selection and use of indicators is also controversial due to a lack of publicly available data and a consistent methodology that all researchers agree on. Therefore, several methods have emerged over the last few years that attempt to integrate criticality with lifecycle assessment (Schneider et al. 2014; Bach et al., 2016; Cimprich, Karim, & Young, 2017a; Cimprich et al., 2017b; Gemechu, Helbig, Sonnemann, Thorenz, & Tuma, 2015; Helbig et al., 2016a). This is done to better assess the area of natural resources from a socio-economic perspective.

2.3.1 Economic Scarcity Potential (ESP)

The Economic Scarcity Potential (ESP) was developed at TU Berlin to address the gap in the assessment of economic impacts of natural resources. The aim of this work was the development of a new model for the assessment of resource provision capability from an economic angle, complementing existing LCA models. This was done to provide a more realistic assessment of resource availability beyond geological finiteness (Schneider et al. 2014). Schneider et al. argue that supply risks concerning the continued resource provision capability should be assessed in addition to geologic availability. The focal point of the AoP needs to be extended to include limited supply (scarcity) of resources caused by economic (e.g., distributional or political) or social (e.g., human rights abuse) restraints or risks. The consideration of these additional dimensions complements existing models for the analysis of resources, as it goes beyond an environmental function towards the comprehensive assessment of resource availability in the context of LCSA.

Schneider et al. also identify several economic criteria that could potentially affect resource supply and present indicators that can be used to assess the supply security of resources. Based on a life cycle perspective, the supply risk associated with resource use can be assessed, and bottlenecks within the supply chain can be identified with the ESP methodology. It presents different impact categories and the respective indicators used to measure the impacts as mentioned below:

- Reserve availability/ Mining capacity: this measures the depletion time of resources with the category indicator reserve-to-annual production ratio
- Recycling: measures the recycled content of a resource by the category indicator new material content
- Country concentration: represents the concentration of mine production in certain countries and is measured by the HHI, which is an index calculated by squaring the market share of each company or country with regard to the production or reserves.
- Governance stability: Measures the stability of governance in producing countries by using the World Governance Indicators (WGI) published by World Bank Group
- Socioeconomic stability: Measures the progress of human development in producing countries and is assessed using the Human Development Index (HDI) which is published by the UNDP.
- Demand growth: Measures the increase of resource demand based on past trends and future demand scenarios.
- Trade barriers: Measured by the percentage share of mine production under trade barriers.
- Companion metal fraction: Measures the percentage of a metal that is mined as a by- product

This study provided an assessment of economic resource availability considering a life cycle perspective. Schneider et al. (2014) presented the impact categories for modeling the economic dimension of resource provision capability that were developed analogously to existing LCA terminology. Thus, the method can be applied in connection with existing life cycle-based approaches and it contributes towards extending the LCSA approach.

There are still several limitations to the ESP, including the scale of the system and the use of primary resource supply. The supply risk measured in this methodology is determined as the average global risk. LCA however, is a method that assesses the impacts at a product level, and in terms of criticality assessments the development of a product scale supply risk assessment is important. The ESP method, since it takes the global data; does not account for supply risks at a country or firm level.

2.3.2 Integrated method to assess resource efficiency – ESSENZ

The ESSENZ method was also developed at TU Berlin as an evolution of the ESP method. This method was developed to serve as a starting point to carry out a comprehensive assessment of resource efficiency. As companies need operational tools and approaches, a comprehensive method was developed to measure resource efficiency of products, processes and services in the context of sustainable development. For a comprehensive assessment of all related impacts of resource extraction and use all three sustainability dimensions have to be taken into account: economic, environmental and social aspects.

To avoid shifting impacts and to capture all potential effects associated with resource use life cycle based approaches should be used as a basis for evaluation (Bach et al. 2016). By considering the life cycle of a product system important aspects regarding resource efficiency such as recycling and reuse of resources (Ardente and Mathieux, 2014) in the different supply chain stages are measured as well. As many companies already use LCA for assessing their environmental impacts, ESSENZ is established to be integrated into LCA where the all three sustainability dimensions are considered.

Medium-term availability is influenced by socio-economic aspects (e. g. political stability) inhibiting the supply security of resources and leading to a restriction in availability. For example, political instability of countries due to corruption can disrupt the capacity to effectively implement robust policies including ones related to resource extraction, export, etc. Thus, the availability of a specific resource produced in such a country could be limited. This aspect as well as other socio-economic factors can lead to restrictions of resource availability at different supply chain stages.

Overall six key aspects of governance for over 210 countries are established: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law and control of corruption. As all six world governance indicators reflect parts of an unstable system, in ESSENZ they are all combined as an aggregated evenly weighted index (WGI_x).

Overall 21 categories are established to measure impacts on the environment, physical and socio-economic availability of the used resources as well as their societal acceptance. For the categories socio-economic availability and societal acceptance, new approaches are developed, and characterization factors are provided for a portfolio of 36 metals and four fossil raw materials. The impact categories are similar to the ESP method and are described below:

- Country concentration: represents the concentration of mine production in certain countries and is measured by the HHI, which is an index calculated by squaring the market share of each company or country with regard to the production or reserves.
- Governance stability: Measures the stability of governance in producing countries by using the World Governance Indicators (WGI) published by World Bank Group
- Feasibility of exploration projects: Measures the political and societal factors influencing opening of mines with the Policy Perceptions Index (PPI).
- Demand growth: Measures the increase of resource demand based on past trends and future demand scenarios.
- Trade barriers: Measured by the percentage share of mine production under trade barriers.
- Companion metal fraction: Measures the percentage of a metal that is mined as a by- product.
- Reserve availability/ Mining capacity: this measures the depletion time of resources with the category indicator reserve-to-annual production ratio
- Price fluctuation
- Recycling: measures the recycled content of a resource by the category indicator new material content

Availability and criticality of resource supply on macro (country), meso (company) and micro (product) level has been a topic of discussion in various working groups recently (European Commission, 2014; Gemechu et al., 2016; Graedel et al., 2012; Schneider et al., 2013; Sonnemann et al., 2015). However, existing approaches are often only applicable for assessing the risk of limited availability on country level (e.g European Commission, 2014) or are not easily integrated into existing approaches already applied by companies like Life Cycle Assessment (LCA) (e. g. Graedel et al. (2012) and Schneider et al. (2013)). Therefore, the ESSENZ approach was developed to determine the resource efficiency of product systems and for decision making support on a product level and in the context of sustainable development.

For determining the socio-economic availability, the ESSENZ approach complements existing approaches as it can be integrated in existing life cycle assessment based schemes. Therefore, companies which already use LCA for determining their environmental impacts can adapt their framework and integrate the assessment of additional aspects more easily. One limitation for this method however, is the use of many indicators. Bach et al. (2016) argue that the communication of the results can be challenging due to the several indicators, especially with regard to stakeholders with less experience in the field of LCA and sustainability. Thus, identifying key indicators which represent the individual dimensions is important from an industry perspective where practitioners can use these results to make decisions about the materials used in their products.

2.3.3 Geopolitical Supply Risk Assessment

While criticality assessment methods have been developed, there has been very little work in relating this to companies at a product level. Therefore, the need to integrate criticality assessment to LCA has been discussed from two perspectives. Firstly, there is a limited applicability to integrate criticality assessments with LCA on a product-level because they lack a connection to a functional unit of a given product – a central concept in LCA. The second reason is the fact that LCA does not evaluate the Natural Resources Area of Protection adequately. The shortfalls of LCA in this category are discussed by the group at Bordeaux who argue that a comprehensive study for companies should include the short-term supply risks (Sonnemann, et al., 2015).

Given the need to address the limited availability of resources (both short-term and long-term), and the need to better evaluate the natural resources AoP, a strong interest has emerged in recent years to integrate resource criticality assessment with life-cycle assessment under the LCSA framework (Sonnemann et al., 2015). Dewulf et al. (2015) provided a new framework that elaborates on the definition of the AoP natural resources to evaluate direct impacts from their use either within the classical LCA or other methods that attempt to assess the socio-economic implications of resource consumption within the LCSA framework. Following the “supply chain” perspective proposed by Dewulf et al. (2015) and the criticality assessment framework by Sonnemann et al. (2015), Gemechu et al. (2015a) proposed a new method to assess the geopolitical supply risk of a material under an LCA characterization model. The GPSR was proposed as a midpoint characterization factor for LCSA similar to environmental midpoint indicators, with a value between 0 and 1. The supply concentration is evaluated with the Herfindahl-Hirschman Index (HHI) which represents the country concentration of resources, along with the World Bank’s Worldwide Governance Indicators (WGI), which measure the relative governance quality of a country. According to this work and the work by Helbig et al. (2016), the GPSR indicator for commodity A imported to country c is calculated by:

$$GPSR_{Ac} = HHI_A \sum_i g_i \frac{f_{Aic}}{p_{Ac}+F_{Ac}}$$ **Equation (1)**

where HHI_A = Herfindahl-Hirschman Index for commodity *A*,

g_i = political (in)stability of (producing) country *i*, assessed using the Worldwide Governance Indicator (WGI) – Political Stability and Absence of Violence/Terrorism,

f_{Aic} = import tonnage of commodity *A* from country *i* to country *c*,

F_{Ac} = total import tonnage of commodity *A* to country *c*,

p_{Ac} = domestic production of commodity *A* in country *c*

This provides assessment of the supply risk at a national scale as it looks at international trade data and uses the WGI indicators for governance to calculate the geopolitical supply risk for a material. The WGI are based on six broad dimensions of governance that include:

- Voice and accountability
- Political stability and absence of violence
- Government effectiveness
- Regulatory quality
- Rule of law
- Control of corruption

The GPSR method currently only uses the WGI scored for political stability and absence of violence. However, for some companies' other issues such as corruption, government effectiveness or rule of law among others could also affect the supply risk. These are published yearly by the World Bank for all countries and are available online. The WGI indicators are considered to be reliable and often used for national level data.

There have been other indicators proposed as well, which include the Global Political Risk Index (GPRI), and the Policy Potential Index (PPI). The former aggregates political, social, and economic aspects into a single risk index (IW Consult, 2009). The PPI published by the Fraser Institute measures policy and regulatory risk factors, such as taxes and environmental regulations that may impose restrictions on resource accessibility. However, there have not been any studies done to include those in the assessment of supply risks.

The GPSR method is suitable for country-level supply risk assessment, though it is more narrowly focused on supply risks arising from political (in)stability of trade partners from which inventory flows are imported (Cimprich et al. 2019). The method still has several limitations, such as lack of assessment at a firm level due to data availability and limited computational capability. The need for improved computational power and speed of calculations has been discussed by several researchers (Helbig et al, 2016; Cimprich et al. 2017) to make this method more manageable for companies as a decision-making tool as currently a single calculation can take up to a few hours due to being data intensive. This would increase the spatial resolution by assessing regional and firm-level supply risk factors not captured by existing country-level assessments (Cimprich et al. 2019).

2.4 Responsible Sourcing

Responsible sourcing is an approach that aims to inform and manage aspects associated with the location of production of natural resources (Young 2018). Policymakers, consumers and companies refer to 'responsible sourcing' as a way to address sustainability risks in global mineral supply chains, but the term is used to refer to a wide range of sustainability objectives under a variety of approaches (van den Brink et al. 2019). Van den Brink et al. define responsible sourcing as "the management of social, environmental and/or economic sustainability in the supply chain through production data" (van den Brink et al. 2019).

While most previous research regarding the impacts of materials has focused on the environmental side, attention to social sustainability has recently grown with respect to responsible sourcing of materials (Yawar and Seuring 2017). The growing interest in social aspects of sustainable development coupled with an increased concern from consumers and reputational risks for corporations has led to an expectation of socially responsible sourcing being an integral part of a company's purchasing strategy (Ageron et al., 2012). This is evident by several company and industry reports that follow due diligence guidelines in order to increase their transparency and identify areas of social risks in their supply chains (Duclos et al. 2010, Drive Sustainability 2018).

Furthermore, there has been a long-standing concern that companies have an important part to play in the development of communities and in maintaining sustainable supply chains (Seuring and Müller 2008). Companies using global supply chains can play an important role in sustainable management of natural resources (Kolotzek et al. 2018). Increasing extraction of raw materials and the complexity of supply chains has also led to a newer connection between sustainable management of supply chains. The responsibility of downstream companies has become more important to ensure that they follow responsible sourcing guidelines which started with a particular focus on the so-called ‘conflict minerals’ (tin, tantalum, tungsten and gold, in short ‘3 TG’) (van den Brink et al. 2019). Here the responsible sourcing of minerals is linked to "supply chain due diligence". The Organization for Economic Cooperation and Development (OECD) describes due diligence as “an on-going, pro-active and reactive process through which companies can ensure that they respect human rights and do not contribute to conflict” (OECD 2016).

The leading guidance in responsible and ‘conflict-free’ sourcing of minerals and metals is by the Organization for Economic Cooperation and Development (OECD): the “Due diligence guidelines for responsible supply chains from conflict affect and high-risk areas (CAHRA)” (OECD 2010). While not legally binding, the OECD Due Diligence Guidance for Responsible Supply Chains has been widely adopted as a framework used by regulators (US NRC, 2008; EC, 2018), industry schemes (RMI, RJI) and other instruments like the Global Reporting Initiative (GRI 2019).

According to a 2018 position paper on responsible sourcing by the London Metal Exchange, the OECD guidelines are the most widely adopted in this field, including at the governmental level (LME 2018). The guidelines provide a framework to help companies respect human rights and avoid contributing to conflict through their sourcing decisions. Conflict-affected and high-risk areas are identified by the presence of armed conflict, widespread violence or other risks of harm to people and may include areas of political instability or repression, institutional weakness, insecurity, collapse of civil infrastructure and widespread violence (OECD 2010).

The European Commission also published a recommendation guideline to identify CAHRAs which it defines as: “Areas in a state of armed conflict or fragile post-conflict as well as areas witnessing weak or non-existing governance and security, such as failed states, and widespread and systematic violations of international law, including human rights abuses (EC, 2018).”

Based on the key words in the definition, the European Commission report groups the potential risks into three categories of accessible information. These are:

- Conflict – assessment of whether an area is in a ‘state of armed conflict’ or is a ‘fragile post-conflict’ area
- Governance – assessment of the extent to which areas witness weak or non-existent governance and security

- Human rights – assessment of whether an area is affected by widespread and systematic violations of international law, including human rights abuses

While there is significant overlap between these three areas of risk, there has been very little work done so far to figure out if there is an alignment or correspondence between these three broad areas of social indicators. To date, the responsible sourcing guidelines have also not been incorporated or developed into an LCA tool or method. Interestingly however, two of the areas of responsibility mentioned overlap with the issues discussed in the previous sections.

In the OECD framework the human rights category corresponds to the idea of social indicators but also includes labor conditions, gender rights, etc. The governance category includes stability, and business risks that might affect trade or commerce in a country or working with country and this corresponds to supply risk of materials which is an important part of conducting criticality assessments. Lastly, OECD adds conflict as a category, and in fact this was the original concern with respect to conflict minerals.

2.4.1 OECD 5-step Framework

The OECD guidance (2016) provides a five-step framework, of which one is to identify and assess risks in the supply chain, followed by a step to mitigate them. The risks are based on so-called 'red flags' for locations, suppliers or circumstances (OECD, 2016). The due diligence approach in the context of minerals focuses on the upstream supply chain – mining and refining – and on social requirements and human rights. As such it is therefore to be categorized as 'socially responsible sourcing' (van den Brink et al. 2019). The guidance aims to help companies address human rights issues and avoid contributing to conflict associated with their sourcing decisions, including the choice and management of suppliers.

The 5-step framework for company due diligence:

1. Establish strong company management systems
2. Identify and assess risk in the supply chain.
3. Design and implement a strategy to respond to identified risks.
4. Carry out independent third-party audit of supply chain due diligence at identified points in the supply chain.
5. Report on supply chain due diligence

A risk-based approach has as a disadvantage that the guidance provided must identify specific risks with respect to specific issues (thereby excluding environmental risks, for example) and specific geographic areas (conflict and high-risk). The OECD due diligence guidance currently applies to tin, tantalum, tungsten and gold (3 TG), but it is noted that supplements on other minerals may be added to the guidance in the future (OECD, 2016).

2.4.2 Industry Reports

As of late 2019, several company and association reports have been published that follow the OECD guidelines, following the 5-step framework that highlights certain social aspects that manufacturers and downstream companies are reporting on. Table 1 identifies several companies that have followed the due diligence framework and have published Step-5 reports with reference to the indicators that they use to assess socio-economic conditions in countries in their supply chain. A detailed list of recommended indicators is provided in the Appendix (Table A3) based on reports published by industry associations including the EU Commission, Drive Sustainability and Responsible Minerals Initiative (RMI).

Table 1. Indicators used by companies (mostly smelters) to establish due diligence in supply chains based on the OECD Responsible Sourcing Guidelines

Company Name	Conflict Indicators
Thaisarco	Heidelberg Conflict Barometer Fragile States Index (FSI)
PT Tirus	Heidelberg Conflict Barometer INFORM Index for Risk Management
Resind Industria e Comércio Ltda	Geneva Academy Rule of Law in Armed Conflict RiskMap Human Development Index
Exotech - tantalum smelter	Heidelberg Conflict Barometer Fragile States Index (FSI)
Wolfram - tungsten company	Heidelberg Conflict Barometer ControlRisks INFORM Index for Risk Management

2.5 Comprehensive Assessment Methodology for Sustainable Supply Chain Management

There have been very few studies that look at a comprehensive tool for companies to assess the sustainability impacts and risks associated with their raw material supply chains. Kolotzek et al. (2018) present a comprehensive assessment model for companies to assess the risks and impacts associated with sourcing of raw materials. They employ a life-cycle management approach that includes criticality assessment, life cycle impact assessment and social life cycle assessment as the main tools that cover all three dimensions of the triple bottom line of sustainability. The paper identifies relevant quantitative and categorical indicators for structuring the assessment model and for calculating corresponding indicator weightings and presents a case study to apply the model practically. The approach by Kolotzek et al. is one of the first attempts to develop a comprehensive risk and impact assessment tool to help companies in sourcing raw materials taking sustainability aspects into consideration.

Kolotzek et al. mention the need to address the research gap in the social dimension to select applicable and quantifiable indicators for all stakeholder categories. A recent development in this area that is specifically applicable to conflict affected and high-risk areas is the OECD Due Diligence guidelines that lay down a framework to help companies undertake responsible sourcing practices. To date, no one has linked these guidelines to LCA and this presents an interesting opportunity to integrate the environmental and social impacts and the supply risk of materials into a single tool based on the LCA methodology to help companies make more informed decisions.

Based on the literature review, there are several gaps in the literature regarding sustainable management of raw material supply chains. These relate to the areas of LCA, criticality assessment and responsible sourcing – which have not previously been linked together. In LCA, there is a lack of indicators to assess the socio-economic impacts of natural resources. To better evaluate these impacts such as the supply risk of materials, the criticality assessment methodology has been integrated into an LCA approach. However, this only considers geopolitical conditions based on the WGI for political stability and does not include other factors that could affect supply risk such as conflicts or human rights violations. The guidelines for responsible sourcing identify three main categories of conflict, governance and human rights that should be considered while sourcing materials. These guidelines have not been linked to LCA or criticality assessments from an academic perspective, but there has been some industry work to help companies assess the supply risks.

Therefore, this research explores these connections to better understand how companies can assess the social supply risks in their supply chain.

2.6 Proposed Framework

A framework is suggested in Figure 2 which draws upon concepts from the literature to help in understanding the various supply risks of raw materials. It follows the lifecycle assessment approach of using midpoint indicators that point to endpoint areas of protection. This framework is adapted from Sonnemann et al. (2015) which integrates criticality assessment methodology to a LCA standards. Therefore, the framework is a good starting point to explore the relationships between different social aspects that can affect the supply risk of materials based on their trade patterns and material production concentration.

The framework presented by Sonnemann et al. (2015) and Gemechu et al. (2016) added geopolitical and social midpoints to account for supply risk implications. The model integrated the concept of supply risk as a parameter of criticality assessment into the LCA framework. The proposed framework in Figure 2 further divides geopolitical and social availability of materials into the 3 categories of risk defined in responsible sourcing guidelines. Thus, the geopolitical and social supply risk implications which are affected by the geopolitical and social conditions of a region have been divided into areas of governance, human rights and conflict. This provides a more detailed analysis that also has the potential to focus on a separate social issue or risk that is relevant to a company's supply chain.

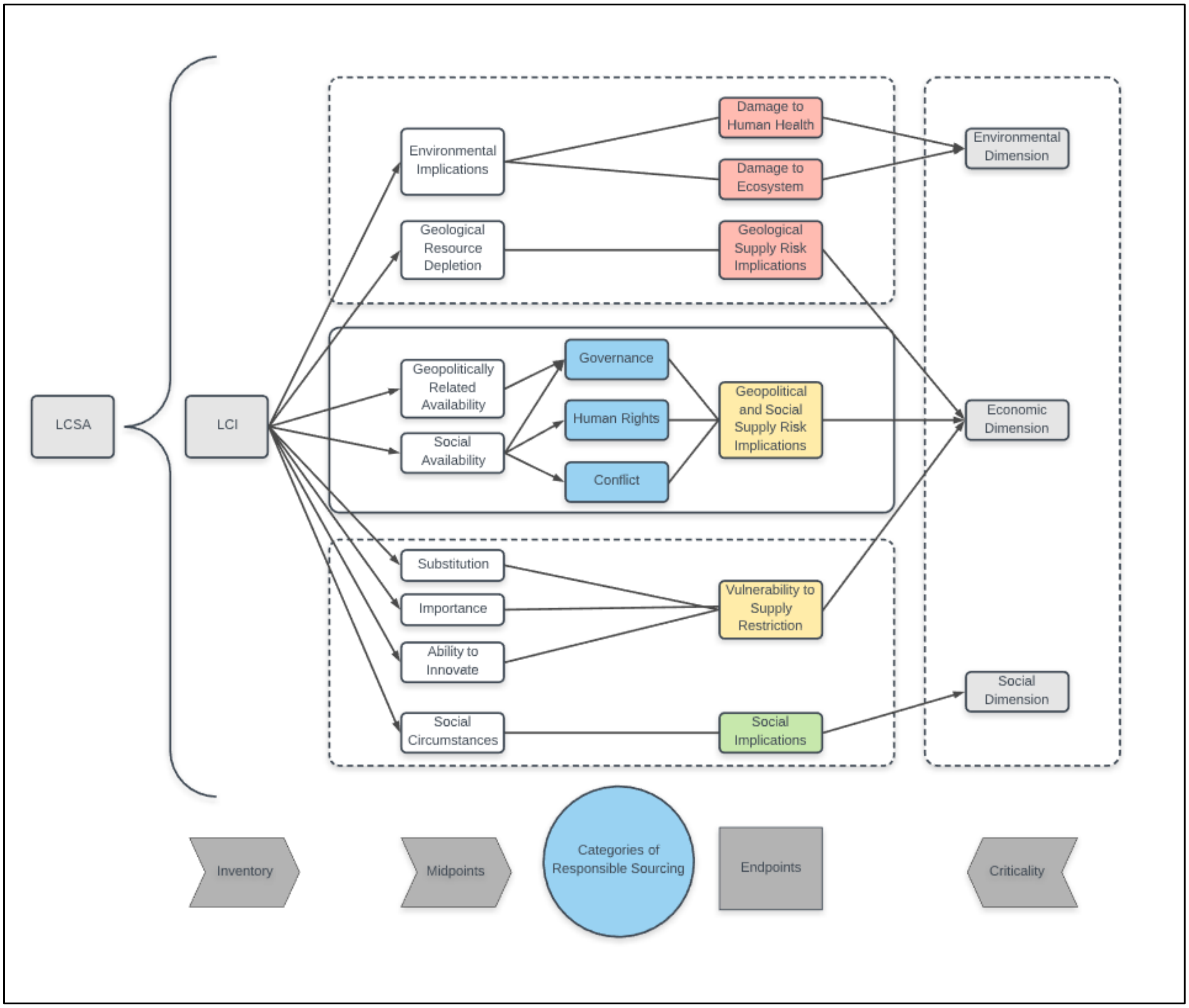


Figure 3. Integration of social and geopolitical supply risk and other criticality components within the life cycle sustainability assessment framework. The criticality assessment indicators are adapted from Graedel and colleagues (2012). The responsible sourcing categories are adapted from the European Union Commission's recommendations.

LCI = life cycle inventory; LCSA = life cycle sustainability assessment.

3.0 Methods and Data

This chapter explains the approach taken to develop a tool and database for calculation of the social and geopolitical supply risk. This chapter also presents the research methods and description of the system that was studied. The general research approach is defined, and the method to develop the web application and database is presented to help the reader understand how the GPSR methodology is extended to integrate responsible sourcing indicators for an assessment of the social and geopolitical supply risk of raw materials.

The first section presents the research approach and the development of the research tool including all the steps and tools used to build the tool. This section also talks about the extension of the GPSR by adding additional indicators in the formula.

The next section presents the data and the development of the database that is used in the tool. This section talks about the production and trade data and also introduces the nine indicators that were selected for this study.

The last section presents the system description and case study selected to test and operationalize the tool.

3.1 Research Approach

The research included both the development of a computational tool, divided into two phases as described below, and a case study that was used to demonstrate the tool and to assess the supply risks based on the various different social indicators for the materials in a lithium ion battery.

The tool comprised a web-application and supporting database. These were developed to compute the GPSR value for a specified country and material with increased computational speed and ease of use in performing the calculation, as compared to previous versions (Gemechu et al., 2016; Helbig et al., 2016; Cimprich et al., 2017). Furthermore, the database and computational ability tool was extended to allow using indicators additional to the WGI such as the HDI or CPI. The collection of data and development of a database were done iteratively and throughout the development of the tool to test for additional materials and countries. This development is covered separately in section 3.2.

The first phase in the tool development was to rebuild the GPSR and to automate the calculation because it is data intensive and was slow to use in Microsoft Excel. To replicate the steps for the GPSR calculation, a database was created, and Python code was used to automate the calculation. Python is a programming language that can be used for various purposes, including web development and data analysis. A web-application was also developed using Python and the web framework "Flask" to help increase the speed of calculations and to allow to save and download the results so that they can be further analyzed (http://flask.palletsprojects.com/en/1.1.x/).

The GPSR is proposed as a midpoint characterization factor for LCSA similar to environmental midpoint indicators, with a value between 0 and 1. The supply concentration is evaluated with the Herfindahl-Hirschman Index (HHI) which represents the country concentration of resources, along with the World Bank's Worldwide Governance Indicators (WGI), which measure the relative governance quality of a country. According to this work and the work by Gemechu et al. (2014), the GeoPol indicator for commodity *A* imported to country *c* is calculated by formula 1 as described in section 2.3.3. This provides assessment of the supply risk at a national scale, as it looks at the incoming international trade for a material and uses the WGI indicators for governance to calculate the geopolitical supply risk associated with each material.

In the second phase of development of the tool in the current project, additional country indicators were added to the database to understand how the use of different metrics affects the supply risk calculation. In addition to the WGI indicator that was originally used in the GPSR calculation, other indicators as described in section 3.2.3 were added to the database for use in the GPSR calculation, as an alternative to the WGI indicator. A feature was presented in the tool to allow users to select which country indicator they want to use in the GPSR calculation.

This methodology was used to make the GPSR calculation more efficient and more importantly, because decisions for companies also involve responsible sourcing guidelines and practices that use various other indicators. Therefore, the selection of other country indicators was based on practice demonstrated in company reports, which in turn are based on the OECD guidance for responsible sourcing. The European Commission has interpreted the types of risks and provided recommendations for country risk indicators, also providing the indicator sources used in assessing supply risks for companies including categories of governance, conflict and human rights. The WGI indicator measures political (in)stability and governance and therefore is used to assess the "geopolitical" supply risk. Using other indicators, such as the Heidelberg Conflict Barometer that measures conflict, and such as the

Human Development Indicator that measures human rights and development measures; allows for assessing the social supply risk of materials based on responsible sourcing guidelines. The methodology begins with LCA and criticality assessment with the GPSR calculation while growing in the direction of responsible sourcing.

The two phases of development of the tool and web application are described in detail below. Once the tool was complete, it was used to calculate the GPSR scores for several materials, countries and indicators.

3.1.1 GPSR tool and web development

1. Used Python code to load and extract data, and format tables in Python environment
    a. The Python code read and extracted data from the Excel database file
    b. Used Python code to format data and to make the tables for:
        i. Countries
        ii. Materials
        iii. Indicators
        iv. USGS Production data
        v. UN Comtrade data
    c. Production data was used to generate HHI values based on formula 2

$$HHI_A = \sum \left(\frac{Country\ Production}{World\ Production}\right)^2 \qquad \textbf{Equation (2)}$$

2. Calculation of the GPSR was performed according to equation (1).
3. Web application was developed using the Flask framework.
    a. Made a web-application using Flask. Flask is a Python web framework that allows quick and agile development of web-based applications. The framework was used to deploy

    the calculation tool on a web server to allow other users to be able to use the tool on their local computers. This increased the ease of use and replicability of the tool for other academics and professionals.

   b. The web application included features to save the results and an option to download the stored results for further analysis

The web-app worked like a calculator with certain inputs (Country Code, HS Code, year and indicator) to give the calculated supply risk score.

3.1.2 Extension of GPSR + Additional Indicators

1. Addition of other indicators to the database and inclusion of indicators in GPSR formula.
   a. Several indicators were selected based on availability, authenticity and comparability to the WGI.
   These indicators were selected based on company reports and guidance that had referred to these or had used them previously. The raw scores of the indicators was collected and then recorded on the Excel file.
   b. The indicator scores were converted to a scale of 0 – 1 to be consistent with the WGI scale where a score closer to 1 represents a high risk or high level of political instability while a score of 0 represents low risk or high level of political stability.
   c. The updated formula is given below:

$$\boldsymbol{GPSR_{Ac} = HHI_A \sum_i X_i \frac{f_{Aic}}{p_{Ac}+F_{Ac}}} \qquad \textbf{Equation (3)}$$

where $\boldsymbol{HHI_A}$ = Herfindahl-Hirschman Index for commodity *A*,

$\boldsymbol{X_i}$ = indicator score of (producing) country *i*, assessed using the chosen indicator,

$\boldsymbol{f_{Aic}}$ = import tonnage of commodity *A* from country *i* to country *c*,

$\boldsymbol{F_{Ac}}$ = total import tonnage of commodity *A* to country *c*,

$\boldsymbol{p_{Ac}}$ = domestic production of commodity *A* in country *c*

d. The additional indicators were then used to compute the GPSR

The addition of other indicators allows the tool to extend the GPSR methodology by adding option to select indicator and therefore calculate supply risks based on global trade and production data and the relevant social aspect indicator.

2. The GPSR results were analyzed using Tableau.

Due to the large amount of data obtained, data visualization tools were needed to analyze the results and find any trends. Tableau was used to make the graphs, find correlations and present the results.

3.2 Data

A database was created to serve the calculation tool. The Python code extracted data from the database to be used in the GPSR calculations. This database was made on Excel and included information from several publicly available sources. The basic information was that of countries and commodities which were assigned their ISO-3 codes and HS codes, respectively, to make it easier to fetch values.

The database also includes the indicator scores for each country, the global production data of each material and the global trade data of countries for the respective materials.

1. Collection of data from online resources
    - USGS Production Data for production of minerals
    - UN Comtrade data for global trade quantities
    - Country indicator data obtained from public sources as outlined in 3.2.3

Data was collected for the years 2008 – 2018 but there were several instances (for certain commodities and years) where the data was of insufficient quality or not readily available. The majority of data for all indicators, production concentration of materials and international trade data is available for the years 2015 – 2018.

2. Creation of database

a. The database was made on Excel using data collected from various sources mentioned above.

   The tables for the database were structured by using HS Codes for commodities, UN country codes for countries and the respective indicators being used to assess the supply risks. As a result, all the tables were indexed with unique identifiers such as the HS Codes, UN country codes and by the year. This helped in pulling out values for the GPSR calculation and in observing and studying the trade patterns of some specific countries and materials.

3.2.1 Production Data

Production data for commodities was obtained from the United States Geological Survey (USGS) data. The United States Geological Survey (USGS) production data is a comprehensive public source of data available for metal and mineral production. It contains information on 130 different commodities including global production data for raw materials and is regularly used by researchers and industries as a trusted source on global mineral production. The production data is important as it is used to calculate the HHI values which shows the country supply concentration of a commodity. The production data is loaded from the Excel files and formatted to a table that is arranged by the year and the HS Code of the commodity.

For some materials such as rhenium and germanium, that are available in small quantities and as by-products with other metals, the USGS provides aggregate production data. In these scenarios, the production data was collected from additional sources such as the EU Report on Critical Raw Materials (EC, 2017). However, for the purpose of this study these data may be incomplete and were not included in the case study.

Uncertainty information is not provided for raw material production from the USGS (2016). An additional factor to consider is the conversion of the weight of production as each commodity is presented in different units of weight. The data in the Excel database is formatted to be in kilograms for all commodities.

3.2.2 Trade Data

Comtrade is a database compiled by the UN to provide trade data and increase transparency of global material flows. It is an extensive database that is available publicly and contains data for the various commodity HS codes. The trade table in the Excel database are indexed according to year (2015 – 2018), commodity HS Code and code for the country that is importing a material. This data is used in the GPSR formula to obtain the adjusted import shares of a country which is then multiplied by the social aspect indicator score.

Trade data can be particularly difficult to obtain for commodities that lack an appropriate commodity code (e.g., the rare earth metals neodymium and gadolinium), or where raw materials are aggregated into a single commodity code (e.g., HS 26 15 90 for "niobium, tantalum, vanadium ores and concentrates"). Uncertainty information is also missing for commodity trade data, such as those from the UN Comtrade database (United Nations, 2018), needed for the GPSR method.

The trade data is provided in mass (units of kilograms) and an additional supplementary quantity for all materials. To keep the units consistent, kilogram values were used throughout the database. For lithium in 2018, where the quantities in kg were not provided, assumptions were made based on the Comtrade data from previous years (2015 – 2017) to estimate the quantity of imported material in kilograms.

3.2.3 Indicator Data

The next phase in the database creation was to select country indicators and then to extend the GPSR methodology to account for other social aspects such as human rights and conflict.

There are several hundreds of available country indicators that provide an indication of social aspects. This is in fact, a problem identified by several researchers while performing S-LCA or a similar assessment in terms of which indicators to select that best reflect the social conditions of a region (Dreyer et al., 2010; Kühnen and Hahn 2017; Popovic et al. 2018). There are also different organizations that publish a list of recommended indicators that are widely used in both academics and industry. The EU commission published a report dividing the indicators into the three categories of responsible sourcing, and the Carleton University has a similar list on their website that provides further information, data accessibility and descriptions of each of the indicators (EU Commission 2018; https://carleton.ca/cifp/conflict-risk-assessment/indicator-descriptions/). A summary of the most common and widely used indicators is provided in the Appendix table A3.

The indicators used to measure these social aspects were chosen based on responsible sourcing guidelines and company reports that had highlighted the importance of those aspects. We choose risk categories because they have already been identified by companies (GE) or industry organizations (RMI, Drive Sustainability) and were therefore judged to be used in practice, and thus relevant to company decision making. Additionally, the current research considered a cross section of country indicators. These were based on the three categories of indicators identified in the OECD in European regulation: Governance, human rights, conflict. Table 2 shows as summary of the country indicators that were chosen for this study to extend the GPSR.

Nonetheless, there were several opportunities to select the indicators and factors considered while selecting the country indicators for the tool included: reputation of the index as being accurate and agreed upon, public availability and free access, categorized according to the OECD guidelines for responsible sourcing, global coverage of all countries (as opposed to some options which provided more regional representation), quantitatively sound and being consistent with the existing GPSR methodology. This means that they had to be converted to a continuous scale of 0 – 1 similar to the WGI-Political (in)stability and Violence (WGI-PV) so that they could be substituted in Equation (3).

Due to the fact that all the indicators have different scales, there is some loss of information in the conversion, and thus the indicator loses vital information for the social aspect that it measures based on the calculation methodology. The conversion of scales was performed so that each of the indicators could be compared with the WGI score, where a score of 1 represents high risk of political instability whereas a score of 0 represents low risk of political instability. Where the conversion was not possible, a least square regression method was applied to approximate the values consistent with a 0-1 scale.

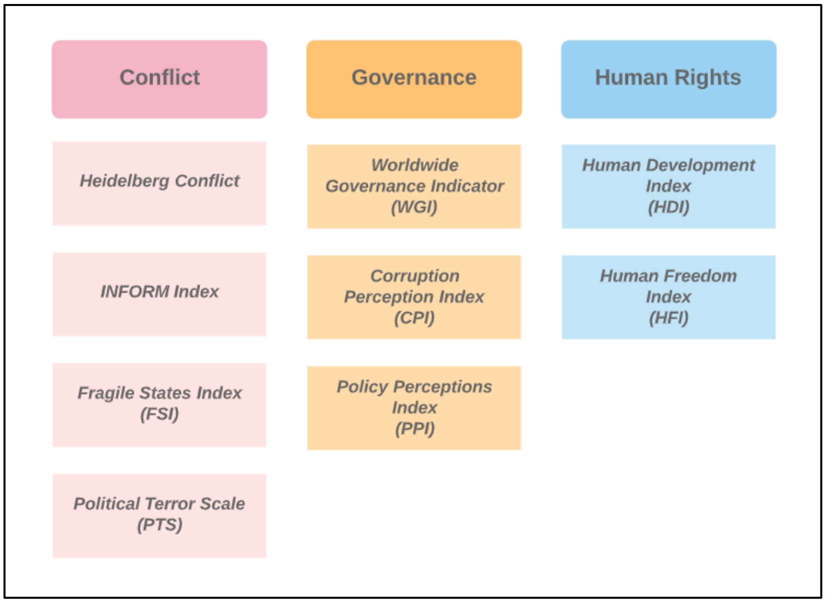


Figure 4. Selected indicators based on responsible sourcing guidelines

3.2.3.1 Conflict

Heidelberg Conflict Database

The Heidelberg Conflict Database provides conflict maps representing an annual snapshot of the presence of armed conflict in countries and regions (https://hiik.de/hiik/methodology/?lang=en). The indicator is published by the Heidelberg Institute for International Conflict Research (HIIK) and is widely used in reference by industry and government. It has been used by several companies in support of OECD due diligence processes and has been recommended by the European Commission in regard to characterizing armed conflict in different regions (EU Commission 2018).

Both national and sub-national resolution are provided, although in the current research only the country-level data are use. The indicator is scaled categorically from 0-5, where 0 indicates no conflict, 1-2 indicate levels of non-violent conflict and a score of 3 or greater represents increasing degree of armed conflict.

The use of this indicator required mathematical manipulation for use in this research, resulting in loss of information. Since the Heidelberg Conflict map provides a categorical indicator, there is no easy means of converting values to a continuous scale. Thus, the conversion is performed using a least squares regression method which results in loss of data as each intensity level is provided a similar indicator score. For each intensity level, the value was raised to the power of five, and then the ratio was taken from the total sum of the powers. For example, an intensity level of 3 would be converted to a value of 0.055 representing the first level of armed conflict while an intensity level of 4 would be converted to a value of 0.231 representing a huge range of values that the intensity level could represent. The large variance in these values shows that there is a wide range of possibilities, but due to the conversion method all countries with an intensity level of 3 get converted to the same score.

Fragile States Index (FSI)

The Fragile States Index (FSI) is produced by The Fund for Peace (FFP), which is a non-profit organization that develops practical tools and approaches for reducing conflict (https://fundforpeace.org/who-we-are/). FSI is a valuable tool in highlighting not only the political, social and conflict pressures that all states experience, but also in identifying when those pressures are outweighing a states' capacity to manage those pressures (https://fragilestatesindex.org/methodology/). By highlighting relevant vulnerabilities which contribute to the risk of state fragility, the Index — and the social science framework and the data analysis tools upon which it is built — makes political risk assessment and early warning of conflict accessible to policy-makers and the public at large.

The FSI for violent conflict and sustainable security provides country-level risk profiles relating to Security Apparatus, Group Grievance, Human Rights and Rule of Law, Human Flight and Brain Drain, Factionalized Elites, etc. The index is scored on a scale of 0-10 where a score of 10 represents a country with extremely high risk of conflict or fragility.

In processing the values of the FSI, as the index is scored on a scale of 0-10, it fits into the current work simply by dividing scores by 10. For this research, only the category of Human Rights and Rule of Law was used since it was used by companies to address conflict risks (e.g. Thaisarco, Exotech).

INFORM Index

The INFORM Global Reporting Initiative (GRI) is a global, open-source risk assessment for humanitarian crises and disasters which is led by The European Commission Joint Research Center (http://www.inform-index.org/). It can support decisions about prevention, preparedness and response. The INFORM Index for Risk Management provides country-level risk profiles relating to humanitarian crises. INFORM provides disaster risk profiles of 191 countries and utilizes 50 different indicators related to the conditions that lead to crises and disasters. It includes data on the area's human and natural hazard risks, the vulnerability of the communities faced with hazards, and the coping capacity of local infrastructure and institutions.

The INFORM model is based on risk concepts published in scientific literature. It includes three dimensions of risk: hazards & exposure, vulnerability and lack of coping capacity dimensions. Each dimension has multiple categories and each category is score from 0-10, where a score of 10 represents high risk.

The total aggregated score for each country is taken for the GPSR formula which takes an average of the score in each category across the three dimensions. The index is scored on a scale of 0-10 and so it fit into the GPSR formula used in this research by dividing the scores by 10.

Political Terror Scale (PTS)

The PTS is a standards-based human rights data set started by researchers and graduate students at Purdue University in the 1980s. Originally developed by Freedom House, the data used in compiling this index comes from two different sources: the yearly country reports of Amnesty International and the U.S. State Department Country Reports on Human Rights Practices. The point of difference between this particular measure and others is that it is more specifically aimed at capturing "state terror", i.e. violations of physical or personal integrity rights carried out by a state (or its agents) (Gibney et al., 2019).

It measures levels of political violence and terror that a country experiences in a particular year based on a 5-level 'terror scale'. Level 1 relates to countries under a secure rule of law, people are not imprisoned for their view, torture is rare or exceptional and political murders are extremely rare. In contrast, level 5 reports that terror has expanded to the whole population. The leaders of these societies place no limits on the means or thoroughness with which they pursue personal or ideological goals.

Since the Political Terror Scale provides intensity levels based on different categories similar to the Heidelberg Conflict Barometer, the use of this indicator required mathematical manipulation resulting in loss of information. Thus, the conversion is performed using a least squares regression method which results in loss of data as each intensity level is provided a similar indicator score. For example, an intensity level of 3 would be converted to a value of 0.055 representing the first level of armed conflict while an intensity level of 4 would be converted to a value of 0.231 representing a huge range of values that the intensity level could represent. The large variance in these values shows that there is a wide range of possibilities but due to the conversion method, all countries with an intensity level of 3 get converted to the same score.

3.2.3.2 Governance

Worldwide Governance Indicators (WGI)

The WGI political stability and absence of violence (WGI-PV) is one of six composite WGI indicators published by the World Bank, the others being voice and accountability, government effectiveness, regulatory quality, rule of law, and control of corruption (https://info.worldbank.org/governance/wgi/). Some criticality assessment methods aggregate some or all of these indicators (Schneider et al. 2014; Bach et al. 2016). It measures perceptions of the likelihood of political instability and/or politically motivated violence, including terrorism. It reports aggregate and individual governance indicators for over 200 countries and territories over the period 1996 – 2018 for those six categories. Due to the reliability and public availability of these indicators, they have been recommended by researchers as an indicator for geopolitical supply risk of raw materials for criticality assessment and this indicator is originally used in the GPSR calculation (Gemechu at al., 2016).

A statistical tool known as an Unobserved Components Model (UCM) is used to make the 0-1 rescaled data comparable across sources, and then to construct a weighted average of the data from each source for each country. The UCM assigns greater weight to data sources that tend to be more strongly correlated with each other. While this weighting improves the statistical precision of the aggregate indicators, it typically does not affect very much the ranking of countries on the aggregate indicators.

The composite measures of governance generated by the UCM are in units of a standard normal distribution, with mean zero, standard deviation of one, and running from approximately -2.5 to 2.5, with higher values corresponding to better governance. For the GPSR formula a conversion was used to change the scale to 0-1.

Corruption Perception Index (CPI)

The Corruption Perceptions Index (CPI) is published by Transparency International and aggregates data from a number of different sources that provide perceptions by business people and country experts of the level of corruption in the public sector (https://www.transparency.org/cpi2018). The index offers an annual snapshot of the relative degree of corruption by ranking countries and territories from all over the globe.

The Corruption Perception Index ranks 180 countries and territories by their perceived levels of public sector corruption according to experts and businesspeople, uses a scale of 0 to 100, where 0 is highly corrupt and 100 is very clean. More than two-thirds of countries score below 50 on this year's CPI, with an average score of just 43. While no country earns a perfect score on the CPI, countries that tend to do best also protect democratic rights and values. The calculation process also incorporates a strict quality control mechanism which consists of parallel independent data collection and calculations conducted by two in- house researchers and two academic advisors with no affiliation to Transparency International.

In processing the values of the CPI, as the index is scored on a scale of 0-100, it fits into the current work simply by dividing scores by 100.

Policy Perception Index (PPI)

The Policy Perception Index (PPI) is a composite index that measures the effects of government policy on attitudes toward exploration investment and the overall policy attractiveness of the 83 jurisdictions in the survey (https://www.fraserinstitute.org/studies/annual-survey-of-mining-companies-2018). The Policy Perception Index captures the opinions of managers and executives on the effects of policies in jurisdictions with which they are familiar and can serve as a report card to governments on how attractive their policies are from the point of view of an exploration manager.

The index is composed of survey responses to policy factors that affect investment decisions. Policy factors examined include uncertainty concerning the administration of current regulations, environmental regulations, regulatory duplication, the legal system and taxation regime, uncertainty concerning protected areas and disputed land claims, infrastructure, socioeconomic and community development conditions, trade barriers, political stability, labor regulations, quality of the geological database, security, and labor and skills availability.

The jurisdiction with the most attractive policies receives a score of 100 and the jurisdiction with the policies that pose the greatest barriers to investment receives a score of 0. To convert the scale to 0-1, the PPI scores were divided by 100. A major limitation of the PPI is that it is restricted to 83 regions that consist of mining jurisdictions. Mines in bigger countries such as the United States, Canada, Australia and Argentina were surveyed separately thereby providing regional scores rather than national level scores. The average score of the PPI was taken for these mines to assign to the parent country and to make it compatible with the GPSR formula.

3.2.3.3 Human Rights

Human Development Index (HDI)

The Human Development Index (HDI) is published by the United Nations Development Programme. The HDI is a summary measure of average achievement in a country in key dimensions of human development: a long and healthy life, being knowledgeable and have a decent standard of living (http://hdr.undp.org/en/content/human-development-index-hdi). This is chosen because it includes issues such as child labor, worker rights, etc. that represent the category “human rights” in the responsible sourcing guidelines.

The HDI is the geometric mean of normalized indices for each of the three dimensions. The HDI is published yearly for 189 countries by the United Nations and is scored on a scale of 0-100. It is a measure of achievement in the basic dimensions of human development across countries.

In processing the values of the HDI, as the index is scored on a scale of 0-100, it fits into the current work simply by dividing scores by 100.

Human Freedom Index (HFI)

The Human Freedom Index report is co-published by the Cato Institute, the Fraser Institute, and the Liberales Institut at the Friedrich Naumann Foundation for Freedom (https://www.cato.org/human-freedom-index-new). It presents the state of human freedom in the world based on a broad measure that encompasses personal, civil, and economic freedom. Human freedom is a social concept that recognizes the dignity of individuals and is defined here as negative liberty or the absence of coercive constraint (Fraser Institute, 2019).

Data for the Human Freedom Index is available for 2015 – 2017 and it uses 76 distinct indicators of personal and economic freedom in the areas of: rule of law, security and safety, movement, religion, association, assembly, and civil society, expression and information, identity and relationships, size of government, legal system and property rights, access to sound money, freedom to trade internationally, regulation of credit, labor, and business.

In processing the values of the HFI, as the index is scored on a scale of 0-10, it fits into the current work simply by dividing scores by 10.

3.3 Case Study – Lithium Ion Battery

To demonstrate the calculation tool, a case study on lithium ion batteries (LIB) was used to assess raw material supply risk. The LIB in the case study were assumed to be manufactured by companies in three different regions using the same eight raw materials. Results of the analysis provide assessment of country-level supply risks and the tool illustrates how different country indicators presents different results of social supply risk, with a potential to use the tool in a firm-level assessment. The regions selected are: USA, Japan and the EU-27 (which consists of all the countries in the European Union in 2019, including the United Kingdom). Materials are obtained from the bill of materials of a LIB and are shown as a list in Table 3.

The GPSR calculation is performed for those sets of materials and countries with two added dimensions of time and the choice of indicators. The database includes data for different years going as far back as 2008. However, for many indicators the data is limited and so to accurately compare results from different indicators, results are only calculated from 2015–2018. Lastly, there is the choice of indicators in the tool that includes categories of governance, conflict and human rights.

The eight materials listed in Table 3 were chosen since they are the most commonly used materials in lithium ion batteries used in electric vehicles (Ellingsen et al., 2013). It is important to note that the quantity of material is not important in the assessment of supply risk (Cimprich et al., 2017) since in terms of supply disruption, regardless of the quantity of material, the risk will remain constant. The sustainable development of eVs is important in the next 10 years to successfully transition to a low carbon economy since transportation is a major source of carbon emissions. While electric vehicles are seen at being at the forefront of spearheading the movement to a lower carbon economy, the management of supply chain and the sourcing of materials used to make a lithium ion battery is equally important to ensure that the production of EV batteries remains sustainable and does not imply supply restrictions for manufacturing companies based on geopolitical or social conditions in the country where those materials are being sourced from.

With respect to the eight materials chosen, six of those materials are characterized at the mining stage and the production data were taken from USGS and represent mine production. These are cobalt, copper, graphite, lithium, manganese and nickel. For aluminum and iron, the data was also collected from the USGS database representing the smelter or processing stage and thus did not include production data for the ores, but the production data obtained at the smelter production level. This provided insights on two stages in mining and metals supply-chain, one in the mining stage and the other in the processing stage.

This was done for two main reasons: firstly, to differentiate between the stages of supply chain and secondly, because the two sets of materials have bottlenecks in different parts of the supply chain. The calculation of supply risks for these two sets of materials shows that the tool is versatile and can be used in any stage of the supply chain depending on availability of data. The two sets of materials also have different impacts and stages in the supply chain where they have more importance. For the six materials in the mining stage, the bottlenecks exist in the primary production stage from where the greatest supply disruptions are evident and include some critical materials identified by the European Union including cobalt, natural graphite and lithium (EC, 2017a). For iron and aluminum, which are bulk materials, the possibility of supply disruption and the greatest risks from an LCA perspective are perceived at the smelting or processing stage, therefore the data used is collected at that stage.

Further contribution analysis is provided on three materials in the results section: lithium, graphite and iron. This analysis is performed by looking at the production and trade data for these materials for the top ten countries in each area. For lithium, the 2018 trade data was not available in kilograms from UN Comtrade, therefore the quantities were estimated based on previous data from 2015 – 2017.

Figure 5. Parameters employed for the lithium ion battery (LIB) case study of social supply risks

4 Results

This chapter describes the results obtained in terms of the development of the tool and the supply risk calculations for the case study presented in Chapter 3. The automated calculation tool was successfully developed allowing users to perform the social supply risk calculations and download the results for further analysis.

GPSR calculations were done for three regions and eight materials that are most commonly found in an EV battery. The three regions are the EU-27, USA and Japan while the eight materials are cobalt, manganese, iron, aluminum, lithium, tungsten, magnesium and graphite. These calculations were done for the years 2015–2018 and the results obtained are shown in this chapter.

The chapter begins by presenting the background results that were collected directly from the Excel database. This shows the indicator scores for the selected regions and the HHI scores for the selected materials. The HHI score represents the supply concentration of a material and so a higher score means that the material production is concentrated in a few countries.

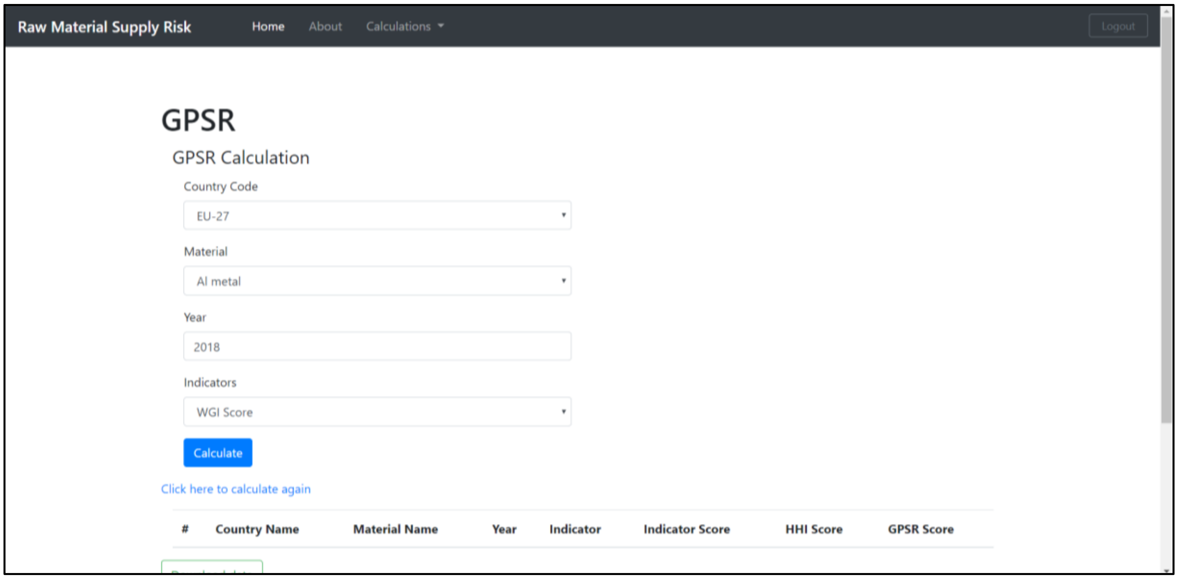
The overall results for GPSR calculations of all the selected indicators, countries and materials are presented in the next section showing the trend across the period 2015–2018. This section also discusses the results for the three selected regions in more detail.

The following section talks about the case study in more detail and looks at which materials from a LIB represent higher geopolitical supply risks. This is followed by a discussion on three materials that show interesting trends: graphite, lithium and iron. A detailed analysis is given from the production and trade patterns of these materials to understand some of the supply risks.

The last section in this chapter compares the choice of indicators to the final GPSR score by using a dummy indicator value of 0.1 for all countries, to better understand how removing the indicator affects the GPSR results. Keeping a constant value of the country indicator scores removes the affect that the indicators have on the GPSR results. This allows for a better understanding on the role that country indicators play in the supply risk assessment.

4.1 Social Supply Risk Calculation Tool

The calculation tool was successfully developed using Python code and a web-application was developed to deploy the tool online and make it accessible to the public. Thus, there are two ways of accessing and using the tool. The first method involves copying the source code and database which are both available online on Github and using the code in a local Python environment on one's laptop. This method involves having Python installed and a virtual environment set up before the code can be run (https://docs.python.org/3/tutorial/venv.html). The second method is using the web-application as shown in Figures 5-6 which can be accessed online through any web browser.



GPSR

GPSR Calculation

Country Code: EU-27

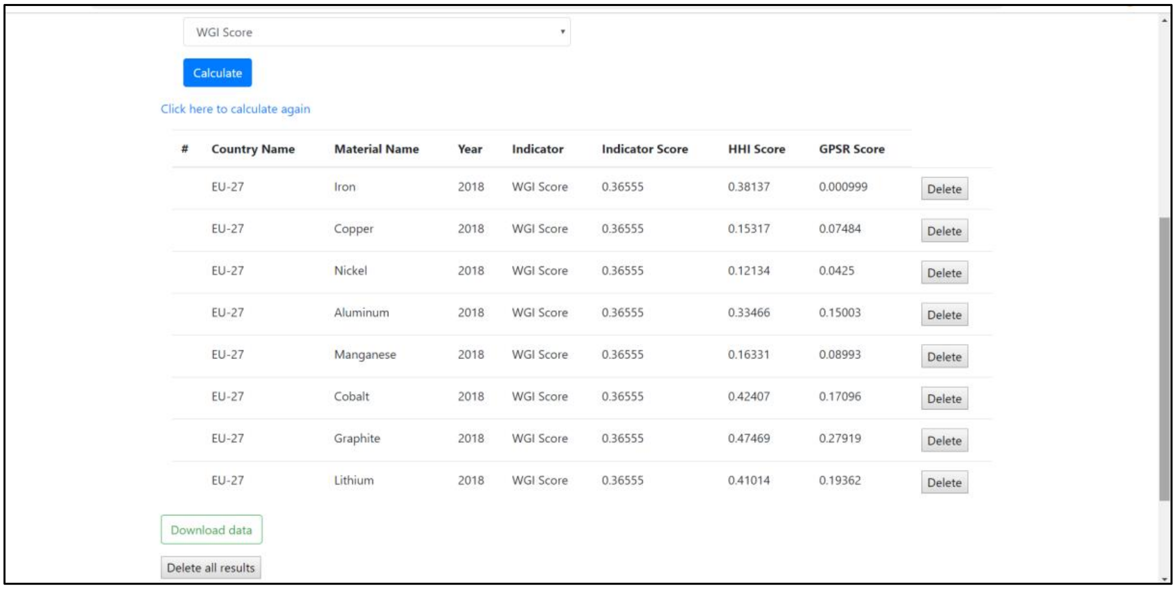
Material: Al metal

Year: 2018

Indicators: WGI Score

#	Country Name	Material Name	Year	Indicator	Indicator Score	HHI Score	GPSR Score

Figure 6. Completed web-application layout



#	Country Name	Material Name	Year	Indicator	Indicator Score	HHI Score	GPSR Score	
	EU-27	Iron	2018	WGI Score	0.36555	0.38137	0.000999	Delete
	EU-27	Copper	2018	WGI Score	0.36555	0.15317	0.07484	Delete
	EU-27	Nickel	2018	WGI Score	0.36555	0.12134	0.0425	Delete
	EU-27	Aluminum	2018	WGI Score	0.36555	0.33466	0.15003	Delete
	EU-27	Manganese	2018	WGI Score	0.36555	0.16331	0.08993	Delete
	EU-27	Cobalt	2018	WGI Score	0.36555	0.42407	0.17096	Delete
	EU-27	Graphite	2018	WGI Score	0.36555	0.47469	0.27919	Delete
	EU-27	Lithium	2018	WGI Score	0.36555	0.41014	0.19362	Delete

Figure 7. Web-application results view layout

The first method gives more control to the user to edit the code and to make any changes for further development or updates to the tool, if required. However, this is more complicated and should be utilized if one has advanced proficiency in Python development. The second method is more applicable for regular users who wish to use the tool to calculate the social supply risks of materials for a certain region for which data is available.

As seen from Figures 6 and 7, the tool provides an option to select the material, country, country indicator and the year for which the supply risk is required. The tool also displays the results in a table format with the option of downloading the results in an Excel file and to delete any stored results.

4.2 Background Results

The background results are shown to better understand the underlying data used in the GPSR calculation. These include comparisons of the selected country indicators relative to the WGI-PV, which was the original indicator used in the GPSR calculation. The comparisons show that most of the country indicators are weakly co-related.

The background data also includes the various indicator scores for EU-27, Japan and the US during the selected time period under study (2015-2018) and the HHI scores of the eight materials studied in an EV battery system for the same time period. These graphs help understand the final GPSR results at a more granular level as they show why certain materials have consistently high supply risks based on production concentration.

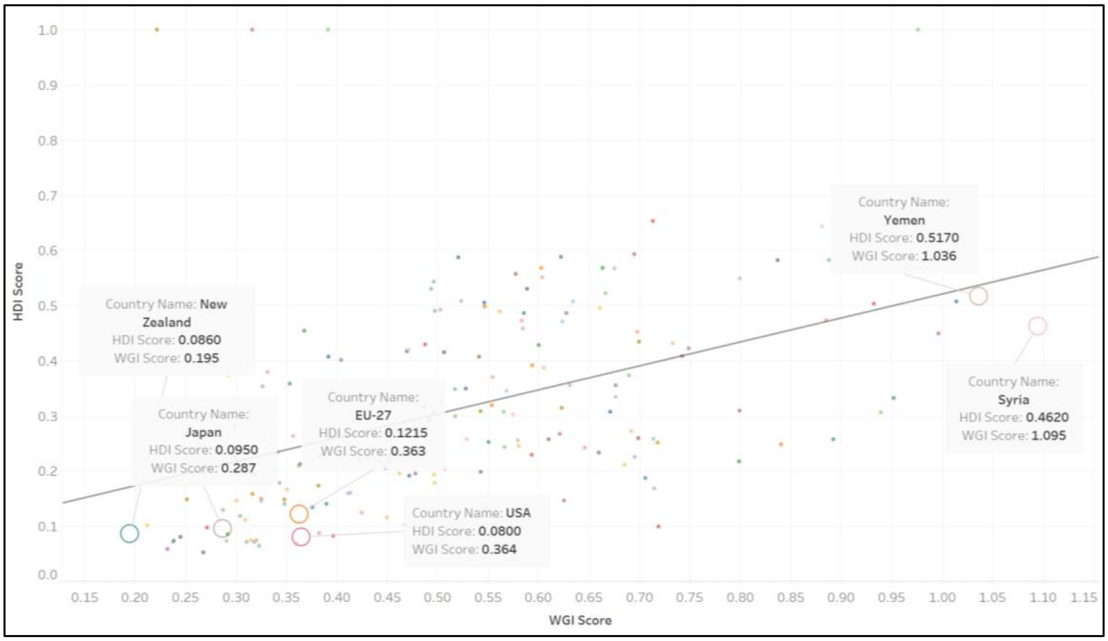


Figure 8. Worldwide Governance Indicators (WGI) correlate weakly to Human Development Index (HDI). The normalized HDI score is plotted against the WGI Score for 2015 (0 represents high political stability and high human development)

Figure 8 shows how the converted HDI score correlates with WGI for the year 2015. The R value of 0.4 shows that the correlation is weak, however from the figure it can be observed that the selected regions (EU-27, Japan and USA) are fairly low risk regions as they appear close to the bottom left, which represents high human development and political stability. As a reference, two countries on the extremes have also been highlighted: New Zealand which represents the highest stability and human development, and Syria where there is civil war and therefore the human development score is very low.

Similar graphs have been plotted for all the selected indicators against the WGI (since the WGI is the original indicator used in the GPSR methodology) and are presented in the appendix, section C. A similar pattern is seen for all the country indicators where the EU-27, Japan and the USA are positioned near the bottom left representing relatively stable governance, low risks of conflict and high human development.

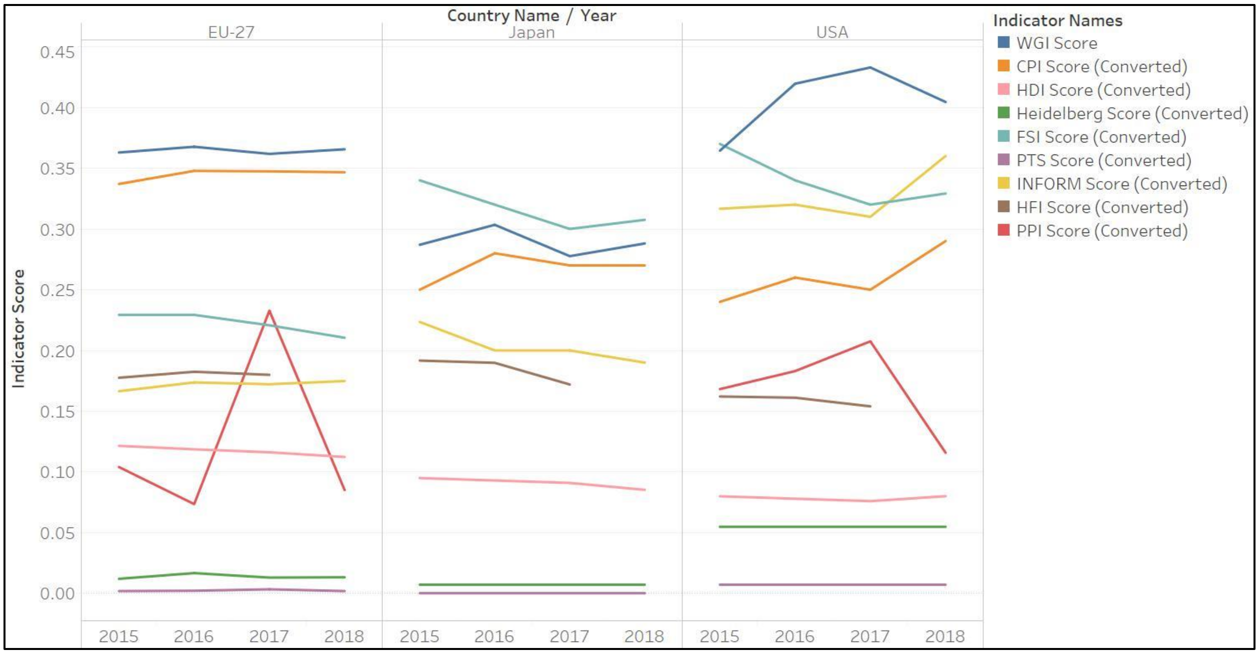


Figure 9. Country indicator scores for EU-27, Japan and USA for the years 2015 – 2018. All indicators have been converted to a scale of 0 – 1, where 0 represents low risk or good governance and 1 represents high risk and poor governance scores. (HFI data not available for 2018).

Figure 9 shows the indicator scores for EU-27, Japan and the United States. All the indicators have been converted to a scale of 0–1 as described in Chapter 3, so that they can be compared with each other and so that the different indicator scores can easily be put in the GPSR formula to replace the WGI-PV scores.

From the figure, it can be seen that the WGI score has the highest average score amongst all the indicators. While the indicator scores in Figure 9 cannot be compared with each other accurately due to the conversions which results in loss of information, the consistently high WGI scores in the 0-1 scale translates to a consistently high supply risk score obtained. Therefore, the values of supply risk obtained using the WGI-PV are higher than those obtained from other country indicators. Due to the conversion of indicator scales, the social supply risk scores can also not be compared to each other as there is a loss of information.

There is not a lot of variation in the scores, and this is most likely due to the time period studied. For most of these indicators, the shift from year to year is quite small unless there is an extreme event such as outbreak of war or some other extreme social circumstance that would increase the risk significantly.

The greatest variation in the indicator scores is seen with the PPI where the score for the US decreases from 2017 to 2018 and for the EU-27 it increases and then decreases again. This indicator measures the effects of government policy on attitudes toward exploration investment and the overall policy attractiveness for 83 regions in the world. The scope of this indicator is global, but it focuses on regions with mines; and for the US and the EU-27, the PPI scores for the individual mines are averaged. Therefore, the score of one or a few individual mines could affect the overall score for these regions resulting in a higher variation during the selected time period.

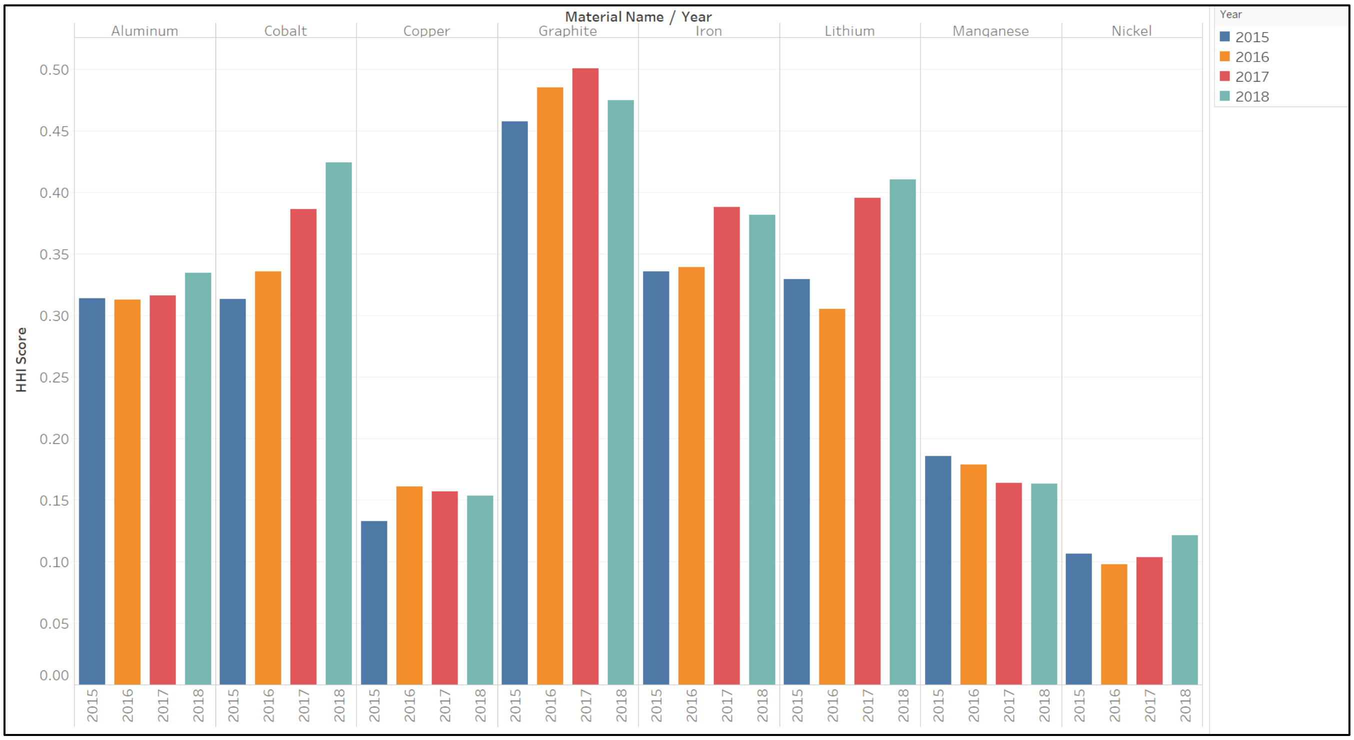


Figure 10. Global HHI scores for aluminum, cobalt, copper, graphite, iron, lithium, manganese and nickel for the years 2015 – 2018.

Figure 10 shows the global HHI scores for the selected materials in the case study. These 8 materials are the most common materials used to manufacture LIBs. The HHI score is an indicator of the materials' production concentration. A high HHI score means that the production of a material is concentrated in certain countries around the world, thus increasing the risk of obtaining access to the material.

It can be seen from Figure 10 that graphite has the highest HHI score and is followed by lithium, cobalt, iron and aluminum, while copper and nickel have lower scores. This reflects that the production of graphite is concentrated in a few countries. To better understand these results, these materials were studied in more detail to observe the production patterns. Figure 10 shows that the HHI of all the materials except for manganese has increased over the last few years, even though production volume of manganese has increased. This suggests that increased production is concentrating in a few countries and thus resulting in the higher HHI scores of these commodities.

Despite being one of the most produced and processed materials on earth, iron has a relatively high HHI score, because almost 50% of global iron production occurs in China. However, the majority of this produced iron is used domestically. Furthermore, the production of iron is spread out throughout the globe and therefore the trade patterns become more dominant in the GPSR calculation, reducing the supply risk.

4.3 Overall GPSR Results

This section presents the comprehensive GPSR results obtained for the selected case study. The GPSR results are the assessment of supply risks obtained from using different country indicators through the developed calculation tool as described in Chapter 3. The complete results obtained as a time series for each country, material and indicator are presented in Figure 11, which presents an opportunity to analyze patterns and materials in more detail. Some of these patterns are discussed below in more detail but due to the abundance of data and potential for further analysis, all the individual results are not described in detail.

This section also presents the GPSR results obtained for each of the selected regions in more detail to provide a better understanding of some of the supply risks that these regions face regarding sourcing of the materials in a LIB. The results show that the tool can be used to assess the social supply risks of materials in different stages of the supply chain.

Figure 11. Results of GPSR score for each country, material and indicator from 2015 – 2018. Each row represents one country and each column represents the indicators used to calculate the GPSR score.

Figure 11 shows the patterns that are common in all three regions, thus highlighting that the social supply risk of materials is largely dependent on global production. The figure shows that graphite and lithium have a consistently higher supply risk across all years for all the countries. The most likely explanation for this is the high HHI scores that represent the limited number of areas where these materials are produced.

Although not clear from Figure 11, iron has the lowest supply risk. This is understandable given its high spread of global production. Thus, even though the HHI score is high, there are several countries (Brazil, Canada, China and Mexico) that dominate supply of exports. This reduces the dependency on one particular country for production of iron and results in a lower supply risk.

The graph also shows that the GPSR scores are not decreasing, meaning that the supply risk is remaining relatively constant. For all 8 materials studied, the supply risk either remains constant or slightly increases from 2015 to 2018. This pattern is similar to how the indicators behave themselves as seen from Figure 9 in the background results. For example, the GPSR score obtained with the PPI shows the greatest variation across the years and this variation is similar to how the indicator performs for each region.

Lastly, the use of different indicators affects the GPSR score but cannot be compared to each other due to the conversion of the country indicators that results in loss of valuable information that each indicator represents. However, the rankings of materials are the same regardless of the type of country indicator selected. Even though the GPSR score itself may be different, the rankings of materials remain the same. This means that the country indicator does not have a high influence on the final GPSR score. Currently, the supply risk score is weighted towards the concentration of sourcing or the HHI score which is dominant in the GPSR calculation.

Figure 12 looks at the GPSR results in more detail for the EU-27 and additional figures are provided in the appendix for detailed supply risks of Japan and the US. The general patterns of the supply risk are discussed in this section for each country and a more detailed analysis is presented in the next section regarding production and trade patterns for graphite, lithium and iron.

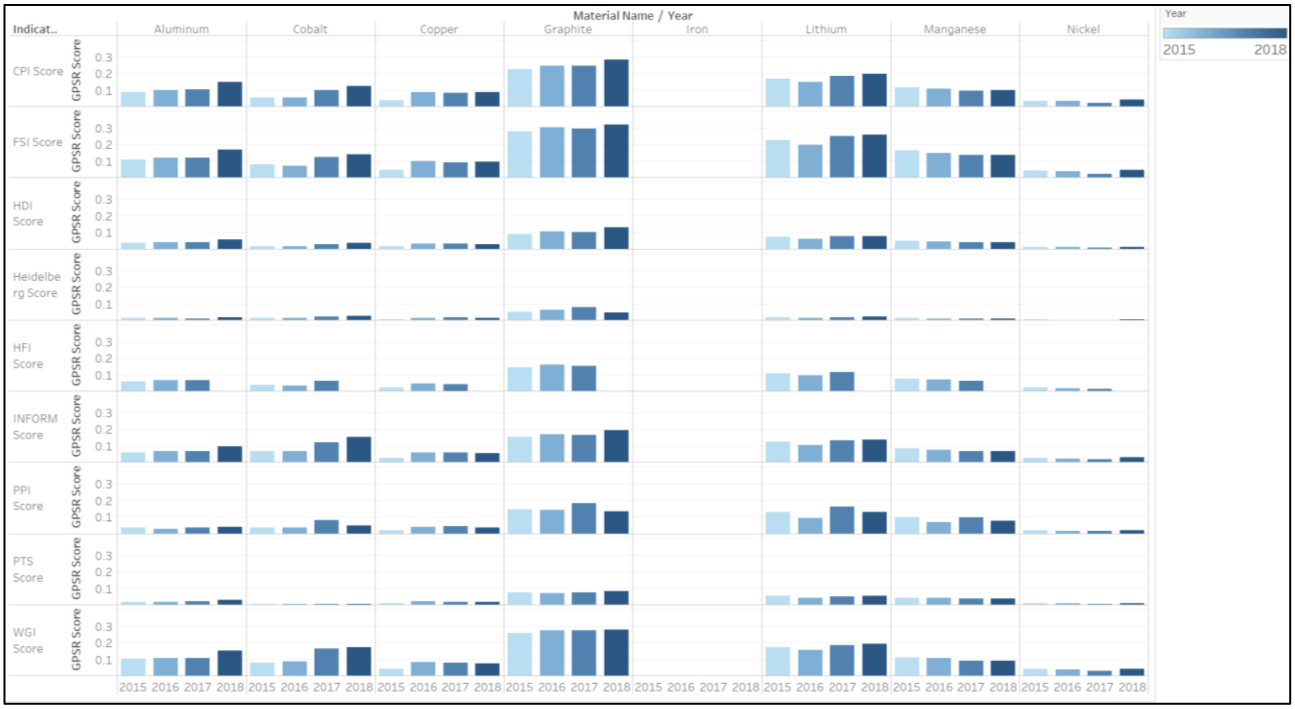


Figure 12. GPSR score for all eight materials and nine indicators from 2015 – 2018 for EU-27. Each row represents one indicator that is used to calculate the GPSR score and each column represents a single material.

Figure 12 shows that the highest supply risks for the EU-27 are for graphite and lithium which also appear to have increased from 2015 to 2018. Iron and nickel have the lowest supply risks. For aluminum and cobalt, the risk has increased by the highest percent from 2015 – 2018. Copper shows a high range of risks based on the different indicators. Lastly, manganese is the only material that shows a decrease in the supply risk, which, as noted is consistent across the three regions.

Similar to the EU-27, the highest supply risks for Japan are for graphite and lithium (appendix figure D1). While the risk for graphite is largely constant in this time period, the supply risk of lithium shows a significant increase from 2015 – 2018. Again, iron and nickel have the lowest supply risks. For Japan, the supply risk of cobalt and copper has increased significantly, while aluminum shows the highest range of values based on the different indicators. Lastly, manganese is the only material that shows a decrease in the supply risk.

The highest supply risks for the US are for graphite and lithium which have increased from 2015–2018. Iron, nickel and copper have the lowest supply risks, while for lithium, the risk has increased by the highest percent from 2015–2018. Again, manganese is the only material that shows a decrease in the supply risk.

The region-specific supply risk results show that the EU-27 and Japan have considerably higher risks than the United States. This is most likely because the US has more domestic production of commodities compared to the other two regions which are largely dependent on the import of these commodities either as raw materials or as processed goods.

Another interesting pattern is how the indicators behave in the calculation of the GPSR score. As shown in the detailed country supply risk figures, the Heidelberg and PTS scores show very low variations and scores. These were the only indicators that had a categorical scale and therefore had to be changed based on taking the ratio of squares.

4.4 Lithium Battery Case Study Results

This section presents the supply risk results obtained for the years 2015–2018 for the case study of the LIB. Figures 13 shows the obtained results where each figure has GPSR scores for 2015 for all three regions, and the results for additional years are provided in the Appendix (Figure D3, D4 and D5). These graphs show the contribution for supply risk of each material in a lithium battery product system. Graphite has the highest supply risks compared to any other material in this product system followed by lithium.

By expressing potential environmental and socioeconomic impacts of material flows in common units of measure, the LCSA framework puts these “loadings” into an additive form. This relates to LCA method and presents an “aggregate” GPSR score for the lithium ion battery product allowing the total load (i.e., category indicator – GPSR score) to be quantified in relation to the functional unit of a given product system (Cimprich et al., 2017). The functional unit provides the basis for product-level assessment, which is significant because decisions made at this level (such as product design and material selection) play an important role in supply chain risk management.

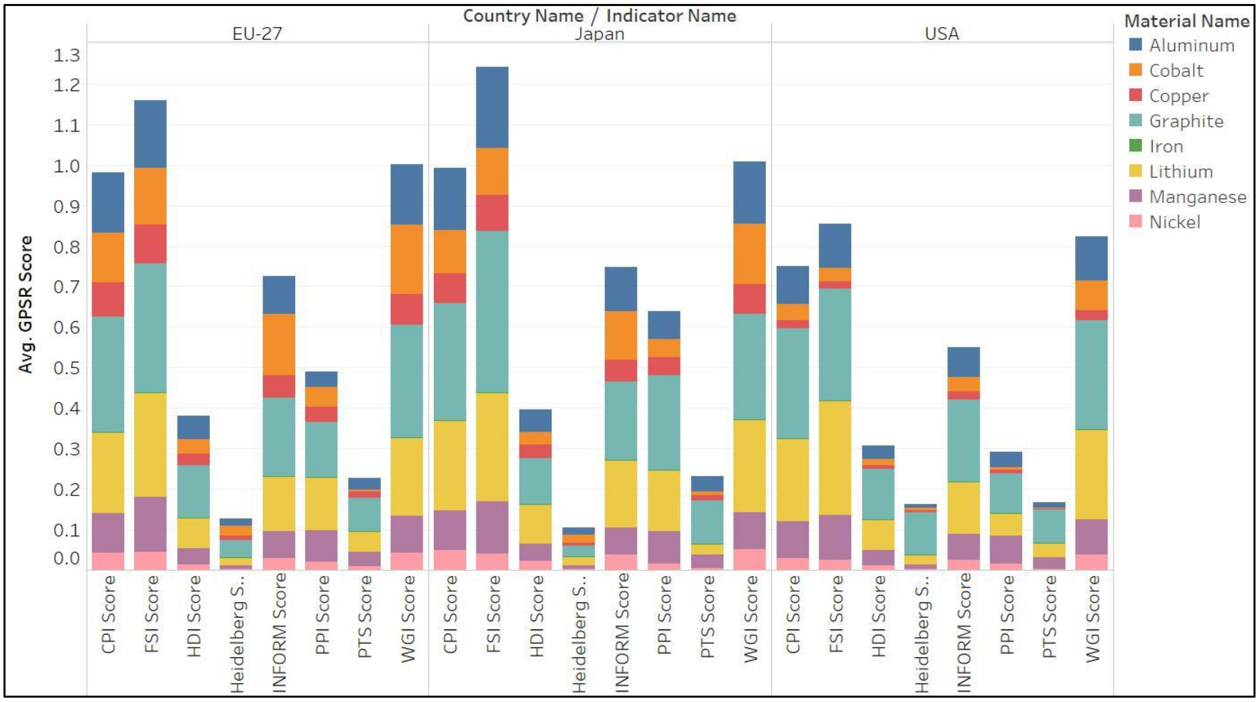


Figure 13. GPSR for each material as share of total for 2018

Figure 13 shows the aggregated GPSR score for the three regions in 2018. Additionally, the results for 2015-2017 are shown in the appendix. It can be observed from the figure that the supply risk for the materials in a LIB have increased for all three countries from 2015–2018. The relative percent contribution of each material in the product system remains constant, however the overall supply risk of the individual materials has increased over the analyzed time period.

Figure 13 also suggests that EU-27 and Japan have higher supply risks than the USA, as was mentioned in the previous section. This is most likely because the US depends less on import of materials compared to either the EU-27 or Japan. Thus, the supply risk is lower for the US as it has a lower dependency on import of materials from countries where there may be a risk of geopolitics or conflict affecting the supply of those materials.

4.4.1 Detailed Results for Lithium, Iron and Graphite

Based on the comprehensive results and the results of the lithium battery case study, three materials were identified to have interesting behavior and therefore selected for a more detailed analysis. This detailed analysis provides an initial attempt to understand some of the supply risks associated with sourcing certain critical materials. For example, understanding why graphite has a high

GPSR score requires looking at the countries where graphite is produced and the social and geopolitical conditions of that region.

To better understand the associated supply risks, it is important to understand for the selected region, where the materials are being imported from and the social and geopolitical conditions of those regions. This can eventually help companies identify areas of high risk in their supply chains in order to develop a plan to mitigate or reduce those risks by shifting the imports of these materials to regions with lower risks. Detailed production and trade data for lithium, iron and graphite, including the quantity of material and the indicator scores of the respective countries is provided in section E of the Appendix.

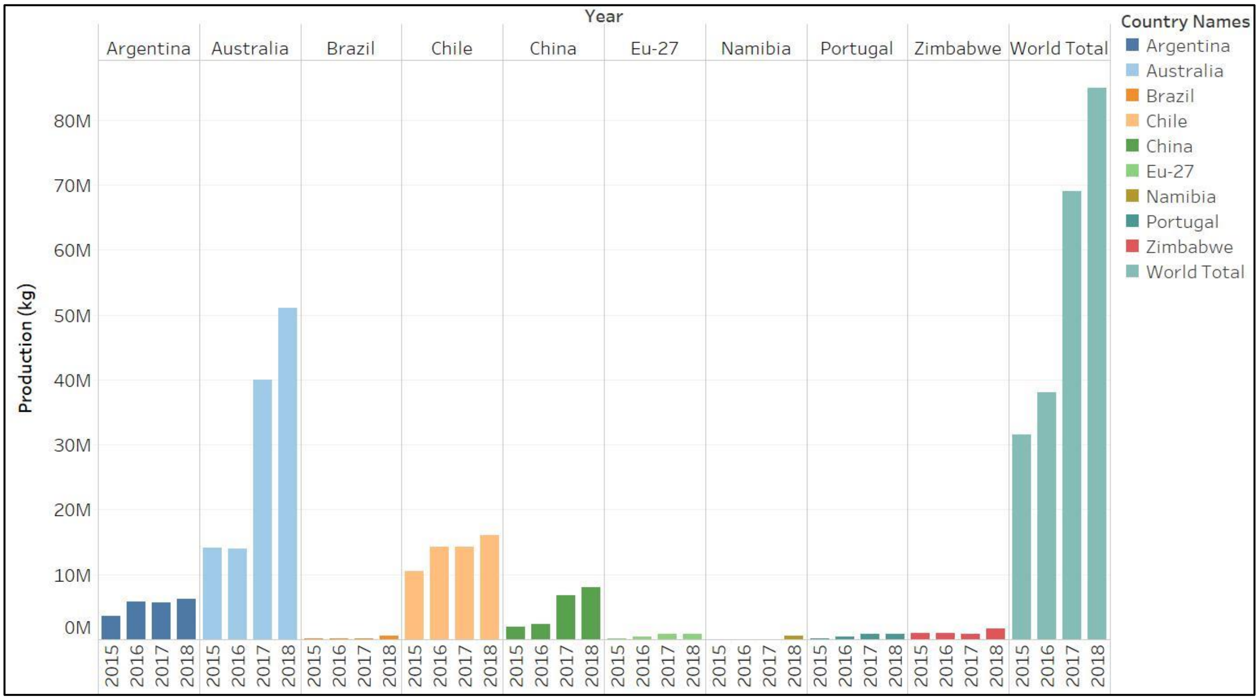


Figure 14. Lithium primary production data for the years 2015 – 2018 based on USGS information for the top 10 producing countries

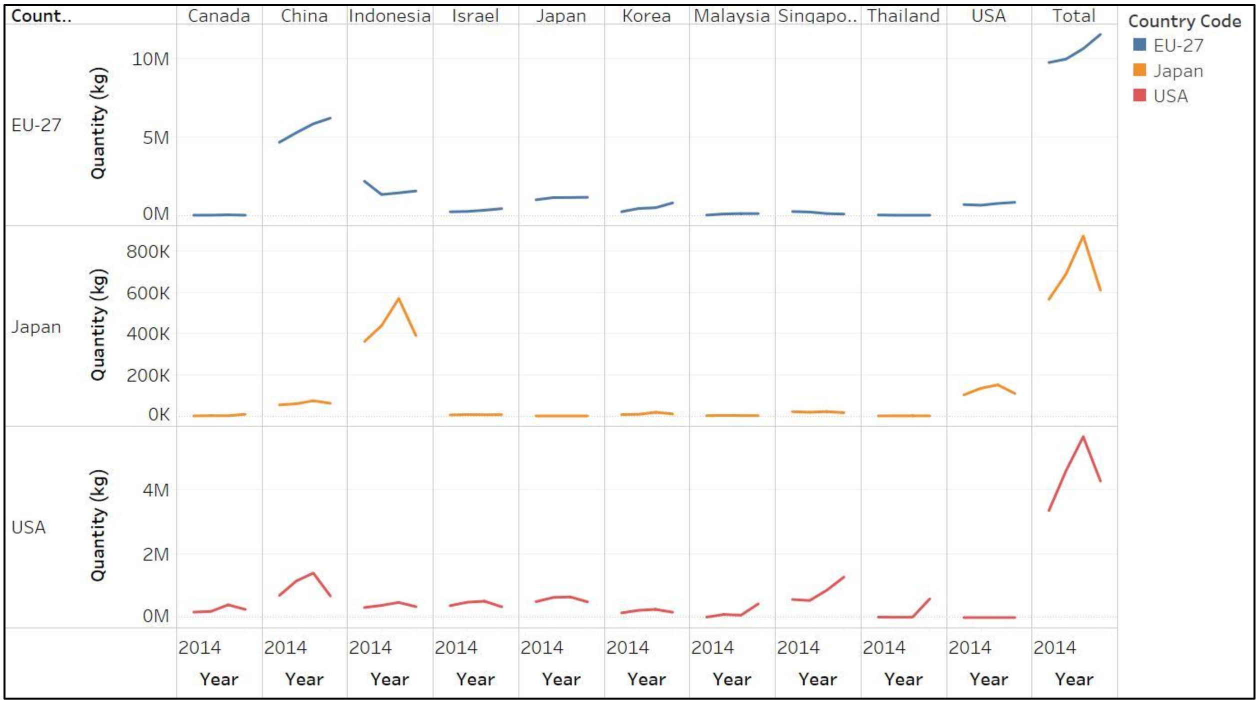


Figure 15. Lithium Trade Data (Top 10 countries from where lithium is imported for the EU-27, Japan and the US).

Figures 14 and 15 present the production and trade data for lithium showing the top producing countries and top ten countries from where it is imported for the EU-27, Japan and the US. Lithium has a high HHI score which is evident from figure 13 which shows the global production data for the material. Production in Australia increased drastically from 2016 to 2017 and in China it also increased significantly from 2016 to 2017. It remained relatively stable in all other countries, thus increasing the concentration of production in those two countries as represented by the increase in HHI scores.

From figure 15, the trade patterns can be observed for the EU-27, Japan and the US regarding imports of lithium. The EU-27 and USA import the majority of lithium from China while for Japan, the majority of their import of lithium comes from Indonesia. These source countries have relatively high risks of governance, conflict and human rights as represented by the indicator scores (Table E2) and thus contribute to the high GPSR scores obtained.

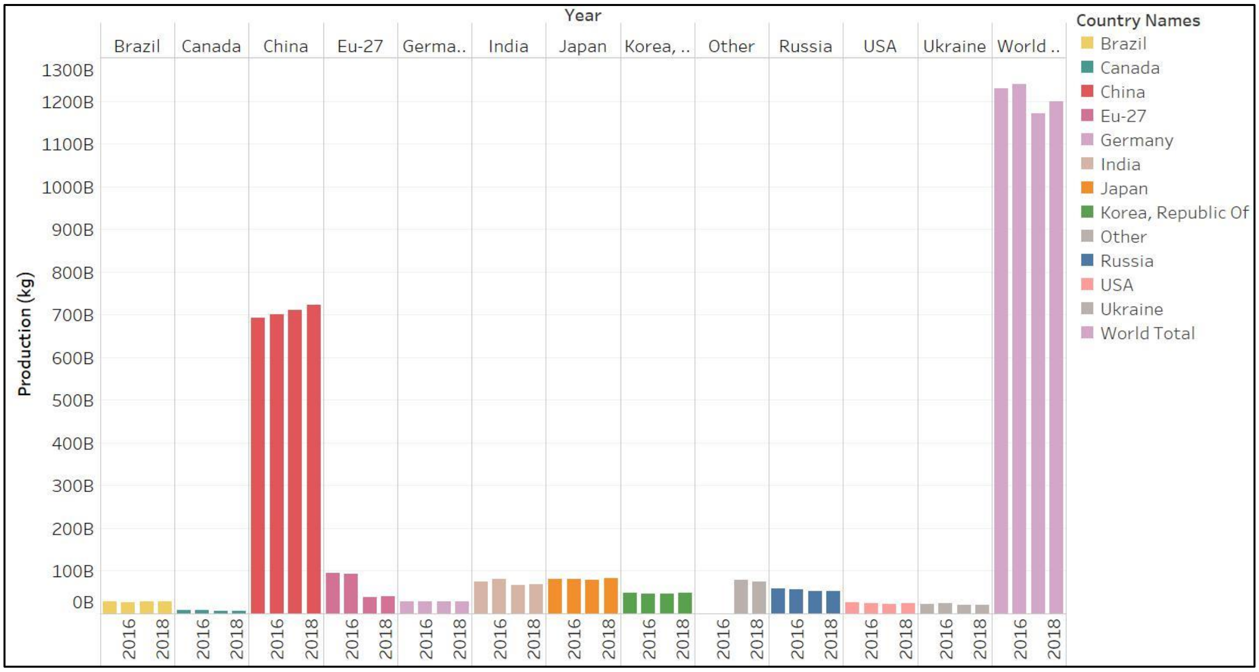


Figure 16. Processed iron primary production data in billions of kg for the years 2015 – 2018 based on USGS information for the top 10 producing countries

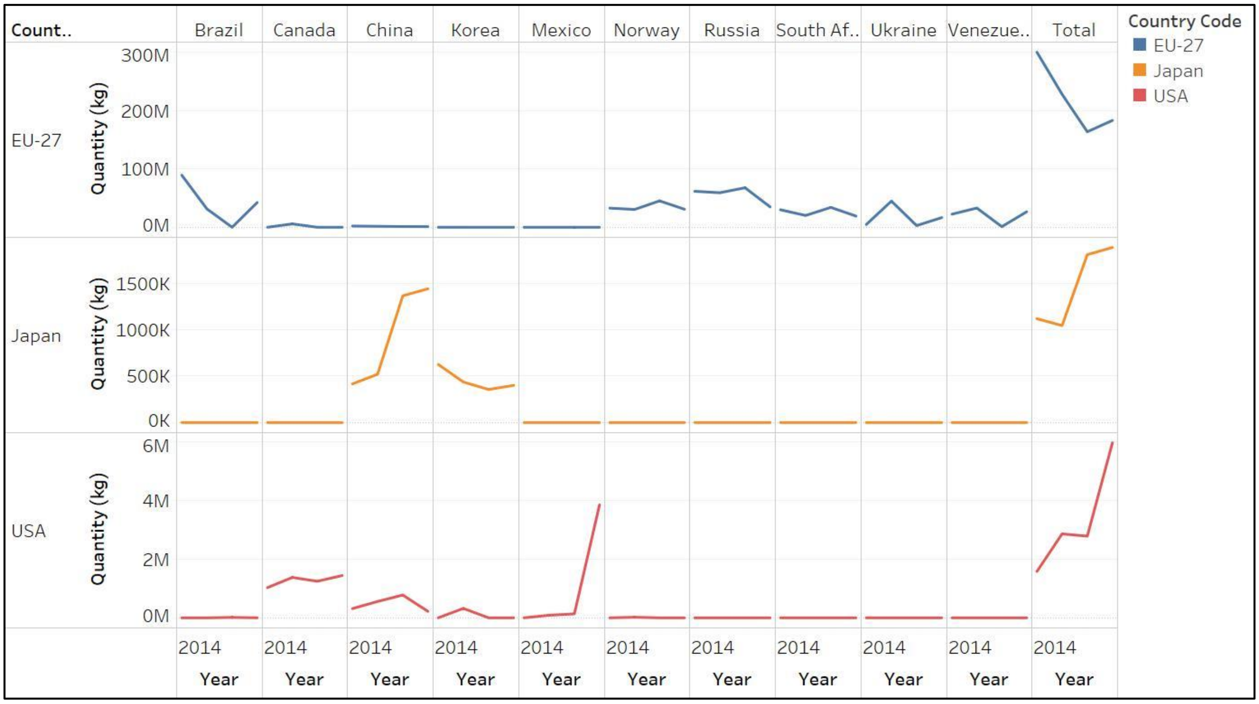


Figure 17. Iron Trade Data (Top 10 countries from where iron is imported for the EU-27, Japan and the US).

Figures 16 and 17 present the production and trade data for iron showing the highest producing countries and top ten countries from where it is imported for the EU-27, Japan and the US. Figure 16 shows that China has the largest share of global iron production, thus also explaining the high HHI score. The global production has slightly decreased from 2015 – 2018 and the production of iron also decreased in the EU-27 during this period. Even though China produces more than 50% of iron globally, the majority of their iron is used domestically. Furthermore, the huge spread of processed iron production amongst countries makes China much less dominant when we look at trade rather than production of iron which helps in reducing the supply risk which is represented by the lower GPSR scores.

From figure 17, the trade patterns can be observed for the EU-27, Japan and the US regarding imports of iron. The EU-27 imports most of its iron from Brazil, but the import share is well spread out and the quantity of iron imported has decreased from 2015-2018. Japan imports more than 50% of its imported iron from China and USA import the majority of lithium from China while for the US, the largest import comes from Canada and Mexico.

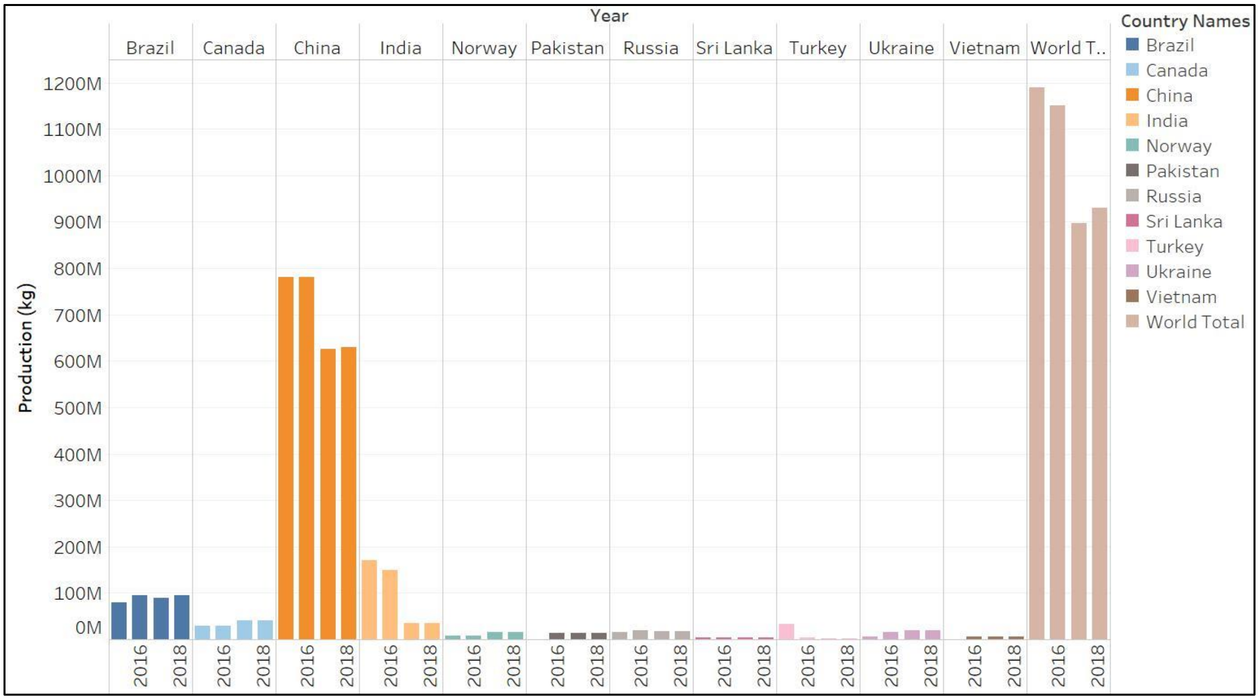


Figure 18. Graphite Production Data

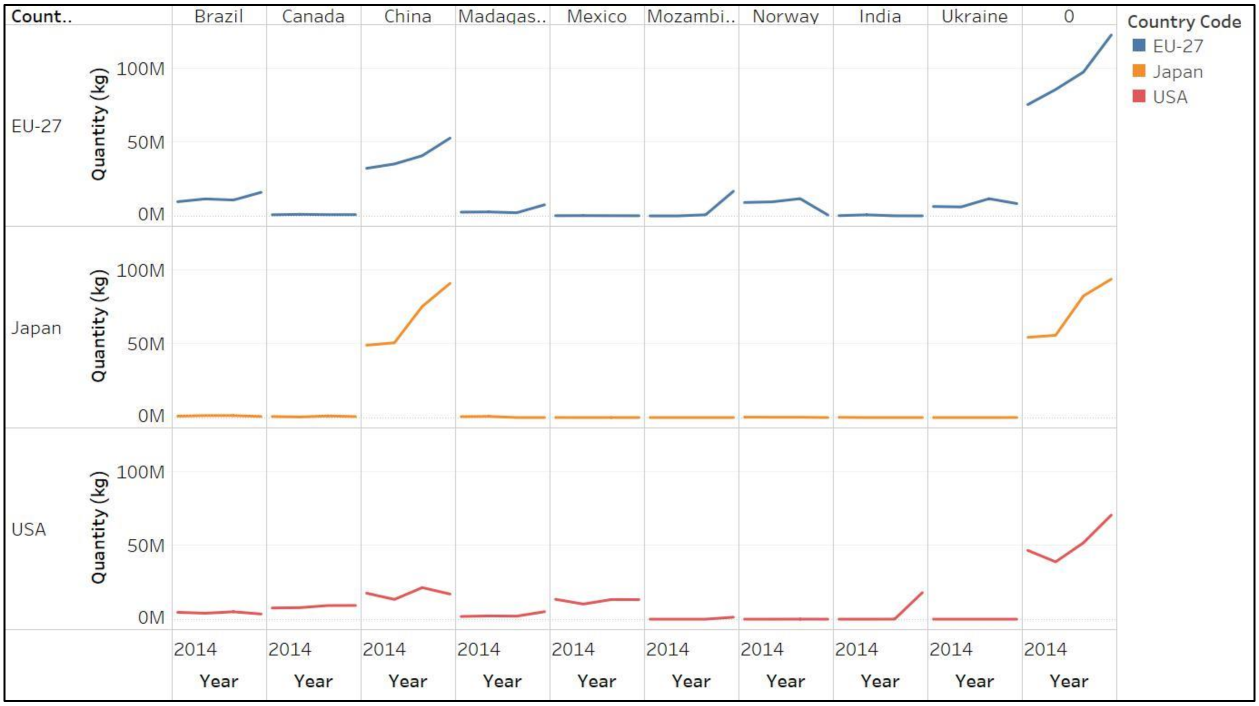


Figure 19. Graphite Trade Data (Top 9 countries from where graphite is imported for the EU-27, Japan and the US).

Figures 18 and 19 present the production and trade data for graphite showing the highest producing countries and top nine countries from where it is imported for the EU-27, Japan and the US. Graphite has the highest HHI score amongst the selected materials. Figure 18 shows that global graphite production has decreased from 2015 – 2018 and China is again the largest producer with over 50% of global production.

From figure 19, the trade patterns can be observed for the EU-27, Japan and the US regarding imports of graphite. All three regions import the majority of graphite from China. China has maintained its dominance as graphite needs have increased which is a leading cause for the high supply risk. The US also imports a large share from Mexico and increasingly from India, while the EU-27 also imports a large share from Brazil and Mozambique. These four countries have relatively high risks of governance, conflict and human rights as represented by the country indicator scores (Table E6) and thus contribute to the high GPSR scores obtained.

4.5 Comparison of Indicators in GPSR Assessment

This section compares the use of indicators in the GPSR calculation following the second research question that asks: **"How does the choice of social indicator influence the assessment of company supply risks?"**

To compare how the indicators performed and whether the choice of indicators affect the GPSR result, a dummy indicator was used with a constant value of 0.1 for all countries. The GPSR score was calculated for the EU-27, Japan and the United States using this constant indicator score of 0.1 and the HHI scores were also calculated. Keeping the indicator constant allowed to comparison of the GPSR results based on the trade patterns and the production concentration of materials.

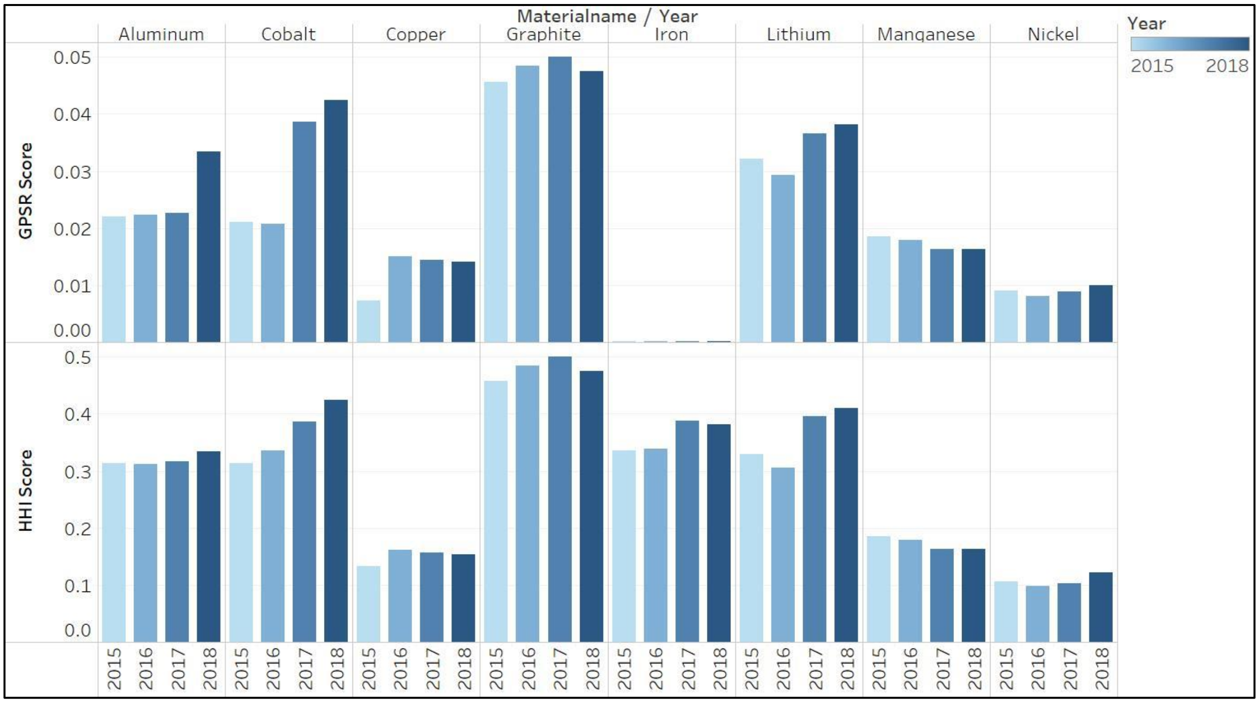


Figure 20. EU dummy indicator

Figure 20 shows the results obtained from these calculations with both the GPSR scores and the HHI scores for the selected materials for the European Union. Additional figures for Japan and the US are provided in the Appendix (D6, D7). There are several interesting patterns that can be observed from these figures. The most common trends that can be seen are that HHI is closely related to the GPSR score and is therefore dominant in the GPSR calculation. This is true for all materials except for iron which has a high HHI score but an extremely low GPSR score. This is most likely because while almost 50% of global iron production occurs in China, the majority of this produced iron is used domestically.

Furthermore, the production of iron is spread out throughout the globe and therefore the trade patterns become more dominant in the GPSR calculation.

Another important result is the relatively high HHI score of graphite (the highest amongst the materials studied) showing that it has a more concentrated production and is largely produced in a select few countries from where it is sourced. China is also the major producer of graphite, but compared with iron, its production is less spread out and therefore it has a high production concentration. Furthermore, for all 3 regions studied, the majority of graphite is imported from countries with high risks and that is represented with the high GPSR score.

Table 2. Supply risk rankings of materials for EU-27 based on categories of country indicators

		Material Name							
Indicator Name	Year	Aluminum	Cobalt	Copper	Graphite	Iron	Lithium	Manganese	Nickel
CPI Score	2015	4	5	6	1	8	2	3	7
	2016	4	6	5	1	8	2	3	7
	2017	3	4	6	1	8	2	5	7
	2018	**3**	**4**	**6**	**1**	**8**	**2**	**5**	**7**
PPI Score	2015	5	4	6	1	8	2	3	7
	2016	6	5	4	1	8	2	3	7
	2017	6	4	5	1	8	2	3	7
	2018	**5**	**4**	**6**	**1**	**8**	**2**	**3**	**7**
WGI Score	2015	4	5	7	1	8	2	3	6
	2016	3	5	6	1	8	2	4	7
	2017	4	3	6	1	8	2	5	7
	2018	**4**	**3**	**6**	**1**	**8**	**2**	**5**	**7**
HDI Score	2015	4	5	6	1	8	2	3	7
	2016	4	6	5	1	8	2	3	7
	2017	4	6	5	1	8	2	3	7
	2018	**3**	**5**	**6**	**1**	**8**	**2**	**4**	**7**
HFI Score	2015	4	5	6	1	8	2	3	7
	2016	4	6	5	1	8	2	3	7
	2017	**3**	**5**	**6**	**1**	**8**	**2**	**4**	**7**
FSI Score	2015	4	5	6	1	8	2	3	7
	2016	4	6	5	1	8	2	3	7
	2017	5	4	6	1	8	2	3	7
	2018	**3**	**4**	**6**	**1**	**8**	**2**	**5**	**7**
Heidelberg Score	2015	3	4	6	1	8	2	5	7
	2016	5	4	3	1	8	2	6	7
	2017	6	2	3	1	8	4	5	7
	2018	**4**	**2**	**5**	**1**	**8**	**3**	**6**	**7**

INFORM Score	2015	5	4	6	1	8	2	3	7
	2016	5	4	6	1	8	2	3	7
	2017	5	3	6	1	8	2	4	7
	2018	**4**	**2**	**6**	**1**	**8**	**3**	**5**	**7**
PTS Score	2015	4	7	6	1	8	2	3	5
	2016	5	7	4	1	8	3	2	6
	2017	4	6	5	1	8	2	3	7
	2018	**4**	**7**	**5**	**1**	**8**	**2**	**3**	**6**

Table 2 provides the supply risk rankings for EU-27 of the eight materials that are categorized based on the three risk categories of governance, human rights and conflict. Similar tables for Japan and the US are provided in the appendix section D. The table shows that graphite has the highest supply risks obtained from all the country indicators selected whereas iron has the lowest supply risks. In most cases, lithium has the second highest supply risks although there is some slight variation where cobalt has the second highest supply risks.

These results show that the country indicators are largely independent and that even though the GPSR scores change with varying indicators, the supply risk ranking of each material remains the same. This is because the HHI is dominant in the GPSR calculation since it is multiplied by the sum of the adjusted import shares. Therefore, the choice of indicator does not matter with the current GPSR calculation as the same materials (graphite and lithium) consistently show high supply risks using different indicators.

It is important to note that this is not an exhaustive list of the results since there is a potential for a lot of further analysis. There is a lot of data obtained as a result of using the tool which made the calculation faster and more efficient. Furthermore, there is opportunity to dig deeper into each of the parameters (country, material, indicator, year) to try and better understand the trends and risks associated with supply of these materials.

5 Discussion

This chapter discusses the development of the tool and its significance and potential in company decision-making. The results obtained are also discussed to understand what the results mean and how they contribute to scholarship and industry practice.

The chapter starts by discussing the contribution of the calculation tool and addresses the limitations and opportunities for further development of the tool for it to be used by companies while assessing supply risks of raw materials. Further development of the tool is required to make it a more accurate representation of the raw material social and geopolitical supply risks. This section ends with a recommendation on integrating the tool with existing LCA software to allow the results of this calculation tool to complement traditional LCA results.

The next section discusses the results presented in the previous chapter, what these results mean and their contribution to scholarship, followed by a discussion on how this can affect and help industry practice. This includes a specific discussion on iron which shows a different pattern of results compared to all the other materials studied. This section also includes a separate discussion on lithium and graphite, which have the highest supply risks from the materials observed in the case study and discusses further opportunities to study these materials from a supply risk perspective.

5.1 Development of calculation tool

The results show the GPSR score for several materials and countries across multiple indicators. This demonstrates the operationalization of the calculation tool based on the GPSR methodology (Sonnemman et al., 2015; Gemechu et al., 2016), which is used to assess the geopolitical supply risk of materials. The tool, therefore, is important in answering the research question initially asked: **"How can raw material social supply risks be efficiently assessed to support company decision-making?"** The research results and analysis show that the tool can be used to assess supply risks based on the GPSR methodology and by using different social aspect indicators that were identified from responsible sourcing guidelines.

The tool is available for public use and the source code is freely available online. Thus, it can be used by researchers as well as companies to evaluate social and geopolitical supply risks in raw material supply chains. The calculation tool provides a significant boost in efficiency of computation and speeds up the GPSR calculations, where previously it could take a couple of hours to obtain a single result

(Gemechu et al., 2016; Helbig et al., 2016; Cimprich et al., 2017). The new tool can provide GPSR results for several materials instantaneously. This makes it more manageable and useful from a company perspective where it can be used in the decision-making process and a company's raw material sourcing strategy.

Therefore, one of the main contributions of the tool is to increase the computational speed by utilizing Python and constructing a separate database. As part of the research, a comprehensive database was developed which includes country indicators, metal production and trade data that are needed in the calculation. This is already available for all the materials studied as well as several other common materials including magnesium, tungsten and platinum. The database provides an improved structure for managing and updating data, which is also important for the calculation tool as it helps in increasing the efficiency of the calculations and giving it the potential for quick updates if required in the future.

The tool was validated using GPSR results replicated from previous studies (Cimprich et al., 2017) and by using external validation methods where external reviewers compared the results obtained from the tool to results obtained from a manual calculation. This provides confidence and added reliability to the calculation process and computational capability provided by the tool.

The tool has practical contributions. It can be used now ("as is") by any company to assess its supply risks and social hotspots based on the sourcing practices. Academics have looked at resource availability from a criticality perspective (Graedel et al., 2012; Sonnemann et al., 2015), but companies have other important considerations such as supply disruption due to money laundering, child labor, etc. in their upstream supply partners.

While the tool does not address all the relevant factors in sustainably managing supply chains such as considerations of recycling, substitution or inclusion of multiple supply chain stages, the results show that it can be used to calculate supply risks at different stages of the chain. The case study was performed on critical materials with data at the mining stage and for bulk materials with data in the processing stage. Thus, currently the tool can be used on a specific stage of the supply chain and having a potential to include multiple stages according to the work done by Helbig et al., 2016. This also highlights the flexibility of the tool and opportunities for further development or context specific use depending on the availability of required data.

In the case study, the selection of two categories of materials: bulk (aluminum and iron) and critical (cobalt, copper, graphite, lithium, manganese and nickel) shows that the tool can be used in different stages of the supply chain. The tool can be used by companies to identify materials that have high supply risks based on the social aspects relevant to the company at any stage of the supply chain for which data is available.

The tool is consistent with OECD and industry guidelines for responsible sourcing and uses indicators that have been previously identified by organizations and companies. Companies have already been using several of these country indicators in their risk assessments, however those reports and tools are often confidential or are not based on any scientific methodologies and are of a qualitative nature. This model uses these indicators that have been recommended by the European Commission and OECD report, along with the trade and mineral production data to relate the supply risks according to the global trade patterns.

Thus, the calculation tool also addresses some of the limitations of the GPSR methodology. It extends the calculation to include social aspects other than the WGI that could disrupt the supply of raw materials, thereby providing a more holistic assessment of the impacts of natural resources. As mentioned before, the GPSR method is seen as being complementary to LCA as the risk assessment provides additional detail on the social risks along with environmental impacts that LCA already assesses (Sonnemann et al. 2015). Furthermore, this method measures the “outside-in” impacts, looking at the effect that social and geopolitical conditions could have on the supply of raw materials (Cimprich et al., 2017). Traditional LCA deals with “inside-out” impacts which deal with how the sourcing behavior of a company can affect the environment and society from where the material is sourced. Thus, it adds another dimension of impacts that have grown in importance in recent years with the OECD Guidelines on Responsible Sourcing.

5.1.1 Limitations of the tool

There are several limitations to the tool developed in this research and thus opportunities for further development that could help make it useful for a company’s decision-making process. This includes looking at multiple system scales e.g., from the firm level to national level and also additional considerations to represent real company supply chains, by adding the ability to calculate the use of secondary materials (recycling) and incorporating multiple stage supply chain calculations (from mine to smelter to refiner, etc.). Some of the limitations are discussed in more detail to recommend directions for future work to address those limitations and improve the accuracy of results in assessing the actual supply risk of raw materials.

The availability of data is a major limitation since, often, the data is hard to collect for some commodities or countries, and often the country indicator data is not easily available. In terms of data, there are three important sources or dimensions which are included in the tool and there are some limitations to all three dimensions: production, trade and country indicators:

For production data, the limitations specifically arise for critical materials or those raw materials that are produced in small quantities or as by-products of other minerals. In such cases, other sources of information are used to calculate the supply risks. For the current study however, this limitation was addressed by using the most common eight materials used in LIBs for which the production data was available in the USGS database.

For trade data, the UN Comtrade often aggregates certain groups of materials and so it is important to understand which material or groups of materials are in a certain category. For the UN Comtrade, this is more significant due to the large amount and complexity of trade data. The Comtrade database is based on the commodity HS Codes and there are often multiple codes to represent a single commodity at different stages of its production. For this study, the most common HS Codes were used based on previous studies on the GPSR method (Cimprich et al., 2107). However, it is important to realize that there is a loss of information as these commodities are traded in different forms ranging from extracted raw materials and processed goods to recycled content. A possible option could be to combine the HS Codes, however, care should be taken to avoid double counting the quantity of material being imported by a certain country.

Another limitation for the trade data in the development of the tool came from lithium, where the quantity of lithium imports was not available for the US or Japan for the year 2018. The database provided the number of items sold but the quantity in kilograms was not provided. To include this data in the GPSR calculation, an estimation of the quantities was made based on import quantities from previous years as described in the Methods section.

For country indicator data, the GPSR method uses only one indicator at a time and so it could be argued that it only assesses using one relevant indicator. This compares to Schneider et al. (2014) and Bach et al. (2016), who utilized a wider set of indicators. The addition of indicators based on responsible sourcing guidelines adds some of the country indicators mentioned in the ESP and ESSENZ methodology, however it still only uses one indicator at a time in the formula which could potentially lead to loss of information in accurately assessing the supply risks.

Also, regarding the use of country indicators in the tool, there are limitations that stem from the fact that all the country indicators had to be converted to a score of 0-1. This allows for simple substitution for the WGI-PV indicator used in the GPSR calculation (Gemechu et al., 2016). Most of the indicators selected for this study were scored from a continuous scale of 0-10 or 0-100 and thus the conversion was performed by simply dividing them by 10 or by 100, respectively. However, for the Heidelberg and PTS, the source methodologies provided a categorical scale ranging from 0-5 where each number represented a level of intensity of conflict for a region. These were the only indicators that had a categorical scale and therefore had to be changed using a ratio of squares. Consequently, with these indicators there is a great loss of information in the conversion since an intensity level of 1 for any country would correspond to the same score and this is represented by the very low variations in the supply risk scores obtained from using these indicators.

Another limitation of the tool is that it only uses country level data to provide the supply risks of materials at a national level. This resolution is not entirely consistent with real supply chains that consist of firm level interactions that often happen between sub-regions in the same country or through multiple stages. However, the versatility of the Python code allows for updates, making it possible to augment the tool to perform sub-regional or firm level analysis and by updating the database. Similarly, this includes addressing the scope of analysis in this study. Traditional criticality studies used to assess supply risk are at a national level due to availability of data. Global supply chains are complex and can include multiple stages before the raw material reaches a certain company for manufacturing or end use. This was a major limitation of the GPSR methodology as well as it provided a supply risk assessment at the country or national level. While the same applies to this study, it can be argued that the development of the tool has decreased the computational time and can thus be further improved to introduce the multiple supply stages to allow for a firm or company level assessment which is more relevant for industry.

The addition of substitution and recycling considerations have already been added to GPSR, as discussed by colleagues (Cimprich et al., 2017). A forthcoming study is in preparation that uses the computational tool developed here, extending the capability to incorporate domestic recycling as a source of metal in a supply chain. These additions show how the GPSR can provide a more holistic assessment of supply risks from an LCA perspective and have significantly advanced the methodology.

However, these additions still require further development and are not within the scope of this thesis. The current tool could relatively easily be extended to address some of these needs where an update to the Python code and database will help increase the accuracy of the approach. Despite the lack of inclusion of these additional considerations to the tool currently, the calculation tool will still be able to provide fast and efficient results for supply risks of raw materials.

5.1.2 Opportunities for further development of tool

There are several opportunities to contribute to further development of the methodology to make the supply risk assessment more accurate and representative of real-world scenarios. This stems from addressing some of the limitations mentioned in the previous section, particularly aspects of recycling and material substitution that could affect access to raw materials. These themes are already being explored, and the tool allows for inclusion of these aspects in future versions. Recycling and substitution can both increase supply of materials thereby reducing the supply risk, but currently this is not measured in the GPSR calculation tool. Therefore, the next step in the advancement of this tool to help companies comprehensively assess the raw material supply risks is to integrate these considerations into the calculation.

Further, the tool and web application itself can be developed further as there is room for improvements in making better and more detailed visualizations. These improvements in the web-application are geared towards integration of the supply risk calculation tool with existing software for LCA such as OpenLCA which presents a unique opportunity to combine it with LCA to provide complementary results. There is also a need to improve the data collection method to update the database. Currently, all the data is uploaded manually but there is an opportunity to automate the collection and synchronize any updates to the web-application.

There is a potential for further development of the tool to account for company level analysis which deals with a smaller scale and is more complex. However, given the versatility and power of Python as a programming language, this is relatively easy to implement for the tool and only requires some minor changes to the source code and additional data. The main limitation in this area will be the availability of indicators and trade data at the company level. It is hoped that researchers or companies can use the tool and change the inputs according to the level of analysis required depending on the relevant case they are addressing.

The tool itself can be changed and improved to add multiple stages of the supply chain based on Helbig et al. 2016 and to use different inputs according to the trade and production data. This is an important direction for future work as incorporating multiple stages of the supply chain will more accurately reflect actual supply risks of materials to demonstrate real supply chains which are often complex in nature.

As mentioned previously, a lot of data is incorporated when using the tool which makes the calculation faster and more efficient. This presents an opportunity to dig deeper into each of the parameters (country, material, indicator, year) to try and better understand the trends and risks associated with supply of these materials. The database provides a starting point for researchers and companies to explore global and national level trends in order to better understand the production and trade patterns of certain materials and how those affect the supply risk. This also presents an opportunity to further build the database so that it includes information on all the relevant raw materials and to try and address the limitation of data availability. Nonetheless, there is sufficient data to allow for reasonable analysis for supply risks at a national level.

5.2 Significance of Case Study Results

A major contribution of this research is an advancement of the GPSR methodology in terms of increasing the calculation speed and including additional social aspects that include human rights and conflict issues along with governance issues which was the original area considered to calculate the geopolitical supply risk. This study expands upon existing literature and the three areas that were reviewed in Chapter 2 (Sonnemann et al. 2015; Gemechu et al. 2015; Young 2018; van den Brink et al. 2019; Bach et al., 2016; Cimprich, Karim, & Young, 2017a; Cimprich et al., 2017b; Helbig et al., 2016a). These three areas include the assessment of environmental impacts, resource criticality assessments and responsible sourcing practices and have developed separately from each other. Although they are connected, there has been very little work done to explore how they can be used to assess for the social supply risks of raw materials. Using principles and guidelines from LCA, criticality assessment and responsible sourcing, this research presents a tool that helps in performing the supply risk assessment based on the GPSR methodology proposed by Gemechu et al. 2016.

5.2.1 Going beyond the WGI to include other "social supply risks"

The development of the tool elaborates on the new concept of social supply risks. Previously, the GPSR method has focused only on the geopolitical supply risk by using the WGI-PV indicator that measures the governance or geopolitical conditions of countries (Graedel et al., 2012; Sonnemann et al., 2015; Gemechu et al., 2016). This study explores other indicators than the WGI which has been used previously in the GPSR method. The selection of indicators used in this research is based on existing company reports (e.g., GE, Thaisarco, Exotech) and academic literature on social aspects (Dreyer et al., 2010; Kühnen and Hahn 2017; Popovic et al. 2018). There has been very little work done in choosing the relevant indicators to assess social risks due to the variety of available indicators and the varying impacts that the indicators measure. Specifically, for social aspects there is a lack of consensus on which indicators best represent the social conditions and have accurate data (Dreyer et al., 2010; Kühnen and Hahn 2017; Popovic et al. 2018).

Using this calculation tool with different country indicators that measure different social aspects allows to incorporate multiple aspects of social supply risks based on the three categories of risk identified by the European Commission: governance, conflict and human rights (EU Commission, 2018). Therefore, the tool uses the OECD Guidelines for Responsible Sourcing and deals with the categories of risk mentioned in the guidelines to select supply risk indicators. The tool thus extends GPSR by adding the option to select an indicator and therefore calculate multiple aspects of supply risks based on global trade and production data and the relevant social aspect indicator.

The CALCAS report on expansion of LCA to Life Cycle Sustainability Assessment mentions deepening and broadening of LCA to incorporate other aspects that traditional LCA fails to accurately assess (CALCAS 2009). Traditional LCA studies mostly address the environment, however questions regarding the assessment of resource use, and the inclusion of social aspects have resulted in several researchers calling for a broadening of LCA to LCSA (CALCAS 2009). The GPSR score is seen as a mid-point characterization factor in traditional LCA methodology and therefore it can be used to complement existing LCA results to provide a more holistic picture of a company's supply chain practices. The GPSR value can be interpreted as a share of commodity imports at risk and can add value to existing LCA results about the risk of sourcing certain materials (Gemechu et al., 2016). Therefore, this research helps in the broadening of LCA according to the guidelines published in the CALCAS paper to properly evaluate the socio-economic impacts that natural resources are associated with and how the social conditions can have an impact on the availability and accessibility of resources.

5.2.2 Choice of country indicator

The case study was used to operationalize the calculation tool, and the results help answer the second research question of this study: **“How does the choice of country-level social indicator influence the assessment of a company’s supply risks?”**

Somewhat surprisingly, the indicator results were consistent across the nine different indicators, even though the GPSR score varied. Rankings of the materials stay constant; for example, graphite and lithium consistently ranked as the materials with highest supply risks. It is important to understand that a supply risk result from one country indicator cannot be compared with a supply risk result from a different indicator. The additional country indicators were selected based on company reports and guidelines for responsible sourcing and the results show that the choice of social indicator does not affect the assessment of supply risks since the ranking of materials is consistent, regardless of the selection of indicator.

This also raises an important consideration in terms of the choice of indicators that can be used to calculate the social supply risks. Choices will be company specific and depend on the social challenges or issues faced by a firm in its supply chain (Popovic et al. 2018; Subramanian et al., 2018). The tool provides choices of several indicators, selected based on recommendations by the EU Commission and industry reports (Drive Sustainability 2018; RMI; LME) where companies are already using these indicators (e.g., Thaisarco, Exotech, GE). As noted, additional indicators could be added to the tool database.

However, before selecting any country indicator it is important to address or acknowledge any limitations arising from selecting the indicator which include converting the scales. This is specifically applicable for country indicators with categorical scales, such as the Heidelberg Conflict scale or the Political Terror Scale (PTS) which are both provided in a categorical scale of 0-5. To use these indicators in the GPSR formula, a conversion is required as mentioned in Chapter 3. The conversion from categorical to continuous scale is done through a relatively simple calculation in this research since the raw data for the Heidelberg Conflict and PTS were not available for the categorical analysis. Thus, options to perform a more scientific and complex conversion of the scores were limited. The conversion method used in this research results in a loss of information that is captured in the original indicator and is translated to the results as these indicators show the lowest supply risk variations amongst all the indicators studied. Therefore, when choosing the country indicators, care must be taken to accurately convert the indicator scores.

5.2.3 Comparison within and between indicator categories

Section 4.5 shows the supply risk results obtained with a focus on the choice of country indicators. As mentioned in the previous section, the choice of country indicator does not have a big effect on the supply risk rankings as the order of material criticality remains the same for most materials (with a few exceptions in some years). Taking the EU-27 as an example, the results from Table 2 show this pattern where graphite is consistently ranked as the material with highest supply risk followed by lithium and in very few instances cobalt, while iron has the lowest supply risk.

This is also true when looking at these patterns within the categories of risk based on the European Commission recommendations (EU Commission, 2018). Patterns are observed within the indicator categories. Results obtained from the PPI, Heidelberg and PTS show slightly different rankings while all the other indicators show similar supply risk rankings within each of the categories. Thus, the CPI and WGI (that both measure governance), HDI and HFI (human rights) and FSI and INFORM (conflict) show very similar supply risks for all the years observed and this reiterates the finding that the choice of country indicator does not have a significant effect on the raw material supply risks. The Heidelberg and PTS indicators show slightly different results, and this is likely due to the conversion method discussed above as a limitation. For the PPI indicator, there is an additional complication. PPI scores are obtained from the Fraser Institute by measuring the attractiveness of mining policies for 83 mining regions in the world, and these scores provided are more regional as they include different mines in each country. Compared to the other indicators, which focus only on country level data, the PPI scores show more variation (Figure 9) which is also reflected in the supply risk rankings.

The supply risk rankings can also be considered across the three indicator categories, with a specific focus across the conflict category using the Heidelberg indicator and the governance using the WGI indicator. Even though the Heidelberg Conflict indicator has limitations as used in this study, it is one of the most widely used indicators used by companies implementing responsible sourcing practices according to the OECD 5-step framework (Table 1). Comparing this to the WGI-PV, which is the original country indicator used in the GPSR formula and used by researchers to use in criticality assessments (Graedel et al., 2015; Gemechu et al., 2016). Therefore, comparing the results obtained from these two country indicators provides an opportunity to relate responsible sourcing practices to criticality assessment methods.

Based on the results of the case study, the results obtained from the country indicators show that the supply risk rankings are consistent across the three categories of risk and thus provides an opportunity to relate these categories of risk and country indicators from responsible sourcing guidelines to criticality assessment indicators. For the EU-27, in 2018 the supply risk ranking obtained using the Heidelberg Conflict indicator is: graphite, cobalt, lithium, aluminum, copper, manganese, nickel and iron. For the same parameters using the WGI-PV indicator, the ranking obtained is: graphite, lithium, cobalt, aluminum, manganese, copper, nickel and iron. Using the WGI-PV, the rankings remain largely constant throughout the years 2015-2018 while a larger variation in the rankings is seen using the Heidelberg indicator as a larger number of materials have a change in the supply risk rankings. These results suggest that the two country indicators are closely related as the average ranking of the materials is similar. A more efficient conversion method for the Heidelberg Conflict indicator could result in a better comparison.

5.2.4 Revisiting the GPSR formula

Another important observation from the results concerns the GPSR formula itself. From the results, it can be seen that the GPSR equation is heavily influenced by the HHI factors used rather than weighted indicator scores, as materials with high HHI generally have high supply risks and vice versa. The weight is significantly towards production concentration, therefore the HHI score has a big impact on the final GPSR score relative to the indicator scores. Thus, it appears the HHI score is dominant in the GPSR calculation and thus ranking of materials in terms of supply risk remains constant. This means that the choice of indicators does not have a big influence on the assessment of social supply risks, as was observed in the case study. The GPSR formula uses the aggregated adjusted import shares and combines that with the HHI score so the weight is shifted towards the production concentration.

Given this, the supply concentration of materials currently dominates the GPSR calculation and the country indicator parameter does not have a big influence on the supply risk result. It can be argued that this does not make a difference and that the supply concentration of materials indeed is more important on raw material supply risks, however the results suggest that the underlying GPSR methodology could be revisited to better understand the influence of parameters and to consider the role that country indicators should have in evaluating the supply risks. This presents an interesting opportunity to further develop and adjust the methodology so that all the relevant criticality indicators are properly used in the evaluation of supply risks. Fortunately, the developed tool can easily and efficiently perform this investigation.

5.2.5 Case study observations

The case study results highlight graphite and lithium as materials with the highest social and geopolitical supply risks while iron has the lowest supply risk for the lithium ion battery product system. These results are consistent with existing literature published by the European Commission on critical raw materials (EC, 2017; Blagoeva et al., 2019). This supports the validity of the tool, which has been successfully operationalized using the case study of LIBs for three regions to provide supply risk scores and give meaningful insights for industry.

Notably, the overall case study results show that the GPSR scores are not decreasing over the years assessed, suggesting that the supply risks have not been mitigated. This is a surprising trend, as it indicates that national and company level efforts to reduce the social supply risks have not been successful. It is important to note, however, that these results are for the period 2015-2018, and that supply risk changes could potentially take from 5-10 years to be significantly affected by global production and trade patterns (Drielsma et al. 2016).

5.2.5.1 Iron

Sourcing of iron showed a distinctly different pattern compared to the other materials in the case study. Iron appears to have a relatively high HHI score yet when the GPSR is calculated it has an extremely low supply risk score. Upon reflection, it appears that the main reason for this is due to the different supply chain stage that data is collected for iron. The data obtained from USGS for iron and aluminum is at the processing stage whereas for all other materials the data collected represents the mine production stage of the supply chain.

Another major reason for the difference in supply risk results of iron are the high number of countries that process iron, including all three countries that were selected for the case study. While iron has a relatively high HHI score because China dominates global production (processing 50% of globally produced iron), the majority of this product is used domestically in China, thus it does not show up in Comtrade data. Furthermore, the quantity of iron produced globally is much higher (almost by a factor of 10 compared to other materials) as shown in Figure 16.

All three regions in the case study (EU-27, Japan and the US) process iron domestically (Figure 16) and thus rely less on the import of iron (Figure 17). The production of iron is also spread out amongst many different countries thus reducing the import risks and dependency of imports from one particular region or country. The quantity of imported iron is significantly lower compared to domestic production. For example, in 2018 the total production of processed iron in the US was 24 billion kg while the total imports for 2018 were 6 million kg based on the USGS and Comtrade data. This consequently results in an extremely low weighted indicator score (adjusted import share). The value for the EU-27 is similar: in 2018 the result has a value of 0.003. When multiplied with the global HHI score of 0.381, according to the GPSR formula, this provides the lowest supply risk score in a lithium battery product system for the EU-27. Logically these results are consistent with criticality assessments at the national level, where iron has not been identified at high risk to supply disruption (see for example, EC 2017).

5.2.5.2 Graphite and lithium

A detailed analysis of the calculations for lithium and graphite shows they have a high production concentration, which is represented by a high HHI score in the GPSR calculation. This plays a big role in the high supply risk results associated with these materials. For graphite and lithium, the supply risk either remained constant or slightly increased from 2015 to 2018 across all selected country indicators. This pattern is similar to how the indicators behave themselves as seen from Figure 9 in the background results. For example, the GPSR score obtained with the PPI shows the greatest variation across the years and this variation is similar to how the indicator performs for each region.

For both graphite and lithium, the three regions considered in the case study import almost all of their raw materials and this is represented by a high weighted indicator score (adjusted import share). For example, for the EU-27 in 2018, these scores for graphite and lithium were 0.588 and 0.472, respectively; and both are much higher compared to that of iron. This also results in the high supply risk scores of these materials.

An important observation regards graphite. Although it is classified as critical by the European Commission (Blagoeva et al., 2019), graphite has not been investigated in studies to the degree of other critical materials such as cobalt and lithium. A study on electric vehicle material supply shows that graphite and lithium are two materials with a huge increase in demand based on the projections for increasing EV production (Ballinger et al. 2019). The supply of graphite is currently dominated by China, which produces the majority of graphite, and given country indicators like those examined here, this increases the social supply risk. The current study provides similar results and shows that graphite is, indeed, a critical material and thus needs careful management to address concerns of future risks. An interesting direction for future studies is to sustainably manage the supply of graphite and that graphite criticality needs more attention.

6. Conclusion

The growth in material extraction, coupled with increasing affluence that results in increased demand of the resources raises need for companies to efficiently assess the raw material social supply risks in their supply chain. Companies in particular have been working on assessing the accessibility to raw materials (Duclos et al. 2010; Yawar and Seuring 2017; Drive Sustainability, 2018) since there are several risks associated with the sourcing practices including physical, economic and reputational risks.

Therefore, this research provides a tool and direction to better understand the social supply risks that companies face when sourcing raw materials. The social supply risks were studied by looking at three broad areas of research that have developed to understand the various impacts that raw materials can have on supply chains: LCA, resource criticality assessments and responsible sourcing. These three areas are converging, and while there have been attempts to integrate some or parts, there has been little work done to combine all three approaches to provide a comprehensive assessment of the associated social risks. The social supply risks are important as they can help a company assess three types of risk: physical risks related to availability of raw materials, economic risks related to price increase and reputation risk that could potentially damage the image of a company.

The research developed a tool based on the GPSR methodology that can provide an assessment of the raw material social supply risks. The tool consists of the Python code that runs the calculations and a database, which contains the country indicators, trade and production data of critical and bulk raw materials. As such, the main contribution of the research is the calculation tool which can be tailored for specific organizations or companies according to their requirements. The tool was developed based on the GPSR methodology that integrates resource criticality assessments to a LCA framework. The purpose of the tool was to increase the computation ability since the calculation itself is data intensive and difficult to perform in Microsoft Excel. Thus, the GPSR calculation was automated and further extended by substituting the original WGI-PV indicator with other country indicators that were selected based on the three broad categories of responsible sourcing practices.

A case study on LIB was selected to show the operationalization of the tool and show it being used. This case study included six critical raw materials in the mining stage (lithium, graphite, manganese, copper, cobalt and nickel) and two bulk materials in the smelting/processing stage (aluminum and iron). Thus, the results show that the tool can be used in multiple stages of the supply chain based on the data inputs and the stage of supply chain under study.

The results obtained from the case study showed that graphite and lithium had the highest social supply risks for all three regions (EU-27, Japan and the US) and this was largely true for each of the country indicators selected. The supply risk of both graphite and lithium either increased or remained constant from 2015-2018 thus suggesting that national level efforts and policies to mitigate the supply risk and increase the availability and accessibility of these materials have been unsuccessful.

The choice of country indicators and their effect on the end GPSR results was also studied. While the indicators themselves cannot be compared since each indicator has a different calculation methodology and scale, the analysis provided an in-depth picture of how to use the tool and how some indicators behave in the calculation. The study of the choice of indicators further showed that the country indicators do not affect the GPSR results as the ranking of materials in terms of their supply risks remained constant with each country indicator.

Lastly, the tool provides several directions for further work and development that have been discussed. Some of these areas include: further development of web-application to improve visualizations and potentially integrate with LCA software; consideration of recycling and substitution to decrease supply risk; addition of multiple stages of the supply chain to provide an aggregate assessment of the overall supply risk; and revisiting the formula itself to better understand the criticality indicators so that the calculation is not biased or weighted towards any one indicator.

7. References

Achzet, Benjamin, and Christoph Helbig. 2013. "How to Evaluate Raw Material Supply Risks—an Overview." *Resources Policy* 38 (4): 435–47. https://doi.org/10.1016/j.resourpol.2013.06.003.

Ageron, Blandine, Angappa Gunasekaran, and Alain Spalanzani. 2012. "Sustainable Supply Management: An Empirical Study." *International Journal of Production Economics* 140 (1): 168–82. https://doi.org/10.1016/j.ijpe.2011.04.007.

Bach, Vanessa, Markus Berger, Martin Henßler, Martin Kirchner, Stefan Leiser, Lisa Mohr, Elmar Rother, et al. 2016. "Integrated Method to Assess Resource Efficiency – ESSENZ." *Journal of Cleaner Production* 137 (November): 118–30. https://doi.org/10.1016/j.jclepro.2016.07.077.

Ballinger, Benjamin, Martin Stringer, Diego R. Schmeda-Lopez, Benjamin Kefford, Brett Parkinson, Chris Greig, and Simon Smart. 2019. "The Vulnerability of Electric Vehicle Deployment to Critical Mineral Supply." *Applied Energy* 255 (December): 113844. https://doi.org/10.1016/j.apenergy.2019.113844.

Bare, Jane C., Patrick Hofstetter, David W. Pennington, and Helias A. Udo de Haes. 2000. "Midpoints versus Endpoints: The Sacrifices and Benefits." *The International Journal of Life Cycle Assessment* 5 (6): 319–26. https://doi.org/10.1007/BF02978665.

Benoît, Catherine, Gregory A. Norris, Sonia Valdivia, Andreas Ciroth, Asa Moberg, Ulrike Bos, Siddharth Prakash, Cassia Ugaya, and Tabea Beck. 2010. "The Guidelines for Social Life Cycle Assessment of Products: Just in Time!" *The International Journal of Life Cycle Assessment* 15 (2): 156–63. https://doi.org/10.1007/s11367-009-0147-8.

Blagoeva, D., Pavel C., Wittmer, D., Huisman, J. and Pasimeni, F., Materials dependencies for dual-use technologies relevant to Europe's defence sector, EUR 29850 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-79- 11102-3, doi:10.2760/570491, JRC117729.

Blengini, Gian Andrea, Philip Nuss, Jo Dewulf, Viorel Nita, Laura Talens Peirò, Beatriz Vidal-Legaz, Cynthia Latunussa, et al. 2017. "EU Methodology for Critical Raw Materials Assessment: Policy Needs and Proposed Solutions for Incremental Improvements." *Resources Policy* 53 (September): 12–19. https://doi.org/10.1016/j.resourpol.2017.05.008.

Brink, Susan van den, René Kleijn, Arnold Tukker, and Jaco Huisman. 2019. "Approaches to Responsible Sourcing in Mineral Supply Chains." *Resources, Conservation and Recycling* 145 (June): 389–98. https://doi.org/10.1016/j.resconrec.2019.02.040.

Cardoso, Sónia R., Ana Paula Barbosa-Póvoa, Susana Relvas, and Augusto Q. Novais. 2015. "Resilience Metrics in the Assessment of Complex Supply-Chains Performance Operating under Demand Uncertainty." *Omega* 56 (October): 53–73. https://doi.org/10.1016/j.omega.2015.03.008.

Cimprich, Alexander, Vanessa Bach, Christoph Helbig, Andrea Thorenz, Dieuwertje Schrijvers, Guido Sonnemann, Steven B. Young, Thomas Sonderegger, and Markus Berger. 2019. "Raw Material Criticality Assessment as a Complement to Environmental Life Cycle Assessment: Examining Methods for Product-level Supply Risk Assessment." *Journal of Industrial Ecology*, April, jiec.12865. https://doi.org/10.1111/jiec.12865.

Cimprich, Alexander, Karim S. Karim, and Steven B. Young. 2018. “Extending the Geopolitical Supply Risk Method: Material ‘Substitutability’ Indicators Applied to Electric Vehicles and Dental X-Ray Equipment.” *The International Journal of Life Cycle Assessment* 23 (10): 2024–42. https://doi.org/10.1007/s11367-017-1418-4.

Cimprich, Alexander, Steven B. Young, Christoph Helbig, Eskinder D. Gemechu, Andrea Thorenz, Axel Tuma, and Guido Sonnemann. 2017. “Extension of Geopolitical Supply Risk Methodology: Characterization Model Applied to Conventional and Electric Vehicles.” *Journal of Cleaner Production* 162 (September): 754–63. https://doi.org/10.1016/j.jclepro.2017.06.063.

Dewulf, Jo, Lorenzo Benini, Lucia Mancini, Serenella Sala, Gian Andrea Blengini, Fulvio Ardente, Marco Recchioni, Joachim Maes, Rana Pant, and David Pennington. 2015. “Rethinking the Area of Protection ‘Natural Resources’ in Life Cycle Assessment.” *Environmental Science & Technology* 49 (9): 5310–17. https://doi.org/10.1021/acs.est.5b00734.

Dreyer, Louise, Michael Hauschild, and Jens Schierbeck. 2006. “A Framework for Social Life Cycle Impact Assessment (10 Pp).” *The International Journal of Life Cycle Assessment* 11 (2): 88–97. https://doi.org/10.1065/lca2005.08.223.

Drielsma, Johannes A., Andrea J. Russell-Vaccari, Thomas Drnek, Tom Brady, Pär Weihed, Mark Mistry, and Laia Perez Simbor. 2016. “Mineral Resources in Life Cycle Impact Assessment—Defining the Path Forward.” *The International Journal of Life Cycle Assessment* 21 (1): 85–105. https://doi.org/10.1007/s11367-015-0991-7.

Duclos, Steven J., Otto, Jeffrey P., and Konitzer, Douglas G. (2010). "Design in an era of Constrained Resources." ASME. *Mechanical Engineering*. September 2010; 132(09): 36–40. https://doi.org/10.1115/1.2010-Sep-3

Feng, Yunting, Qinghua Zhu, and Kee-Hung Lai. 2017. “Corporate Social Responsibility for Supply Chain Management: A Literature Review and Bibliometric Analysis.” *Journal of Cleaner Production* 158 (August): 296–307. https://doi.org/10.1016/j.jclepro.2017.05.018.

Gemechu, Eskinder D., Christoph Helbig, Guido Sonnemann, Andrea Thorenz, and Axel Tuma. 2016. “Import-Based Indicator for the Geopolitical Supply Risk of Raw Materials in Life Cycle Sustainability Assessments: Import-Based Indicator for Geopolitical Supply Risk of Raw Materials.” *Journal of Industrial Ecology* 20 (1): 154–65. https://doi.org/10.1111/jiec.12279.

Gemechu, Eskinder D., Guido Sonnemann, and Steven B. Young. 2017. “Geopolitical-Related Supply Risk Assessment as a Complement to Environmental Impact Assessment: The Case of Electric Vehicles.” *The International Journal of Life Cycle Assessment* 22 (1): 31–39. https://doi.org/10.1007/s11367-015-0917-4.

Gibney, Mark, Linda Cornett, Reed Wood, Peter Haschke, Daniel Arnon, Attilio Pisanò, and Gray Barrett. 2019. The Political Terror Scale 1976-2018. Date Retrieved, from the Political Terror Scale website: http://www.politicalterrorscale.org.

Graedel, T. E., Rachel Barr, Chelsea Chandler, Thomas Chase, Joanne Choi, Lee Christoffersen, Elizabeth Friedlander, et al. 2012. “Methodology of Metal Criticality Determination.” *Environmental Science & Technology* 46 (2): 1063–70. https://doi.org/10.1021/es203534z.

Graedel, T. E., and Philip Nuss. 2014. “Employing Considerations of Criticality in Product Design.” *JOM* 66 (11): 2360–66. https://doi.org/10.1007/s11837-014-1188-4.

Griffin, Gillian, Gabrielle Gaustad, and Kedar Badami. 2019. “A Framework for Firm-Level Critical Material Supply Management and Mitigation.” *Resources Policy* 60 (March): 262–76. https://doi.org/10.1016/j.resourpol.2018.12.008.

Heijungs, Reinout, Gjalt Huppes, and Jeroen B. Guinée. 2010. “Life Cycle Assessment and Sustainability Analysis of Products, Materials and Technologies. Toward a Scientific Framework for Sustainability Life Cycle Analysis.” *Polymer Degradation and Stability* 95 (3): 422–28. https://doi.org/10.1016/j.polymdegradstab.2009.11.010.

Helbig, Christoph, Eskinder D. Gemechu, Baptiste Pillain, Steven B. Young, Andrea Thorenz, Axel Tuma, and Guido Sonnemann. 2016. “Extending the Geopolitical Supply Risk Indicator: Application of Life Cycle Sustainability Assessment to the Petrochemical Supply Chain of Polyacrylonitrile-Based Carbon Fibers.” *Journal of Cleaner Production* 137 (November): 1170–78. https://doi.org/10.1016/j.jclepro.2016.07.214.

Helbig, Christoph, Lars Wietschel, Andrea Thorenz, and Axel Tuma. 2016. “How to Evaluate Raw Material Vulnerability - An Overview.” *Resources Policy* 48 (June): 13–24. https://doi.org/10.1016/j.resourpol.2016.02.003.

Igos, Elorri, Enrico Benetto, Rodolphe Meyer, Paul Baustert, and Benoit Othoniel. 2019. “How to Treat Uncertainties in Life Cycle Assessment Studies?” *The International Journal of Life Cycle Assessment* 24 (4): 794–807. https://doi.org/10.1007/s11367-018-1477-1.

Kolotzek, Christoph, Christoph Helbig, Andrea Thorenz, Armin Reller, and Axel Tuma. 2018. “A Company-Oriented Model for the Assessment of Raw Material Supply Risks, Environmental Impact and Social Implications.” *Journal of Cleaner Production* 176 (March): 566–80. https://doi.org/10.1016/j.jclepro.2017.12.162.

Kühnen, Michael, and Rüdiger Hahn. 2017. “Indicators in Social Life Cycle Assessment: A Review of Frameworks, Theories, and Empirical Experience.” *Journal of Industrial Ecology* 21 (6): 1547–65. https://doi.org/10.1111/jiec.12663.

Malstrom, Cecilia. 2018 “COMMISSION RECOMMENDATION (EU) 2018/ 1149 - of 10 August 2018 - on Non-Binding Guidelines for the Identification of Conflict-Affected and High-Risk Areas and Other Supply Chain Risks under Regulation (EU) 2017/ 821 of the European Parliament and of the Council.”

Mancheri, Nabeel A., Benjamin Sprecher, Sebastiaan Deetman, Steven B. Young, Raimund Bleischwitz, Liang Dong, René Kleijn, and Arnold Tukker. 2018. “Resilience in the Tantalum Supply Chain.” *Resources, Conservation and Recycling* 129 (February): 56–69. https://doi.org/10.1016/j.resconrec.2017.10.018.

Mathieux, Fabrice, Fabrice Mathieux, Fulvio Ardente, Silvia Bobba, Philip Nuss, Gian Andrea Blengini, Patricia Alves Dias, et al. 2017. *Critical Raw Materials and the Circular Economy: Background Report.* http://publications.europa.eu/publication/manifestation_identifier/PUB_KJNA28832ENN.

OECD, ed. 2013. *OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas*. 2. ed. Paris.

Schneider, Laura, Markus Berger, Eckhard Schüler-Hainsch, Sven Knöfel, Klaus Ruhland, Jörg Mosig, Vanessa Bach, and Matthias Finkbeiner. 2014. "The Economic Resource Scarcity Potential (ESP) for Evaluating Resource Use Based on Life Cycle Assessment." *The International Journal of Life Cycle Assessment* 19 (3): 601–10. https://doi.org/10.1007/s11367-013-0666-1.

Seuring, Stefan, and Martin Müller. 2008. "From a Literature Review to a Conceptual Framework for Sustainable Supply Chain Management." *Journal of Cleaner Production* 16 (15): 1699–1710. https://doi.org/10.1016/j.jclepro.2008.04.020.

Sonnemann, Guido, Eskinder Demisse Gemechu, Naeem Adibi, Vincent De Bruille, and Cécile Bulle. 2015. "From a Critical Review to a Conceptual Framework for Integrating the Criticality of Resources into Life Cycle Sustainability Assessment." *Journal of Cleaner Production* 94 (May): 20–34. https://doi.org/10.1016/j.jclepro.2015.01.082.

Stewart, Mary, and Bo Pedersen Weidema. 2005. "A Consistent Framework for Assessing the Impacts from Resource Use - A Focus on Resource Functionality (8 Pp)." *The International Journal of Life Cycle Assessment* 10 (4): 240–47. https://doi.org/10.1065/lca2004.10.184.

Subramanian, Karpagam, C.K. Chau, and Winco K.C. Yung. 2018. "Relevance and Feasibility of the Existing Social LCA Methods and Case Studies from a Decision-Making Perspective." *Journal of Cleaner Production* 171 (January): 690–703. https://doi.org/10.1016/j.jclepro.2017.10.006.

Weidema, Bo P. n.d. "Social Impact Categories, Indicators, Characterisation and Damage Modelling," 17.

Yawar, Sadaat Ali, and Stefan Seuring. 2017. "Management of Social Issues in Supply Chains: A Literature Review Exploring Social Issues, Actions and Performance Outcomes." *Journal of Business Ethics* 141 (3): 621–43. https://doi.org/10.1007/s10551-015-2719-9.

Young, Steven B. 2018. "Responsible Sourcing of Metals: Certification Approaches for Conflict Minerals and Conflict-Free Metals." *The International Journal of Life Cycle Assessment* 23 (7): 1429–47. https://doi.org/10.1007/s11367-015-0932-5.

Young, Steven, Shannon Fernandes, and Michael Wood. 2019. "Jumping the Chain: How Downstream Manufacturers Engage with Deep Suppliers of Conflict Minerals." *Resources* 8 (1): 26. https://doi.org/10.3390/resources8010026.

Zorzini, Marta, Linda C. Hendry, Fahian Anisul Huq, and Mark Stevenson. 2015. "Socially Responsible Sourcing: Reviewing the Literature and Its Use of Theory." *International Journal of Operations & Production Management* 35 (1): 60–109. https://doi.org/10.1108/IJOPM-07-2013-0355.

8. Appendix

A. Social Indicator Tables

Table A1. Indicators grouped according to stakeholder categories and midpoint impact categories for use in Social-LCA (S-LCA).

	Midpoint Impact Categories				
Stakeholder Categories	**Human Rights**	**Working Conditions**	**Health and Safety**	**Cultural Heritage**	**Governance**
Local Community		Local employment	Safe & healthy living conditions	Respect of indigenous rights	Community engagement
		Access to material resources		Delocalization and migration	
Society		Contribution to economic development			Corruption
					Prevention & mitigation of conflicts
Workers	Child labor	Hours of work	Health and safety		
	Forced labor	Social benefits			
	Fair Salary	Freedom of association and			
	Discrimination				

	Gender equality	collective bargaining			
Consumers			Health and safety		
Value chain actors					Promoting social responsibility

Table A2. Indicators and sources for S-LCA midpoint impact categories

Stakeholders	**Subcategory**	**Indicator**	**Source**
Local Community	Local employment	Number of local jobs created in relation to final product energy unit (MJ)	
	Access to material resources		
	Safe & healthy living conditions	Changes in DALY (or QALY) that can be linked to activities in the supply chain	
	Respect of indigenous rights	Human rights Issues faced by indigenous peoples	Amnesty International
		Prevalence of racial discrimination	Business & Human Rights Resource Centre

		Cultural heritage in urgent need of safeguarding	UNESCO Urgent Safeguarding List
	Delocalization and migration	Forced evictions stemming from Economic Development	COHRE’s Global Survey on Forced Eviction
	Community engagement	Qualitative description of level of engagement	
Society	Contribution to economic development	Share of national GDP/changes overtime in national GDP for the specific sector	World Bank, OECD
		Employment stability	
	Corruption	Risk of corruption in the country and/or sub-region	World Bank
	Prevention & mitigation of conflicts	Is the organization doing business in a region with ongoing conflicts?	Heidelberg Conflict Barometer
Workers	Child labor	Evidence that there is no child labor	World Bank, UNICEF
	Forced labor	Evidence that there is no forced labor	
	Fair Salary	Minimum and fair wages for worker	
	Discrimination	Rate of disability employment	
		Ratio of genders in workforce	
		Wage level between genders	

	Freedom of association and collective bargaining	Evidence of restriction to freedom of association and collective bargaining	International Trade Union Confederation (ITUC)
	Hours of work	Per month average working hours	
	Social benefits	% of workers who receive additional social benefits	
	Health and safety	Occupational accident rate	
		Injuries, diseases and fatalities	
Consumers	Health and safety	Presence of consumer complaints	U.S. Consumer Product Safety Commission
		Product health and safety	
Value chain actors	Promoting social responsibility	Suppliers' compliance with human rights and codes of conduct	
		Screening of suppliers and downstream contractors on human rights	

Table A3. Indicators and sources of information for CAHRA areas of interest based on EU Commissions recommendation for responsible sourcing practices.

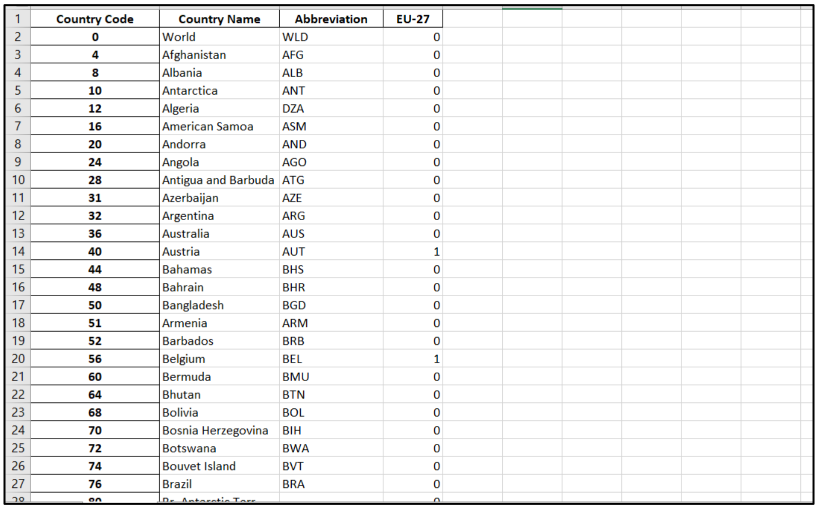
Indicators	Sources of Information	Purpose	Availability
Conflict - Conflict Intensity Level - Refugees (by Country of Origin) - Asylum Seekers - Conflict related deaths - Internally displaced persons	Heidelberg Conflict Barometer	Annual analysis of global conflict events, which includes a detailed examination of conflict dynamics and processes	Yearly
	Geneva Academy Rule of Law in Armed Conflicts	Systematically qualifies situations of armed violence using the definition of armed conflict under international humanitarian law	Yearly
	Uppsala Conflict Data Programme — Georeferenced Event Dataset	Records ongoing violent conflict and provides a number of databases on organized violence and peace-making	
	CrisisWatch	A tool designed to help decision-makers prevent deadly violence by keeping them up-to-date with developments in over 70 conflicts and crises	On-going
	Global Peace Index	Ranks the peacefulness of 162 independent states covering 99.6 percent of the world's population, and gauges global peace	Yearly
	New Post-Conflict Performance Indicators Framework (PCPI)	The PCPI assesses the quality of a country's policy and institutional framework to support a successful	Yearly

		transition and recovery from conflict.	
	International Peace Information Service — Conflict Mapping	Aims to map the various motives of conflict actors in war-torn areas	On-going
	United Nations High Commissioner for Refugees (UNHCR)		
	SIPRI Database	Offers information on all peace operations conducted since 2000	Yearly
Governance - Government Effectiveness - Inequality — GINI Coefficient - Corruption — World Bank - Voice and Accountability - Political Stability - Integrity of the Legal System	Worldwide Governance Indicators	Reports aggregate and individual governance indicators for 215 economies based on 6 dimensions of governance	Yearly
	Fragile States Index	Annual ranking of 178 nations based on their levels of stability and the pressures they face.	Yearly
	Corruption Perception Index	Ranks 180 countries and territories by their perceived levels of public sector corruption according to experts and businesspeople	Yearly
	Polity IV		1946-2013
	World Development Indicators	Presents the most current and accurate global development data available,	Yearly

- Voice and accountability - Regulatory Quality - Rule of Law		and includes national, regional and global estimates	
	Database of Political Indicators, World Bank		
	MAR	University based research project that monitors and analyses the status and conflicts of politically-active communal groups in countries which have a population of at least 50,000	Yearly
	World Bank, Ease of Doing Business		
	World Bank Group, Governance Matters V		
	Heritage Foundation, Index of Economic Freedom	Measures economic freedom of 186 countries based on trade freedom, business freedom, investment freedom, and property rights	Yearly
	UN Rule of Law Indicators	Monitor changes in the performance and fundamental characteristics of criminal justice institutions in conflict and post-conflict situations	Yearly
Human rights	United Nations Security Council Resolutions (UNSC)		

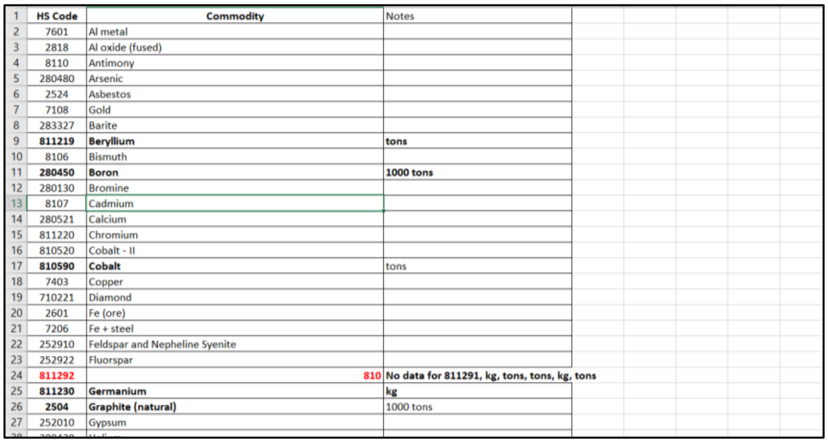
- Physical Integrity Rights Index - Empowerment Rights Index - Freedom of Religion - Worker’s rights - Gender equality - Indigenous rights - Civil Liberties	United Nations Human Rights Council		
	United Nations Development Programme — International Human Development Indicators		
	United Nations High Commissioner for Refugees (UNHCR)		
	Amnesty International		
	Human Rights Watch		
	CIRI Human Rights Index	Contains quantitative information of government respect for 15 internationally recognized human rights practices	
	MAR	University based research project that monitors and analyses the status and conflicts of politically-active communal groups in countries which have a population of at least 50,000	

B. Tool and Database Tables



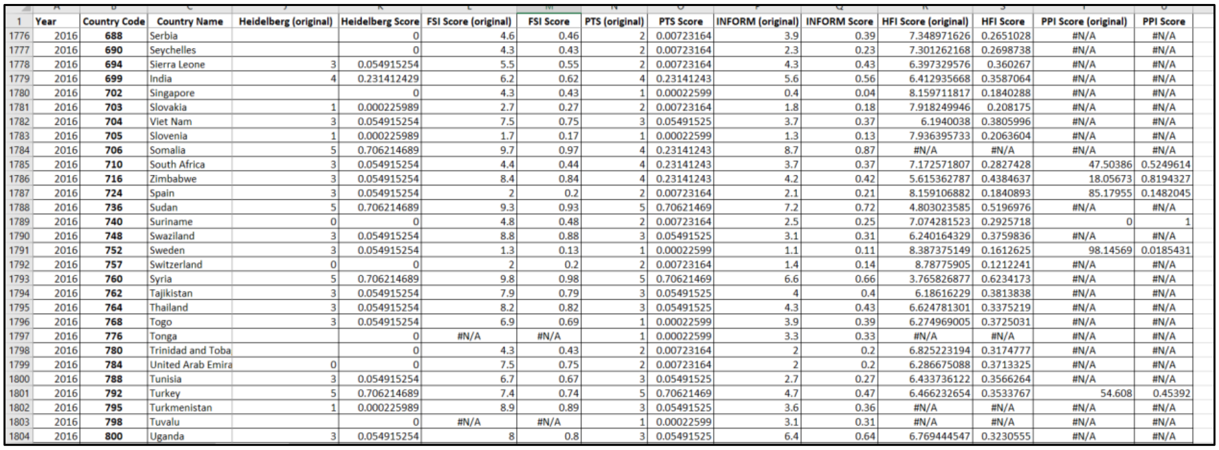
Country Code	Country Name	Abbreviation	EU-27
0	World	WLD	0
4	Afghanistan	AFG	0
8	Albania	ALB	0
10	Antarctica	ANT	0
12	Algeria	DZA	0
16	American Samoa	ASM	0
20	Andorra	AND	0
24	Angola	AGO	0
28	Antigua and Barbuda	ATG	0
31	Azerbaijan	AZE	0
32	Argentina	ARG	0
36	Australia	AUS	0
40	Austria	AUT	1
44	Bahamas	BHS	0
48	Bahrain	BHR	0
50	Bangladesh	BGD	0
51	Armenia	ARM	0
52	Barbados	BRB	0
56	Belgium	BEL	1
60	Bermuda	BMU	0
64	Bhutan	BTN	0
68	Bolivia	BOL	0
70	Bosnia Herzegovina	BIH	0
72	Botswana	BWA	0
74	Bouvet Island	BVT	0
76	Brazil	BRA	0

Figure B1. Country table in Excel database



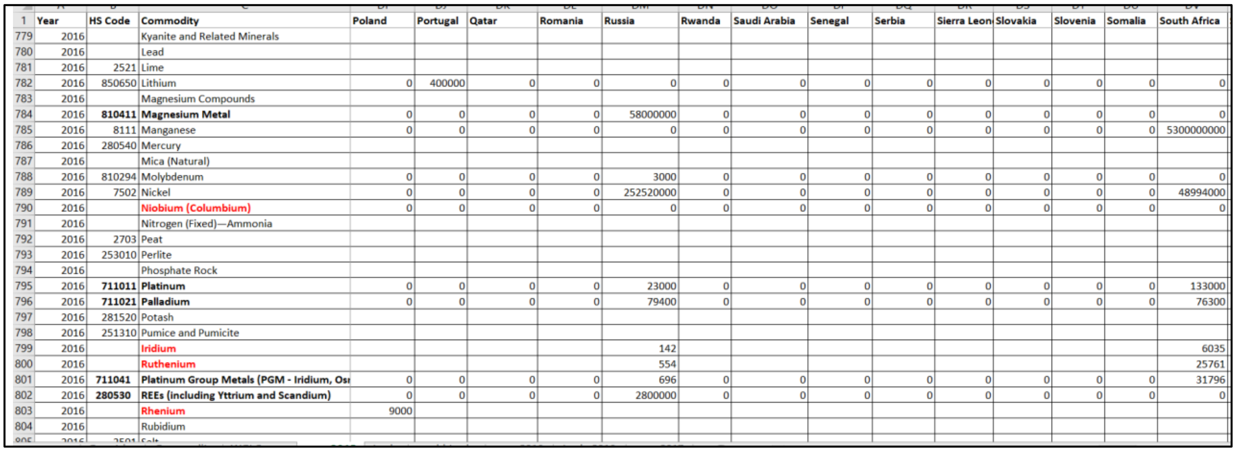
HS Code	Commodity	Notes
7601	Al metal	
2818	Al oxide (fused)	
8110	Antimony	
280480	Arsenic	
2524	Asbestos	
7108	Gold	
283327	Barite	
811219	**Beryllium**	**tons**
8106	Bismuth	
280450	**Boron**	**1000 tons**
280130	Bromine	
8107	Cadmium	
280521	Calcium	
811220	Chromium	
810520	Cobalt - II	
810590	**Cobalt**	tons
7403	Copper	
710221	Diamond	
2601	Fe (ore)	
7206	Fe + steel	
252910	Feldspar and Nepheline Syenite	
252922	Fluorspar	
811292	**810**	**No data for 811291, kg, tons, tons, kg, tons**
811230	**Germanium**	**kg**
2504	**Graphite (natural)**	1000 tons
252010	Gypsum	

Figure B2. Commodity table in Excel database



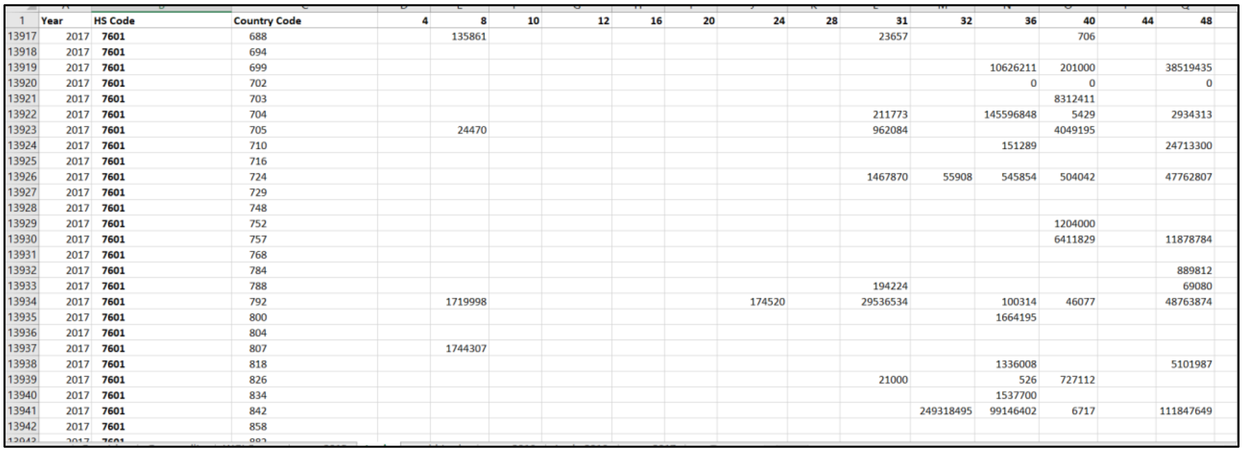
1	Year	Country Code	Country Name	Heidelberg (original)	Heidelberg Score	FSI Score (original)	FSI Score	PTS (original)	PTS Score	INFORM (original)	INFORM Score	HFI Score (original)	HFI Score	PPI Score (original)	PPI Score
1776	2016	**688**	Serbia		0	4.6	0.46	2	0.00723164	3.9	0.39	7.348971626	0.2651028	#N/A	#N/A
1777	2016	**690**	Seychelles		0	4.3	0.43	2	0.00723164	2.3	0.23	7.301262168	0.2698738	#N/A	#N/A
1778	2016	**694**	Sierra Leone	3	0.054915254	5.5	0.55	2	0.00723164	4.3	0.43	6.397329576	0.360267	#N/A	#N/A
1779	2016	**699**	India	4	0.231412429	6.2	0.62	4	0.23141243	5.6	0.56	6.412935668	0.3587064	#N/A	#N/A
1780	2016	**702**	Singapore		0	4.3	0.43	1	0.00022599	0.4	0.04	8.159711817	0.1840288	#N/A	#N/A
1781	2016	**703**	Slovakia	1	0.000225989	2.7	0.27	2	0.00723164	1.8	0.18	7.918249946	0.208175	#N/A	#N/A
1782	2016	**704**	Viet Nam	3	0.054915254	7.5	0.75	3	0.05491525	3.7	0.37	6.1940038	0.3805996	#N/A	#N/A
1783	2016	**705**	Slovenia	1	0.000225989	1.7	0.17	1	0.00022599	1.3	0.13	7.936395733	0.2063604	#N/A	#N/A
1784	2016	**706**	Somalia	5	0.706214689	9.7	0.97	4	0.23141243	8.7	0.87	#N/A	#N/A	#N/A	#N/A
1785	2016	**710**	South Africa	3	0.054915254	4.4	0.44	4	0.23141243	3.7	0.37	7.172571807	0.2827428	47.50386	0.5249614
1786	2016	**716**	Zimbabwe	3	0.054915254	8.4	0.84	4	0.23141243	4.2	0.42	5.615362787	0.4384637	18.05673	0.8194327
1787	2016	**724**	Spain	3	0.054915254	2	0.2	2	0.00723164	2.1	0.21	8.159106882	0.1840893	85.17955	0.1482045
1788	2016	**736**	Sudan	5	0.706214689	9.3	0.93	5	0.70621469	7.2	0.72	4.803023585	0.5196976	#N/A	#N/A
1789	2016	**740**	Suriname	0	0	4.8	0.48	2	0.00723164	2.5	0.25	7.074281523	0.2925718	0	1
1790	2016	**748**	Swaziland	3	0.054915254	8.8	0.88	3	0.05491525	3.1	0.31	6.240164329	0.3759836	#N/A	#N/A
1791	2016	**752**	Sweden	3	0.054915254	1.3	0.13	1	0.00022599	1.1	0.11	8.387375149	0.1612625	98.14569	0.0185431
1792	2016	**757**	Switzerland	0	0	2	0.2	2	0.00723164	1.4	0.14	8.78775905	0.1212241	#N/A	#N/A
1793	2016	**760**	Syria	5	0.706214689	9.8	0.98	5	0.70621469	6.6	0.66	3.765826877	0.6234173	#N/A	#N/A
1794	2016	**762**	Tajikistan	3	0.054915254	7.9	0.79	3	0.05491525	4	0.4	6.18616229	0.3813838	#N/A	#N/A
1795	2016	**764**	Thailand	3	0.054915254	8.2	0.82	3	0.05491525	4.3	0.43	6.624781301	0.3375219	#N/A	#N/A
1796	2016	**768**	Togo	3	0.054915254	6.9	0.69	1	0.00022599	3.9	0.39	6.274969005	0.3725031	#N/A	#N/A
1797	2016	**776**	Tonga		0	#N/A	#N/A	1	0.00022599	3.3	0.33	#N/A	#N/A	#N/A	#N/A
1798	2016	**780**	Trinidad and Toba		0	4.3	0.43	2	0.00723164	2	0.2	6.825223194	0.3174777	#N/A	#N/A
1799	2016	**784**	United Arab Emira	0	0	7.5	0.75	2	0.00723164	2	0.2	6.286675088	0.3713325	#N/A	#N/A
1800	2016	**788**	Tunisia	3	0.054915254	6.7	0.67	3	0.05491525	2.7	0.27	6.433736122	0.3566264	#N/A	#N/A
1801	2016	**792**	Turkey	5	0.706214689	7.4	0.74	5	0.70621469	4.7	0.47	6.466232654	0.3533767	54.608	0.45392
1802	2016	**795**	Turkmenistan	1	0.000225989	8.9	0.89	3	0.05491525	3.6	0.36	#N/A	#N/A	#N/A	#N/A
1803	2016	**798**	Tuvalu		0	#N/A	#N/A	1	0.00022599	3.1	0.31	#N/A	#N/A	#N/A	#N/A
1804	2016	**800**	Uganda	3	0.054915254	8	0.8	3	0.05491525	6.4	0.64	6.769444547	0.3230555	#N/A	#N/A

Figure B3. Indicator table in Excel database



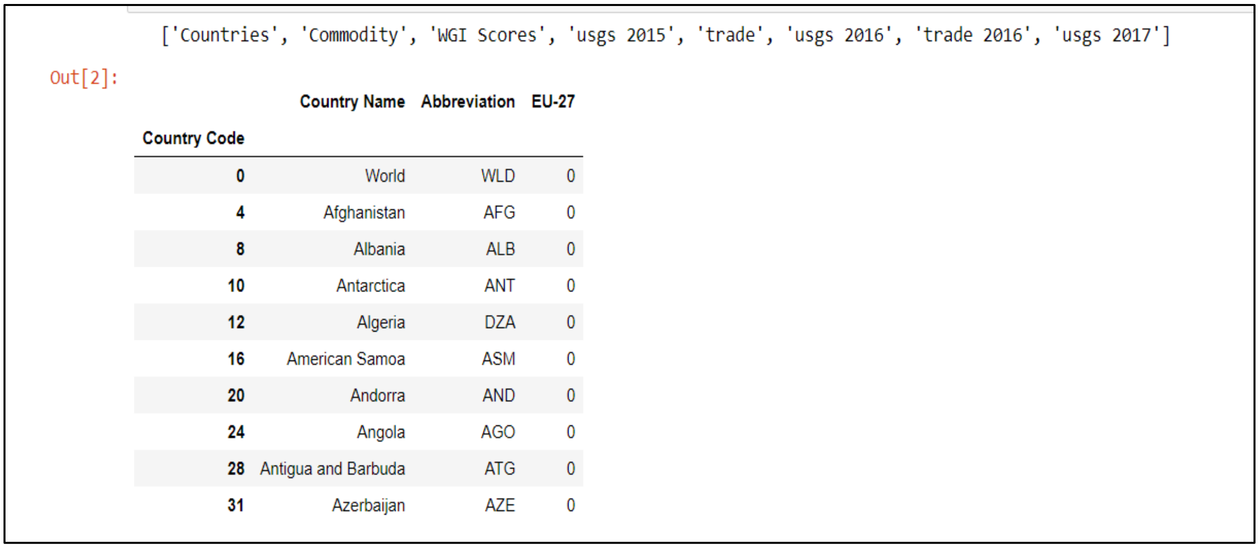
1	Year	HS Code	Commodity	Poland	Portugal	Qatar	Romania	Russia	Rwanda	Saudi Arabia	Senegal	Serbia	Sierra Leon	Slovakia	Slovenia	Somalia	South Africa
779	2016		Kyanite and Related Minerals														
780	2016		Lead														
781	2016	2521	Lime														
782	2016	850650	Lithium	0	400000	0	0	0	0	0	0	0	0	0	0	0	0
783	2016		Magnesium Compounds														
784	2016	**810411**	**Magnesium Metal**	0	0	0	0	58000000	0	0	0	0	0	0	0	0	0
785	2016	8111	Manganese	0	0	0	0	0	0	0	0	0	0	0	0	0	5300000000
786	2016	280540	Mercury														
787	2016		Mica (Natural)														
788	2016	810294	Molybdenum	0	0	0	0	3000	0	0	0	0	0	0	0	0	0
789	2016	7502	Nickel	0	0	0	0	252520000	0	0	0	0	0	0	0	0	48994000
790	2016		**Niobium (Columbium)**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
791	2016		Nitrogen (Fixed)—Ammonia														
792	2016	2703	Peat														
793	2016	253010	Perlite														
794	2016		Phosphate Rock														
795	2016	**711011**	**Platinum**	0	0	0	0	23000	0	0	0	0	0	0	0	0	133000
796	2016	**711021**	**Palladium**	0	0	0	0	79400	0	0	0	0	0	0	0	0	76300
797	2016	281520	Potash														
798	2016	251310	Pumice and Pumicite														
799	2016		**Iridium**					142									6035
800	2016		**Ruthenium**					554									25761
801	2016	**711041**	**Platinum Group Metals (PGM - Iridium, Os**	0	0	0	0	696	0	0	0	0	0	0	0	0	31796
802	2016	**280530**	**REEs (including Yttrium and Scandium)**	0	0	0	0	2800000	0	0	0	0	0	0	0	0	0
803	2016		**Rhenium**	9000													
804	2016		Rubidium														

Figure B4. USGS Production table in Excel database



1	Year	HS Code	Country Code	4	8	10	12	16	20	24	28	31	32	36	40	44	48
13917	2017	**7601**	688		135861							23657			706		
13918	2017	**7601**	694														
13919	2017	**7601**	699											10626211	201000		38519435
13920	2017	**7601**	702											0	0		0
13921	2017	**7601**	703												8312411		
13922	2017	**7601**	704									211773		145596848	5429		2934313
13923	2017	**7601**	705		24470							962084			4049195		
13924	2017	**7601**	710											151289			24713300
13925	2017	**7601**	716														
13926	2017	**7601**	724									1467870	55908	545854	504042		47762807
13927	2017	**7601**	729														
13928	2017	**7601**	748														
13929	2017	**7601**	752												1204000		
13930	2017	**7601**	757												6411829		11878784
13931	2017	**7601**	768														
13932	2017	**7601**	784														889812
13933	2017	**7601**	788									194224					69080
13934	2017	**7601**	792		1719998					174520		29536534		100314	46077		48763874
13935	2017	**7601**	800											1664195			
13936	2017	**7601**	804														
13937	2017	**7601**	807		1744307												
13938	2017	**7601**	818											1336008			5101987
13939	2017	**7601**	826									21000		526	727112		
13940	2017	**7601**	834											1537700			
13941	2017	**7601**	842										249318495	99146402	6717		111847649
13942	2017	**7601**	858														

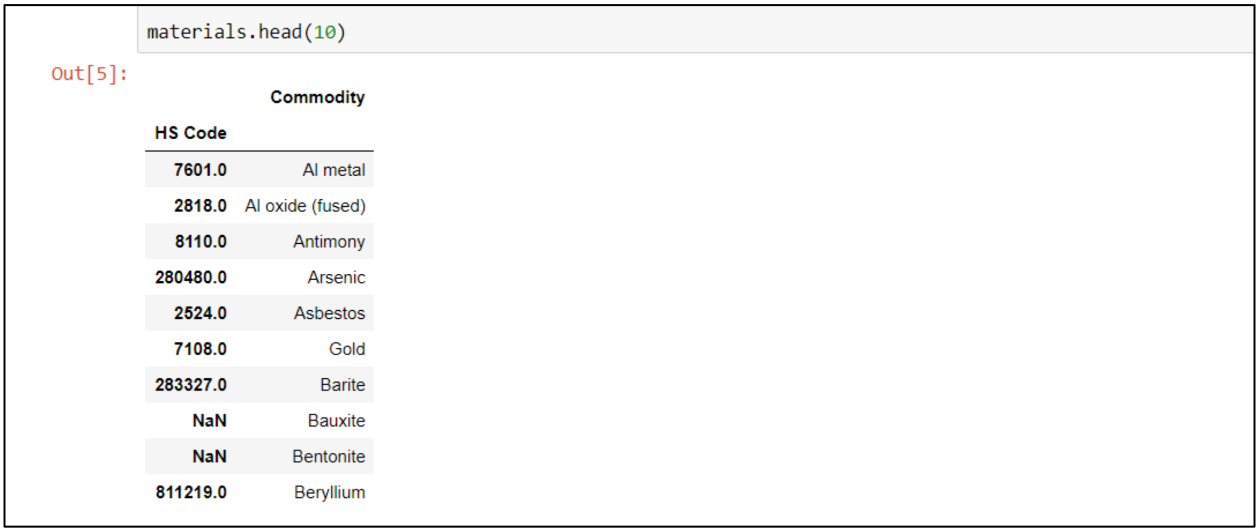
Figure B5. UN Comtrade table in Excel database



```
['Countries', 'Commodity', 'WGI Scores', 'usgs 2015', 'trade', 'usgs 2016', 'trade 2016', 'usgs 2017']
```

	Country Name	Abbreviation	EU-27
Country Code			
0	World	WLD	0
4	Afghanistan	AFG	0
8	Albania	ALB	0
10	Antarctica	ANT	0
12	Algeria	DZA	0
16	American Samoa	ASM	0
20	Andorra	AND	0
24	Angola	AGO	0
28	Antigua and Barbuda	ATG	0
31	Azerbaijan	AZE	0

Figure B6. Country table in Jupyter Notebook



```
materials.head(10)
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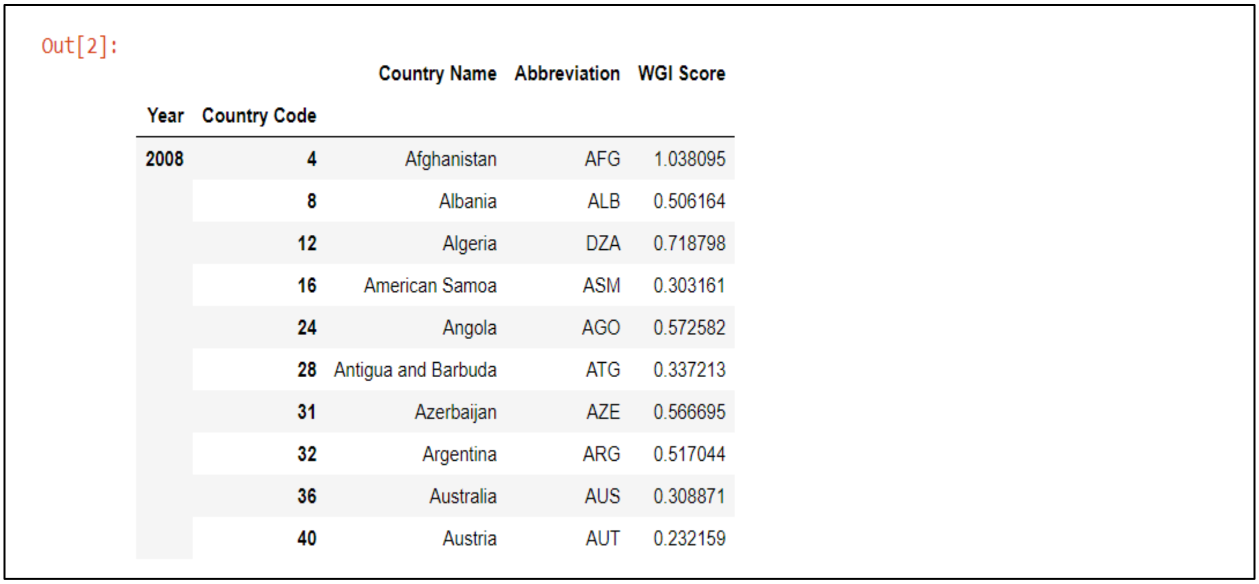
	Commodity
HS Code	
7601.0	Al metal
2818.0	Al oxide (fused)
8110.0	Antimony
280480.0	Arsenic
2524.0	Asbestos
7108.0	Gold
283327.0	Barite
NaN	Bauxite
NaN	Bentonite
811219.0	Beryllium

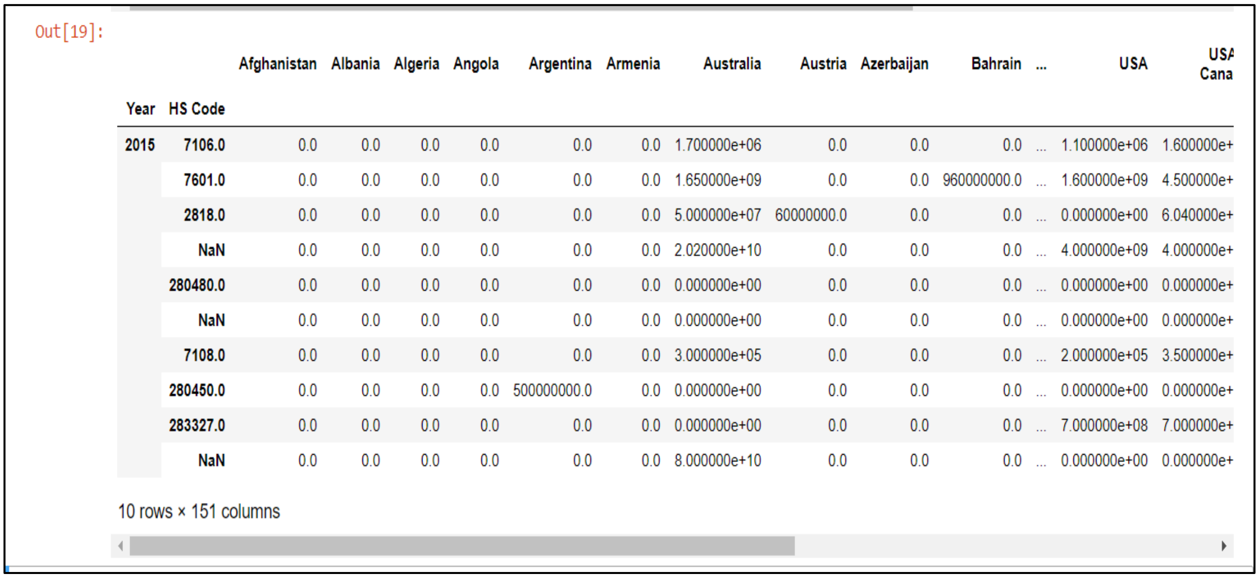
Figure B7. Commodity table in Jupyter Notebook



Out[2]:

Year	Country Code	Country Name	Abbreviation	WGI Score
2008	4	Afghanistan	AFG	1.038095
	8	Albania	ALB	0.506164
	12	Algeria	DZA	0.718798
	16	American Samoa	ASM	0.303161
	24	Angola	AGO	0.572582
	28	Antigua and Barbuda	ATG	0.337213
	31	Azerbaijan	AZE	0.566695
	32	Argentina	ARG	0.517044
	36	Australia	AUS	0.308871
	40	Austria	AUT	0.232159

Figure B8. Indicator table in Jupyter Notebook

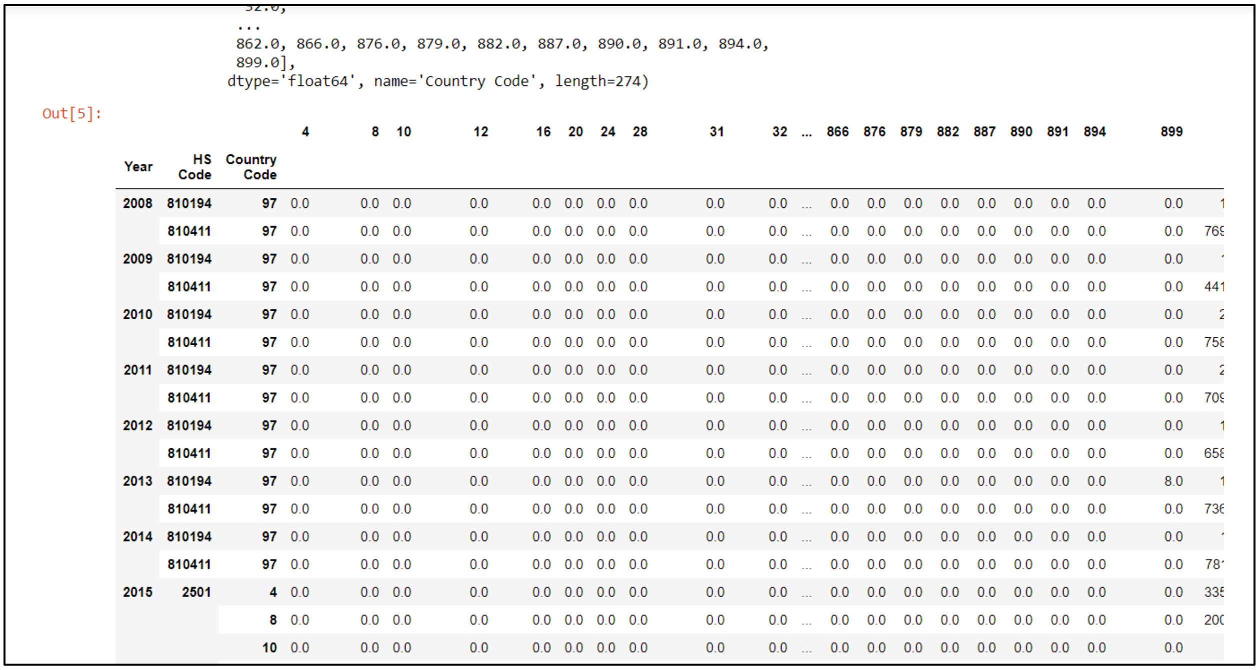


Out[19]:

Year	HS Code	Afghanistan	Albania	Algeria	Angola	Argentina	Armenia	Australia	Austria	Azerbaijan	Bahrain	...	USA	USA Cana
2015	7106.0	0.0	0.0	0.0	0.0	0.0	0.0	1.700000e+06	0.0	0.0	0.0	...	1.100000e+06	1.600000e+
	7601.0	0.0	0.0	0.0	0.0	0.0	0.0	1.650000e+09	0.0	0.0	960000000.0	...	1.600000e+09	4.500000e+
	2818.0	0.0	0.0	0.0	0.0	0.0	0.0	5.000000e+07	60000000.0	0.0	0.0	...	0.000000e+00	6.040000e+
	NaN	0.0	0.0	0.0	0.0	0.0	0.0	2.020000e+10	0.0	0.0	0.0	...	4.000000e+09	4.000000e+
	280480.0	0.0	0.0	0.0	0.0	0.0	0.0	0.000000e+00	0.0	0.0	0.0	...	0.000000e+00	0.000000e+
	NaN	0.0	0.0	0.0	0.0	0.0	0.0	0.000000e+00	0.0	0.0	0.0	...	0.000000e+00	0.000000e+
	7108.0	0.0	0.0	0.0	0.0	0.0	0.0	3.000000e+05	0.0	0.0	0.0	...	2.000000e+05	3.500000e+
	280450.0	0.0	0.0	0.0	0.0	500000000.0	0.0	0.000000e+00	0.0	0.0	0.0	...	0.000000e+00	0.000000e+
	283327.0	0.0	0.0	0.0	0.0	0.0	0.0	0.000000e+00	0.0	0.0	0.0	...	7.000000e+08	7.000000e+
	NaN	0.0	0.0	0.0	0.0	0.0	0.0	8.000000e+10	0.0	0.0	0.0	...	0.000000e+00	0.000000e+

10 rows × 151 columns

Figure B9. USGS Production table in Jupyter Notebook



```
         32.0,
         ...
         862.0, 866.0, 876.0, 879.0, 882.0, 887.0, 890.0, 891.0, 894.0,
         899.0],
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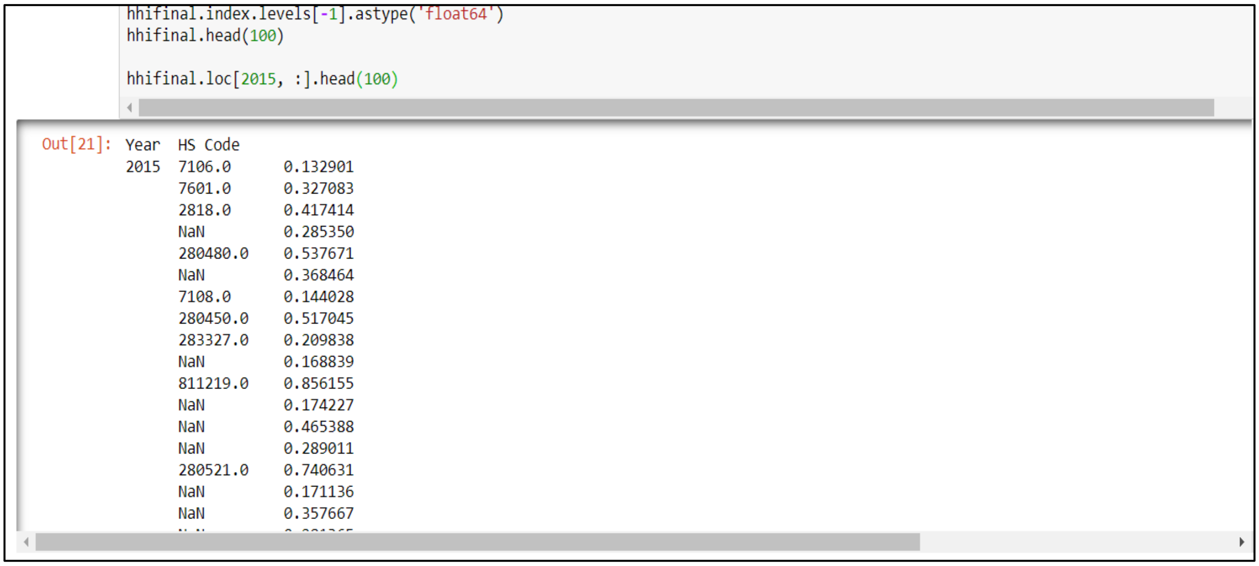
Out[5]:

Year	HS Code	Country Code	4	8	10	12	16	20	24	28	31	32	...	866	876	879	882	887	890	891	894	899	
2008	810194	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
	810411	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	769
2009	810194	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
	810411	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	441
2010	810194	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2
	810411	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	758
2011	810194	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2
	810411	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	709
2012	810194	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
	810411	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	658
2013	810194	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0	1
	810411	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	736
2014	810194	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
	810411	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	781
2015	2501	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	335
		8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	200
		10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Figure B10. UN Comtrade table in Jupyter Notebook



```
hhifinal.index.levels[-1].astype('float64')
hhifinal.head(100)

hhifinal.loc[2015, :].head(100)
```

```
Out[21]: Year  HS Code
         2015  7106.0      0.132901
               7601.0      0.327083
               2818.0      0.417414
               NaN         0.285350
               280480.0    0.537671
               NaN         0.368464
               7108.0      0.144028
               280450.0    0.517045
               283327.0    0.209838
               NaN         0.168839
               811219.0    0.856155
               NaN         0.174227
               NaN         0.465388
               NaN         0.289011
               280521.0    0.740631
               NaN         0.171136
               NaN         0.357667
```

Figure B11. HHI table generated from USGS Production data in Jupyter Notebook

C. Indicator Data

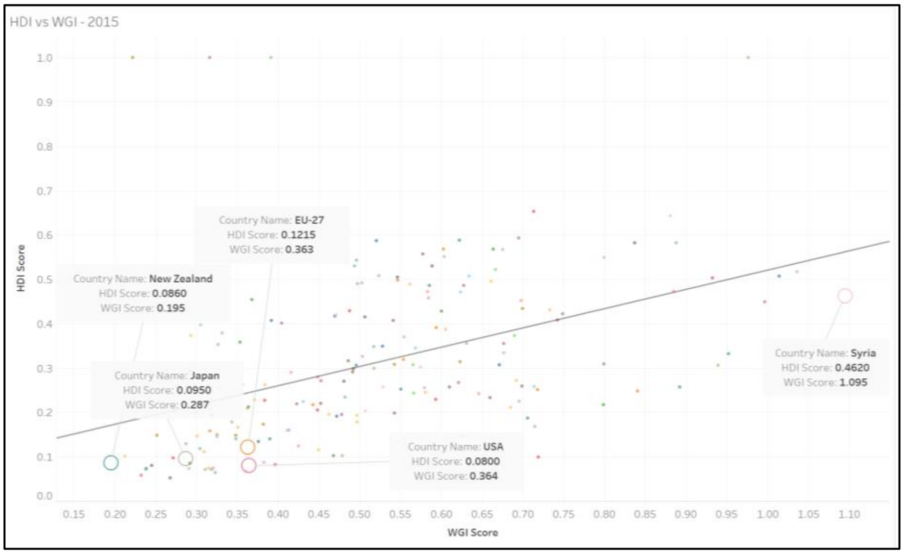


Figure C1. Worldwide Governance Indicators (WGI) correlate weakly to Human Development Index (HDI). The normalized HDI score is plotted against the WGI Score for 2015 (0 represents high political stability and high human development)

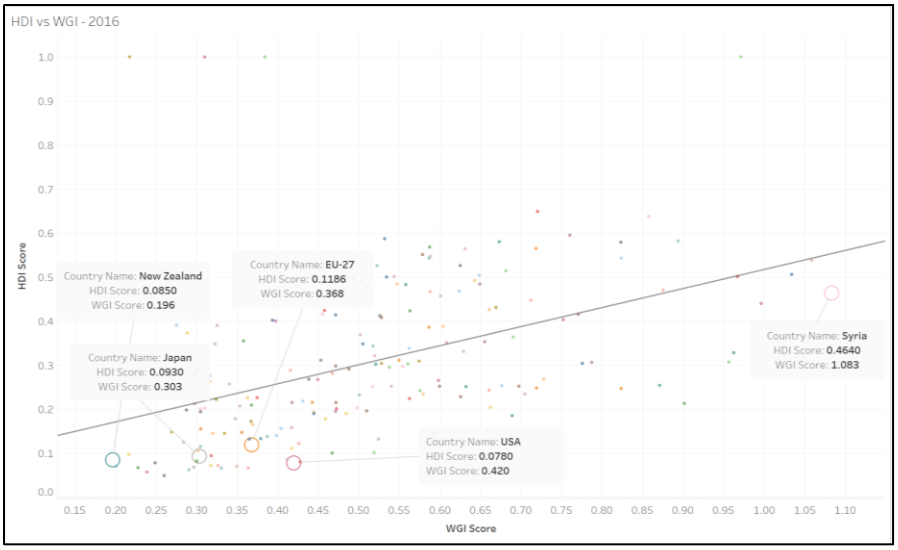


Figure C2. Worldwide Governance Indicators (WGI) correlate weakly to Human Development Index (HDI). The normalized HDI score is plotted against the WGI Score for 2016 (0 represents high political stability and high human development)

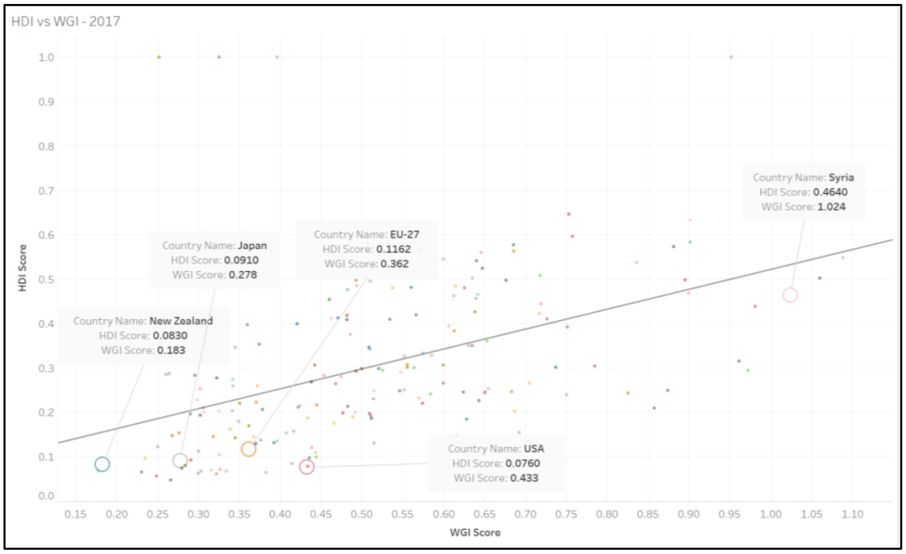


Figure C3. Worldwide Governance Indicators (WGI) correlate weakly to Human Development Index (HDI). The normalized HDI score is plotted against the WGI Score for 2017 (0 represents high political stability and high human development)

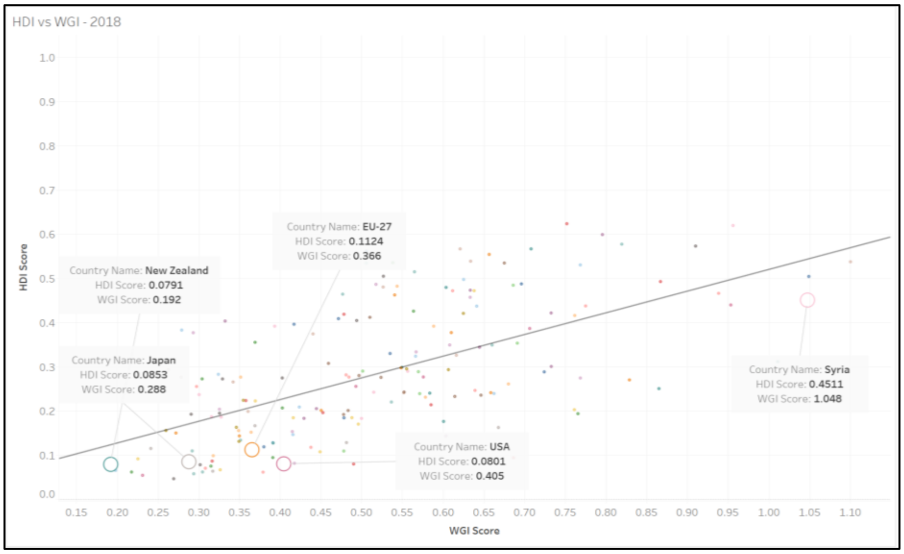
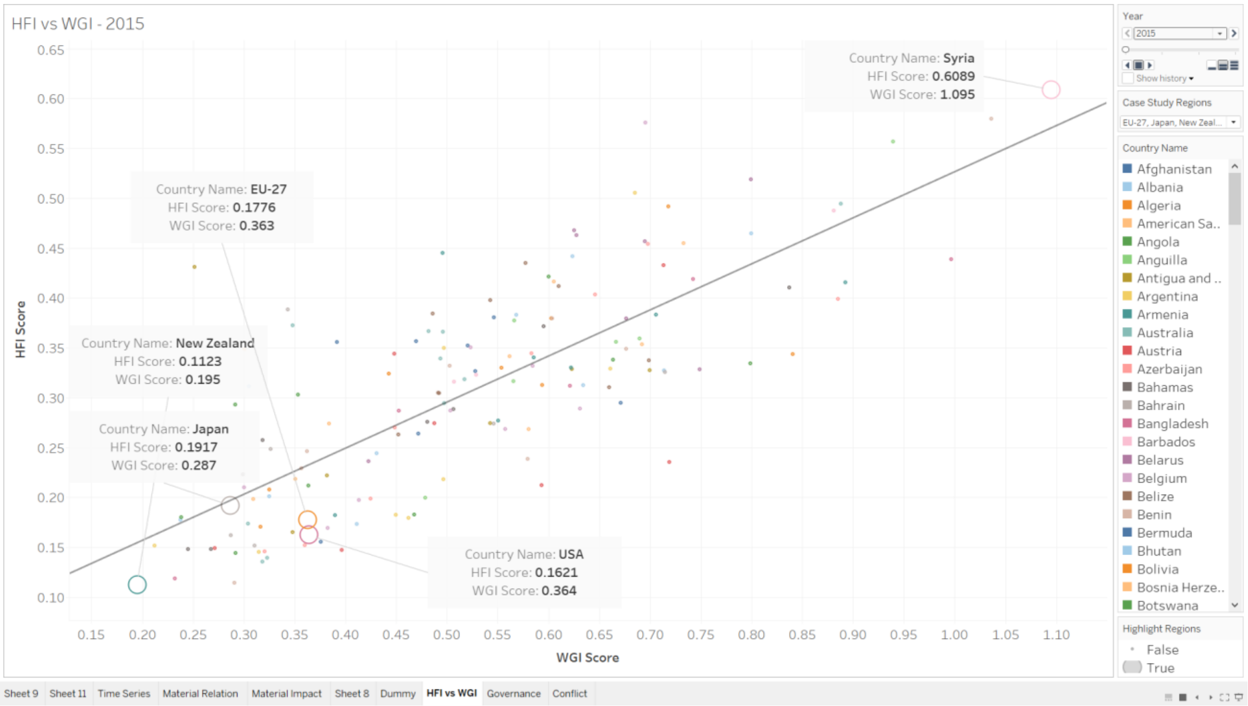


Figure C4. Worldwide Governance Indicators (WGI) correlate weakly to Human Development Index (HDI). The normalized HDI score is plotted against the WGI Score for 2018 (0 represents high political stability and high human development)



Country Name: **Syria**
HFI Score: **0.6089**
WGI Score: **1.095**

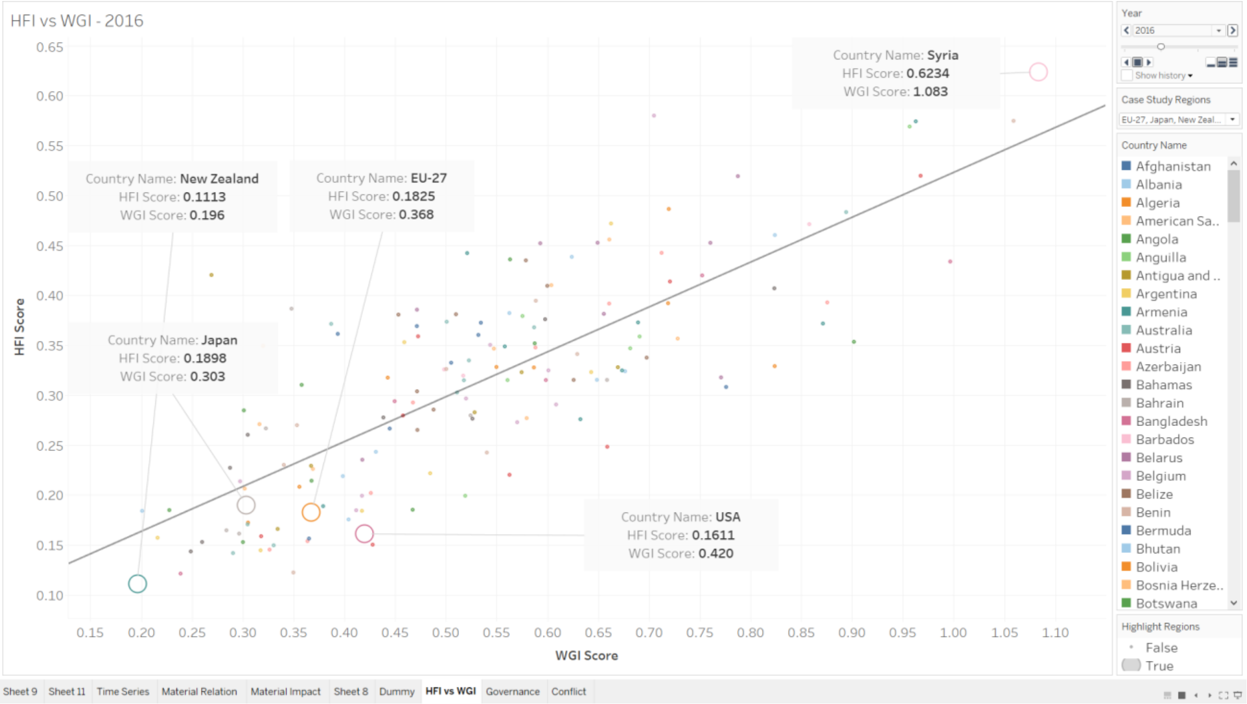
Country Name: **EU-27**
HFI Score: **0.1776**
WGI Score: **0.363**

Country Name: **New Zealand**
HFI Score: **0.1123**
WGI Score: **0.195**

Country Name: **Japan**
HFI Score: **0.1917**
WGI Score: **0.287**

Country Name: **USA**
HFI Score: **0.1621**
WGI Score: **0.364**

Figure C5. Worldwide Governance Indicators (WGI) correlate weakly to Human Freedom Index (HFI). The normalized HFI score is plotted against the WGI Score for 2015 (0 represents high political stability and high human development)



Country Name: **Syria**
HFI Score: **0.6234**
WGI Score: **1.083**

Country Name: **New Zealand**
HFI Score: **0.1113**
WGI Score: **0.196**

Country Name: **EU-27**
HFI Score: **0.1825**
WGI Score: **0.368**

Country Name: **Japan**
HFI Score: **0.1898**
WGI Score: **0.303**

Country Name: **USA**
HFI Score: **0.1611**
WGI Score: **0.420**

Figure C6. Worldwide Governance Indicators (WGI) correlate weakly to Human Freedom Index (HFI). The normalized HFI score is plotted against the WGI Score for 2016 (0 represents high political stability and high human development)

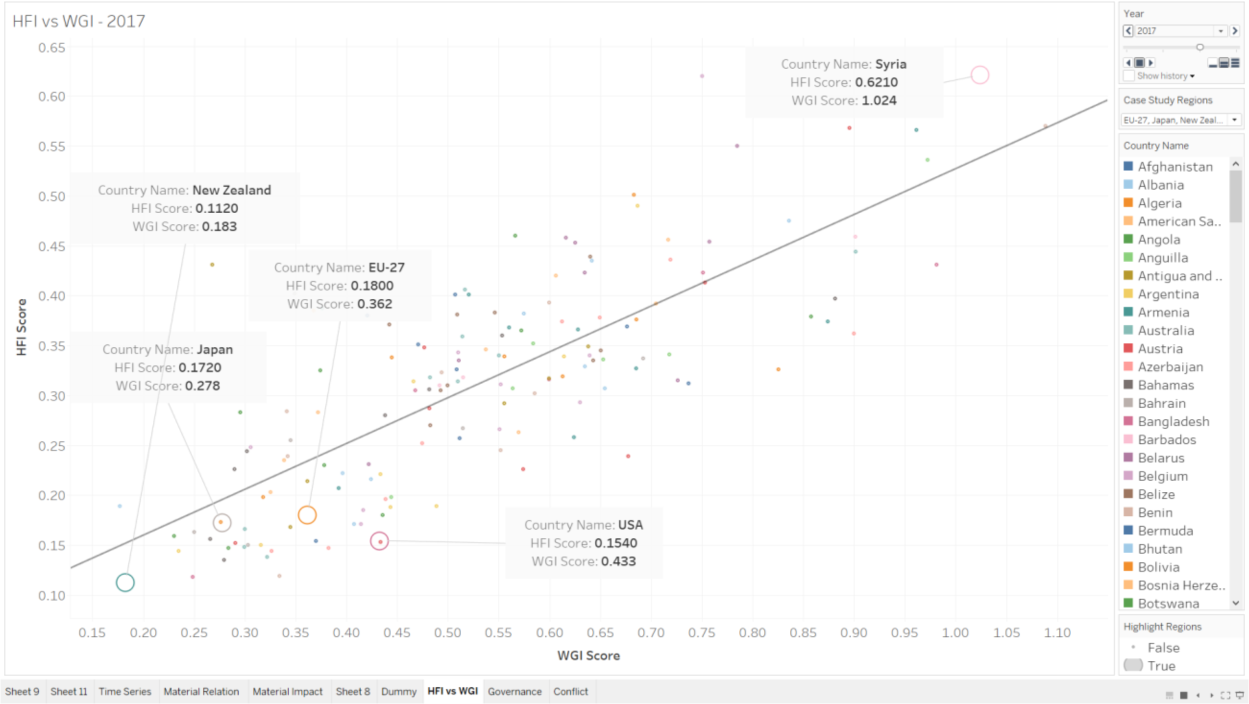
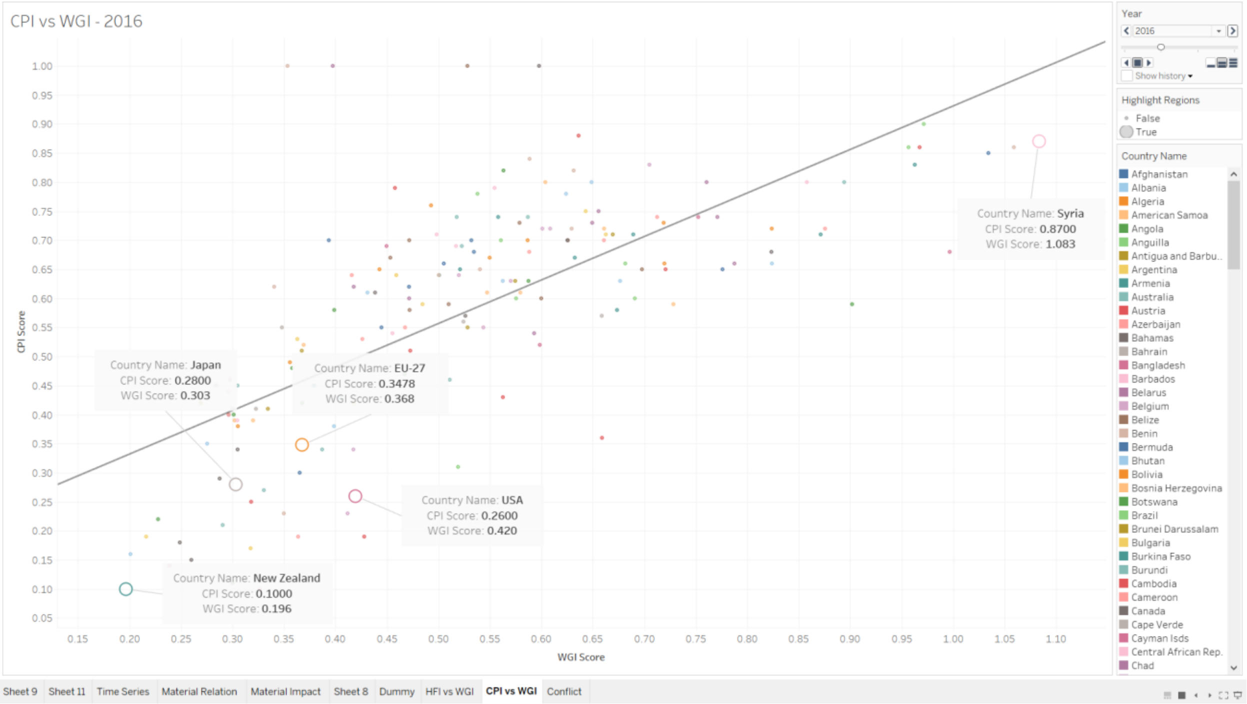


Figure C7. Worldwide Governance Indicators (WGI) correlate weakly to Human Freedom Index (HFI). The normalized HFI score is plotted against the WGI Score for 2017 (0 represents high political stability and high human development)

Figure C8. Worldwide Governance Indicators (WGI) correlate weakly to Corruption Perception Index (CPI). The normalized CPI score is plotted against the WGI Score for 2015 (0 represents high political stability and low corruption)



Country Name: **Syria**
CPI Score: **0.8700**
WGI Score: **1.083**

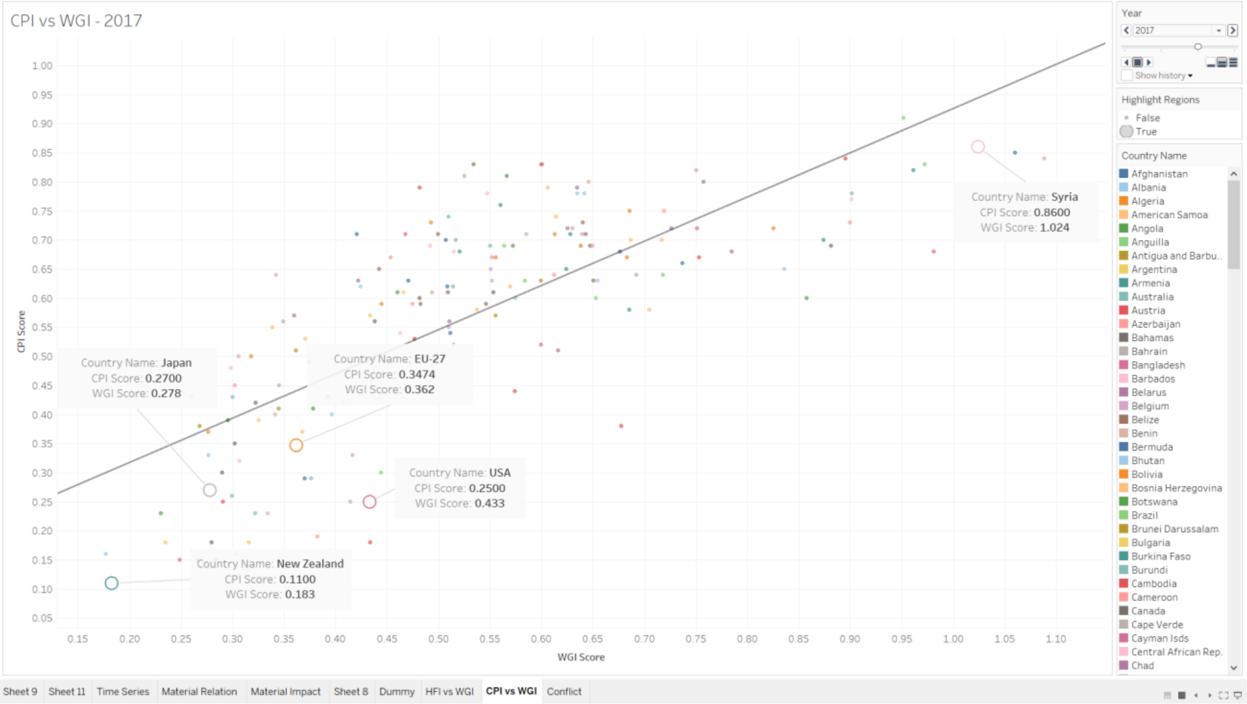
Country Name: **Japan**
CPI Score: **0.2800**
WGI Score: **0.303**

Country Name: **EU-27**
CPI Score: **0.3478**
WGI Score: **0.368**

Country Name: **USA**
CPI Score: **0.2600**
WGI Score: **0.420**

Country Name: **New Zealand**
CPI Score: **0.1000**
WGI Score: **0.196**

Figure C9. Worldwide Governance Indicators (WGI) correlate weakly to Corruption Perception Index (CPI). The normalized CPI score is plotted against the WGI Score for 2016 (0 represents high political stability and low corruption)



Country Name: **Syria**
CPI Score: **0.8600**
WGI Score: **1.024**

Country Name: **Japan**
CPI Score: **0.2700**
WGI Score: **0.278**

Country Name: **EU-27**
CPI Score: **0.3474**
WGI Score: **0.362**

Country Name: **USA**
CPI Score: **0.2500**
WGI Score: **0.433**

Country Name: **New Zealand**
CPI Score: **0.1100**
WGI Score: **0.183**

Figure C10. Worldwide Governance Indicators (WGI) correlate weakly to Corruption Perception Index (CPI). The normalized CPI score is plotted against the WGI Score for 2017 (0 represents high political stability and low corruption)

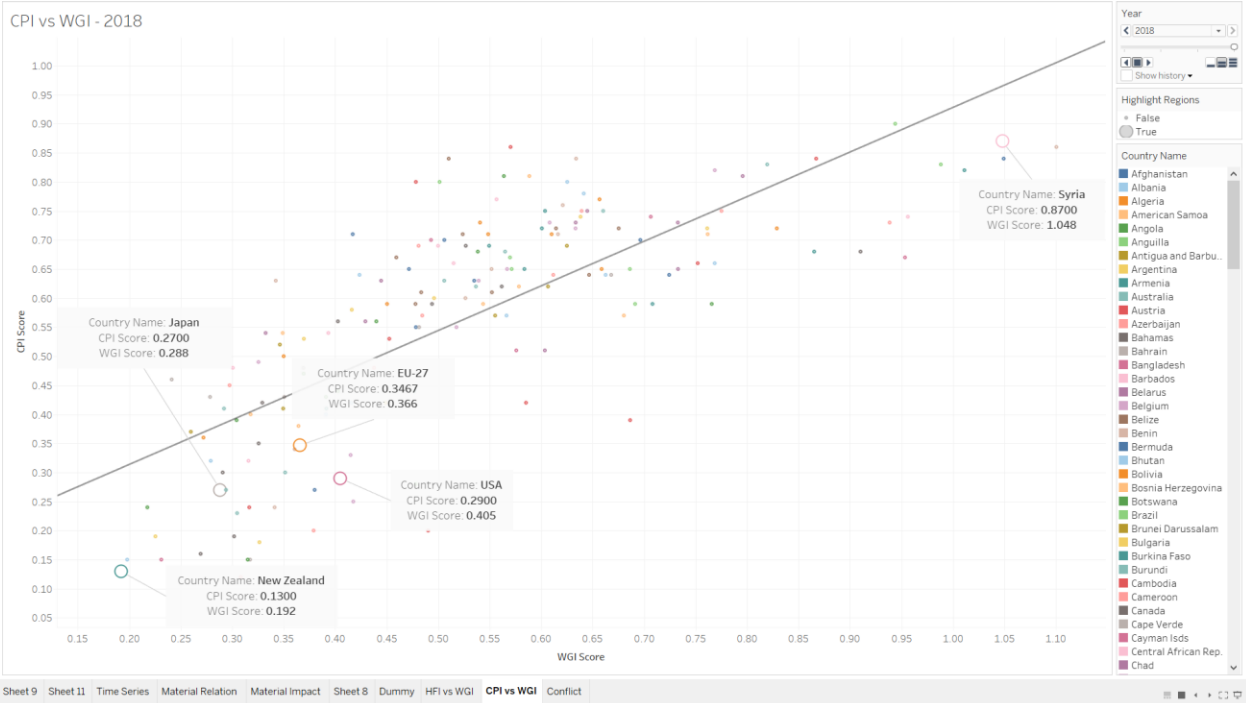


Figure C11. Worldwide Governance Indicators (WGI) correlate weakly to Corruption Perception Index (CPI). The normalized CPI score is plotted against the WGI Score for 2018 (0 represents high political stability and low corruption)

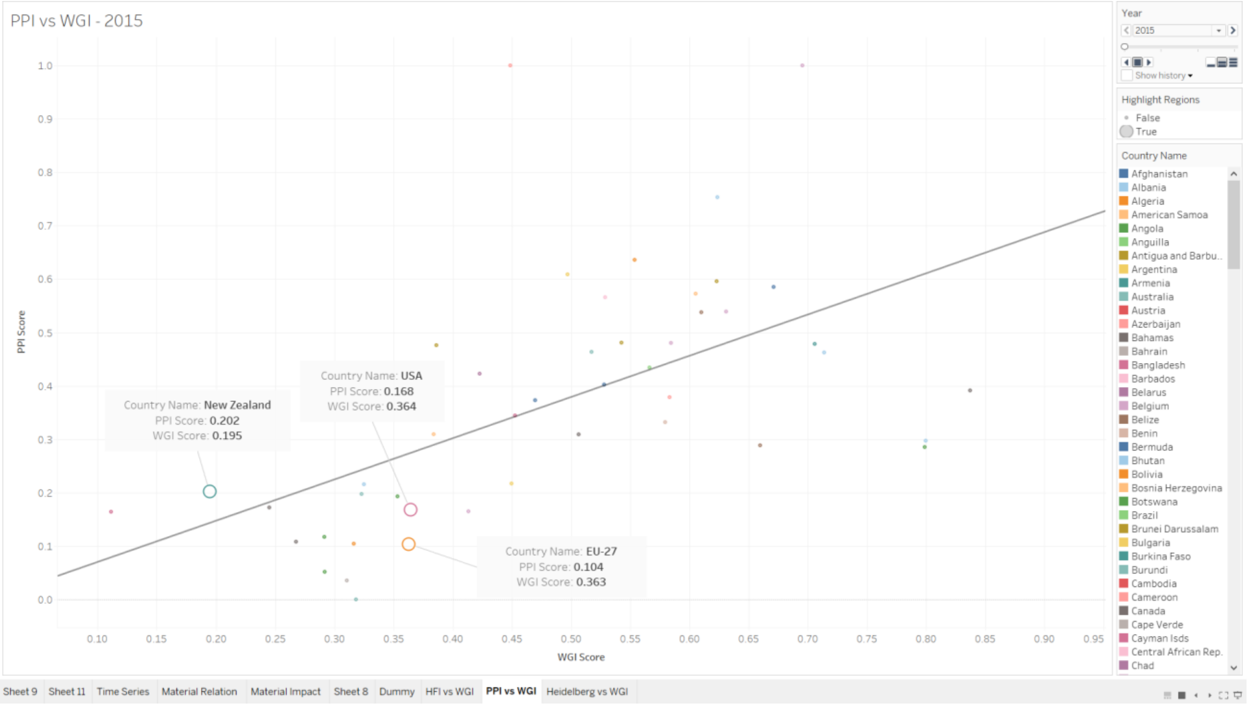


Figure C12. Worldwide Governance Indicators (WGI) correlate weakly to Policy Perception Index (PPI). The normalized PPI score is plotted against the WGI Score for 2015 (0 represents high political stability and attractive policies)

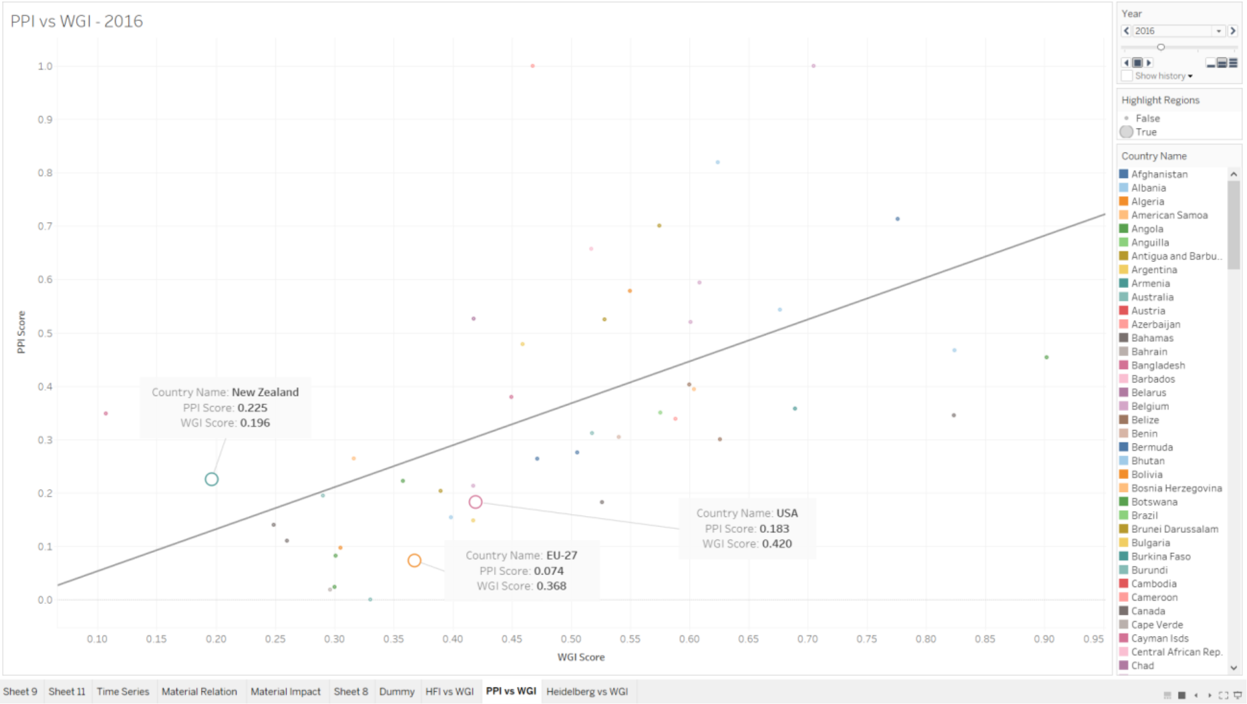


Figure C13. Worldwide Governance Indicators (WGI) correlate weakly to Policy Perception Index (PPI). The normalized PPI score is plotted against the WGI Score for 2016 (0 represents high political stability and attractive policies)

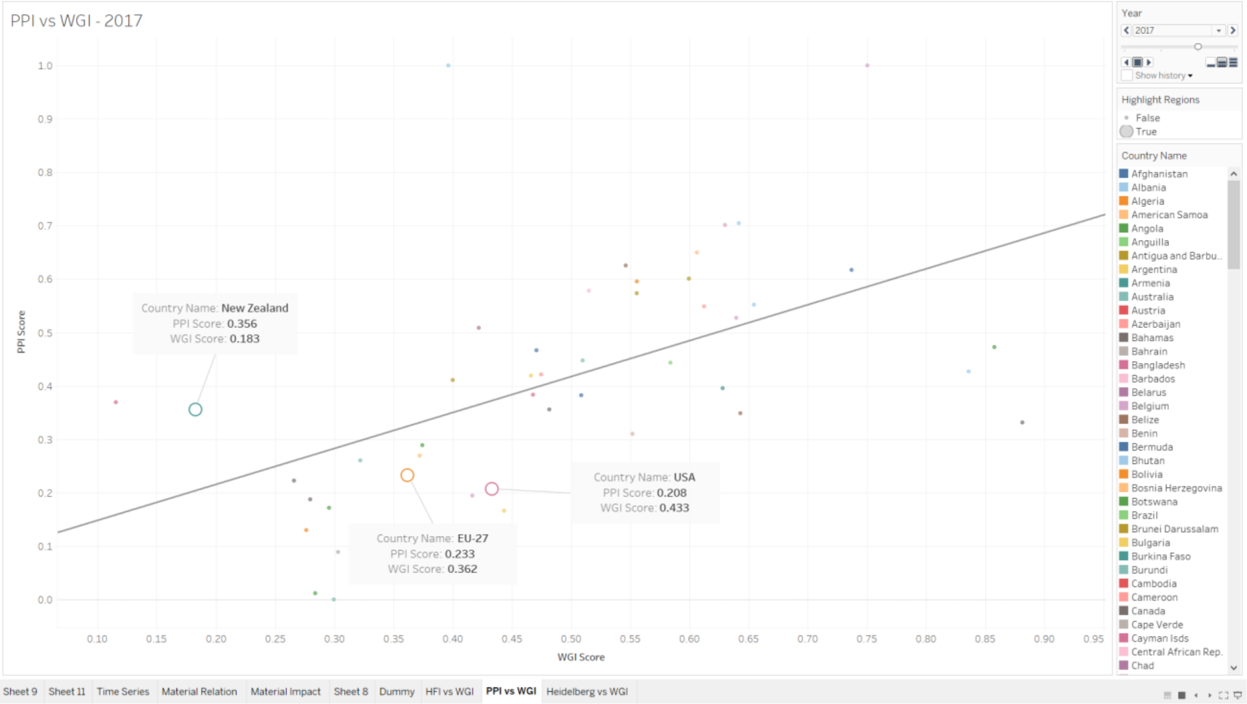


Figure C14. Worldwide Governance Indicators (WGI) correlate weakly to Policy Perception Index (PPI). The normalized PPI score is plotted against the WGI Score for 2017 (0 represents high political stability and attractive policies)

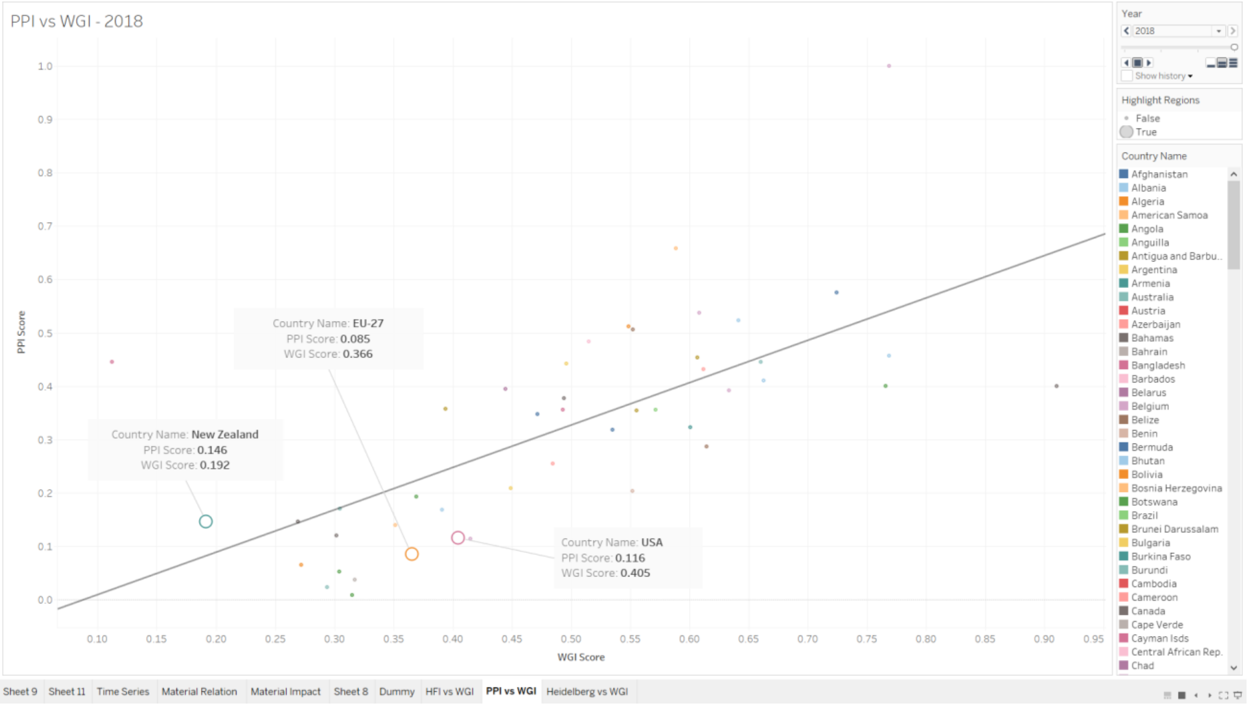


Figure C15. Worldwide Governance Indicators (WGI) correlate weakly to Policy Perception Index (PPI). The normalized PPI score is plotted against the WGI Score for 2018 (0 represents high political stability and attractive policies)

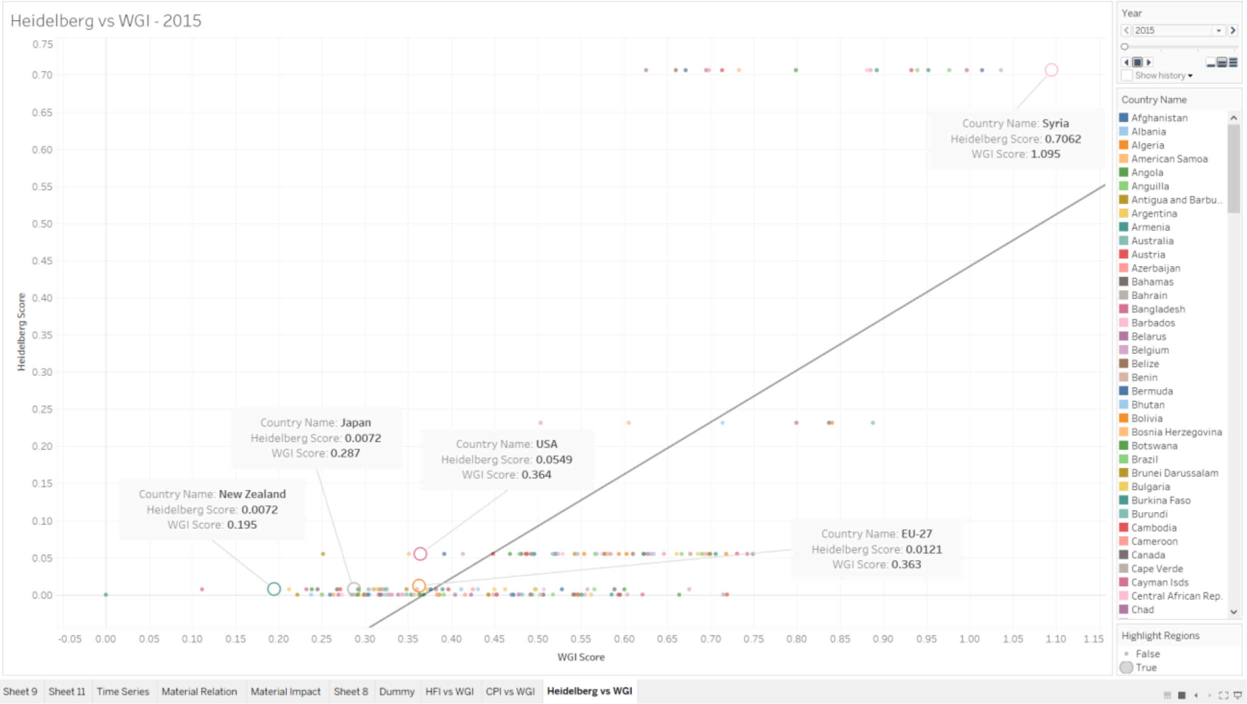


Figure C16. Worldwide Governance Indicators (WGI) correlate weakly to Heidelberg. The normalized Heidelberg score is plotted against the WGI Score for 2015 (0 represents high political stability and low level of conflict)

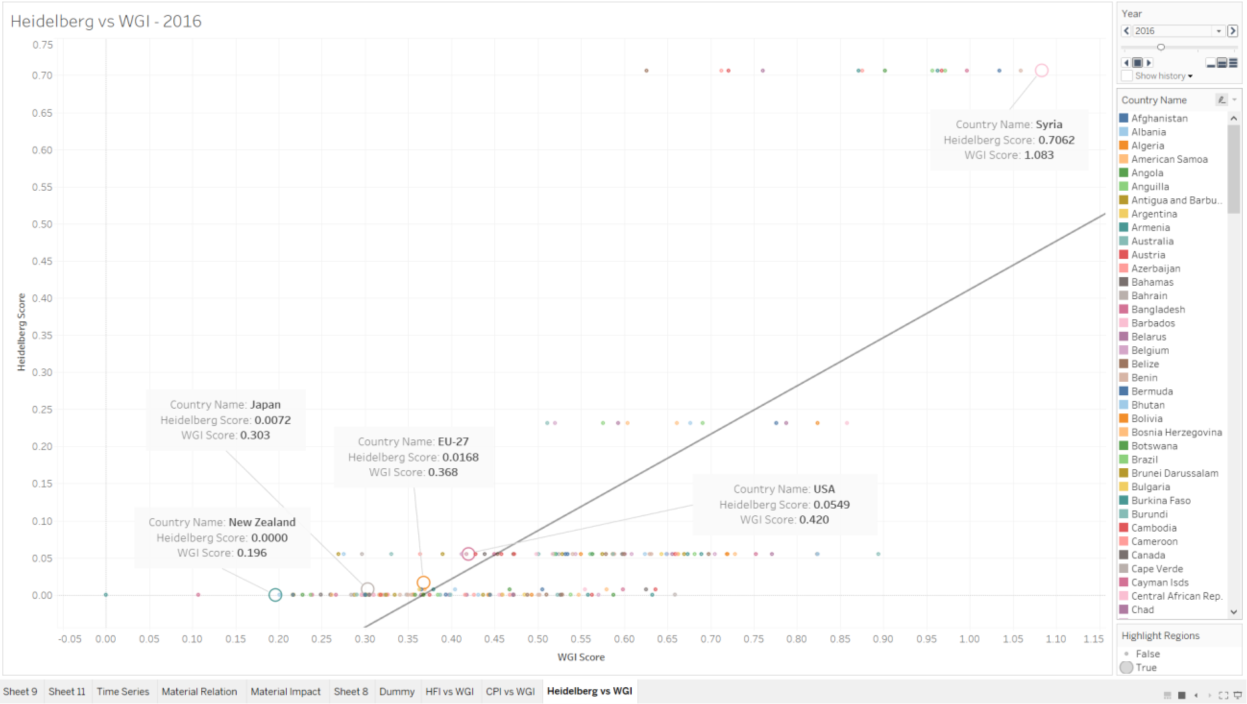


Figure C17. Worldwide Governance Indicators (WGI) correlate weakly to Heidelberg. The normalized Heidelberg score is plotted against the WGI Score for 2016 (0 represents high political stability and low level of conflict)

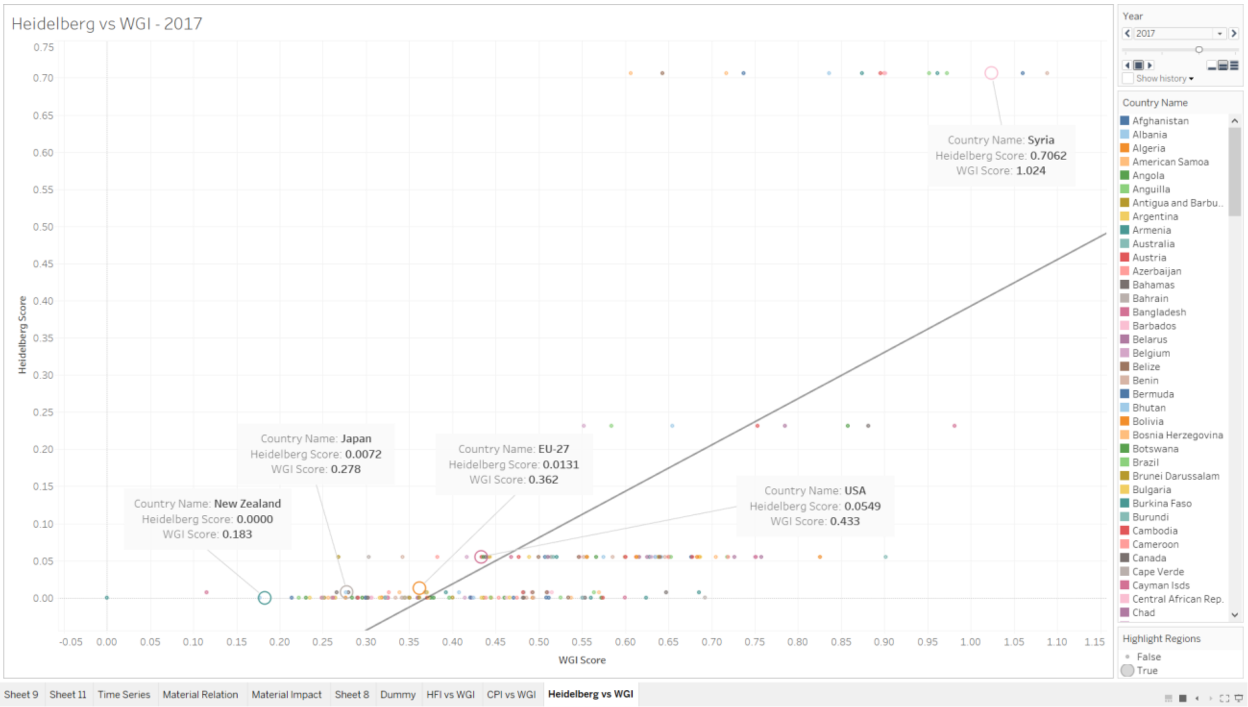
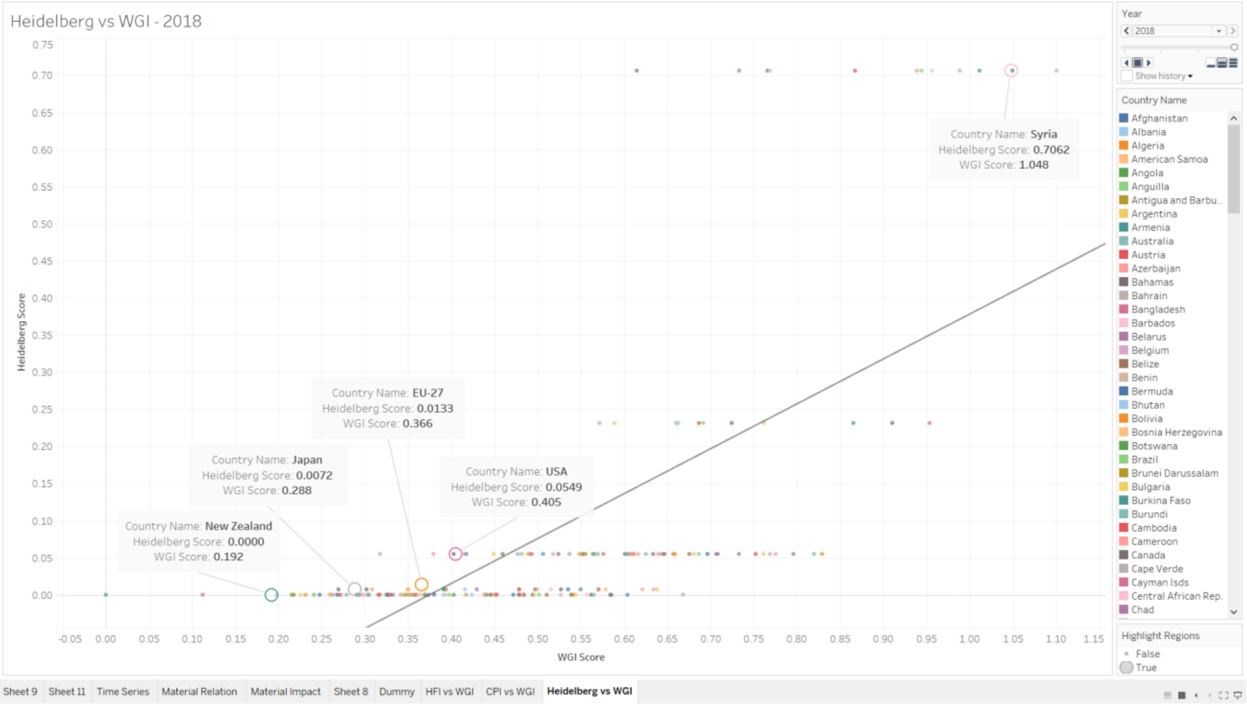


Figure C18. Worldwide Governance Indicators (WGI) correlate weakly to Heidelberg. The normalized Heidelberg score is plotted against the WGI Score for 2017 (0 represents high political stability and low level of conflict)



Heidelberg vs WGI - 2018

Country Name: Syria
Heidelberg Score: 0.7062
WGI Score: 1.048

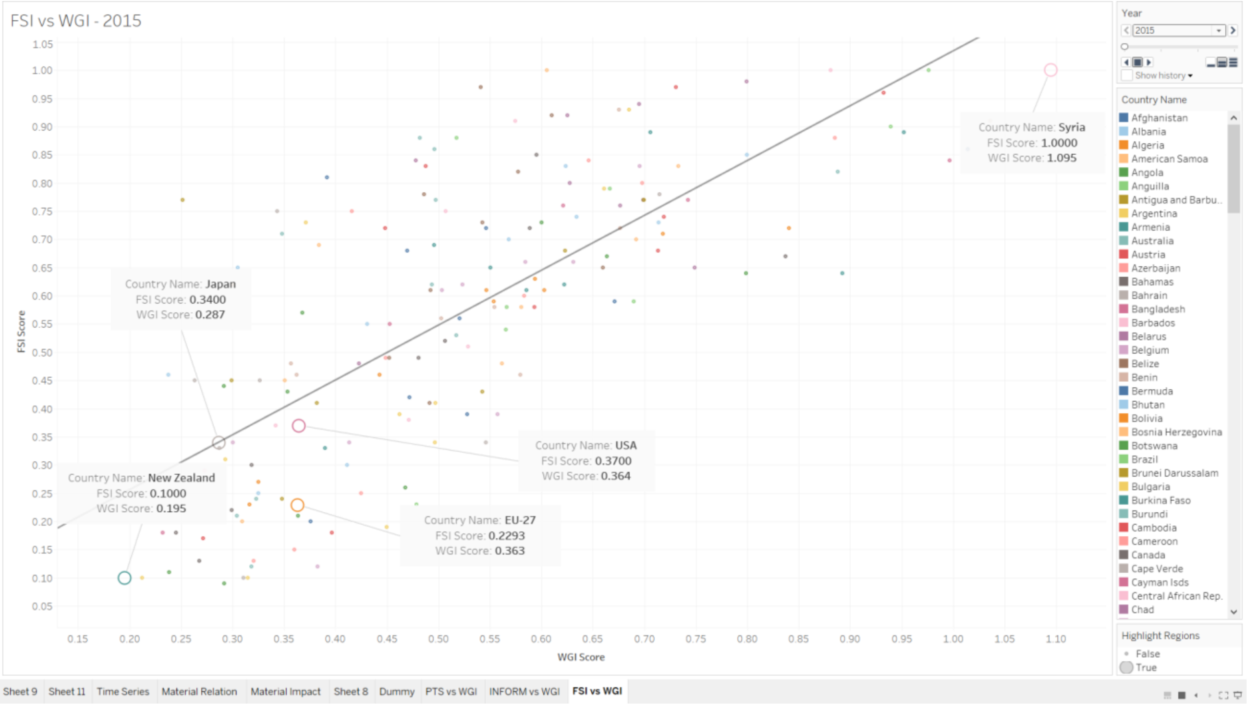
Country Name: EU-27
Heidelberg Score: 0.0133
WGI Score: 0.366

Country Name: Japan
Heidelberg Score: 0.0072
WGI Score: 0.288

Country Name: USA
Heidelberg Score: 0.0549
WGI Score: 0.405

Country Name: New Zealand
Heidelberg Score: 0.0000
WGI Score: 0.192

Figure C19. Worldwide Governance Indicators (WGI) correlate weakly to Heidelberg. The normalized Heidelberg score is plotted against the WGI Score for 2018 (0 represents high political stability and low level of conflict)



FSI vs WGI - 2015

Country Name: Syria
FSI Score: 1.0000
WGI Score: 1.095

Country Name: Japan
FSI Score: 0.3400
WGI Score: 0.287

Country Name: USA
FSI Score: 0.3700
WGI Score: 0.364

Country Name: New Zealand
FSI Score: 0.1000
WGI Score: 0.195

Country Name: EU-27
FSI Score: 0.2293
WGI Score: 0.363

Figure C20. Worldwide Governance Indicators (WGI) correlate weakly to Fragile States Index (FSI). The normalized FSI score is plotted against the WGI Score for 2015 (0 represents high political stability and low level of conflict)

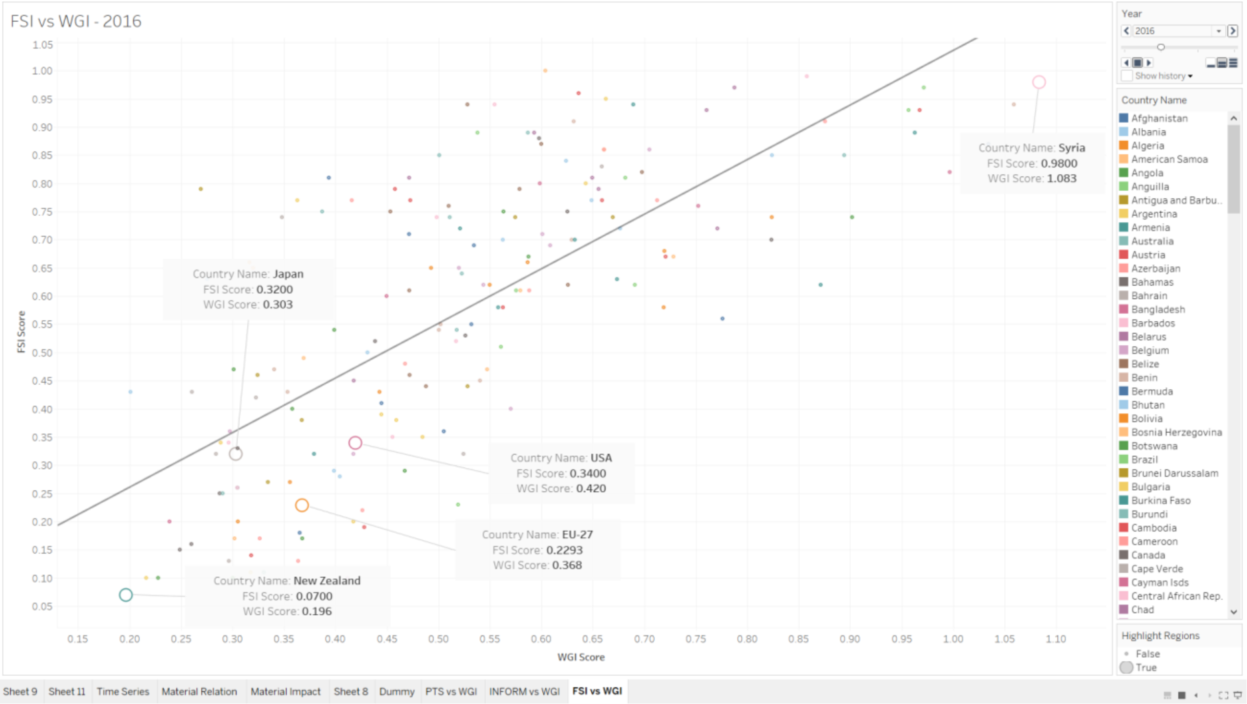


Figure C21. Worldwide Governance Indicators (WGI) correlate weakly to Fragile States Index (FSI). The normalized FSI score is plotted against the WGI Score for 2016 (0 represents high political stability and low level of conflict)

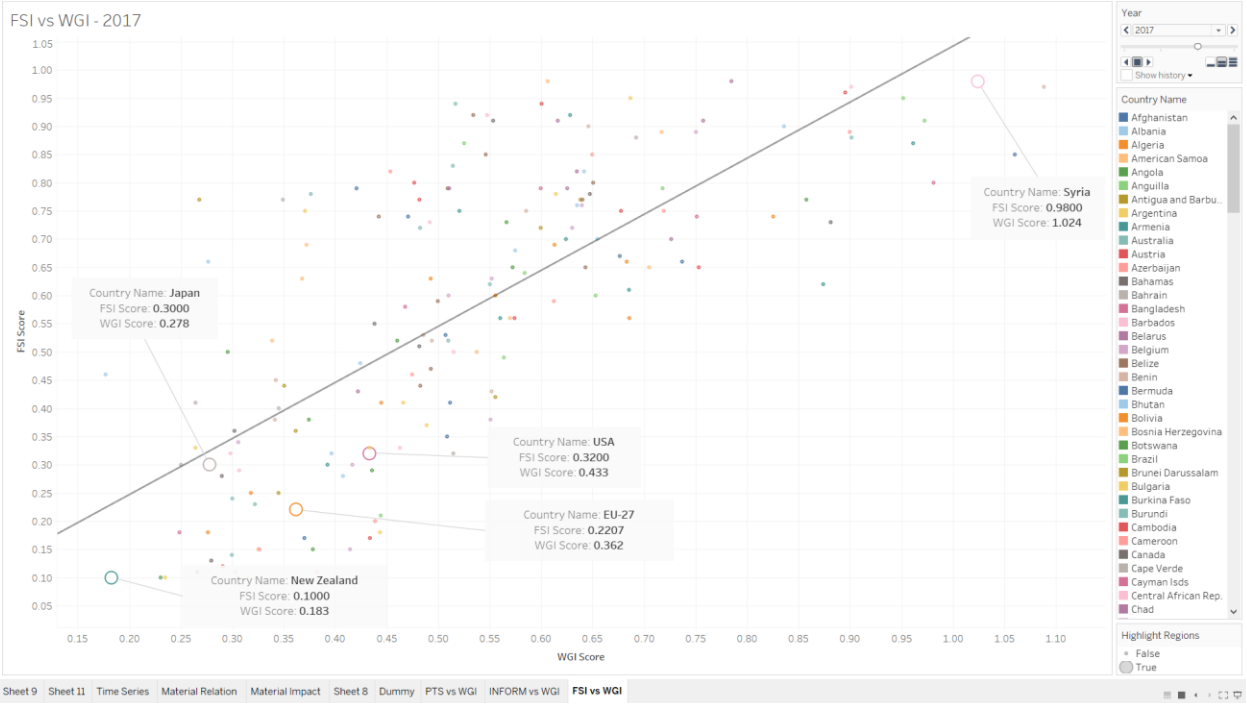
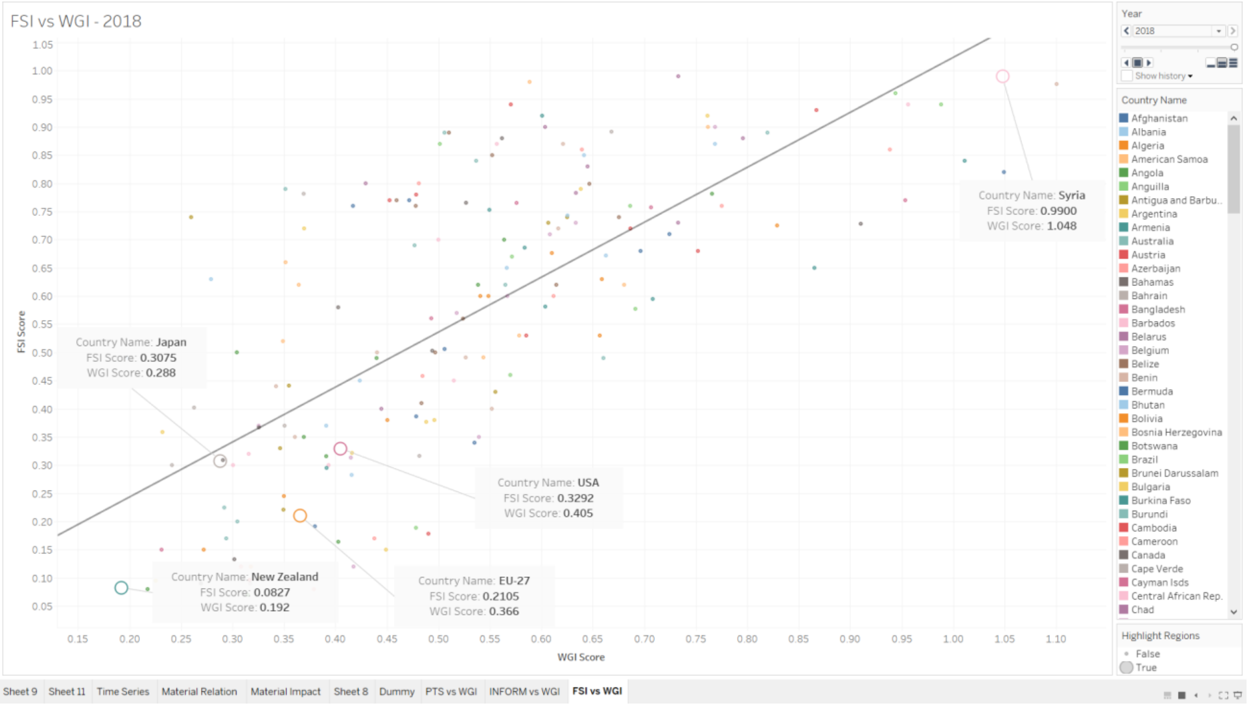


Figure C22. Worldwide Governance Indicators (WGI) correlate weakly to Fragile States Index (FSI). The normalized FSI score is plotted against the WGI Score for 2017 (0 represents high political stability and low level of conflict)



Country Name: **Syria**
FSI Score: **0.9900**
WGI Score: **1.048**

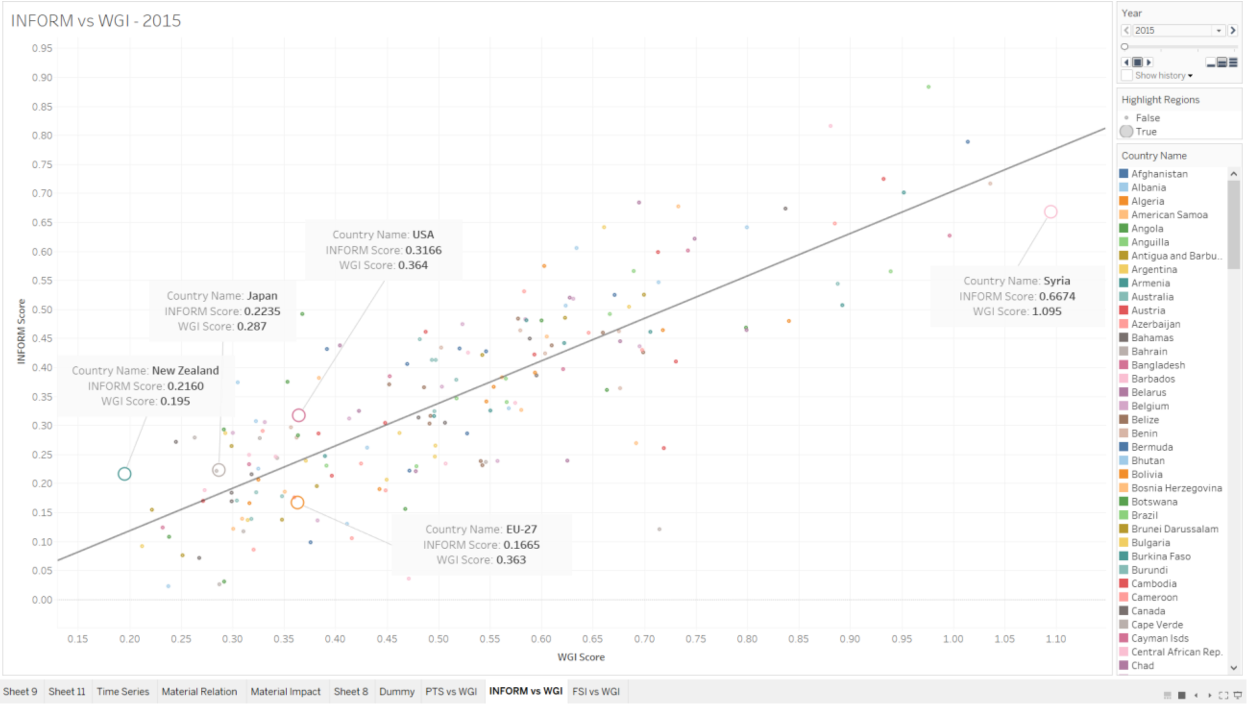
Country Name: **Japan**
FSI Score: **0.3075**
WGI Score: **0.288**

Country Name: **USA**
FSI Score: **0.3292**
WGI Score: **0.405**

Country Name: **New Zealand**
FSI Score: **0.0827**
WGI Score: **0.192**

Country Name: **EU-27**
FSI Score: **0.2105**
WGI Score: **0.366**

Figure C23. Worldwide Governance Indicators (WGI) correlate weakly to Fragile States Index (FSI). The normalized FSI score is plotted against the WGI Score for 2018 (0 represents high political stability and low level of conflict)



Country Name: **USA**
INFORM Score: **0.3166**
WGI Score: **0.364**

Country Name: **Japan**
INFORM Score: **0.2235**
WGI Score: **0.287**

Country Name: **New Zealand**
INFORM Score: **0.2160**
WGI Score: **0.195**

Country Name: **Syria**
INFORM Score: **0.6674**
WGI Score: **1.095**

Country Name: **EU-27**
INFORM Score: **0.1665**
WGI Score: **0.363**

Figure C24. Worldwide Governance Indicators (WGI) correlate weakly to INFORM Index. The normalized INFORM score is plotted against the WGI Score for 2015 (0 represents high political stability and low level of conflict)

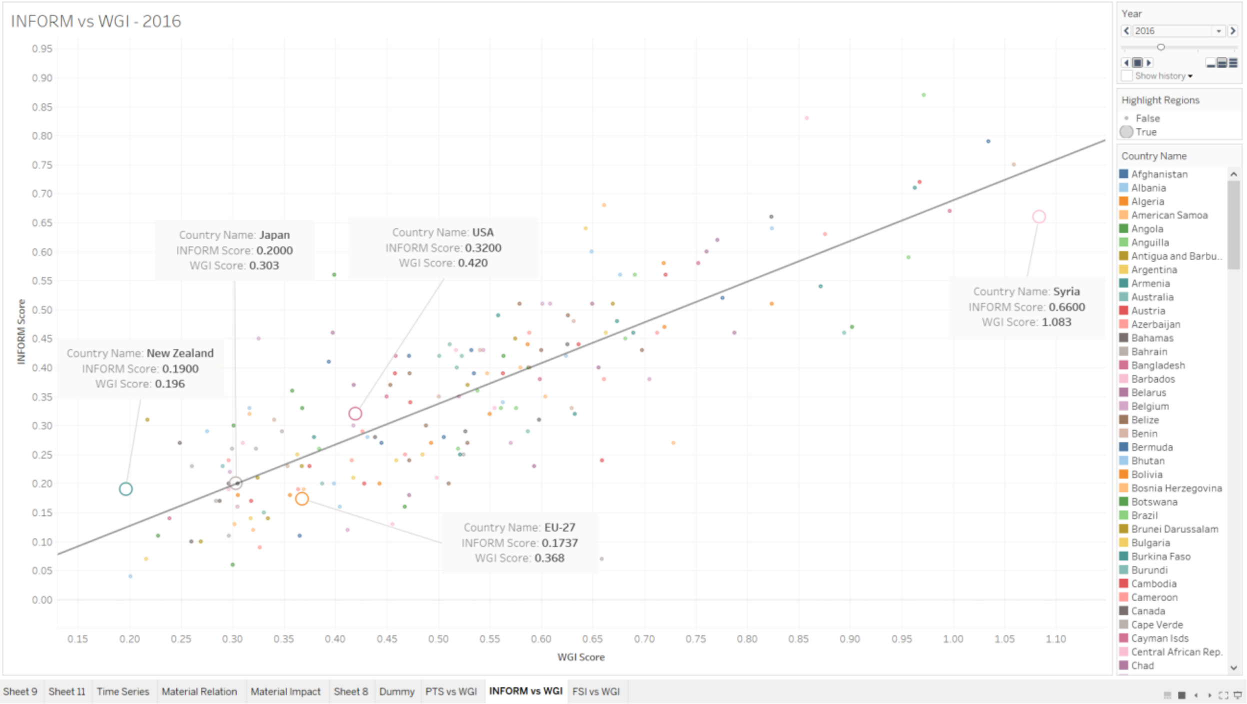


Figure C25. Worldwide Governance Indicators (WGI) correlate weakly to INFORM Index. The normalized INFORM score is plotted against the WGI Score for 2016 (0 represents high political stability and low level of conflict)

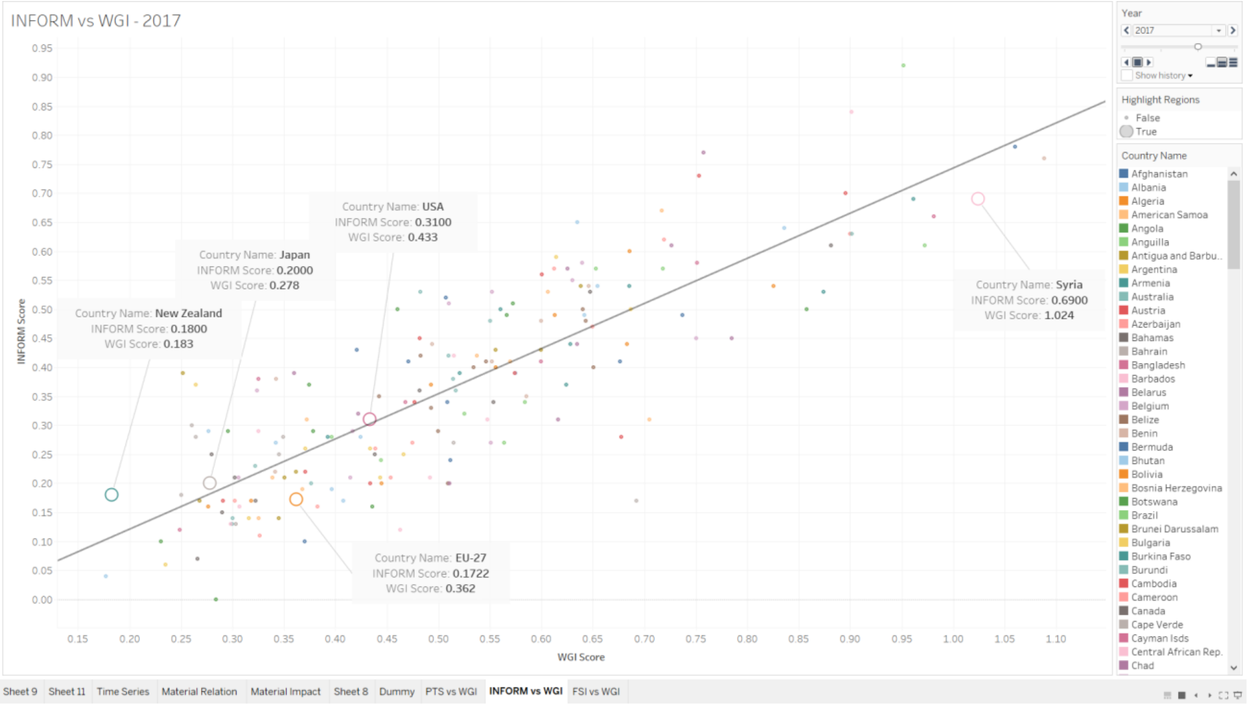
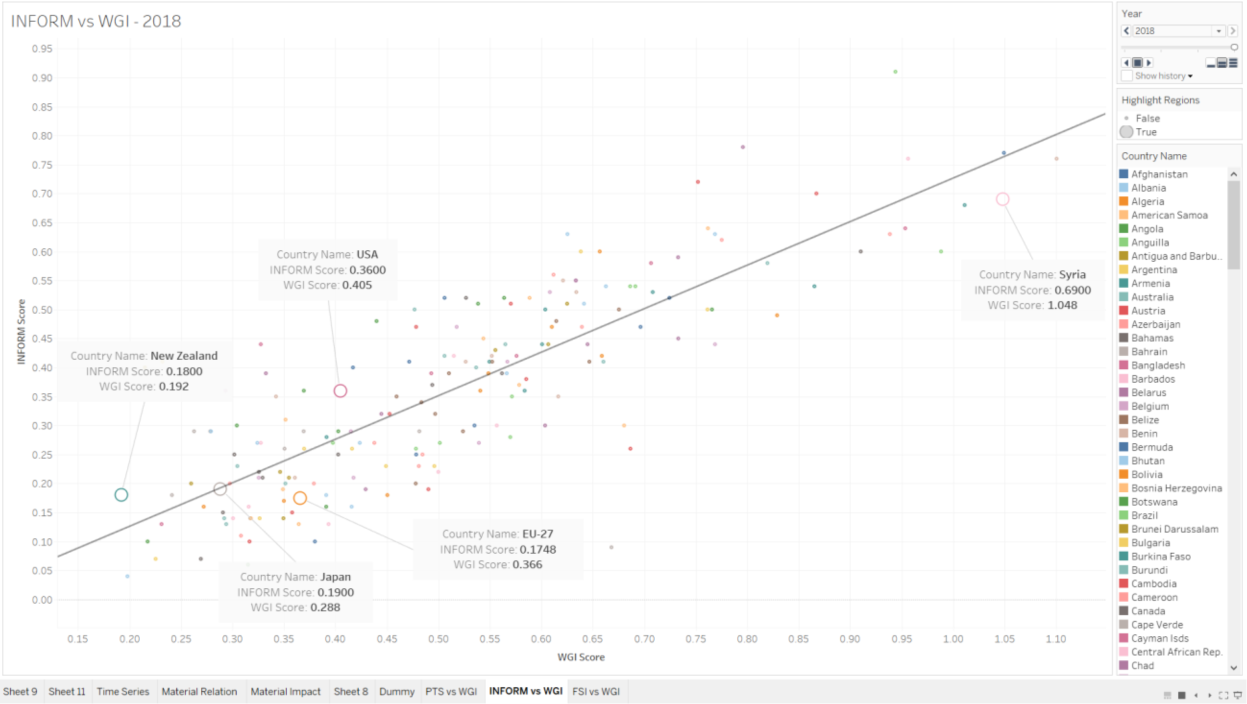


Figure C26. Worldwide Governance Indicators (WGI) correlate weakly to INFORM Index. The normalized INFORM score is plotted against the WGI Score for 2017 (0 represents high political stability and low level of conflict)



Country Name: **USA**
INFORM Score: **0.3600**
WGI Score: **0.405**

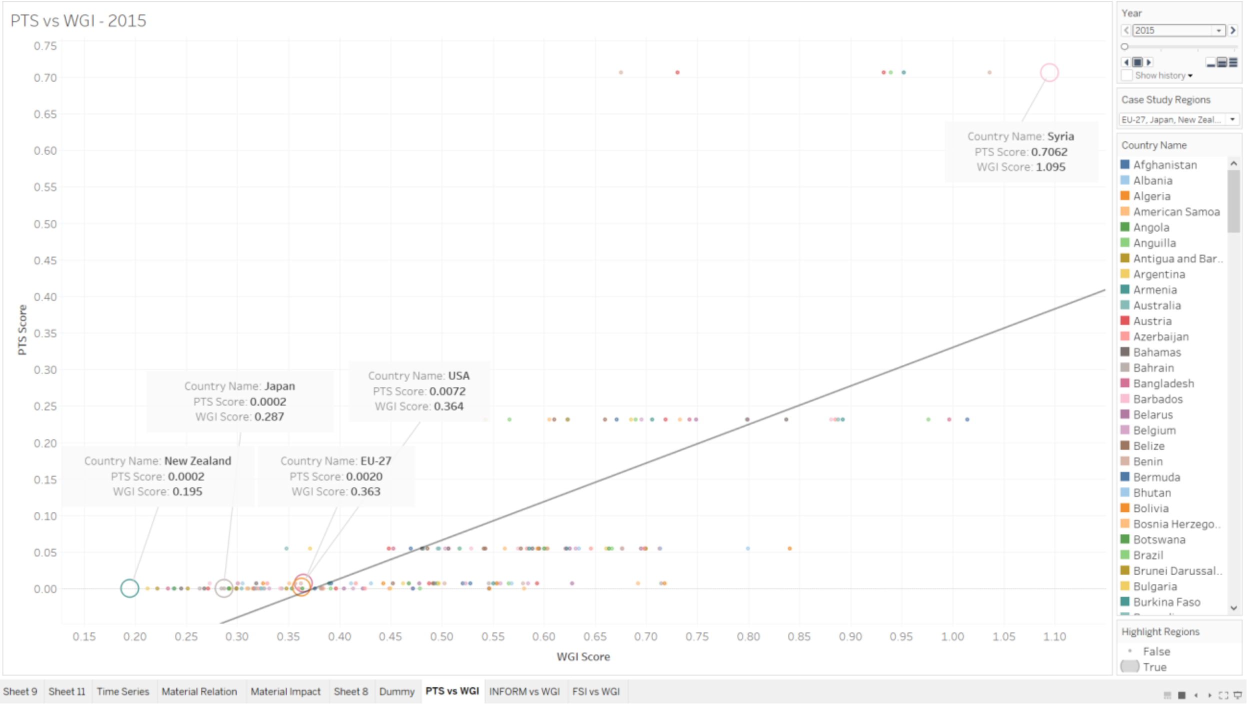
Country Name: **New Zealand**
INFORM Score: **0.1800**
WGI Score: **0.192**

Country Name: **Syria**
INFORM Score: **0.6900**
WGI Score: **1.048**

Country Name: **EU-27**
INFORM Score: **0.1748**
WGI Score: **0.366**

Country Name: **Japan**
INFORM Score: **0.1900**
WGI Score: **0.288**

Figure C27. Worldwide Governance Indicators (WGI) correlate weakly to INFORM Index. The normalized INFORM score is plotted against the WGI Score for 2018 (0 represents high political stability and low level of conflict)



Country Name: **Syria**
PTS Score: **0.7062**
WGI Score: **1.095**

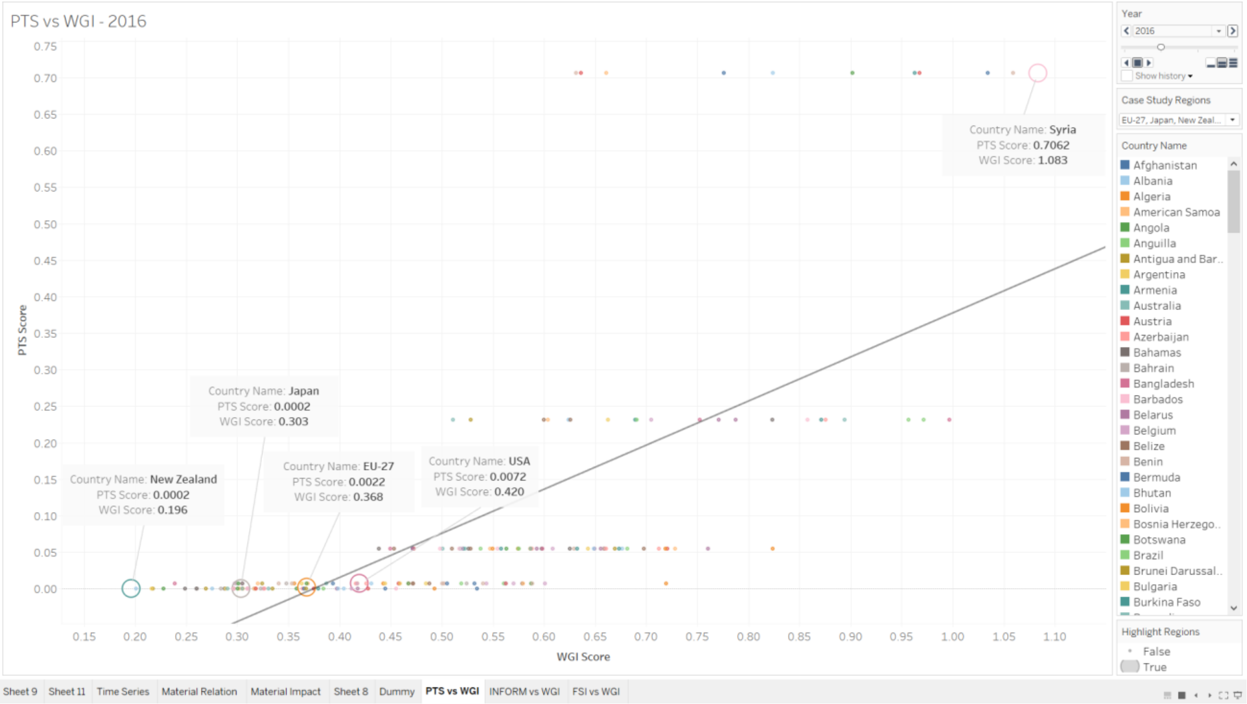
Country Name: **Japan**
PTS Score: **0.0002**
WGI Score: **0.287**

Country Name: **USA**
PTS Score: **0.0072**
WGI Score: **0.364**

Country Name: **New Zealand**
PTS Score: **0.0002**
WGI Score: **0.195**

Country Name: **EU-27**
PTS Score: **0.0020**
WGI Score: **0.363**

Figure C28. Worldwide Governance Indicators (WGI) correlate weakly to Political Terror Scale (PTS). The normalized PTS score is plotted against the WGI Score for 2015 (0 represents high political stability and low level of conflict)



Country Name: **Syria**
PTS Score: **0.7062**
WGI Score: **1.083**

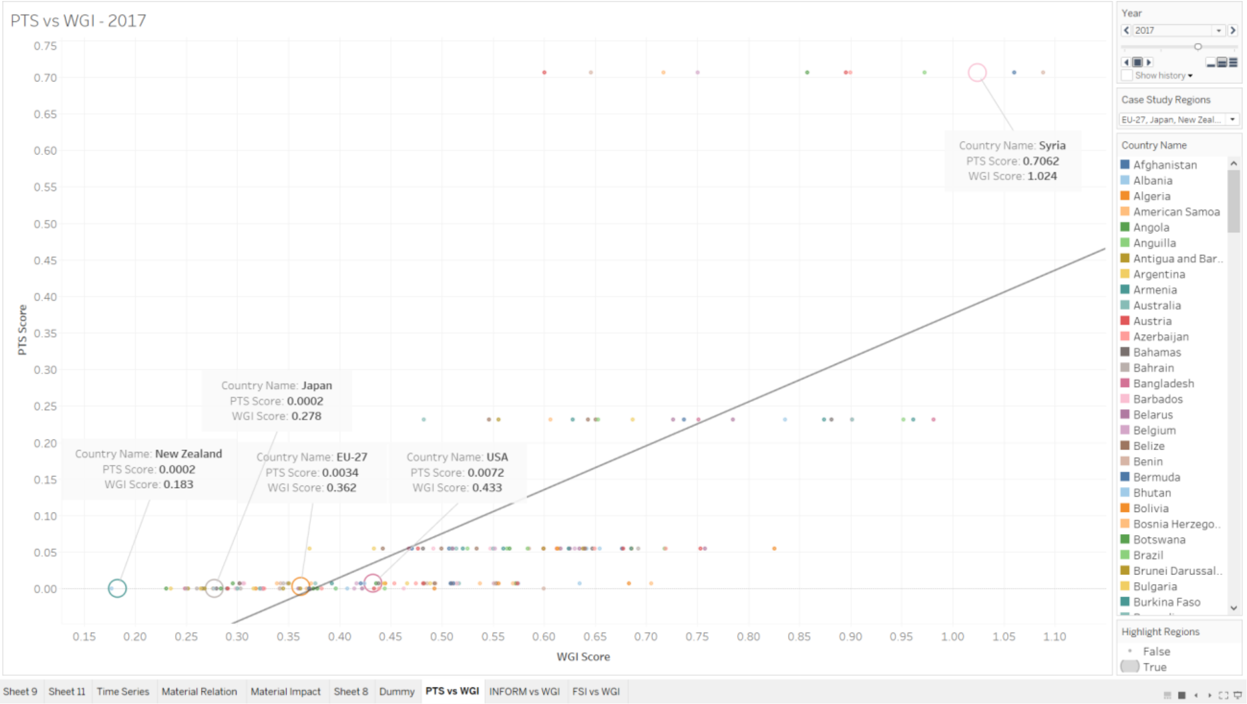
Country Name: **Japan**
PTS Score: **0.0002**
WGI Score: **0.303**

Country Name: **New Zealand**
PTS Score: **0.0002**
WGI Score: **0.196**

Country Name: **EU-27**
PTS Score: **0.0022**
WGI Score: **0.368**

Country Name: **USA**
PTS Score: **0.0072**
WGI Score: **0.420**

Figure C29. Worldwide Governance Indicators (WGI) correlate weakly to Political Terror Scale (PTS). The normalized PTS score is plotted against the WGI Score for 2016 (0 represents high political stability and low level of conflict)



Country Name: **Syria**
PTS Score: **0.7062**
WGI Score: **1.024**

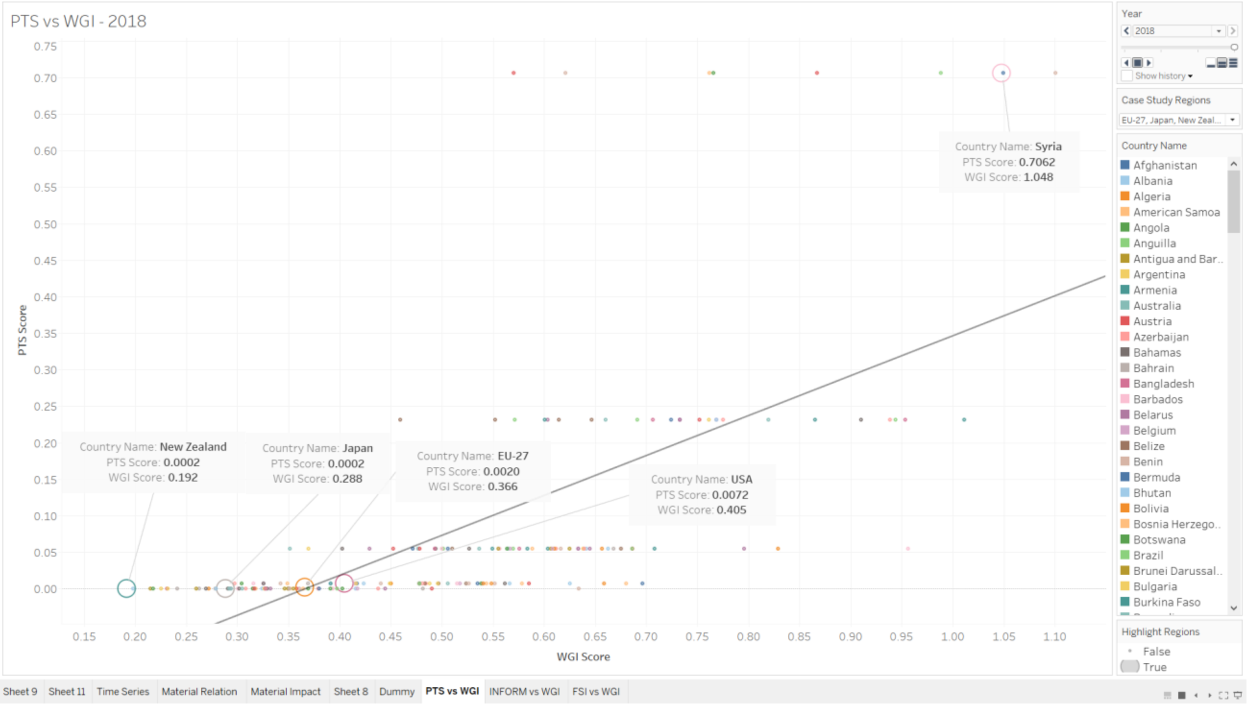
Country Name: **Japan**
PTS Score: **0.0002**
WGI Score: **0.278**

Country Name: **New Zealand**
PTS Score: **0.0002**
WGI Score: **0.183**

Country Name: **EU-27**
PTS Score: **0.0034**
WGI Score: **0.362**

Country Name: **USA**
PTS Score: **0.0072**
WGI Score: **0.433**

Figure C30. Worldwide Governance Indicators (WGI) correlate weakly to Political Terror Scale (PTS). The normalized PTS score is plotted against the WGI Score for 2017 (0 represents high political stability and low level of conflict)



Country Name: **Syria**
PTS Score: **0.7062**
WGI Score: **1.048**

Country Name: **New Zealand**
PTS Score: **0.0002**
WGI Score: **0.192**

Country Name: **Japan**
PTS Score: **0.0002**
WGI Score: **0.288**

Country Name: **EU-27**
PTS Score: **0.0020**
WGI Score: **0.366**

Country Name: **USA**
PTS Score: **0.0072**
WGI Score: **0.405**

Figure C31. Worldwide Governance Indicators (WGI) correlate weakly to Political Terror Scale (PTS). The normalized PTS score is plotted against the WGI Score for 2018 (0 represents high political stability and low level of conflict)

D. Detailed Social Supply Risk Results

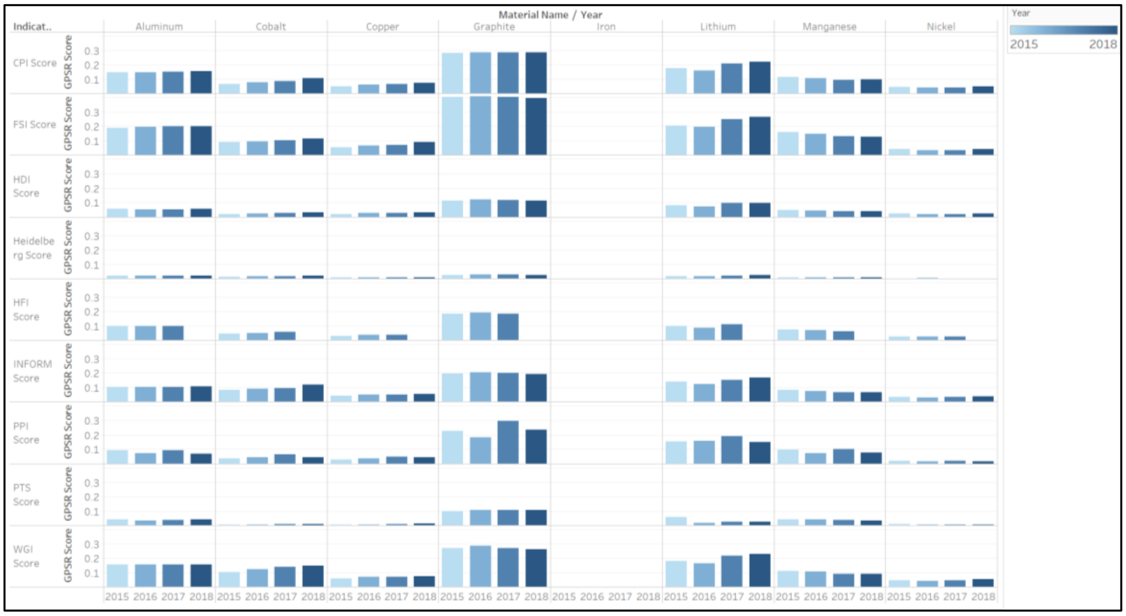


Figure D1. GPSR score for all eight materials and nine indicators from 2015 – 2018 for Japan. Each row represents one indicator that is used to calculate the GPSR score and each column represents a single material.

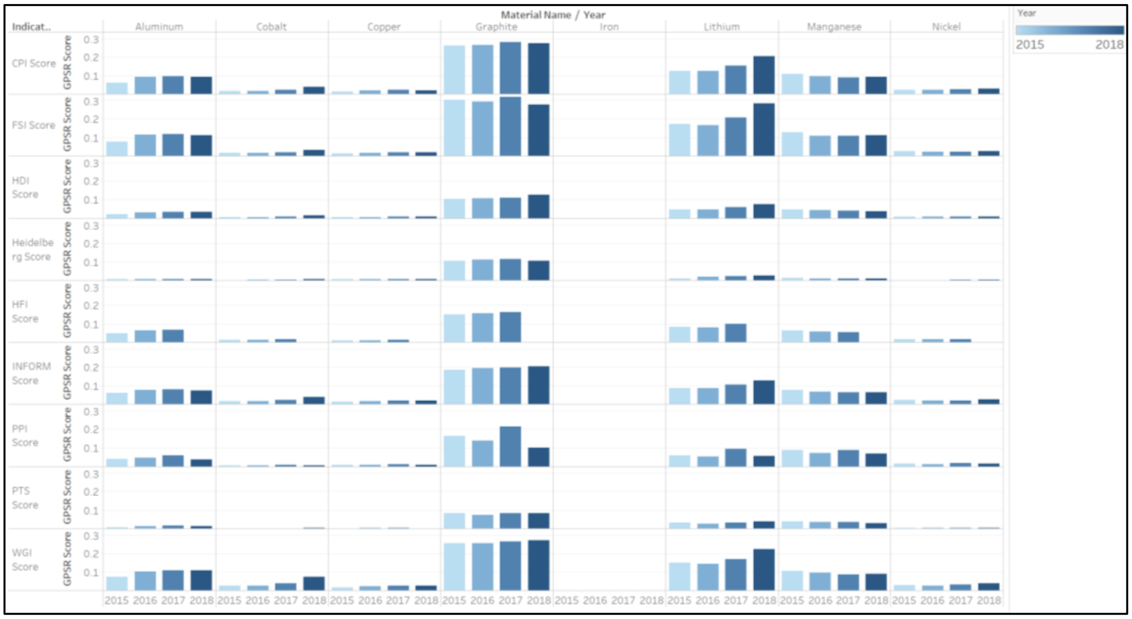


Figure D2. GPSR score for all eight materials and nine indicators from 2015 – 2018 for USA. Each row represents one indicator that is used to calculate the GPSR score and each column represents a single material.

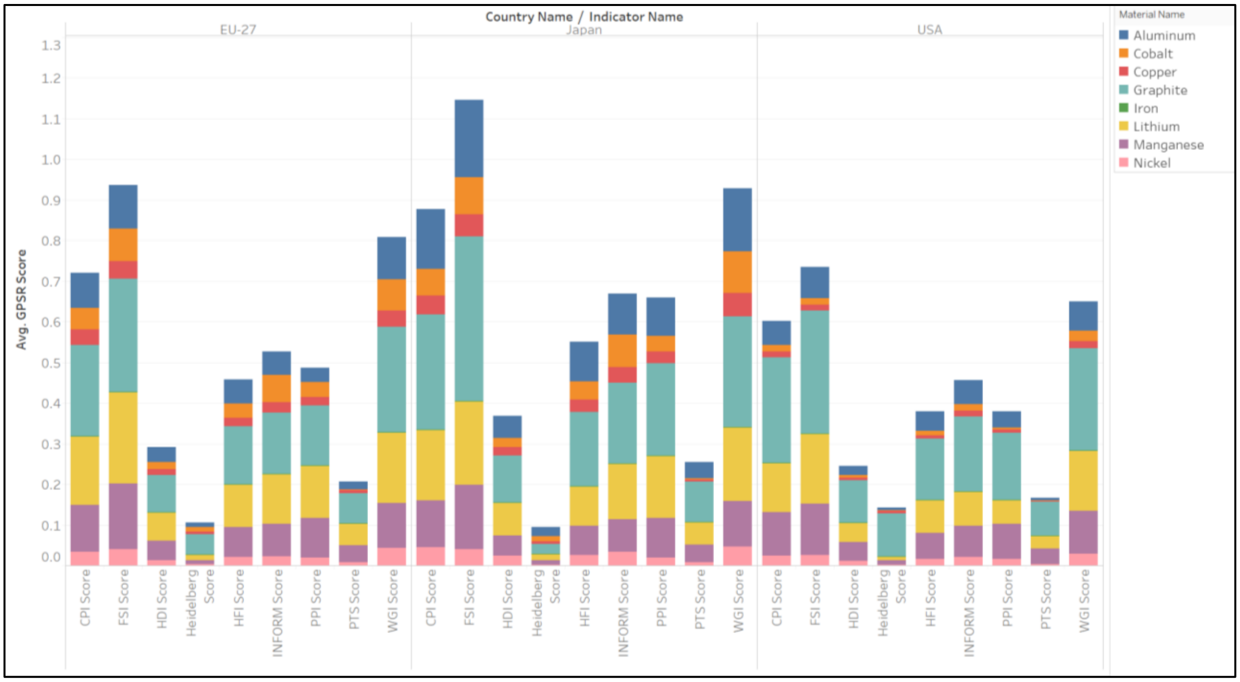


Figure D3. GPSR for each material as share of total for 2015

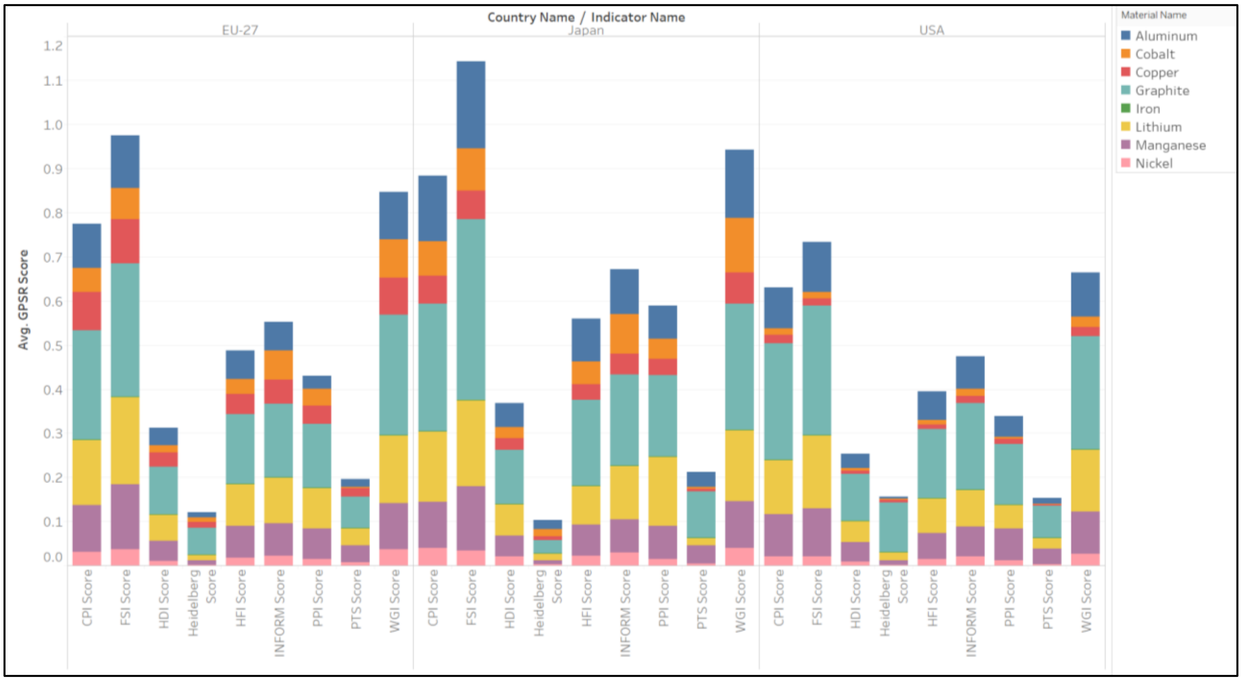


Figure D4. GPSR for each material as share of total for 2016

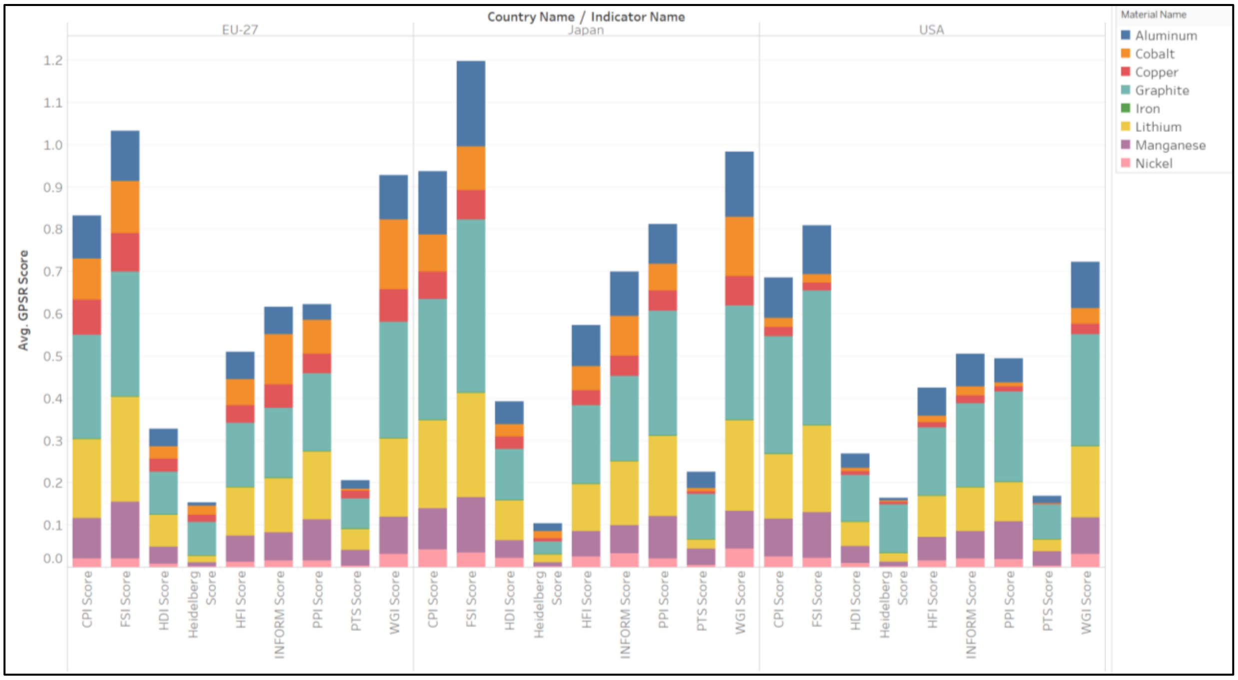


Figure D5. GPSR for each material as share of total for 2017

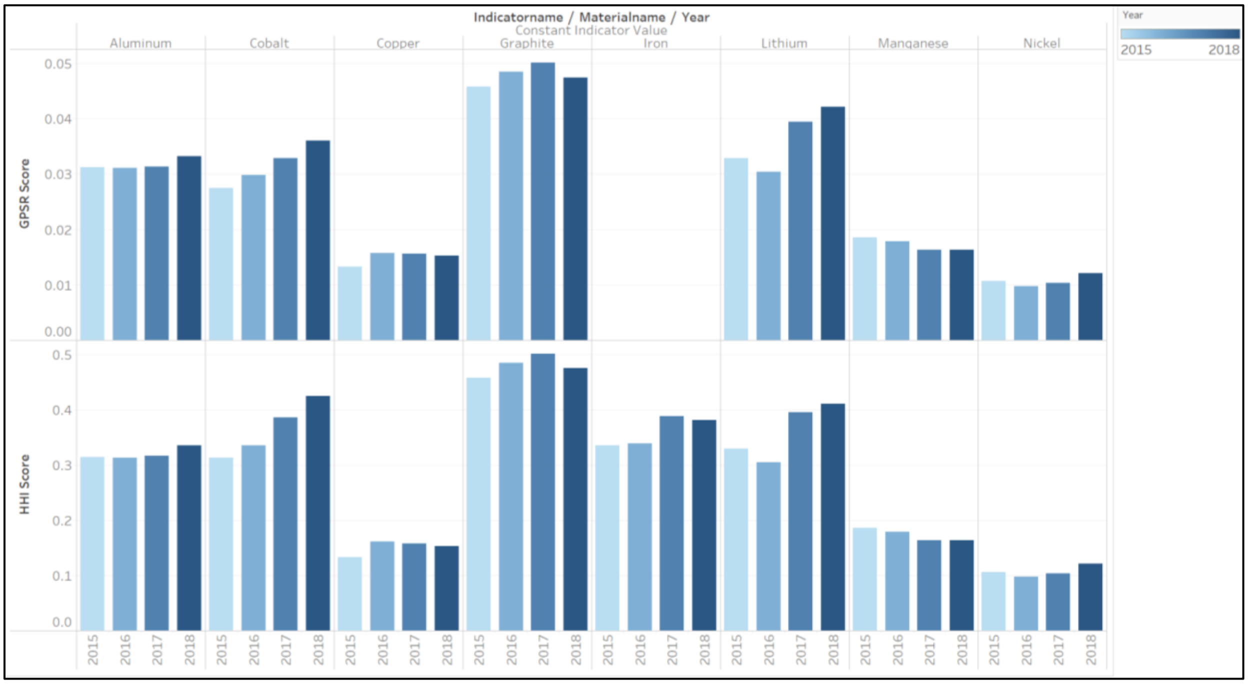


Figure D6. Japan dummy indicator

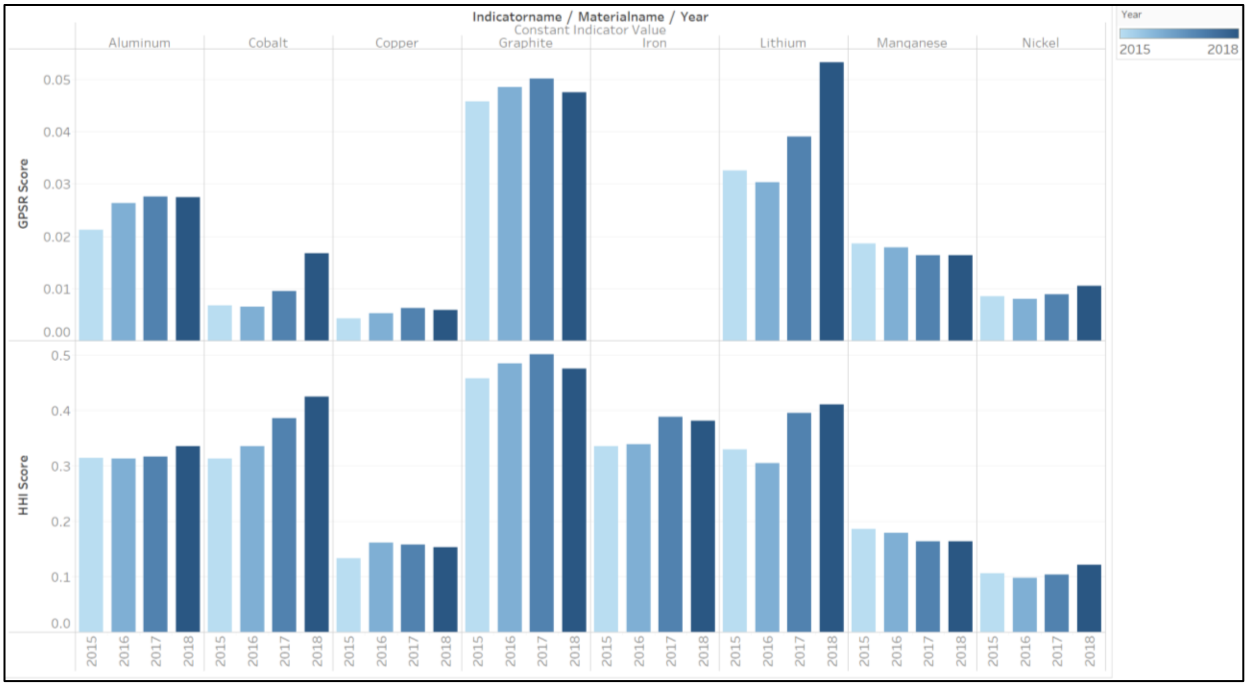


Figure D7. USA dummy indicator

Table D1. Supply risk rankings of materials for Japan based on categories of country indicators

		Material Name							
Indicator Name	**Year**	**Aluminum**	**Cobalt**	**Copper**	**Graphite**	**Iron**	**Lithium**	**Manganese**	**Nickel**
CPI Score	2015	3	5	6	1	8	2	4	7
	2016	3	5	6	1	8	2	4	7
	2017	3	5	6	1	8	2	4	7
	2018	**3**	**4**	**6**	**1**	**8**	**2**	**5**	**7**
PPI Score	2015	4	5	6	1	8	2	3	7
	2016	3	5	6	1	8	2	4	7
	2017	4	5	6	1	8	2	3	7
	2018	**4**	**6**	**5**	**1**	**8**	**2**	**3**	**7**
WGI Score	2015	3	5	6	1	8	2	4	7
	2016	3	4	6	1	8	2	5	7
	2017	3	4	6	1	8	2	5	7
	2018	**3**	**4**	**6**	**1**	**8**	**2**	**5**	**7**
HDI Score	2015	3	6	7	1	8	2	4	5
	2016	3	6	5	1	8	2	4	7
	2017	3	6	5	1	8	2	4	7
	2018	**3**	**6**	**5**	**1**	**8**	**2**	**4**	**7**
HFI Score	2015	2	5	6	1	8	3	4	7
	2016	2	5	6	1	8	3	4	7

	2017	**3**	**5**	**6**	**1**	**8**	**2**	**4**	**7**
FSI Score	2015	3	5	6	1	8	2	4	7
	2016	2	5	6	1	8	3	4	7
	2017	3	5	6	1	8	2	4	7
	2018	**3**	**5**	**6**	**1**	**8**	**2**	**4**	**7**
Heidelberg Score	2015	2	4	6	1	8	3	5	7
	2016	2	4	6	1	8	3	5	7
	2017	3	4	6	1	8	2	5	7
	2018	**3**	**4**	**6**	**1**	**8**	**2**	**5**	**7**
INFORM Score	2015	3	5	6	1	8	2	4	7
	2016	3	4	6	1	8	2	5	7
	2017	3	4	6	1	8	2	5	7
	2018	**4**	**3**	**6**	**1**	**8**	**2**	**5**	**7**
PTS Score	2015	4	7	6	1	8	2	3	5
	2016	3	7	5	1	8	4	2	6
	2017	2	5	6	1	8	4	3	7
	2018	**2**	**6**	**5**	**1**	**8**	**4**	**3**	**7**

Table D2. Supply risk rankings of materials for the US based on categories of country indicators

		Material Name							
Indicator Name	**Year**	**Aluminum**	**Cobalt**	**Copper**	**Graphite**	**Iron**	**Lithium**	**Manganese**	**Nickel**
CPI Score	2015	4	6	7	1	8	2	3	5
	2016	4	7	6	1	8	2	3	5
	2017	3	6	7	1	8	2	4	5
	2018	**3**	**5**	**7**	**1**	**8**	**2**	**4**	**6**
PPI Score	2015	4	7	6	1	8	3	2	5
	2016	4	7	6	1	8	3	2	5
	2017	4	7	6	1	8	2	3	5
	2018	**4**	**7**	**6**	**1**	**8**	**3**	**2**	**5**
WGI Score	2015	4	6	7	1	8	2	3	5
	2016	3	6	7	1	8	2	4	5
	2017	3	5	7	1	8	2	4	6
	2018	**3**	**5**	**7**	**1**	**8**	**2**	**4**	**6**
HDI Score	2015	4	6	7	1	8	2	3	5
	2016	4	7	6	1	8	2	3	5
	2017	4	7	6	1	8	2	3	5
	2018	**4**	**5**	**7**	**1**	**8**	**2**	**3**	**6**
HFI Score	2015	4	6	7	1	8	2	3	5
	2016	3	6	7	1	8	2	4	5
	2017	**3**	**6**	**7**	**1**	**8**	**2**	**4**	**5**

FSI Score	2015	4	6	7	1	8	2	3	5
	2016	3	7	6	1	8	2	4	5
	2017	3	6	7	1	8	2	4	5
	2018	**3**	**5**	**7**	**2**	**8**	**1**	**4**	**6**
Heidelberg Score	2015	4	7	5	1	8	3	2	6
	2016	5	6	4	1	8	2	3	7
	2017	5	6	4	1	8	2	3	7
	2018	**5**	**4**	**6**	**1**	**8**	**2**	**3**	**7**
INFORM Score	2015	4	6	7	1	8	2	3	5
	2016	3	7	6	1	8	2	4	5
	2017	3	5	7	1	8	2	4	6
	2018	**3**	**5**	**7**	**1**	**8**	**2**	**4**	**6**
PTS Score	2015	4	7	6	1	8	3	2	5
	2016	4	7	6	1	8	3	2	5
	2017	4	7	6	1	8	3	2	5
	2018	**4**	**6**	**7**	**1**	**8**	**2**	**3**	**5**

E. Detailed Production and Trade Data (Li, Fe, C)

Table E1. Lithium production and Indicator data

Year	Country Code	Country Name	Production (kg)	WGI Score	HDI Score	CPI Score	Heidelberg	FSI Score	PTS	INFORM	HFI Score	PPI Score
2015	32	Argentina	3600000	0.50	0.82	32.00	2.00	4.10	2.00	2.65	6.50	39.12
	36	Australia	14100000	0.32	0.94	79.00	2.00	2.40	1.00	1.85	8.61	80.25
	76	Brazil	200000	0.57	0.76	38.00	3.00	5.80	4.00	3.40	6.23	56.57
	97	EU-27	200000	0.36	0.88	66.30	2.11	2.29	1.25	1.66		89.59
	152	Chile	10500000	0.41	0.84	70.00	3.00	3.40	1.00	3.12	8.03	83.50
	156	China	2000000	0.61	0.74	37.00	3.00	9.20	4.00	4.38	5.88	46.22
	516	Namibia	0	0.35	0.64	53.00	0.00	4.30	1.00	3.75	6.97	80.70
	620	Portugal	200000	0.32	0.84	64.00	2.00	2.30	1.00	1.66	8.30	89.56
	716	Zimbabwe	900000	0.62	0.53	21.00	3.00	8.30	4.00	5.06	5.58	24.67
2016	32	Argentina	5800000	0.46	0.82	36.00	1.00	3.80	2.00	2.40	6.47	52.14
	36	Australia	14000000	0.29	0.94	79.00	1.00	2.50	1.00	2.30	8.58	80.52
	76	Brazil	200000	0.58	0.76	40.00	4.00	6.10	3.00	3.30	6.21	64.97
	97	EU-27	400000	0.37	0.88	65.22	1.41	2.29	1.29	1.74		92.64
	152	Chile	14300000	0.42	0.84	66.00	3.00	3.20	2.00	3.00	8.01	78.68
	156	China	2300000	0.60	0.75	40.00	3.00	8.70	4.00	4.30	5.91	59.71
	516	Namibia	0	0.36	0.65	52.00	0.00	4.00	1.00	3.60	6.90	77.77
	620	Portugal	400000	0.31	0.85	62.00	0.00	2.00	1.00	1.80	8.28	90.30
	716	Zimbabwe	1000000	0.62	0.53	22.00	3.00	8.40	4.00	4.20	5.62	18.06
2017	32	Argentina	5700000	0.47	0.83	39.00	1.00	4.10	2.00	2.50	6.86	58.08
	36	Australia	40000000	0.32	0.94	77.00	1.00	2.30	1.00	2.30	8.62	73.97
	76	Brazil	200000	0.58	0.76	37.00	4.00	6.40	3.00	3.40	6.48	55.66
	97	EU-27	800000	0.36	0.88	65.26	1.15	2.21	1.25	1.72		76.73
	152	Chile	14200000	0.42	0.84	67.00	3.00	3.00	2.00	2.90	8.15	80.55
	156	China	6800000	0.55	0.75	41.00	3.00	8.50	4.00	4.10	6.17	37.46
	516	Namibia	0	0.37	0.65	51.00	0.00	3.80	1.00	3.70	6.75	71.11
	620	Portugal	800000	0.28	0.85	63.00	0.00	1.80	1.00	1.60	8.27	87.01
	716	Zimbabwe	800000	0.64	0.54	22.00	3.00	8.20	3.00	4.90	5.65	29.54
2018	32	Argentina	6200000	0.50	0.83	40.00	1.00	3.80	2.00	2.30		55.78
	36	Australia	51000000	0.30	0.94	77.00	0.00	2.00	1.00	2.30		82.98
	76	Brazil	600000	0.57	0.76	35.00	4.00	6.70	4.00	3.50		64.43
	97	EU-27	800000	0.37	0.89	65.33	1.19	2.10	1.25	1.75		91.49
	152	Chile	16000000	0.41	0.85	67.00	3.00	3.13	2.00	2.90		88.61
	156	China	8000000	0.55	0.76	39.00	3.00	8.50	4.00	4.10		49.39
	516	Namibia	500000	0.37	0.65	53.00	0.00	3.50	1.00	3.60		80.71
	620	Portugal	800000	0.27	0.85	64.00	0.00	1.50	1.00	1.60		93.50
	716	Zimbabwe	1600000	0.64	0.56	22.00	3.00	8.50	3.00	5.10		47.68

Table E2. Lithium trade and Indicator data

Year	Country Code	Country Name	WGI Score	HDI Score	CPI Score	Heidelberg	FSI Score	PTS	INFORM	HFI Score	PPI Score
2015	124	Canada	0.25	0.92	83.00	2.00	1.80	1.00	2.71	8.52	82.78
	156	China	0.61	0.74	37.00	3.00	9.20	4.00	4.38	5.88	46.22
	360	Indonesia	0.62	0.69	36.00	3.00	6.80	4.00	4.85	6.71	40.41
	376	Israel	0.72	0.90	61.00	1.00	7.40	4.00	2.61	7.65	
	392	Japan	0.29	0.91	75.00	2.00	3.40	1.00	2.23	8.08	
	410	Rep. of Korea	0.47	0.90	54.00	3.00	2.60	2.00	1.56	8.17	
	458	Malaysia	0.45	0.80	50.00	3.00	7.20	3.00	3.04	6.56	
	702	Singapore	0.24	0.93	85.00		4.60	1.00	0.23	8.23	
	764	Thailand	0.70	0.74	38.00	3.00	7.70	3.00	4.26	6.63	
	842	USA	0.36	0.92	76.00	3.00	3.70	2.00	3.17	8.38	83.18
2016	124	Canada	0.25	0.92	82.00	1.00	1.50	1.00	2.70	8.57	86.01
	156	China	0.60	0.75	40.00	3.00	8.70	4.00	4.30	5.91	59.71
	360	Indonesia	0.57	0.69	37.00	3.00	7.40	3.00	4.50	6.77	29.93
	376	Israel	0.66	0.90	64.00	3.00	7.70	3.00	2.40	7.52	
	392	Japan	0.30	0.91	72.00	2.00	3.20	1.00	2.00	8.10	
	410	Rep. of Korea	0.47	0.90	53.00	2.00	2.90	2.00	1.60	8.15	
	458	Malaysia	0.47	0.80	49.00	3.00	7.70	3.00	3.40	6.41	
	702	Singapore	0.20	0.93	84.00		4.30	1.00	0.40	8.16	
	764	Thailand	0.70	0.75	35.00	3.00	8.20	3.00	4.30	6.62	
	842	USA	0.42	0.92	74.00	3.00	3.40	2.00	3.20	8.39	81.70
2017	124	Canada	0.28	0.93	82.00	2.00	1.30	1.00	2.50	8.65	81.26
	156	China	0.55	0.75	41.00	3.00	8.50	4.00	4.10	6.17	37.46
	360	Indonesia	0.60	0.69	37.00	3.00	7.20	3.00	4.30	6.83	39.92
	376	Israel	0.68	0.90	62.00	3.00	7.50	3.00	2.80	7.61	
	392	Japan	0.28	0.91	73.00	2.00	3.00	1.00	2.00	8.28	
	410	Rep. of Korea	0.44	0.90	54.00	3.00	2.90	2.00	1.60	8.20	
	458	Malaysia	0.48	0.80	47.00	3.00	8.00	3.00	3.40	6.52	
	702	Singapore	0.18	0.93	84.00		4.60	1.00	0.40	8.11	
	764	Thailand	0.65	0.76	37.00	3.00	8.00	4.00	4.00	6.55	
	842	USA	0.43	0.92	75.00	3.00	3.20	2.00	3.10	8.46	79.25
2018	124	Canada	0.30	0.92	81.00	2.00	1.33	1.00	2.50		88.00
	156	China	0.55	0.76	39.00	3.00	8.50	4.00	4.10		49.39
	360	Indonesia	0.61	0.71	38.00	3.00	7.30	3.00	4.40		54.64
	376	Israel	0.69	0.91	61.00	4.00	7.20	3.00	2.60		
	392	Japan	0.29	0.91	73.00	2.00	3.07	1.00	1.90		
	410	Rep. of Korea	0.39	0.91	57.00	2.00	3.16	1.00	1.60		

	458	Malaysia	0.45	0.80	47.00	1.00	7.70	3.00	3.20		
	702	Singapore	0.20	0.93	85.00		4.90	1.00	0.40		
	764	Thailand	0.65	0.76	36.00	3.00	7.99	4.00	4.10		
	842	USA	0.40	0.92	71.00	3.00	3.29	2.00	3.60		88.42

Table E3. Iron production and Indicator data

Year	Country Code	Country Name	Production (kg)	WGI Score	HDI Score	CPI Score	Heidelberg	FSI Score	PTS	INFORM	HFI Score	PPI Score
2015	76	Brazil	27803000000	0.57	0.76	38.00	3.00	5.80	4.00	3.40	6.23	56.57
	97	EU-27	93951000000	0.36	0.88	66.30	2.11	2.29	1.25	1.66		89.59
	124	Canada	7353000000	0.25	0.92	83.00	2.00	1.80	1.00	2.71	8.52	82.78
	156	China	6.9141E+11	0.61	0.74	37.00	3.00	9.20	4.00	4.38	5.88	46.22
	276	Germany	28392000000	0.36	0.93	81.00	2.00	1.50	1.00	1.76	8.48	
	392	Japan	81011000000	0.29	0.91	75.00	2.00	3.40	1.00	2.23	8.08	
	410	Rep. of Korea	47639000000	0.47	0.90	54.00	3.00	2.60	2.00	1.56	8.17	
	643	Russian Federation	57851000000	0.71	0.81	29.00	3.00	8.90	4.00	4.61	6.17	52.15
	699	India	74621000000	0.69	0.63	38.00	3.00	5.90	4.00	5.66	6.41	
	804	Ukraine	21863000000	0.89	0.74	27.00	5.00	6.40	4.00	5.07	5.84	
	842	USA	26500000000	0.36	0.92	76.00	3.00	3.70	2.00	3.17	8.38	83.18
2016	76	Brazil	26031000000	0.58	0.76	40.00	4.00	6.10	3.00	3.30	6.21	64.97
	97	EU-27	91980000000	0.37	0.88	65.22	1.41	2.29	1.29	1.74		92.64
	124	Canada	7640000000	0.25	0.92	82.00	1.00	1.50	1.00	2.70	8.57	86.01
	156	China	7.0074E+11	0.60	0.75	40.00	3.00	8.70	4.00	4.30	5.91	59.71
	276	Germany	27864000000	0.36	0.93	81.00	3.00	1.30	1.00	1.90	8.46	
	392	Japan	80170000000	0.30	0.91	72.00	2.00	3.20	1.00	2.00	8.10	
	410	Rep. of Korea	46327000000	0.47	0.90	53.00	2.00	2.90	2.00	1.60	8.15	
	643	Russian Federation	57529000000	0.69	0.82	29.00	3.00	9.40	4.00	4.60	6.27	64.22
	699	India	81464000000	0.69	0.64	40.00	4.00	6.20	4.00	5.60	6.41	
	804	Ukraine	23613000000	0.87	0.75	29.00	5.00	6.20	4.00	5.40	6.28	
	842	USA	24110000000	0.42	0.92	74.00	3.00	3.40	2.00	3.20	8.39	81.70
2017	76	Brazil	28000000000	0.58	0.76	37.00	4.00	6.40	3.00	3.40	6.48	55.66
	97	EU-27	39000000000	0.36	0.88	65.26	1.15	2.21	1.25	1.72		76.73
	124	Canada	6000000000	0.28	0.93	82.00	2.00	1.30	1.00	2.50	8.65	81.26
	156	China	7.11E+11	0.55	0.75	41.00	3.00	8.50	4.00	4.10	6.17	37.46

	276	Germany	28000000000	0.38	0.94	81.00	3.00	1.10	1.00	1.60	8.53	
	392	Japan	78000000000	0.28	0.91	73.00	2.00	3.00	1.00	2.00	8.28	
	410	Rep. of Korea	47000000000	0.44	0.90	54.00	3.00	2.90	2.00	1.60	8.20	
	643	Russian Federation	52000000000	0.63	0.82	29.00	3.00	9.20	4.00	4.40	6.34	60.44
	699	India	66000000000	0.65	0.64	40.00	3.00	6.00	4.00	5.70	6.64	
	804	Ukraine	20000000000	0.87	0.75	30.00	5.00	6.20	4.00	5.30	6.26	
	842	USA	22000000000	0.43	0.92	75.00	3.00	3.20	2.00	3.10	8.46	79.25
2018	76	Brazil	29000000000	0.57	0.76	35.00	4.00	6.70	4.00	3.50		64.43
	97	EU-27	41000000000	0.37	0.89	65.33	1.19	2.10	1.25	1.75		91.49
	124	Canada	7000000000	0.30	0.92	81.00	2.00	1.33	1.00	2.50		88.00
	156	China	7.23E+11	0.55	0.76	39.00	3.00	8.50	4.00	4.10		49.39
	276	Germany	29000000000	0.38	0.94	80.00	3.00	0.80	1.00	2.00		
	392	Japan	82000000000	0.29	0.91	73.00	2.00	3.07	1.00	1.90		
	410	Rep. of Korea	49000000000	0.39	0.91	57.00	2.00	3.16	1.00	1.60		
	643	Russian Federation	53000000000	0.60	0.82	28.00	3.00	9.20	4.00	4.40		67.71
	699	India	69000000000	0.69	0.65	41.00	4.00	5.77	4.00	5.40		
	804	Ukraine	21000000000	0.87	0.75	32.00	4.00	6.50	4.00	5.40		
	842	USA	24000000000	0.40	0.92	71.00	3.00	3.29	2.00	3.60		88.42

Table E4. Iron trade and Indicator data

Year	Country Code	Country Name	WGI Score	HDI Score	CPI Score	Heidelberg	FSI Score	PTS	INFORM	HFI Score	PPI Score
2015	76	Brazil	0.57	0.76	38.00	3.00	5.80	4.00	3.40	6.23	56.57
	124	Canada	0.25	0.92	83.00	2.00	1.80	1.00	2.71	8.52	82.78
	156	China	0.61	0.74	37.00	3.00	9.20	4.00	4.38	5.88	46.22
	410	Rep. of Korea	0.47	0.90	54.00	3.00	2.60	2.00	1.56	8.17	
	484	Mexico	0.66	0.77	31.00	5.00	6.50	4.00	4.60	6.90	71.14
	579	Norway	0.27	0.95	88.00	2.00	1.30	1.00	0.71	8.52	89.19
	643	Russian Federation	0.71	0.81	29.00	3.00	8.90	4.00	4.61	6.17	52.15
	710	South Africa	0.54	0.69	44.00	3.00	4.30	4.00	4.21	7.26	51.91
	804	Ukraine	0.89	0.74	27.00	5.00	6.40	4.00	5.07	5.84	
	862	Venezuela	0.70	0.78	17.00	3.00	8.30	4.00	4.36	4.24	0.00

2016	**76**	**Brazil**	0.58	0.76	40.00	4.00	6.10	3.00	3.30	6.21	64.97
	124	**Canada**	0.25	0.92	82.00	1.00	1.50	1.00	2.70	8.57	86.01
	156	**China**	0.60	0.75	40.00	3.00	8.70	4.00	4.30	5.91	59.71
	410	**Rep. of Korea**	0.47	0.90	53.00	2.00	2.90	2.00	1.60	8.15	
	484	**Mexico**	0.63	0.77	30.00	5.00	6.20	4.00	4.90	6.85	69.97
	579	**Norway**	0.26	0.95	85.00	1.00	1.60	1.00	1.00	8.47	88.98
	643	**Russian Federation**	0.69	0.82	29.00	3.00	9.40	4.00	4.60	6.27	64.22
	710	**South Africa**	0.53	0.70	45.00	3.00	4.40	4.00	3.70	7.17	47.50
	804	**Ukraine**	0.87	0.75	29.00	5.00	6.20	4.00	5.40	6.28	
	862	**Venezuela**	0.70	0.77	17.00	3.00	8.60	4.00	3.80	4.20	0.00
2017	**76**	**Brazil**	0.58	0.76	37.00	4.00	6.40	3.00	3.40	6.48	55.66
	124	**Canada**	0.28	0.93	82.00	2.00	1.30	1.00	2.50	8.65	81.26
	156	**China**	0.55	0.75	41.00	3.00	8.50	4.00	4.10	6.17	37.46
	410	**Rep. of Korea**	0.44	0.90	54.00	3.00	2.90	2.00	1.60	8.20	
	484	**Mexico**	0.64	0.77	29.00	5.00	6.50	4.00	4.80	6.65	65.13
	579	**Norway**	0.27	0.95	85.00	2.00	1.10	1.00	0.70	8.44	77.75
	643	**Russian Federation**	0.63	0.82	29.00	3.00	9.20	4.00	4.40	6.34	60.44
	710	**South Africa**	0.56	0.70	43.00	3.00	4.20	4.00	4.30	7.08	42.66
	804	**Ukraine**	0.87	0.75	30.00	5.00	6.20	4.00	5.30	6.26	
	862	**Venezuela**	0.75	0.76	18.00	3.00	8.90	5.00	4.50	3.80	0.00
2018	**76**	**Brazil**	0.57	0.76	35.00	4.00	6.70	4.00	3.50		64.43
	124	**Canada**	0.30	0.92	81.00	2.00	1.33	1.00	2.50		88.00
	156	**China**	0.55	0.76	39.00	3.00	8.50	4.00	4.10		49.39
	410	**Rep. of Korea**	0.39	0.91	57.00	2.00	3.16	1.00	1.60		
	484	**Mexico**	0.61	0.77	28.00	5.00	6.20	4.00	4.80		71.32
	579	**Norway**	0.27	0.95	84.00	2.00	0.90	1.00	0.70		85.38
	643	**Russian Federation**	0.60	0.82	28.00	3.00	9.20	4.00	4.40		67.71
	710	**South Africa**	0.56	0.70	43.00	3.00	4.30	3.00	4.30		64.57
	804	**Ukraine**	0.87	0.75	32.00	4.00	6.50	4.00	5.40		
	862	**Venezuela**	0.77	0.73	18.00	3.00	9.00	4.00	4.40		0.00

Table E5. Graphite production and Indicator data

Year	Country Code	Country Name	Production (kg)	WGI Score	HDI Score	CPI Score	Heidelberg	FSI Score	PTS	INFORM	HFI Score	PPI Score
2015	76	Brazil	80000000	0.57	0.76	38.00	3.00	5.80	4.00	3.40	6.23	56.57
	124	Canada	30000000	0.25	0.92	83.00	2.00	1.80	1.00	2.71	8.52	82.78
	144	Sri Lanka	4000000	0.48	0.77	37.00	1.00	8.80	3.00	4.48	6.33	
	156	China	780000000	0.61	0.74	37.00	3.00	9.20	4.00	4.38	5.88	46.22
	579	Norway	8000000	0.27	0.95	88.00	2.00	1.30	1.00	0.71	8.52	89.19
	586	Pakistan	0	1.00	0.55	30.00	5.00	8.40	4.00	6.27	5.61	
	643	Russian Federation	15000000	0.71	0.81	29.00	3.00	8.90	4.00	4.61	6.17	52.15
	699	India	170000000	0.69	0.63	38.00	3.00	5.90	4.00	5.66	6.41	
	704	Viet Nam	0	0.49	0.68	31.00	3.00	7.80	3.00	3.65	6.16	
	792	Turkey	32000000	0.80	0.78	42.00	5.00	6.40	4.00	4.68	6.66	71.46
	804	Ukraine	5000000	0.89	0.74	27.00	5.00	6.40	4.00	5.07	5.84	
2016	76	Brazil	95000000	0.58	0.76	40.00	4.00	6.10	3.00	3.30	6.21	64.97
	124	Canada	30000000	0.25	0.92	82.00	1.00	1.50	1.00	2.70	8.57	86.01
	144	Sri Lanka	4000000	0.50	0.77	36.00	3.00	8.50	3.00	4.20	6.27	
	156	China	780000000	0.60	0.75	40.00	3.00	8.70	4.00	4.30	5.91	59.71
	579	Norway	8000000	0.26	0.95	85.00	1.00	1.60	1.00	1.00	8.47	88.98
	586	Pakistan	14000000	1.00	0.56	32.00	5.00	8.20	4.00	6.70	5.66	
	643	Russian Federation	19000000	0.69	0.82	29.00	3.00	9.40	4.00	4.60	6.27	64.22
	699	India	149000000	0.69	0.64	40.00	4.00	6.20	4.00	5.60	6.41	
	704	Viet Nam	5000000	0.45	0.69	33.00	3.00	7.50	3.00	3.70	6.19	
	792	Turkey	4000000	0.90	0.79	41.00	5.00	7.40	5.00	4.70	6.47	54.61
	804	Ukraine	15000000	0.87	0.75	29.00	5.00	6.20	4.00	5.40	6.28	
2017	76	Brazil	90000000	0.58	0.76	37.00	4.00	6.40	3.00	3.40	6.48	55.66
	124	Canada	40000000	0.28	0.93	82.00	2.00	1.30	1.00	2.50	8.65	81.26
	144	Sri Lanka	3500000	0.51	0.77	38.00	3.00	8.30	3.00	3.80	6.41	
	156	China	625000000	0.55	0.75	41.00	3.00	8.50	4.00	4.10	6.17	37.46
	579	Norway	15500000	0.27	0.95	85.00	2.00	1.10	1.00	0.70	8.44	77.75
	586	Pakistan	14000000	0.98	0.56	32.00	4.00	8.00	4.00	6.60	5.69	
	643	Russian Federation	17000000	0.63	0.82	29.00	3.00	9.20	4.00	4.40	6.34	60.44
	699	India	35000000	0.65	0.64	40.00	3.00	6.00	4.00	5.70	6.64	
	704	Viet Nam	5000000	0.44	0.69	35.00	3.00	7.40	3.00	3.50	6.29	
	792	Turkey	2300000	0.86	0.79	40.00	4.00	7.70	5.00	5.00	6.21	52.74
	804	Ukraine	20000000	0.87	0.75	30.00	5.00	6.20	4.00	5.30	6.26	
2018	76	Brazil	95000000	0.57	0.76	35.00	4.00	6.70	4.00	3.50		64.43
	124	Canada	40000000	0.30	0.92	81.00	2.00	1.33	1.00	2.50		88.00
	144	Sri Lanka	4000000	0.54	0.78	38.00	3.00	8.40	3.00	4.00		
	156	China	630000000	0.55	0.76	39.00	3.00	8.50	4.00	4.10		49.39

	579	Norway	16000000	0.27	0.95	84.00	2.00	0.90	1.00	0.70		85.38
	586	Pakistan	14000000	0.95	0.56	33.00	4.00	7.70	4.00	6.40		
	643	Russian Federation	17000000	0.60	0.82	28.00	3.00	9.20	4.00	4.40		67.71
	699	India	35000000	0.69	0.65	41.00	4.00	5.77	4.00	5.40		
	704	Viet Nam	5000000	0.46	0.69	33.00	3.00	7.70	4.00	3.50		
	792	Turkey	2000000	0.77	0.81	41.00	5.00	7.82	5.00	5.00		59.98
	804	Ukraine	20000000	0.87	0.75	32.00	4.00	6.50	4.00	5.40		

Table E6. Graphite trade and Indicator data

Year	Country Code	Country Name	WGI Score	HDI Score	CPI Score	Heidelberg	FSI Score	PTS	INFORM	HFI Score	PPI Score
2015	76	Brazil	0.57	0.76	38.00	3.00	5.80	4.00	3.40	6.23	56.57
	124	Canada	0.25	0.92	83.00	2.00	1.80	1.00	2.71	8.52	82.78
	156	China	0.61	0.74	37.00	3.00	9.20	4.00	4.38	5.88	46.22
	450	Madagascar	0.59	0.51	28.00	1.00	6.10	3.00	4.81	6.60	
	484	Mexico	0.66	0.77	31.00	5.00	6.50	4.00	4.60	6.90	71.14
	508	Mozambique	0.60	0.43	31.00	3.00	6.10	3.00	5.74	6.20	
	579	Norway	0.27	0.95	88.00	2.00	1.30	1.00	0.71	8.52	89.19
	699	India	0.69	0.63	38.00	3.00	5.90	4.00	5.66	6.41	
	804	Ukraine	0.89	0.74	27.00	5.00	6.40	4.00	5.07	5.84	
2016	76	Brazil	0.58	0.76	40.00	4.00	6.10	3.00	3.30	6.21	64.97
	124	Canada	0.25	0.92	82.00	1.00	1.50	1.00	2.70	8.57	86.01
	156	China	0.60	0.75	40.00	3.00	8.70	4.00	4.30	5.91	59.71
	450	Madagascar	0.56	0.52	26.00	0.00	5.80	3.00	4.90	6.51	
	484	Mexico	0.63	0.77	30.00	5.00	6.20	4.00	4.90	6.85	69.97
	508	Mozambique	0.72	0.44	27.00	3.00	5.80	3.00	5.80	6.08	
	579	Norway	0.26	0.95	85.00	1.00	1.60	1.00	1.00	8.47	88.98
	699	India	0.69	0.64	40.00	4.00	6.20	4.00	5.60	6.41	
	804	Ukraine	0.87	0.75	29.00	5.00	6.20	4.00	5.40	6.28	
2017	76	Brazil	0.58	0.76	37.00	4.00	6.40	3.00	3.40	6.48	55.66
	124	Canada	0.28	0.93	82.00	2.00	1.30	1.00	2.50	8.65	81.26
	156	China	0.55	0.75	41.00	3.00	8.50	4.00	4.10	6.17	37.46
	450	Madagascar	0.56	0.52	24.00	0.00	5.60	3.00	5.00	6.32	
	484	Mexico	0.64	0.77	29.00	5.00	6.50	4.00	4.80	6.65	65.13
	508	Mozambique	0.69	0.44	25.00	3.00	5.60	3.00	6.00	6.24	
	579	Norway	0.27	0.95	85.00	2.00	1.10	1.00	0.70	8.44	77.75
	699	India	0.65	0.64	40.00	3.00	6.00	4.00	5.70	6.64	

	804	**Ukraine**	0.87	0.75	30.00	5.00	6.20	4.00	5.30	6.26	
2018	**76**	**Brazil**	0.57	0.76	35.00	4.00	6.70	4.00	3.50		64.43
	124	**Canada**	0.30	0.92	81.00	2.00	1.33	1.00	2.50		88.00
	156	**China**	0.55	0.76	39.00	3.00	8.50	4.00	4.10		49.39
	450	**Madagascar**	0.60	0.52	25.00	0.00	5.81	3.00	5.00		
	484	**Mexico**	0.61	0.77	28.00	5.00	6.20	4.00	4.80		71.32
	508	**Mozambique**	0.66	0.45	23.00	3.00	5.30	3.00	6.00		
	579	**Norway**	0.27	0.95	84.00	2.00	0.90	1.00	0.70		85.38
	699	**India**	0.69	0.65	41.00	4.00	5.77	4.00	5.40		
	804	**Ukraine**	0.87	0.75	32.00	4.00	6.50	4.00	5.40		