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Yasmina Ziad, Nathalie Fabbe-Costes

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Upstream supply chain vulnerability assessment: a collaborative research project with a car manufacturer

Yasmina ZIAD

*Aix Marseille Univ, CRET-LOG, Aix-en-Provence, France
&*

Nathalie FABBE-COSTES

Aix Marseille Univ, CERGAM, Aix-en-Provence, France

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Yasmina ZIAD (yasmina.ziad@etu.univ-amu.fr)
Aix Marseille Univ, CRET-LOG, Aix-en-Provence, France

Nathalie FABBE-COSTES (nathalie.fabbe-costes@univ-amu.fr)
Aix Marseille Univ, CERGAM, Aix-en-Provence, France

Abstract

This paper focuses on the concept of supply chain (SC) vulnerability and how to assess it. In the context of an action research project, we conducted an SC vulnerability analysis for an automotive manufacturer. Our goal is to help SC managers prevent risks and SC disruptions, which in turn can improve the robustness of the SC. We propose a number of categories of vulnerability, which are drawn from both the literature and from practice. Using a specific SC case, we present the steps of our assessment approach and discuss the different categories used, how to assess them and how to assess overall SC vulnerability.

Keywords: Upstream supply chain, Vulnerability assessment, Automotive industry

Introduction

Recent events have left their mark on global supply chains (SCs), revealing once again their vulnerability to risk and constant uncertainty. The electronic components crisis, for example, caused major losses for companies in the automotive sector, which were severely impacted by the shortage of parts. The automotive industry lost more than \$200 billion and about eleven million fewer vehicles were produced (Walsh, 2022). Beyond the various crises and uncertainties in the environment, SC risk is also due to how entities interact in the SC. According to Chapman et al. (2002), lack of visibility, misapplication of just-in-time practices, and inaccurate forecasting are factors of risk. The 3rd Supply Chain Risk Barometer (2022) recently ranked the lack of supplier capacity and sourcing problems in the first and fourth places of their top-10 list of SC risks. This same barometer also shows that in 2021 (p.10), 69% of the crises experienced by the companies participating in the study were caused by problems related to suppliers of tier-1, tier-2, tier-3 and beyond, while only 1% of these crises were caused by customers. The barometer also states (p.5) that "*it is therefore urgent for companies to gain some insight into how they can accurately assess their vulnerability and strengthen their strategies and control systems*". In terms of financial impacts, Hendricks and Singhal (2003) found that

announcements of SC failures due to parts shortages were associated with an abnormal decrease in shareholder value of 8.16%.

A large body of academic literature on SCM has focused on SC risks from different perspectives (Zsidisin and Wagner, 2010). However, SC vulnerabilities have received less attention, and even less work has been done on vulnerability assessment to proactively reduce a firm's exposure to risk (Ekanayake et al., 2022; Sharma et al., 2021). Since identifying and reducing SC vulnerability can reduce the number of disruptions and their impact (Wagner and Neshat, 2012) and increase the robustness of the SC system (Asbjørnslett, 2009) as well as its ability to bounce back after a disruption, it is important to develop a methodology for vulnerability assessment, especially for the upstream SC of a global company. Recent crises have revealed that SC managers underestimate the vulnerability of their upstream SC and are not sufficiently prepared for disruptions down the chain (Blackhurst et al., 2018). As a result, recent papers have proposed vulnerability assessment tools and/or methods (Blackhurst et al., 2018; Sharma et al., 2021; Wagner and Neshat, 2012), though very few have studied vulnerabilities all the way back to raw materials. Our goal is to develop a methodology to assess the vulnerability of upstream SCs and answer the following research question: *how can a global industrial company assess the vulnerabilities of its entire upstream SC?*

Based on action research, this paper focuses on the identification and analysis of vulnerability, which is defined as the exposure of the SC to internal or external hazards. The scope of the analysis in this study is part of a carmaker's upstream SC. For the carmaker, the upstream SC is a strategic area for its future development, especially as it is the part most affected by crises.

In this paper we describe what we did to assess the vulnerability of the upstream SC for a car manufacturer, the difficulties we encountered and how we dealt with them. Based on the literature and a real case study, we show how we analysed the vulnerable points in the upstream SC of an automotive component by adding an analysis of raw materials, which play a critical role in the many shortages occurring at the moment. The objective of this vulnerability analysis is to help SC managers prevent risks and avoid SC disruptions. It could therefore be used to improve the resilience and robustness of the SC.

Literature review

Vulnerability: definition, drivers and assessment

Vulnerability is a multidisciplinary concept that applies to individuals, populations and ecological systems. According to the Merriam Webster dictionary, vulnerability is the capacity to be physically or emotionally injured and is synonymous with being exposed or susceptible. It is derived from the Latin "vulnus", meaning injury. In order to explore the concept of vulnerability, we draw on the climate change literature where it has been studied extensively (O'Brien et al., 2004). In the sixth report of the Intergovernmental Panel on Climate Change (IPCC) (Begum et al., 2022), the panel defined vulnerability as the propensity or predisposition to experience adverse effects. The authors of the report consider that vulnerability is composed of three dimensions: exposure, sensitivity or susceptibility to hazards, and the lack of adaptive capacity to cope with them. Exposure is defined as a set of characteristics that can be negatively affected. Sensitivity reflects the extent to which the system is negatively affected by climate variability or change. Finally, adaptive capacity or adaptability pertains to an adjustment process that helps to

mitigate negative consequences or derive benefits. Thus, the system may be less vulnerable if it is less exposed or less sensitive to certain hazards and/or if it has adaptive capacity.

Ontological questions aside, vulnerability is recognized in the SCM literature as important due to the numerous events that regularly alter or stop SC flows. Thus, SC vulnerability is often defined as the exposure of the SC to disruptions (Chapman et al., 2002; Garnett et al., 2020), due to internal or external risks. In other papers, vulnerability is defined as an inherent characteristic of SCs (Deshpande et al., 2023; Wagner and Bode, 2006). Recently, Deshpande et al. (2023), drawing on the work of O'Brien et al. (2007) in relation to the climate change literature, proposed the following definition of the concept of SC vulnerability: *"It is an inherent characteristic of the SC (independent of hazards) and is defined by its present inability to cope with and adapt to the impacts of hazards. SC vulnerability is the result of contextual conditions of an SC, which act as drivers of SC vulnerability. SC vulnerability drivers determine the exposure, sensitivity, adaptive capacity and potential adaptive responses of an SC to hazards."* Deshpande et al.'s (2023) definition recognizes that vulnerability, which is a characteristic of the SC, would be present even in the absence of risk.

According to Wagner and Bode (2006), vulnerability is a multi-faceted concept and there are many factors that contribute to vulnerability. Indeed, Peck (2006) considers that the vulnerability of SCs originates at several levels in a systemic way: value stream / product / process, asset and infrastructure dependencies, organizations and interorganizational networks and the environment in which SC organizations operate. Vulnerability factors are preconditions for the manifestation of risk (Deshpande et al., 2023; Sharma et al., 2021). Among these factors, Wagner and Bode (2006) empirically proved that certain characteristics, such as dependence on certain customers and suppliers, the degree of single sourcing, and dependence on global sourcing, increase the vulnerability of the SC to certain risks. In a recent paper, Sharma et al. (2021) also found that certain practices adopted by firms increased the SC's exposure to risk. The authors identified 26 predominant vulnerability factors in the manufacturing industry. Using an analytic hierarchy process (AHP), they showed that the most critical vulnerability factors are critical parts suppliers, supplier location, long SC lead times, process improvement, and poor strategic alignment in the SC. Similarly, through interviews with different companies, Pettit et al. (2010) identified seven categories of vulnerability factors: turbulence, deliberate threats, external pressures, resource limitations, sensitivity, connectivity, and supplier/customer disruption.

Few papers analyze SC vulnerabilities compared to those on risk analysis (Blackhurst et al., 2018; Sharma et al., 2021) and even fewer propose an approach to assess upstream SC vulnerabilities. A significant body of literature proposes various tools and methodologies for risk assessment at different points in the SC and with different scopes (Deshpande et al., 2023; Zsidisin and Wagner, 2010). However, according to Asbjørnslett (2009), the difference between a risk analysis and a vulnerability analysis lies in its purpose. While risk analysis focuses on the identification and evaluation of a negative event and its impact on the organization, vulnerability analysis focuses on the mission of the system and its survival. Asbjørnslett (2009) developed a seven-step approach to evaluate different vulnerability scenarios for a production system. With a different approach, Blackhurst et al. (2018) propose a combination of two methods of mathematical

and graphical analysis to assess the vulnerability of SCs to disturbances on the basis of a structural analysis. Their proposed method is to reconstruct the propagation path of disruptive events, which can unveil the vulnerabilities arising from SC design, including SC structure, connectivity and dependence. Liu et al. (2016) also relied on an analytical method in combination with relational theory to address the shortcomings of the failure mode and effect analysis (FMEA) method. An enhanced version of the FMEA process allowed the authors to analyze the vulnerability of five SC processes: planning; sourcing, making, delivering and returning.

Based on existing vulnerability definitions and related drivers, and considering current approaches for assessing SC vulnerability, the objective of our research is to develop a dedicated method to analyze the vulnerability of a car manufacturer's upstream SC. Given the high vulnerability of today's SCs to disruptions (Wagner and Neshat, 2012), and the lack of a grounded analysis of the vulnerability of a given SC, conducted in collaboration with practitioners, our approach aims to contribute to a better understanding of the difficulties and solutions associated with vulnerability assessment in the upstream SC in a real-world context.

Design/methodology/approach

The automotive industry plays a major role in the global economy and mobility has become a strategic issue in many countries. The large number of upstream and downstream SC actors, combined with constant cost-cutting has contributed to SC complexity and globalization. Over the past three years, companies in the automotive sector have been very much at the mercy of the Covid-19 pandemic and, even more so, the crisis in electronic components. According to the 3rd SC Risk Barometer, only 9.7 million vehicles were sold in Europe in 2021, one of the lowest volumes since 1990. Moreover, in the coming years, the automotive industry will face several challenges: accelerating the transition to electric vehicles to meet the European Commission's plan to end sales of internal combustion engine vehicles by 2035, addressing declining global volumes, and the development of shared mobility, etc.¹ In addition to these challenges, the industry has been caught in a massive financial trap by the ongoing semiconductor crisis, with the confirmed risk of shortages of certain raw materials.

Our study is based on a collaborative industry-academia research project with a French automotive company. The "risk of SC failure" and "global warming risk" were identified by the company's Corporate Risk Management department as two of the most significant risks to the company in a global risk mapping exercise. In order to reduce the "risk of SC failure", the car company suggested that the researchers work on a methodology to improve knowledge of their SC and to better understand its vulnerabilities. One of the authors of this article is involved in an action research project with the company, while the other participated in a number of key meetings during the study.

Frequent non-directive one-on-one interviews were held with various managers from the automotive company, as well as regular meetings with a group of experts (from the same company) dedicated to developing an approach to SC vulnerability assessment. We interacted with managers from different backgrounds: SC, purchasing, raw material specialists, the engineer in charge of each car component, and the corporate risk manager.

¹ <https://www2.deloitte.com/content/dam/Deloitte/us/Documents/manufacturing/us-automotive-supplier.pdf>

The data was collected in real time using a diary book. We chose strategic car components as a starting point. Together with various expert groups in the company, we tried to trace the flow of suppliers and components back to the raw materials and we identified sources of vulnerability. Based on this experience, we propose a six-step vulnerability analysis and a set of categories derived from both literature and practice. Ultimately, the case demonstrates how challenging it is to assess the vulnerability of an upstream SC.

Upstream supply chain vulnerability assessment

To illustrate our approach, this paper looks at the supply chain of a given component. Together with a group of experts, we chose a component called an exhaust gas differential pressure sensor. It is used to measure the difference in pressure between two points in a system. The differential pressure sensor is part of the emission control system fitted to diesel engine vehicles to meet European emissions regulations. More than half of the cars expected to be sold by the end of 2023 will be equipped with this technology. As a result, any potential failure in this sub-SC will have an impact on more than half of the company's annual vehicle sales. The component is an assembly of several sub-components, including an electronic component, a plastic box and a steel box. The approach to analyzing and attempting to assess the vulnerability of the sensor's SC can be broken down into six steps, which are outlined below.

Step (1): Defining the scope of the vulnerability assessment

There are different starting points for an SC analysis. On the upstream side, it is possible to start by analysing a supplier and its SC, or to start from a given component and/or raw material. With our group of experts, we decided to identify a strategic component as the starting point for our analysis. In other words, we chose a component with a strong impact in case of subcomponent shortage, difficult to replace quickly. In terms of scope, we chose to focus on suppliers' production facilities. Indeed, the data on the product supply network is limited beyond tier-1 to the location of sub-suppliers' production plants.

Step (2): Development of the categories, sub-categories and criteria for component analysis

As shown in other articles on SC vulnerability assessment (for example Deshpande et al., 2023 and Sharma et al., 2021), the assessment approaches are based on a set of categories and their criteria. The categories we used in our assessment came from two sources. Some of the categories were identified in the literature on vulnerability factors presented above. The others were selected by the experts on the basis of categories used in tier-1 supplier assessment documents. Table 1 presents the categories and sub-categories together with their respective definitions. Due to lack of space, it was impossible to include the different assessment criteria for each sub-category.

Almost all of the selected categories are already used by the manufacturer to evaluate tier-1 suppliers. These categories have been identified in the literature. Only one subcategory was added by the expert group, relating to product substitution lead time in case of parts shortages, which we did not find in the academic literature.

Table 1 – vulnerability categories and sub-categories

Category		Sub-category	Category definition
Product characteristic**	A	Alternatives**	The lack of alternatives makes SCs vulnerable. Dependence can originate from customer or supplier due to single sourcing or single customer, for example, which in turn increases risk exposure (Zsidisin et al., 2000).
	B	Life cycle and technology used in the production system**	Product lifecycles are much shorter. The same applies to the technology used to produce the product, which creates vulnerabilities (Pettit et al., 2010).
	C	External pressures**	Influences not specifically targeted at the business that constrain or prevent the business from operating (Pettit et al., 2010).
(SC) structure (Restricted to supplier's facilities)*	D	Location of supplier's plant **	The design characteristics of the SC increase the severity of an SC disruption (Craighead et al., 2007) as well as the location of the facilities, which in turn makes the facilities of the SC vulnerable to disruptions.
	E	Density*	
	F	Complexity*	
Lead time **	G	Product substitution lead time***	The lead time for product substitution refers to the time it takes to obtain an alternative or to obtain an alternative from a second source (Norrman and Jansson, 2004).
	H	Production lead time**	The manufacturing lead time implies a long process lead time and the high number of decision points in the process increases the complexity of the business process (Sharma et al., 2021).
Supplier's capacity **	I	Dedicated lines**	The number of dedicated lines, i.e. those which have a given percentage of their capacity reserved for the production of the component, and the total number of production lines that may be called on. These are important parameters in assessing the level of SC vulnerability as they represent production constraints and reflect the availability of production factors (Pettit et al., 2010).
	J	Number of production lines**	
Demand variation**	K	Demand variation **	Unpredictability of demand by the manufacturer can make the SC vulnerable due to other constraints (Pettit et al., 2010).

(*): Derived from the literature. (**): Derived from the meetings and mentioned in the literature. (***): Derived from the meetings and not mentioned in the literature.

Step (3): Upstream SC mapping

Any company whose SC is known for its complexity must have a mapping system. SC mapping has become an essential tool both for risk prevention and for crisis management. The manufacturer gave us access to its SC tier-n mapping documentation, in particular its Component Supply Chain Charts (CSCC). These documents are completed by tier-1 suppliers following the supplier selection process. When a CSCC is received, it is first

loaded into a file storage system and then into an SC mapping system. From the information in the CSCC, it is possible to know part of the SC structure. In our case, the tier-1 supplier mentions 13 sub-components, of which 12 components come from its own suppliers. During our review of the CSCC, we found that the supplier did not provide any information on the raw materials and their origin. To overcome these difficulties, we suggested analysing the MDS (material data sheet) of assemblies and materials provided by the tier-1 supplier. We analysed the MDS for the studied component and extracted information about the raw materials considered critical by the manufacturer, and we included the criticality rating in the vulnerability categories. This means that we did not have to evaluate the raw materials, we just had to identify them in order to assign a criticality ranking, which is mentioned in the raw material criticality assessment.

In fact, most critical raw materials are analysed by a dedicated department within the manufacturer. For confidentiality reasons, it is not possible to disclose this list of critical raw materials. However, the most critical raw materials in the world are identified in the academic and professional literature. For example, cobalt is generally considered to be a critical material due to its scarcity and its concentration in a critical geographical area: the Democratic Republic of the Congo. Furthermore, in terms of analysis methodology, the approach taken by the manufacturer's experts is similar to that of Yale University analyses (Helbig et al., 2016). The evaluation criteria are price, delivery and ESG data (environmental, social and governance). Analysing critical raw materials allows the company to prioritise the measures to be taken to reduce the risk of raw material shortages in the medium and long term.

Step 4: Data collection for missing information.

Not all of the information requested was available internally, so we had to send a questionnaire to the tier-1 supplier to collect information relating to the following categories: life cycle, process, production technology, lead time and production lines.

Step 5: Category assessment by experts

It was decided that the categories would be assessed by in-house experts. The expert group decided to leave the assessment of vulnerability to the commodity experts, i.e. the engineer, the key account manager and finally the supply planner. One of the researchers organized the meetings and prepared the information needed, i.e. collected the supplier documentation for the selected component and checked the CSCC to see if there was any missing information. We also had a meeting with the key account manager and the engineer to verify the information concerning the tier-n suppliers and their location, as this had not been done previously.

Step 6: Supply chain vulnerability assessment: analysis of categories

The starting point of the analysis is the examination of the available alternatives (A). It is well known that, from a risk perspective, double sourcing is less risky than mono-sourcing. The differential pressure sensor is a component for which there is no known alternative at any stage of the SC. Regarding the life cycle and the technology (B) used in the production process, the supplier did not mention the possibility of a downward trend in production of the component. The technology will continue to be used next year, although according to the manufacturer's experts, there will be some changes due to new regulations regarding the emissions control system. With regards to external pressure (C),

the experts pointed to new regulations as part of the political/regulatory changes mentioned by Pettit et al. (2010), which can be a factor of vulnerability.

For the SC structure (limited to suppliers' factories), the facilities were mainly located (D) in Southeast Asia. Of the 13 suppliers, five were in Malaysia, with the remainder spread between Singapore, the Philippines and China. The manufacturer has its own risk classification of countries based on two criteria: geopolitical and environmental risk. Overall, 8 out of 13 suppliers were located in countries vulnerable to environmental or geopolitical risk or both. Supplier concentration (E) was considered a highly critical parameter, given the significant presence of several suppliers in the same geographical area. Similarly, the complexity (F) of the SC (which we assess by looking at the number of actors involved) was also considered to be highly critical. In addition, the tier-1 supplier has not documented its entire SC, which extends well beyond its 13 suppliers.

The production substitution lead time (G) varies from one component to another. For the evaluation of this category, we were not able to collect all the information on the different subcomponents. The experts estimated that if there were a shortage of the electronic component, the substitution lead time would be quite high, between 6 and 12 months. Similarly, we were not able to obtain precise information on production lead times (H), except for the tier-1 supplier.

In terms of supplier capacity, production lines (I) were only dedicated to the parts closest to the tier-1 supplier; the further away from tier-1, the fewer lines were dedicated to the component studied. Regarding the number of production lines (J), the tier-1 supplier had only one line dedicated to the production of the part.

Variation in demand (K) is known by the supply planner, who has full information about the SC's response to such variation. This was very common at the time due to the crisis in electronic components. Therefore, this parameter was considered very sensitive.

Based on our case study of an upstream SC, we have developed an approach to vulnerability analysis through action research. The steps we have highlighted represent the main steps followed. Due to space constraints, it is not possible to elaborate on the criteria for the analysis in Table 1. However, we can provide further information on request. By developing the criteria, we were able to create a multi-criteria matrix for the company which facilitates the analysis and presentation of SC weaknesses. The case of the differential pressure sensor shows the complexity of the approach. The SC for the sensor appeared to be highly vulnerable to disruption, as discussed with the experts. To take the analysis further, other parameters such as inventory levels, the presence or absence of an additional production line in another geographical area need to be considered. Our approach thus provides a preliminary methodology to study the level of SC vulnerability. Further studies with other components and more intensive data collection should enable us to better explore the vulnerability of the entire upstream SC.

Discussion

By conducting this vulnerability assessment for the SC of a differential pressure sensor, we were able to identify vulnerabilities in the SC of a component that is used in over a million vehicles. There are several key steps in our approach. Mapping the SC – highlighted by Harland et al. (2003) – is a crucial element of our approach. For the case we studied, the mapping provided by the manufacturer gives us a partial vision of the SC structure. However, it is still very complicated for companies to obtain a complete vision, be it upstream or downstream (Fabbe-Costes et al., 2020). Similarly, from the perspective

of the focal firm, the 'visible horizon' is limited and subject to constraints the further one moves away from the focal firm, as argued by Carter et al. (2015) and echoed in Fabbe-Costes et al. (2020). Thus, for the case we studied, since the suppliers themselves do not, in most cases, hold all the information about their tier-n, the mapping is limited to the information that the tier-1 supplier has itself or wants to communicate to the focal firm. Similarly, in analysing the different mapping sheets of the subcomponents, we noticed that the quantity and quality of information varies from one component / supplier to another. However, this does not prevent a vulnerability analysis from being carried out to identify strategic or more vulnerable suppliers, beyond first-tier suppliers, even though the mapping is partial. Regarding the categories we evaluated, most had already been identified in the literature. Another category, related to substitution lead times, was proposed by the expert group. In our opinion, this category is very useful for assessing the vulnerability of the upstream chain: it serves to assess the time needed to validate a second technical alternative in case of a shortage. Furthermore, the studied component is sourced from a single supplier at all levels of the chain. This represents a significant dependency. While mono-sourcing has its advantages, it leaves little room for finding an alternative solution if the alternative must undergo very long quality-control processes (Wagner and Neshat, 2012). In terms of the quality of the information found, there is still much to be done in terms of transparency of information. Similarly, there is very little data available at an individual company level, so a collaborative approach to data collection and analysis with suppliers would be a more interesting way of anticipating weaknesses and triggering corrective action. Likewise, the various mapping and risk analysis tools available on the market are becoming increasingly powerful, and can overcome the complexity of non-digital data collection and analysis, but vulnerabilities are context-dependent (Deshpande et al., 2023) and the mapping provided by external tools is aggregated from different companies, which may be irrelevant to a given company.

Conclusion

Our findings have both academic and managerial implications. Firstly, our literature review showed that very few studies deal with upstream SC vulnerability analysis. By conducting this action research, we found new insights into the difficulties and solutions of upstream SC analysis, rooted in the reality on the ground. From a managerial point of view, our approach allowed us to demonstrate to the various experts we consulted at the manufacturer and some of its suppliers the complexity of analyzing vulnerabilities beyond the tier-1 supplier and the imperfections of SC mapping as well as of available data. It also illustrated the problem of missing data and the lack of transparency between SC actors. Our research has certain limitations. As few components were investigated in this stage of our research, it is impossible to generalize the results. Moreover, the choice of categories was not based on the Delphi method or a quantitative prioritizing method such as AHP, which limits our study and constitutes an avenue for future research. Indeed, an approach whereby vulnerability would be analyzed through categories and scoring criteria would allow us to create an analytical tool with relevant scoring to assess the overall vulnerability of the upstream SC, which is one of our objectives in the next stage of our research.

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