Material criticality assessment as supply chain risk management tool

Lamia Mouloudi *† [1], Karine Evrard Samuel * ‡ [1]

[1] Centre d´tudes et de recherches appliquées à la gestion – Université Grenoble Alpes : EA7521 – 150, rue de la chimie - Domaine universitaire - 38400 Saint Martin d'Hères, France

Supply chains of companies evolves in a complex, hostile, dynamic and uncertain environment, which generates several undesirable events that may disturb or interrupt the flows of materials and information. Thus, to ensure the continuity of their flows, companies implement supply chain risk management (SCRM) approaches, that includes risk identification, risk evaluation and risk mitigation. These approaches define a clear framework to reduce vulnerability towards risks and globally increase supply chain resilience. However, the implementation of SCRM and the effectiveness of risks mitigation hugely depend on the types of risks considered, which are strongly linked to the company's context and the visibility in its supply chain. In this paper, we assume that material criticality assessment could be integrated into SCRM as a new tool to consider supply risks linked to the growing scarcity of certain raw materials. Material criticality assessment is a method used to identify materials that may become difficult to obtain for several reasons. We particularly consider the access to all materials necessary to achieve digital and energetics transitions. Indeed, by increased utilization of digital communication technologies and deployment of clean energy to meet environmental considerations, the consumption of certain elements, for example some metals like gold or platinum, or rare earths needed has increased drastically for the last twenty years, and the supply is becoming more and more uncertain if the rhythm of consumption stays at the same level. The availability of some elements is more and more uncertain and generates high probability of supply disruptions due to geopolitical, economic, and/or technical factors. For these reasons, critical materials are as a source of vulnerability to supply chains and their identification is an issue as this source of risk is not considered yet as a key element of SCRM. The purpose of this paper is to establish the relationship between these two concepts, material criticality assessment and supply chain risk management, in order to integrate material criticality as a new tool for SCRM. Based on a literature review on material criticality assessment and SCRM, we highlight the absence of structured SCRM and the lack of consideration of critical materials in current practices.

Keywords: Raw material, Criticality, Supply Chain Risk Management, Resilience

*Speaker
†Corresponding author: lamia.mouloudi@univ-grenoble-alpes.fr
‡Corresponding author: karine.samuel@grenoble-inp.fr

MATERIAL CRITICALITY ASSESSMENT
AS A SUPPLY CHAIN RISK MANAGEMENT TOOL

Work in progress

Abstract

Supply chains of companies evolves in a complex, hostile, dynamic and uncertain environment, which generates several undesirable events that may disturb or interrupt the flows of materials and information. Thus, to ensure the continuity of their flows, companies implement supply chain risk management (SCRM) approaches, that includes risk identification, risk evaluation and risk mitigation. These approaches define a clear framework to reduce vulnerability towards risks and globally increase supply chain resilience. However, the implementation of SCRM and the effectiveness of risks mitigation hugely depend on the types of risks considered, which are strongly linked to the company's context and the visibility in its supply chain. In this paper, we assume that material criticality assessment could be integrated into SCRM as a new tool to consider supply risks linked to the growing scarcity of certain raw materials. Material criticality assessment is a method used to identify materials that may become difficult to obtain for several reasons. We particularly consider the access to all materials necessary to achieve digital and energetics transitions. Indeed, by increased utilization of digital communication technologies and deployment of clean energy to meet environmental considerations, the consumption of certain elements, for example some metals like gold or platinum, or rare earths needed has increased drastically for the last twenty years, and the supply is becoming more and more uncertain if the rhythm of consumption stays at the same level. The availability of some elements is more and more uncertain and generates high probability of supply disruptions due to geopolitical, economic, and/or technical factors. For these reasons, critical materials are as a source of vulnerability to supply chains and their identification is an issue as this source of risk is not considered yet as a key element of SCRM. The purpose of this paper is to establish the relationship between these two concepts, material criticality assessment and supply chain risk management, in order to integrate material criticality as a new tool for SCRM. Based on a literature review on material criticality assessment and SCRM, we highlight the absence of structured SCRM and the lack of consideration of critical materials in current practices.

Key words: Raw material; Criticality; Supply Chain Risk Management; Resilience.

1. INTRODUCTION

Supply chain can be considered as a complex system built to control, manage and improve the physical and informational flows from suppliers to end customer (Hassan 2006; Philip et Theodor 2018). We consider the supply chain as a complex system “one in which there are multiple interactions between many different components." (Rind 1999). In this case, each supplier, distributor and customer acts as a component of that system (Kenyon et Neureuther 2012). The complexity of this supply chain results from the growing complexity of products and services as well as the increasing outsourcing and globalization (Harland, Brenchley, et Walker 2003). This system evolves in a complex, hostile, dynamic and uncertain environment, which generates several risks that may disturb or interrupt the flow of materials and information.

These risks can result from man-made problems or natural disasters and can have major consequences for organizations and problems for supply chain management. Such as the earthquake in Japan in 2011 whereby auto maker Nissan experienced serious disruptions, as 12% of its engines were purchased in the seismic zone (Merzifonluoglu 2015). Another well-known example is the fire at supplier's semiconductor plant in New Mexico, which caused to Ericsson the loss of 400 million euros in 2000. At least, the catastrophic floods of October 2011 in Thailand affected the supply chains of computer manufacturers that rely on hard disk drives and disrupted the supply chains of Japanese automotive companies with factories in Thailand(Chopra et Sodhi 2004; Ho et al. 2015). These crises and catastrophes abruptly reminded companies how vulnerable their global supply chains are (Wieland et Marcus Wallenburg 2012).

In this context where risks are paramount, and to ensure viability of the supply chain, the concept of Supply Chain Risk Management (SCRM) emerged as a natural extension of SCM. According to (Blos et al. 2009), this management originates from the intersection of risk management and supply chain management and its main goal is to identify the sources of potential risks, suggest suitable measures to mitigate them (Singhal, Agarwal, et Mittal 2011), and increase supply chain’s resilience (Nyoman Pujawan et Geraldin 2009).

To achieve these objectives, it is important to define tools adapted to the activities of companies and the characteristics of the environment in which they operate. Some threats may impact one industry more than another without considering their level of resilience, but only due to the nature of their activity. The case of industries using raw materials that are subject to high levels of disturbance due to geological, environmental, political, logistical and other factors, clearly reflects this need. These materials are influenced by external factors outside the companies' capacity for action. These factors disturb the supply of raw materials which as a domino effect impact the continuity of activity of the company. Thus, this threat is called critical materials.

Critical materials have been characterized as a source of risk to the supply chain by several researchers(Griffin, Gaustad, et Badami 2019; Miehe et al. 2016) and their identification has been addressed in several studies and at different levels of analysis (Graedel et al. 2012; EU 2017; Miehe et al. 2016; Rosenau-Tornow et al. 2009). This identification was then considered as a part of the sustainability tool box (Cimprich et al. 2019; Sonnemann et al. 2015). But after a literature review, we found no studies that linked this assessment to supply chain risk management by considering it as a tool for identifying sources of risk.

Anchored to the concepts of supply chain risk management and criticality assessment of materials, this paper aims to provide a framework for integrating concerns about these materials into supply chain risk management. We thus address the following research questions:

(1) How can criticality evaluation of materials contribute to SCRM?
(2) How can criticality of materials be integrated into the SCRM as a concept?

The following sections first describe as a central concept in supply chain risk management and discusses approaches for managing these risks. In section 2, we describe the concept of critical materials and the assessment methodologies. At least, section 3 analyze ways to integrate the criticality assessment of materials in the supply chain risk management process from different models proposed by the researchers.

2. SUPPLY CHAIN RISK MANAGEMENT

2.1. Supply chain risk

According to (Beck, Giddens, et Lash 1994), our society has entered into the age of risk. However, the concept of risk, which is at the origin of all the approaches discussed in this paper, is not the same for all research communities. An effort has been made by the International Organization for Standardization in the ISO 31000 standard on risk management by proposing a definition of risk which states that risk is the effect of uncertainty on the possibility of achieving the organization's objectives. As uncertainty is the lack of information regarding the understanding or knowledge of an event and its consequences(Purdy 2010). Based on this definition and the explanations provided, the risk can be positive or negative depending on the context. In our study, we will only consider negative deviations from objectives.

A further effort to find an acceptable definition by the research community was conducted by Terje Aven, who studied the definition and meaning of the concept of risk by conducting a review of trends in its historical development. (Aven 2012) concluded that the most appropriate definition for the concept was that risk is equal to the two-dimensional combination of events/consequences (of an activity) and associated uncertainties. In other words:

Risk = Consequences/damage/severity of these + Uncertainty

He argues that this perspective facilitates a clear distinction between the risk concept and how it is measured. Thus, probability enters the scene when we would like to describe or measure the uncertainties and thus risk. Probability is not a part of the risk concept per se.

For the supply chain community, the supply chain risk has a various definition which may impact the approaches for managing them (Heckmann, Comes, et Nickel 2015). For (Jüttner, Peck, et Christopher 2003), SCR is “the variation in the distribution of possible supply chain outcomes, their likelihoods, and their subjective values”. As the definition of risk by the ISO 31000 this definition doesn’t referred to only the negative variation. (Zsidisin et Ritchie 2008) see the supply chain risk as “potential occurrence of an event related to inbound supply activities that may result in the inability of the company as a purchasing organization to meet customer demand". According to (Christopher et Lee 2004) supply chain risk can be broadly defined as an exposure to an event which causes disruption, thus affecting the efficient management of the SC network. According to (Ho et al. 2015), supply chain risk is "the likelihood and impact of unexpected macro and/ or micro level events or conditions that adversely influence any part of a supply chain leading to operational, tactical, or strategic level failures or irregularities". His definition gives more information about the factors that may influence the supply chain and their possible impact on the unit of analysis.

These supply chain risks require management to ensure the viability and continuity of the supply chain. This is how the SCRM has emerged as a management of risk that are related to the supply chain.

2.2. SCRM definition

(Brindley 2017) considers SCRM as "the management of supply chain risk through coordination or collaboration among supply chain partners in a way that ensures profitability and continuity". (Ho et al. 2015) defines it as "an inter-organizational collaborative enterprise using quantitative and qualitative risk management methods to identify, assess, mitigate and monitor unanticipated events or conditions at the macro and micro levels that could adversely affect any part of the supply chain".

According to the literature review carried out by (Kilubi et Haasis 2015) considering studies on the SCRM published between 2000 and 2015, there are no definitions related to the SCRM that are widely and commonly available. Most of the proposed definitions are used as a research basis for their proposal and based on its analysis, there are similarities but also slight modifications between the different definitions.

The similarities that (Fan et Stevenson 2018) observed from the literature review he conducted on the definitions of the SCRM, include the final objective of this management, the process or steps to be followed to build it, the pathway. Based on this observation, he proposed a new definition which states that management of the supply chain risk is about "the identification, assessment, treatment, and monitoring of supply chain risks, with the aid of the internal implementation of tools, techniques and strategies and of external coordination and collaboration with supply chain members so as to reduce vulnerability and ensure continuity coupled with profitability, leading to competitive advantage".

In our point of view, the definition proposed by (Wieland, 2012) which define SCRM as the implementation of strategies to manage both every day and exceptional risks along the supply chain with the objective of reducing vulnerability and ensuring continuity, is the most suitable for our analyses because it consider SCRM as an approach with objectives and don't specify the way how to manage risks.

Having been able to understand the objectives of this management, it is still necessary to understand its place in company processes, since can be considered as a standard in supply chain management (enabler, 2015), or the extends of traditional risk management approaches by integrating risks of partners upstream and downstream the supply chain (Wieland, 2012)

The question is: how is responsible to provide and apply a structured management of supply chain risk? Risk manager or supply chain manager?

Our literature review could not provide a conclusive answer on the who, but provided more information on how to build this management based on widely discussed models and processes.

In the next section, we will present the most discussed approaches to manage supply chain risk which is called SCRM model or process.

2.3. SCRM process

As presented in the definition, SCRM process is about the identification, the assessment, the treatment and the monitoring of supply chain risks. Several authors pointed the fact that there is no consensus among researchers regarding the steps, either in terms of their number or terminology. From our point of view, the approaches proposed to achieve the objective of this management are provided by researchers from different backgrounds, a consensus is difficult to find. However, efforts have been made to propose a harmonized model of the SCRM. According to (de Oliveira et al. 2017) a first work was carried out by (Khan et Burnes 2007). This work resulted in a risk management approach based on three steps. the first step is the identification of risks which is associated with the identification of failures and negative consequences. the second step is the risk estimation in where a quantification of the risk is performed. the third step consists in assessing the risks by establishing a level of acceptability allowing a comparison between the identified risks.

Another effort has been made by (de Oliveira et al. 2017) to propose a harmonized supply chain risk management process based on the ISO 31000 risk management standard by reviewing 27 studies (see figure 1).

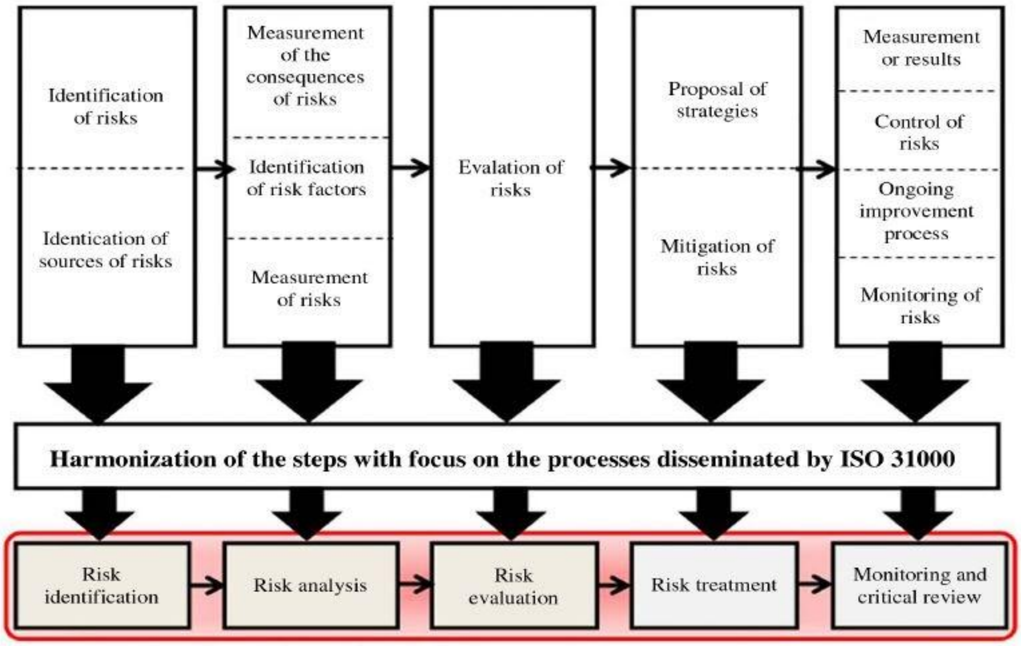

Figure 1: SCRM process according to de Oliveira *et al.* (2017)

In this second effort, work has been done to harmonize the terms used to designate the steps and the number of steps that have been established based on the risk management process proposed by standard 31000. Compared to the work carried out in 2017, two other steps have been added: 1) risk treatment which involves strategic choices leading to measures to be implemented for instance companies use different solutions depending on their capabilities ; 2) monitoring and critical review that are two essential actions to improve management. this step requires updates that depend upon the changing environment and the needs of organizations.

The SCRM process is a generic model that can be applied by all types of companies, it provides several steps to address risks of disruption in the supply chain (de Oliveira et al. 2017). Based on different needs and context, it is not feasible to develop a procedure to manage risks in supply chain that would fulfill all companies need and requirement (de Oliveira et al. 2017). Hence, the company must not only use a risk management model but also tools adapted to its context, its activities, its vulnerability, by studying its needs and threats. According to the literature review conducted by (Gardner et Colwill 2016), there is an apparent lack of awareness by industries with regards to supply risks linked to critical materials at a business or product level (Miehe et al. 2016).

In this article, we focus on a specific source of risk linked to raw materials essential for some industries. In the next section, we will provide an overview of the concept of criticality of materials and explain how to identify them.

3. CRITICAL MATERIAL

3.1. Origin of the concept

In the context of raw materials, the term ‘criticality’ was first used in 1939 in the “Strategic and Critical Materials Stock Piling Act” (Achzet et Helbig 2013; Glöser et al. 2015). As a concept, it emerged from concerns about the unavailability of materials (Graedel et Nuss 2014). It is a relative (Schellens et Gisladottir 2018) complex and multidisciplinary phenomenon (Lapko, Trucco, et Nuur 2016) that depends on several factors such as geological deposits, geographical concentration of deposits or processing facilities, social issues, regulatory structures, geopolitics, environmental issues, recycling potential, and sustainability (Graedel et Nuss 2014).

3.2. Definitions

In general, materials criticality is characterized by a high probability of supply constraints and the high impact of supply disruption (Erdmann et Graedel 2011; Peck, Kandachar, et Tempelman 2015). The term ‘criticality’ describes a potentially dangerous development in the context of resources. It characterizes a certain risk of the user (Miehe et al. 2016). This characteristic of a material depends on the period under consideration and the scope concerned, therefore critical ‘for who’? (Frenzel et al. 2017).

Although the term ‘critical materials’ is usefully used interchangeably with ‘strategic materials’, but a distinction between the two is important. According to (Clark et Flemings 1986; National Research Council (U.S.) et al. 2008) the main difference is related to the impact of the unavailability of the material. For instance, ‘critical’ refers to materials that have an impact on national, regional or industrial economies, while ‘strategic’ refers almost exclusively to military and defense needs. From this point of view, all strategic materials are critical (National Research Council (U.S.) et al. 2008).

Definitions of critical materials show that they represent a source of risk for companies. Thus, the use of such materials by a company increases the probability of disruption or cessation of its activities and the achievement of its objectives. Therefore, the assessment of the level of materials criticality is a process that must be integrated into the daily practices of supply chain managers. It is about level of criticality because it is a matter of degree and not state of being (Graedel, 2014). Thus, the result obtained will provide a vision of the company's current situation in the context of long-term and medium-term supply disruption for better decision-making at the strategic and operational levels. Also, the identification of such a material lead to predict supply chain disruptions.

3.3. Material criticality assessment

Since 2008, several criticality assessment methods have been developed and according to (Knoeri et al. 2013), the pioneers are the US National Research Council (NRC) and the European Union. U.S. National Research Council NRC (2008) proposed a criticality matrix that represents the first criticality assessment methodology and the most common tool for the assessment and communication of raw material criticality (Glöser et al. 2015). This methodology suggests an evaluation of criticality based on two dimensions indicated by the definition. the first one is the importance of the material used which can be evaluated based on its impact in case of supply disruption. the second represents the availability of the material, in the long term by considering the shortage and in the short medium term by considering the supply risk.

Based on this methodology, it is possible to assess the criticality of materials, by first define their importance of use based on their impact on achieving goals. Secondly, by evaluating the scarcity of material for the long-term consideration, and for the short medium term by evaluating the probability of supply disruption (see figure 2).

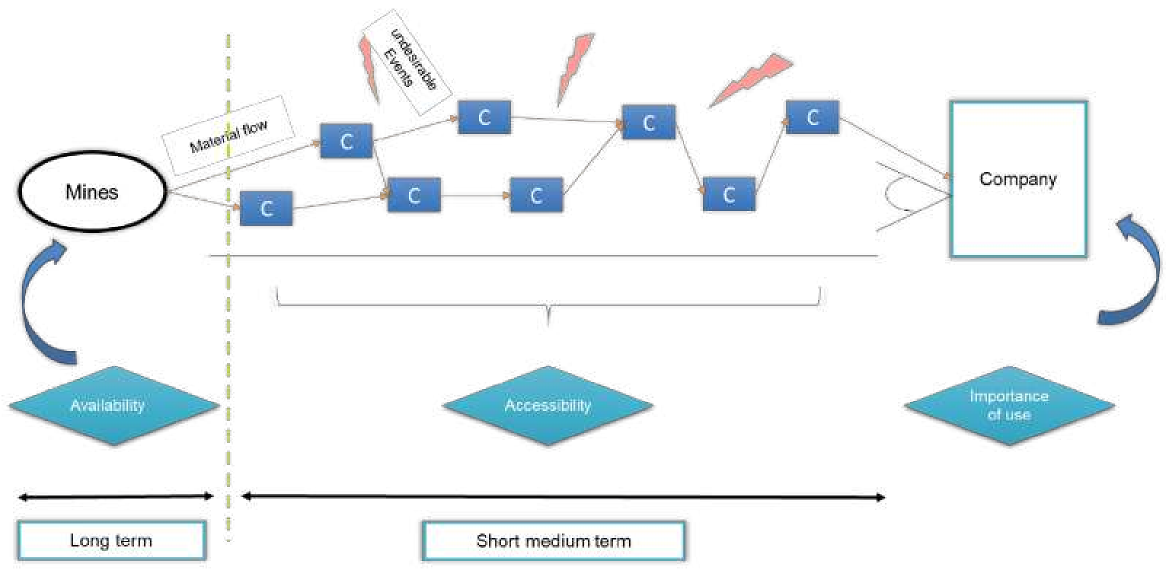

Figure 2: Critical material definition

According to different literature reviews conducted on criticality evaluation methodologies (Graedel et Reck 2016; Frenzel et al. 2017; Dewulf et al. 2016; Jin, Kim, et Guillaume 2016) as well as on the factors used to evaluate the criticality of materials (Achzet et Helbig 2013; Helbig et al. 2016), the most common procedure for criticality assessment is to compile sets of different indicators into aggregate scores (Frenzel et al. 2017) for the dimension of supply risk and the dimension of vulnerability. In 2012, (Graedel et al. 2012) introduced a third dimension: the environmental issues.

Regarding indicators used to characterize the dimensions, there are several indicators used for the same dimension (Glöser et al. 2015). As a matter of fact, (Achzet et Helbig 2013) studied the different indicators related to the dimension of supply risk and found that the factors most commonly used to characterize supply risk are: 1) country concentration, 2) country risk, 3) depletion time, 4) by-product dependency. The latter were used by more than half of the studies reviewed, so it was assumed that they are the most relevant factors for this dimension. Following the same goal, (Helbig et al. 2016) studied the factors that are used to characterize vulnerability the factors most commonly used are: 1) substitutability, 2) product value, 3) future demand and 4) strategic importance.

In the case of the indicators, there is also a divergence between the aggregation methods chosen to complete the indicators to obtain the score of a dimension. According to (Frenzel et al. 2017) they can be sub-divided into the following three groups: Additive, Multiplicative, Mixed.

There is no consensus about the methods of aggregation and visualization of criticality (final criticality score) as we found criticality matrices, criticality indices, and quantitative future supply and demand analysis (Erdmann et Graedel 2011). The concept of material criticality assessment has recently attracted the attention of various research communities, but is still in the conceptualization phase (Lapko, Trucco, et Nuur 2016). Since the conceptual foundations have not yet been established, there are differences in its interpretation (Dewulf et al. 2016) and several variations between studies with a similar scope (Frenzel et al. 2017). The authors expose several elements that contribute to the assessment: dimensions, factors, and aggregation methods. Despite these unconsolidated results, the methodologies used provide different approaches. For example, the European Commission periodically uses the customized criticality matrix to provide a list of materials considered critical for the European Union (Kim et al. 2019**).** However, the question of whether companies operating in the European area can use this list and consider the materials identified as critical to their business remains.

According to (Graedel et Reck 2016), this implication must be discouraged. The fact is, the criticality of the material depends on the context of its assessment., defining the scope of the methodology is a key step in identifying the level of material criticality because each scope has its own context and concerns. For example, if we consider the evaluation of the criticality at the global level, the focus is on the impact of the unavailability of the material on the global economy, while at the national level the focus is on the local economy (Miehe et al. 2016).

Since the scope of our study is devoted to the company level, we will present in the following section the studies that have sought to identify critical material at this level.

3.4. Material criticality at the firm level

It is important to underline that the degree of interest in each scope is not the same. Numerous studies have been published on the global, national and sector, while little research has been conducted at the business level (Miehe et al. 2016).

Regarding the contextual character of the criticality (Malinauskienė et al. 2016), (Miehe et al. 2016) define the term 'resource criticality' from a business perspective as "the risk of damage to a certain unit of analysis due to the utilization of certain resources". Thus, the resources used can create a negative variation in the objectives of a product, process or organization. In the same perspective (Griffin, Gaustad, et Badami 2019) suggests that the definitions of a critical material is related to two dimensions for firms the supply disruptions and the high economic and/or strategic importance.

To assess material criticality for this scope of analysis, an initial proposal to measure supply risks was made by Rosenau-Tornow (Miehe et al. 2016) based on an analysis of the evolution of the raw materials market over the last 50 years, which laid the foundations for an assessment in five categories: current supply and demand, production costs, geostrategic risks, market power, supply and demand trends. But according to (Miehe et al. 2016), this analysis neglects other aspects considered as essential to consider supply risk, such as ecological and social risks and those related to vulnerability. Also (Griffin, Gaustad, et Badami 2019) proposed to evaluate the criticality of materials based only on internal factors that support the assessment of supply risk can be controlled by individual firms. This factor was used based on the avaibility and the accessibility of data and the potential for firms to influence the data being collected.

Both studies focused only on supply risk and didn't give a step that company may use to assess materials criticality, both of them focus on indicators and not at how we can aggregate them to obtain a final list that can describe the level of criticality.

4. RELATIONSHIP BETWEEN SCRM AND CRITICAL MATERIALS

The assessment of materials criticality can be considered as a black box with information as an input and results as an output. The input data are in the form of indicators of supply risk and vulnerability and the output data as a list of materials that may disrupt the supply chain.

Criticality assessment provides a better understanding of the current situation of companies in terms of vulnerability. It gives a very useful picture when assessing supply chain risks. It provides information to better anticipate disruptions in the supply chain.

The context-dependent nature of the SCRM requires knowledge about the companies' situation in order to assess their level of vulnerability and improve risk identification. At this stage, the assessment of the criticality of materials is essential (see figure 3).

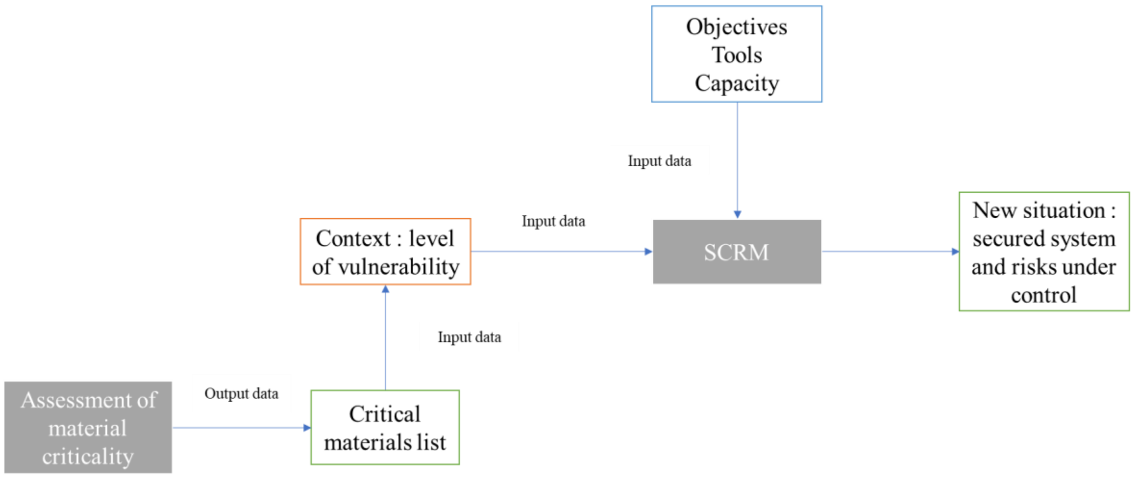

Figure 3: the relationship between SCRM and critical materials

The study presented by (Miehe et al. 2016) helps to open this box to further discuss the assessment process in detail. They suggest a five-steps approach that companies can execute to implement critical materials assessment into their organization (see figure 4).

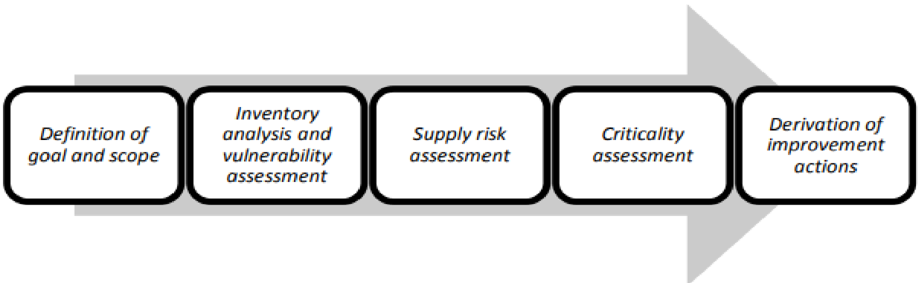

Figure 4: Five-step approach for organizational criticality assessment (Miehe et al. 2016)

The first step proposes the establishment of the preconditions of the analysis. It relates to the objective of the company. For reasons of simplification, (Miehe et al. 2016) suggest that the objective is "to provide a customer with the desired product in the required quality and time". The second point is related to the definition of the scope. It refers to the unit of analysis that can be the company, process or product. The last point is the choice of the time horizon that will impact the results of analysis.

The third step is to assess the supply risk which will provide the probability of shortfalls, for this analysis he divided the system into two parts the first concerns the upstream system. in this case he used indicators such as the number of suppliers and the concentration of reserves and an indicator about the supplier's country. The second system is the downstream system, it says that supply stoppage can also be due to social perception. this can be due to the customer's refusal to buy the product or that government regulations prohibit the use of a certain resource.

The fourth step is related to the assessment of the criticality of materials which follows the criticality matrix. The last steps and according to the results of the criticality matrix, appropriate actions must be done such as R&D, changes suppliers, review stock-keeping.

This proposal offers a very interesting approach. It provides steps that companies can follow. But this approach neglects the modeling of the supply chain to have a visibility up to the mine level or the use of risk identification tools to obtain indicators adapted to the context of the companies. Also, it neglects the aggregation methods to get results from supply risk assessment and vulnerability assessment steps. However, they have made the effort to provide an initial answer to the question of how to carry out a criticality assessment of materials at the company level.

CONCLUSION

The purpose of this paper is to demonstrate the need to integrate the assessment of material criticality in the approaches to supply chain risk management. Also, to introduce this concept as an important element considered in organizational practices. It highlighted its usefulness in assessing the level of vulnerability of companies, although as a tool for identifying problems or tensions that could arise over access to resources (Buijs et Sievers 2011). It has considerable input in the area of risk analysis and supply chain security. Hence, knowing the level of criticality of the materials used will allow the implementation of operational solutions such as changing suppliers, contractual conditions, stock levels, or strategic decisions such as the modification of materials used that will impact the design of the supply chain.

Therefore, a sound methodology of assessing material criticality, based on theoretical foundations and empirical data, is required.

Given, the conceptualization suffers phase of this tool efforts remain to be done to adapt it to companies to fill all the methodological and theoretical gaps. Also, several challenges were highlighted by (Slowinski, Latimer, et Mehlman 2013) as the complexity of the supply chains of industrial then the more layers of suppliers increase, the lower the level of knowledge. Another difficulty is underlined by (Miehe et al. 2016) which consist in the complexity of the resource market, which is only a consequence of the complexity of the products used.

REFERENCES

Achzet, Benjamin, et 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.

Aven, Terje. 2012. « The risk concept—historical and recent development trends ». *Reliability Engineering & System Safety* 99: 33‑ 44. https://doi.org/10.1016/j.ress.2011.11.006.

Beck, Ulrich, Anthony Giddens, et Scott Lash. 1994. *Reflexive Modernization: Politics, Tradition and Aesthetics in the Modern Social Order*. Stanford University Press.

Blos, Mauricio F., Mohammed Quaddus, H.M. Wee, et Kenji Watanabe. 2009. « Supply chain risk management (SCRM): a case study on the automotive and electronic industries in Brazil ». *Supply Chain Management: An International Journal* 14 (4): 247‑ 52. https://doi.org/10.1108/13598540910970072.

Brindley, Clare. 2017. *Supply Chain Risk*. Taylor & Francis.

Buijs, Bram, et Henrike Sievers. 2011. « Critical Thinking about Critical Minerals: Assessing Risks Related to Resource Security », 19.

Chopra, Sunil, et M.S Sodhi. 2004. « Managing Risk to Avoid Supply-Chain Breakdown ». MIT Sloan Management Review. 2004. https://sloanreview.mit.edu/article/managing-risk-to-avoid-supplychain-breakdown/.

Christopher, Martin, et Hau Lee. 2004. « Mitigating supply chain risk through improved confidence ». *International Journal of Physical Distribution & Logistics Management* 34 (5): 388‑ 96. https://doi.org/10.1108/09600030410545436.

Cimprich, Alexander, Vanessa Bach, Christoph Helbig, Andrea Thorenz, Dieuwertje Schrijvers, Guido Sonnemann, Steven B. Young, Thomas Sonderegger, et 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* 23 (5): 1226‑ 36. https://doi.org/10.1111/jiec.12865.

Clark, Joel P., et Merton C. Flemings. 1986. « Advanced Materials and the Economy ». *Scientific American* 255 (4): 50‑ 57.

Dewulf, Jo, Gian Andrea Blengini, David Pennington, Philip Nuss, et Nedal T. Nassar. 2016. « Criticality on the international scene: Quo vadis? » *Resources Policy* 50 (décembre): 169‑ 76. https://doi.org/10.1016/j.resourpol.2016.09.008.

Erdmann, Lorenz, et Thomas E. Graedel. 2011. « Criticality of Non-Fuel Minerals: A Review of Major Approaches and Analyses ». *Environmental Science & Technology* 45 (18): 7620‑ 30. https://doi.org/10.1021/es200563g.

EU. 2017. « Methodology for establishing the eu list of critical raw materials ». https://www.certifico.com/component/attachments/download/5823.

Fan, Yiyi, et Mark Stevenson. 2018. « A Review of Supply Chain Risk Management: Definition, Theory, and Research Agenda ». *International Journal of Physical Distribution & Logistics Management*, avril. https://doi.org/10.1108/IJPDLM-01-2017-0043.

Frenzel, M., J. Kullik, M. A. Reuter, et J. Gutzmer. 2017. « Raw Material 'Criticality'—Sense or Nonsense? » *Journal of Physics D: Applied Physics* 50 (12): 123002. https://doi.org/10.1088/1361-6463/aa5b64.

Gardner, Liam, et James Colwill. 2016. « A Framework for the Resilient use of Critical Materials in Sustainable Manufacturing Systems ». *Procedia CIRP*, Research and Innovation in Manufacturing: Key Enabling Technologies for the Factories of the Future - Proceedings of the 48th CIRP Conference on Manufacturing Systems, 41 (janvier): 282‑ 88. https://doi.org/10.1016/j.procir.2016.01.003.
Glöser, Simon, Luis Tercero Espinoza, Carsten Gandenberger, et Martin Faulstich. 2015. « Raw material criticality in the context of classical risk assessment ». *Resources Policy* 44 (juin): 35‑ 46. https://doi.org/10.1016/j.resourpol.2014.12.003.
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., et Philip Nuss. 2014. « Employing Considerations of Criticality in Product Design ». *JOM* 66 (11): 2360‑ 66. https://doi.org/10.1007/s11837-014-1188-4.
Graedel, T. E., et Barbara K. Reck. 2016. « Six Years of Criticality Assessments: What Have We Learned So Far? » *Journal of Industrial Ecology* 20 (4): 692‑ 99. https://doi.org/10.1111/jiec.12305.
Griffin, Gillian, Gabrielle Gaustad, et Kedar Badami. 2019. « A framework for firm-level critical material supply management and mitigation ». *Resources Policy* 60 (mars): 262‑ 76. https://doi.org/10.1016/j.resourpol.2018.12.008.
Harland, Christine, Richard Brenchley, et Helen Walker. 2003. « Risk in supply networks ». *Journal of Purchasing and Supply Management*, Supply Chain Management: Selected Papers from the European Operat ions Management Association (EurOMA) 8th International Annual Conference, 9 (2): 51‑ 62. https://doi.org/10.1016/S1478-4092(03)00004-9.
Hassan, Mohsen M. D. 2006. « Engineering Supply Chains as Systems ». *Systems Engineering* 9 (1): 73‑ 89. https://doi.org/10.1002/sys.20042.
Heckmann, Iris, Tina Comes, et Stefan Nickel. 2015. « A critical review on supply chain risk – Definition, measure and modeling ». *Omega* 52 (avril): 119‑ 32. https://doi.org/10.1016/j.omega.2014.10.004.
Helbig, Christoph, Lars Wietschel, Andrea Thorenz, et Axel Tuma. 2016. « How to evaluate raw material vulnerability - An overview ». *Resources Policy* 48 (juin): 13‑ 24. https://doi.org/10.1016/j.resourpol.2016.02.003.
Ho, William, Tian Zheng, Hakan Yildiz, et Srinivas Talluri. 2015. « Supply chain risk management: a literature review ». *International Journal of Production Research* 53 (16): 5031‑ 69. https://doi.org/10.1080/00207543.2015.1030467.
Jin, Yanya, Junbeum Kim, et Bertrand Guillaume. 2016. « Review of critical material studies ». *Resources, Conservation and Recycling* 113 (octobre): 77‑ 87. https://doi.org/10.1016/j.resconrec.2016.06.003.
Jüttner, Uta, Helen Peck, et Martin Christopher. 2003. « Supply chain risk management: outlining an agenda for future research ». *International Journal of Logistics Research and Applications* 6 (4): 197‑ 210. https://doi.org/10.1080/13675560310001627016.
Kenyon, George, et Brian D. Neureuther. 2012. « An Adaptive Model for Assessing Supply Chain Risk ». *Journal of Marketing Channels* 19 (2): 156‑ 70. https://doi.org/10.1080/1046669X.2012.667765.
Khan, Omera, et Bernard Burnes. 2007. « Risk and supply chain management: creating a research agenda ». *The International Journal of Logistics Management* 18 (2): 197‑ 216. https://doi.org/10.1108/09574090710816931.
Kilubi, Irène, et Hans Haasis. 2015. « Supply Chain Risk Management Enablers - A Framework Development Through Systematic Review of the Literature from 2000 to

2015 ». SSRN Scholarly Paper ID 2728911. Rochester, NY: Social Science Research Network. https://papers.ssrn.com/abstract=2728911.
Kim, Juhan, Jungbae Lee, BumChoong Kim, et Jinsoo Kim. 2019. « Raw material criticality assessment with weighted indicators: An application of fuzzy analytic hierarchy process ». *Resources Policy* 60 (mars): 225‑ 33. https://doi.org/10.1016/j.resourpol.2019.01.005.
Knoeri, Christof, Patrick A. Wäger, Anna Stamp, Hans-Joerg Althaus, et Marcel Weil. 2013. « Towards a dynamic assessment of raw materials criticality: Linking agent-based demand — With material flow supply modelling approaches ». *Science of The Total Environment* 461‑ 462 (septembre): 808‑ 12. https://doi.org/10.1016/j.scitotenv.2013.02.001.
Lapko, Yulia, Paolo Trucco, et Cali Nuur. 2016. « The business perspective on materials criticality: Evidence from manufacturers ». *Resources Policy* 50 (décembre): 93‑ 107. https://doi.org/10.1016/j.resourpol.2016.09.001.
Malinauskienė, Milda, Irina Kliopova, Milda Slavickaitė, et Jurgis Kazimieras Staniškis. 2016. « Integrating Resource Criticality Assessment into Evaluation of Cleaner Production Possibilities for Increasing Resource Efficiency ». *Clean Technologies and Environmental Policy* 18 (5): 1333‑ 44. https://doi.org/10.1007/s10098-016-1091-5.
Merzifonluoglu, Yasemin. 2015. « Impact of risk aversion and backup supplier on sourcing decisions of a firm ». *International Journal of Production Research* 53 (22): 6937‑ 61. https://doi.org/10.1080/00207543.2014.999956.
Miehe, Robert, Ralph Schneider, Ferdinand Baaij, et Thomas Bauernhansl. 2016. « Criticality of Material Resources in Industrial Enterprises – Structural Basics of an Operational Model ». *Procedia CIRP*, The 23rd CIRP Conference on Life Cycle Engineering, 48 (janvier): 1‑ 9. https://doi.org/10.1016/j.procir.2016.03.035.
National Research Council (U.S.), Committee on Critical Mineral Impacts on the U.S. Economy, National Research Council (U.S.), Committee on Earth Resources, National Research Council (U.S.), Board on Earth Sciences and Resources, National Research Council (U.S.), et Division on Earth and Life Studies. 2008. *Minerals, Critical Minerals, and the U.S. Economy*. Washington, D.C.: National Academies Press. http://public.eblib.com/choice/publicfullrecord.aspx?p=3378344.
Nyoman Pujawan, I., et Laudine H. Geraldin. 2009. « House of risk: a model for proactive supply chain risk management ». *Business Process Management Journal* 15 (6): 953‑ 67. https://doi.org/10.1108/14637150911003801.
Oliveira, Ualison Rébula de, Fernando Augusto Silva Marins, Henrique Martins Rocha, et Valério Antonio Pamplona Salomon. 2017. « The ISO 31000 standard in supply chain risk management ». *Journal of Cleaner Production* 151 (mai): 616‑ 33. https://doi.org/10.1016/j.jclepro.2017.03.054.
Peck, David, Prabhu Kandachar, et Erik Tempelman. 2015. « Critical materials from a product design perspective ». *Materials & Design (1980-2015)* 65 (janvier): 147‑ 59. https://doi.org/10.1016/j.matdes.2014.08.042.
Philip, Nuss, et Ciuta Theodor. 2018. « Visualization of raw material supply chains using the EU criticality datasets ». In . https://doi.org/10.2760/751342.
Purdy, Grant. 2010. « ISO 31000:2009—Setting a New Standard for Risk Management ». *Risk Analysis* 30 (6): 881‑ 86. https://doi.org/10.1111/j.1539-6924.2010.01442.x.
Rind, D. 1999. « Complexity and Climate ». *Science* 284 (5411): 105‑ 7. https://doi.org/10.1126/science.284.5411.105.
Rosenau-Tornow, Dirk, Peter Buchholz, Axel Riemann, et Markus Wagner. 2009. « Assessing the long-term supply risks for mineral raw materials—a combined

evaluation of past and future trends ». *Resources Policy* 34 (4): 161‑ 75. https://doi.org/10.1016/j.resourpol.2009.07.001.

Schellens, Marie K., et Johanna Gisladottir. 2018. « Critical Natural Resources: Challenging the Current Discourse and Proposal for a Holistic Definition ». *Resources* 7 (4): 79. https://doi.org/10.3390/resources7040079.

Singhal, Piyush, Gopal Agarwal, et Murali Lal Mittal. 2011. « Supply Chain Risk Management: Review, Classification and Future Research Directions », 28.

Slowinski, Gene, Darin Latimer, et Stewart Mehlman. 2013. « Dealing with Shortages of Critical Materials ». *Research-Technology Management* 56 (5): 18‑ 24. https://doi.org/10.5437/08956308X5605139.

Sonnemann, Guido, Eskinder Demisse Gemechu, Naeem Adibi, Vincent De Bruille, et 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 (mai): 20‑ 34. https://doi.org/10.1016/j.jclepro.2015.01.082.

Wieland, Andreas, et Carl Marcus Wallenburg. 2012. « Dealing with supply chain risks: Linking risk management practices and strategies to performance ». *International Journal of Physical Distribution & Logistics Management* 42 (10): 887‑ 905. https://doi.org/10.1108/09600031211281411.

Zsidisin, George A., et Bob Ritchie. 2008. *Supply Chain Risk: A Handbook of Assessment, Management, and Performance*. Springer Science & Business Media.