Supply Chain Disruption Management: how to cope with the semiconductor shortage problem in the automotive industry

The case study of Volkswagen Autoeuropa

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Abstract

Nowadays, the automotive industry has been facing a major supply chain disruption (SCD) caused by semiconductor shortages. As a result, automotive supply chains (SCs) are exposed to several supply chain risks (SCRs) that can negatively impact companies' operations and jeopardize supply chain resilience (SCRES). This work was developed in partnership with Volkswagen Autoeuropa (VW AE) and has two main objectives: 1) perform a thorough study of VW AE´s semiconductor SC, in order to cope with the problem of semiconductor shortages; and 2) contribute to the literature with the development of a real case study in an automotive company that addresses the referred problem and studies the concepts of SCD, Supply Chain Risk Management (SCRM) and SCRES. The SCRM process was chosen as the main methodology to study the SCRs that the semiconductor SC of VW AE has been facing. This holistic process permitted: 1) identifying the two most relevant risks (supply failure and production failure); 2) assessing the overall risk score of occurring a production failure; and 3) proposing new mitigation measures to decrease the probability of occurring a production failure and increase SCRES in VW AE´s SC.

Keywords: Supply Chain Disruption; Supply Chain Risk Management; Supply Chain Resilience; Automotive Industry; Semiconductor Industry.

1 Introduction

Nowadays, SCs are becoming more and more complex, interdependent and exposed to SCRs (Shekarian & Mellat Parast, 2021), which enhances the occurrence of SCDs that negatively impact companies' operations (Katsaliaki et al., 2021). The automotive sector is no exception and has been facing a major SCD due to semiconductor shortages, induced by the COVID-19 pandemic (Ramani et al., 2022). This worldwide semiconductor crisis has been causing a massive ripple effect that has affected automotive companies. Volkswagen (VW) and Toyota have closed production facilities in China, while Fiat Chrysler has suspended production lines in Mexico and Canada, and Nissan and Daimler reduced their automotive production in Japan and Europe (Wu et al., 2021). According to the consulting firm *AlixPartners*, the ongoing semiconductor chip crisis might have generated a total loss in revenues for the global automotive industry equal to 110 billion dollars, in 2021 (Wayland, 2021). As a result, due to these chip shortages, automakers are closely collaborating with semiconductor suppliers, signing deals to secure supplies in the future, reducing the risk of supply failures, as did BMW with Inova Semiconductors and Global Foundries or Stellantis with Foxconn (Ramani et al., 2022). Moreover, knowing that semiconductors play a significant role in modern society, not only for the automotive industry but also for technological companies (Mckinsey, 2022), governments and other international institutions are fostering investments to increase the production of semiconductors. In February 2022, the European Commission presented a proposal for a European Chips Act to reinforce the whole European chips value chain (Ragonnaud, 2022) and in July 2022, the United States congress also approved a 50-billion-dollar plan to build up the American semiconductor industry (Swanson, 2022).

The case study of this work was developed in VW AE, an automotive plant located in Portugal and belonging to the VW Group, that has been severely affected by the semiconductor crisis, being obliged to stop its production lines several times in 2021 due to semiconductor shortages. These production halts led to backorders, a high increase in customer lead time and a decrease in profits. Although some reactive measures have been already applied, the crisis persists and a comprehensive study that analyses the problem urges to be developed, focusing on the whole SCRM process. Thus, this work aims to perform a thorough study of VW AE´s semiconductor SC, in order to cope with the problem of semiconductor shortage that is affecting all company´s operations. Simultaneously, it also intends to contribute to the literature with the development of a real case study in an automotive company that addresses the referred problem and studies the concepts of SCD, SCRM and SCRES.

The rest of the work is structured as follows: section 2 reviews the related literature; section 3 presents the methodology and the discussion of the work developed, and section 4 concludes the work and proposes future directions.

2 Literature Review

Semiconductors play a crucial role in contemporary society since they are considered the brain of modern electronics (Semiconductor Industry Association, 2022). Without semiconductors, there would be no computers, cars, smartphones, drones or advanced medical equipment. Besides, semiconductors are more and more used in modern cars to perform a variety of functions, such as safety and driver assistance, connectivity or entertainment (Kumar, 2021). However, these components are not used directly by the Original Equipment Manufacturer (OEM) because they are embedded into modules. These modules are, in turn, integrated into several subsystems of the car that are delivered by the first-tier suppliers and are used to transmit the flow of information and execute orders (Matsuo, 2015).

The recent global disruption in the semiconductor industry severely affected the automotive industry and showed the fragile equilibrium existent in the whole semiconductor SC (Ramani et al., 2022). The main cause of this crisis might have been the great imbalance between supply and demand generated by the COVID-19 pandemic (Wu et al., 2021). Besides, some supply disruptions, such as a cold snap in Texas at the beginning of 2021 that impacted the production of several semiconductor plants (Inagaki & Campbell, 2021) and a fire at Renesas Electronics Corporation in Japan (Inagaki et al., 2021), also contributed for the global disruption. Ramani et al. (2022) developed a comprehensive paper that presented a thematic model of the causes and effects of the semiconductor crisis and explains in detail these and other causes. Nevertheless, the COVID-19 pandemic only exposed the fragile resilience that already existed in the semiconductor SC in the automotive industry. This lack of resilience exists because of the distinct SC characteristics of these two industries, which are highly exposed when there is a significant disruption, like it happened in 2011 after the Tohoku disaster (Matsuo, 2015). Forster et al. (2013) developed a thorough paper that explains in detail the differences in SC characteristics between both industries, namely in terms of cyclicity and volatility; product life cycle; supply of spare parts; quality; lead times; planning horizons and production flexibility. Overall, the market of semiconductors is highly exposed to risks and can be easily threatened. The great concentration of the market in terms of players and geographical area in Asia originates long lead times and difficulty in complying with customer orders (Ramani et al., 2022). Besides, despite being considered the fastest-growing semiconductor market segment in the next decade, the automotive segment will continue to be less important in the customer portfolio of semiconductor companies than the computing and communications segments (Mckinsey, 2022), which seems to limit the bargaining power of automotive companies. The automotive industry also has some risks, namely the low levels of inventory associated mainly with JIT and JIS policies (Graf, 2006), that could jeopardize production if shortages occur.

As SCDs are expected to increase in number and severity in the future (Pereira et al., 2020), automotive companies must be aware of their SCRs and how to deal with them. To do this, SCRM plays a critical role since this methodology helps to identify, assess, mitigate and monitor the risks that can be the source of a disruption and contributes to fostering SCRES and robustness (el Baz & Ruel, 2021). However, although it is recognized as an important methodology, the majority of works in the literature that apply the SCRM process are theoretical in nature and have not been validated empirically, as stated by Ho et al. (2015), which is a research gap that the present work intends to bridge, applying the SCRM process to a real automotive company (VW AE). Moreover, Louis & Pagell (2019) stated that supply chain risk identification (SCRI) is the less studied stage of SCRM and exists a research gap that is urged to be explored. Thus, the present work also intends to contribute to this research gap, developing a new holistic risk categorization. This study will also contribute to the need of studying systemic disruptions, identified by Ramani et al. (2022), since researchers tend to focus on disruptions that have an individual or local impact, instead of systemic disruptions that have a global impact.

3 Methodology and Discussion

In this work, the SCRM process is going to be used as the main methodology since it permits studying the SCRs that the VW AE's semiconductor SC has been facing in a comprehensive manner. The SCRM process proposed by Fan & Stevenson (2018) is going to be adopted, being composed of four stages: SCRI; supply chain risk assessment (SCRA); supply chain risk treatment (SCRT); and SCR monitoring.

3.1 SCRI stage

SCRI is the first stage of every SCRM process and plays a critical role because triggers the following stages of the process (Kleindorfer & Saad, 2005) since only risks that are identified can be afterwards assessed, treated and monitored (Fan & Stevenson, 2018). In this study was chosen the semi-structured interview as the method to collect information regarding the risks that are affecting the semiconductor SC of VW AE. In total, six oral interviews were performed during July 2022, in VW AE's installations. The interviewees were carefully selected, taking into account their responsibilities and experience in the automotive industry and the SCM field. In this way, were selected one SC planner, four SC coordinators and one SC manager. This selection was made to encompass several organizational hierarchy levels, in order to obtain different perspectives and enrich data collection. All interviewees agreed to record the interview, which allows the collection of all information, being this procedure considered the most accurate interview documentation technique (Spieske, et al., 2022; Yin, 2014). It was developed an interview questionnaire to guide the interview and ensure the reliability and comparability of responses (Yin, 2014). This interview protocol was based on a comprehensive literature review of SCD, SCRM and SCRES.

In this work, it is considered a SCR every factor or threat, with a specific likelihood of occurrence, that could produce a negative impact on VW AE's SC. With the semi-structured interviews performed, it was possible to identify several SCRs that affected VW AE's SC: 1) SC disruption risk; 2) supply failure; 3) supplier delay; 4) lack of supplier capacity; 5) delay in transporting supplies; 6) production failure; and 7) incapacity of satisfying car demand within normal lead time.

Several classifications can be applied to classify the SCRs identified. In this work, the classifications of Wagner & Bode (2008) and Ho et al. (2015) are going to be considered, as well as a new proposed risk classification. On the one hand, the classification proposed by Wagner & Bode (2008) has four risk types: demand risk; supply risk; regulatory, legal and infrastructure risk; and catastrophic risk. On the other hand, the classification proposed by Ho et al. (2015) has two main risk types: macro-risks (natural and man-made risks) and micro-risks (demand, manufacturing, supply and infrastructural risks). To the best of my knowledge, these two types of classifications, despite being wide-ranging, have one common limitation: they do not include the possibility of existing a disruption that is not caused by natural disasters or man-made disasters. Therefore, a systemic disruption like the one that is affecting the semiconductor and automotive industries (Ramani et al., 2022), that was not originated from a natural disaster or a man-made disaster, would not be classified as disruption if does not exist a disruption risk responsible for originating it. In this way, it is crucial to create a new comprehensive classification of SCRs that encompasses in the disruption/catastrophic risk category (macro risk category) the subcategory "systemic risk". This new subcategory would include events responsible for originating systemic/market disruptions, that affect SCs and industries worldwide, such as the semiconductor crisis. This new comprehensive classification will also contribute to the need of studying systemic disruptions, identified by Ramani et al. (2022). In this way, this study suggests a new SCR classification, represented in Figure 1, which is an extension of the classification proposed by Ho et al. (2015). Therefore, this new classification encompasses two main types of risk, as Ho et al. (2015) proposed: micro-risks and macro-risks. Micro-risks are going to be considered frequent events that can happen inside the company's SC network, including the relationships established with partners located at all levels of the SC, or outside the company's SC network. This new classification is going to include all the micro-risks suggested by Ho et al. (2015) (demand, supply, manufacturing and infrastructure) as micro-risks "internal to the company´s SC network". Like Ho et al., (2015) did, infrastructure risk is going to be decomposed into information-technology risk, transportation risk and financial risk. Moreover, it is also going to be considered another new subcategory of micro-risks, named "external to the company's SC network", which includes political, environmental and social risks. Another point that, to the best of my belief, was not addressed in the literature, is the dynamic evolution of micro-risks to macro-risks, this is, how the evolution in the severity of one micro-risk or the conjunction of several micro-risks can cause one macro-risk. In the case of the semiconductor crisis, was the conjunction of several micro risks that culminate in the disruption, namely the imbalance between the supply and the demand during the COVID-19 pandemic, this is, the conjunction of supply and demand risks was the main contributor to the systemic risk that originated the disruption. However, this evolution of micro-risks to macro-risks must be deeply studied, remaining a research gap.

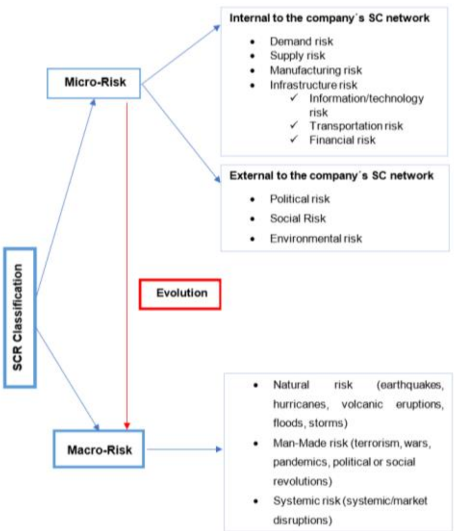

Figure 1 - Proposed SCR Classification

In Table 1, the SCRs identified in VW AE´s SC are classified according to the classifications developed by Wagner & Bode (2008) and Ho et al. (2015) and the one proposed in this study.

Table 1 - SCR classifications comparison

SCR	**SCR Type/Classification according to** Wagner & Bode (2008)	**SCR Type/Classification according to** Ho et al. (2015)	**Proposed SCR Type/Classification**
1	Supply	Micro > Supply	Macro > Systemic
2	Supply	Micro > Supply	Micro > Supply
3	Supply	Micro > Supply	Micro > Supply
4	Supply	Micro > Supply	Micro > Supply
5	Supply	Micro > Infrastructure > Transportation System	Micro > Infrastructure > Transportation System
6	-	Micro > Manufacturing	Micro > Manufacturing
7	Demand	Micro > Demand	Micro > Demand

3.2 SCRA Stage

After performing the SCRI stage, it is going to be developed the SCRA stage. This is the second stage of every SCRM process and, according to the majority of researchers, has the main goal of analysing and evaluating each risk in detail, namely, its likelihood of occurrence and the impact that it can generate (Kern et al., 2012). However, a SCR prioritization must be performed since, as managing risks is a process that requires a substantial investment, companies cannot deal with all risks with the same urgency (Fan & Stevenson, 2018). Therefore, considering the information collected during the semi-structured interview with the SC manager, it was decided to continue studying in the SCRM process the two risks that have a higher impact on VW AE's operations:

1. <u>Supply failure</u> – This risk occurs when a first-tier supplier fails its delivery and it can also be considered the main cause of the production failure risk. As VW AE has very low inventory levels due to the JIT/JIS policies, even an isolated supply failure can lead to a production failure.
2. <u>Production Failure</u> – This risk happens when there is a failure in the production of VW AE and encompasses two situations: the stoppage of the assembly line; and the production of incomplete cars. During 2021 and 2022 this risk occurred several times, either due to the stoppage of the assembly lines or the production of incomplete cars, originated by the lack of semiconductor supplies. This production failure risk is mainly originated by supply failures and can also contribute to originate a systemic disruption that affects the whole SC.

As was possible to acknowledge, these two risks are interconnected since the supply failure is the main cause of the production failure. Therefore, the main objective of this stage will be assessing the probability and impact of occurring a production failure, taking into account the probability of occurring a supply failure. For doing this, the Bayesian Network (BN) theory is going to be used. Thus, a BN that represents VW AE's plant and the first-tier semiconductor suppliers is going to be developed. This BN will be based on the work of Hosseini & Ivanov (2019) and it is represented in Figure 2. Each first-tier supplier, X_i, is represented by a node and can have two possible binary states: failure or not failure. The state failure occurs when the supplier fails the deliver to VW AE's plant and not failure the opposite. The node production failure in VW AE is the ultimate node and it is conditioned on first-tier supplier nodes $X_1, \ldots, X_4$, which implies that the failure of at least one supplier can induce the production failure of VW AE. The node production failure in VW AE can have two possible binary states: failure or not failure. The shortage of microchips in suppliers can induce two distinct situations in VW AE. When the shortage is of indispensable subsystems, called job stoppers, without which the assembly could not proceed, the assembly line is forced to stop until these subsystems are supplied. On the other hand, if the scarcity is of components or parts that could be assembled *a posteriori*, the assembly continue and the car leave the assembly stage incomplete. Therefore, two intermediate auxiliary nodes, job stopper and non-job stopper, were included in the BN to differentiate the supplies that can automatically stop the assembly line from the supplies that originate the production of incomplete cars. These two auxiliary nodes, represented by Y_i, can also have 2 states: failure and no failure. Each node Y_i, whose parents, represented by X_i, are in state x, is in state y with a probability $\mathrm{P(y|x)}$ and $\sum_{\mathrm{y}} \mathrm{P(y|x)} = 1$ for every realization of the states of parent nodes. The conditional probabilities $P(y|x)$ are risk parameters and usually are represented in a Conditional Probability Table (CPT). As each node has two binary states, there are 2^n risk parameters at a node with n parents. Only one supply, power steering, is a job stopper, being the others non-job stoppers. When the first-tier supplier X_4 fails to deliver the power steering subsystem, the production failure is certain.

The unconditional probabilities of each first-tier supplier, $X_1, \dots, X_4$, are assumed to be 3%, as stated by Hosseini & Ivanov (2019), which means that each supplier has a 3% probability of failing the delivery. The failure of a first-tier supplier can cause a failure in the VW AE's production with a specific probability (conditioned probabilities). Each auxiliary node with parents needs a CPT and, as a result, two CPT are needed. The CPT associated with the auxiliary node "non-job stopper" is going to have sixteen risk parameters ($2^4 = 16$) since each one of the four nodes (the "non-job stopper" and the three first-tier suppliers) has two binary states (failure and not failure). Applying the same reasoning, the CPT associated with the auxiliary node "job stopper" has only four risk parameters ($2^2 = 4$). The ultimate node (production failure in VW AE) results from the concatenation of the two auxiliary nodes. Therefore, the probability of occurring a production failure in VW AE will be the sum of the probability of a non-job stopper failure and a job stopper failure, this is, the probability of producing incomplete cars and the probability of existing a stoppage in the assembly line, respectively.

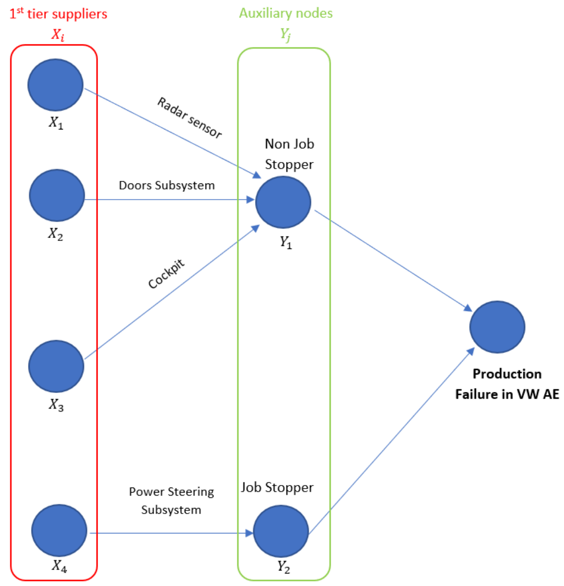

Figure 2 - Proposed BN for representing VW AE's Production Failure

As it is very difficult to obtain the conditional probabilities needed, it has been done an estimation taking into account the percentage of incomplete cars produced due to missing parts of each first-tier non-job stopper supplier in the universe of the cars produced by VW AE in the considered period of time (approximately one year and one month). The missing parts analysed were: radar sensors, door modules, and MIBs, Climatronics and Displays (included in the cockpit). As VW AE produces approximately 200,000 cars per year (eleven months of production), from May 06th, 2021, to June 16th, 2022, were produced approximately 220,000 cars. In this way, the risk parameters for the first CDT are ratios between cars produced with missing parts due to the failure of each supplier and the total number of cars produced. As $\sum_y \mathrm{P}(\mathrm{y}|\mathrm{x}) = 1$, the risk parameters associated with the no failure of the non-job stopper node are complementary events of the conditional probabilities associated with the failure of the non-job stopper node. Table 2 sums up all the risk parameters with the non-job stopper node.

Table 2 - CPT of the non-job stopper node

X_1	Failure				No Failure			
X_2	Failure		No Failure					
X_3	Failure	No Failure	Failure	No Failure	Failure	No Failure	Failure	No Failure
Non-Job Stopper - Failure	0.177	0.094	0.112	0.029	0.148	0.065	0.083	0.000
Non-Job Stopper - No Failure	0.823	0.906	0.888	0.971	0.852	0.935	0.917	1.000

The marginal probability of occurring a failure in a non-job stopper can be computed using the conditional probabilities illustrated in Table 2 and the unconditional probabilities of each first-tier supplier, $X_1, \dots, X_4$, fail its delivery, that are assumed to be 3%. Thus:

$$\mathrm{P\ (Non\ Job\ Stopper\ failure)} = \sum_{X_1,X_2,X_3,} \mathrm{P(Non\ Job\ Stopper\ failure\ }|X_1, X_2, X_3) \times \mathrm{P}(X_1) \times \mathrm{P}(X_2) \times \mathrm{P}(X_3) \quad (1)$$

After performing all the calculations, the probability of a non-job stopper supplier failure obtained is equal to 0.513 %, this is, the probability of producing incomplete cars is equal to 0.513 %. As stated before, the CPT associated with the auxiliary node job stopper has only four risk parameters. If the supplier X_4 fails the delivery, the disruption occurs automatically. Otherwise, the disruption does not happen. Therefore:

$$\mathrm{P(Job\ stopper\ failure}|X_4 = \mathrm{failure}) = 1 \text{ and } \mathrm{P(Job\ stopper\ failure}|X_4 = \mathrm{no\ failure}) = 0 \quad (2)$$

As $\sum_y \mathrm{P}(y|x) = 1$, thus:

$$\mathrm{P(Job\ stopper\ no\ failure}|X_4 = \mathrm{failure}) = 0 \text{ and } \mathrm{P(Job\ stopper\ no\ failure}|X_4 = \mathrm{no\ failure}) = 1 \quad (3)$$

Table 3 sums up all the risk parameters with the job stopper node (failure and no failure).

Table 3 - CPT of the job stopper node

X_4	Failure	No Failure
Job Stopper - Failure	1.000	0.000
Job Stopper – No Failure	0.000	1.000

The marginal probability of occurring a failure in a job stopper can be computed using the conditional probabilities illustrated in Table 3 and the unconditional probabilities of the first-tier job stopper supplier, X_4, fails its delivery, that are assumed to be 3%, as stated by Hosseini & Ivanov (2019). Thus:

$$\mathrm{P\ (Job\ Stopper\ failure)} = \sum_{X_4} \mathrm{P(Job\ Stopper\ failure\ }|X_4) \times \mathrm{P}(X_4) = \quad (4)$$

$$= \mathrm{P(Job\ stopper\ failure}|X_4 = \mathrm{failure}) \times \mathrm{P}(X_4 = \mathrm{failure}) +$$

$$+ \mathrm{P(Job\ stopper\ failure}|X_4 = \mathrm{no\ failure}) \times \mathrm{P}(X_4 = \mathrm{no\ failure}) = 1 \times 0.03 = 3\%$$

Thus, the probability of existing a job stopper supplier failure is equal to 3%, this is, the probability of existing a stoppage in the assembly line is equal to 3%. As stated before, the production failure in VW AE results from the concatenation of the two auxiliary nodes. Thus:

$$\mathrm{P\ (production\ failure\ in\ VW\ AE)} = \mathrm{P\ (Non\ Job\ Stopper\ failure)} + \mathrm{P\ (Job\ Stopper\ failure)} \quad (5)$$
$$= 0.513\% + 3\% = 3.513\%$$

In this way, the probability of VW AE suffering from a production failure due to a failure of a first-tier supplier belonging to the semiconductor SC is equal to 3.513%.

After computing the probability of occurrence of the production failure risk and considering the impact associated with the risk, it is possible to build a probability-impact risk matrix. A probability-impact risk matrix is considered the most used method in SCRA, both by researchers and company practitioners (Fan & Stevenson, 2018). The probability-impact risk matrix built to assess the production failure risk is going to have two variables (probability and impact), such that each variable has an ordinal scale with five score levels. In the probability variable, each score level has one likelihood interval associated, as it is possible to see in Table 4. These intervals were based on the work of Raydugin (2012). The probability variable is going to be fed by the probability obtained through the BN model. The impact variable considers the number of cars not produced in normal conditions and the definition of the five score levels can be consulted in Table 5. This definition was made considering the opinion of the VW AE´s SC manager. The overall risk scores were defined through the probability-impact risk matrix presented in Figure *3*, in which the risk events are ordered in an impact-averse way, this is, the higher the impact score the higher the overall risk score. This probability-impact risk matrix was based on the work of Dinis et al., (2019). Moreover, it was used a colour-coded scheme to visualize risk events according to their overall risk score, in a total of five risk groups. Each definition of risk group, as well as the overall risk score associated with each risk group, can be consulted in Table 6.

In the case of the production failure risk of VW AE, the probability of occurrence was estimated as 3.513%, which belongs to the interval [0.1%;10.0%] and, therefore, has a score equal to 2. According to the VW AE´s SC manager, with this probability of occurrence, approximately 7,700 cars are not produced with normal conditions. In this way, since 7,700 belongs to the interval]5,000; 10,000], this risk has an impact score of 3. Therefore, the overall score of the production failure risk is equal to 12, which can be classified as a medium risk. This overall score is highlighted with a blue circle in the probability-impact risk matrix represented in Figure *3*. Considering that the overall score of the production failure risk is medium, measures should be applied to decrease the probability of occurrence and/or the impact generated by the risk.

Through this comprehensive SCRA stage, it was possible to obtain an overall risk score for the VW AE's production failure risk, combining a quantitative method (a BN) with a qualitative approach (probability-impact risk matrix), which enriches the SCRM process. It is important to notice that this production failure risk is a result of other risks, namely: the stoppage of the assembly line; the production of incomplete cars and supply failures. Indeed, the supply failure risk is the major contributor to generating the production failure risk. Therefore, in the next stage of the SCRM process (SCRT), measures to address the supply failure risk and to strengthen the resilience of the semiconductor SC in the automotive industry are going to be adopted.

Table 4 - Ordinal Scale for probability of occurrence of the production failure risk

Score	Definition
5	Probability of occurrence of the production failure risk higher than 90%
4	Probability of occurrence of the production failure risk higher than 50% and lower or equal to 90%
3	Probability of occurrence of the production failure risk higher than 10% or lower or equal to 50%
2	Probability of occurrence of the production failure risk equal or higher than 0.1% and lower or equal to 10%
1	Probability of occurrence of the production failure risk lower than 0.1%

Table 5 - Ordinal Scale for impact of the production failure risk

Score	Definition
5	Number of cars not produced in normal conditions higher than 28,000
4	Number of cars not produced in normal conditions higher than 10,000 and lower or equal to 28,000
3	Number of cars not produced in normal conditions higher than 5,000 and lower or equal to 10,000
2	Number of cars not produced in normal conditions higher or equal to 1,000 and lower or equal to 5,000
1	Number of cars not produced in normal conditions lower than 1,000

Figure 3 - Probability-Impact Risk Matrix

Table 6 - Risk Groups Definition

Risk Group Colour	Overall Risk Score	Definition
	21-25	Very High Risk
	16-20	High Risk
	11-15	Medium Risk
	6-10	Low Risk
	1-5	Very Low Risk

3.3 SCRT Stage

SCRT is the third stage of every SCRM process and can include five types of risk strategies: acceptance; avoidance; transfer; sharing; and mitigation (Fan & Stevenson, 2018). However, risk mitigation is the main risk treatment type selected to deal with the risks that arise from the semiconductor crisis in VW AE´s SC. Two semi-structured interviews were conducted in this stage with the SC manager and the logistics business unit manager in order to collect information regarding the mitigation strategies already applied by VW AE and to discuss other proposed measures. The procedure followed in these two interviews was similar to the one applied in the six oral interviews performed in the SCRI stage and it was developed a specific interview questionnaire to guide these two interviews.

The mitigation measures proposed and discussed during the interviews are:

1. Firstly, the possibility of raising the level of stocks considering the criticality of the semiconductor supplier, this is, doing a selective banking process. In spite of obliging the VW AE plant or the first-tier suppliers to do a 15-day stock for every semiconductor modules/subsystems, it would be more convenient to perform an analysis to decide the level of stock that each plant or first-tier should have. In this way, analysing the historical data of suppliers´ reliability and the actual demand patterns would allow VW AE to differentiate the most critical suppliers from the others. Thus, the necessary level of stock would be determined according to the criticality of suppliers. Moreover, it would make more sense to raise stocks where the problem is located. During this semiconductor crisis, the supply failures were originated mainly due to the lack of semiconductors in second-tier or third-tier suppliers, which were not able to deliver modules to first-tier suppliers. Therefore, in spite of raising the stocks of final products/ subsystems in VW plants or first-tier suppliers' facilities, it would be more convenient to raise the stocks of raw materials (semiconductors or modules) in second or third-tier suppliers. As this is a problem of lack of semiconductors, and as in general first-tier suppliers have production capacity if they have the supplies that they need available, the stocks should be done upstream in the SC. This raise of stocks upstream also saves costs since it is much more difficult and costly to make and move stock of final subsystems than semiconductors or modules. This measure can be seen as a proactive mitigation measure since the increase of stocks is considered one of the most effective measures to foster redundancy (Sheffi & Rice, 2005).
2. The need to decrease complexity. VW is a group that not only offers a wide variety of car models to clients but also gives them a gigantic possibility of customization. In this way, in the same car model, there are hundreds of possible combinations that increase the complexity when managing the SC because more customizations imply more parts and suppliers to manage. The case of semiconductor modules is no exception. Contrary to other car brands, VW needs an enormous quantity of semiconductors to perform the required functions. An example presented by the logistics business unit manager was the case of the door modules, which vary from one car model to the other, despite having all similar functions, which obliges the sub-suppliers to produce several different modules, raising the human resources and the time needed to do it. This different door modules increase the complexity and the difficulty of managing the suppliers. Besides, as each module is different and has a high degree of specification, it is very difficult to find a substitute. Finding a substitute more easily can decrease the supply failure and, therefore, decrease the probability of occurring future production failures. In this way, this reduction in complexity works also as an effective proactive mitigation measure since it decreases the probability of existing future failures.
3. Connected to the decrease of complexity, it is essential the adoption of standardization and postponement. If, instead of several different door modules, VW requests only one or two standard types of door modules from suppliers, will highly decrease the complexity. Then, if needed, it can be done a software specification *a posteriori* in VW plants, this is, the product specification is delayed to a final step, which enhances product flexibility and decreases the dependency on a specific supplier. The adoption of standardization and postponement works also as a proactive measure (Hendricks & Singhal, 2011).
4. Another point suggested to VW AE's managers was the diversification of suppliers through multiple sourcing, which would allow VW AE to decrease the probability of occurrence of the supply failure risk and, as a result, also diminish the probability of occurrence of the production failure risk. Despite being very difficult to have multiple sourcing in first-tier suppliers since it would require a high investment in connecting all the electronic data interchange systems of VW AE with the first-tier suppliers, this option must be studied. Specifically, the diversification of suppliers more upstream in the SC might be easier to implement since it is there where the main supply issues are located and it is cheaper to invest in upstream suppliers than downstream suppliers.

3.4 Supply Chain Risk Monitoring

SCR monitoring is the last stage of every SCRM process and, perhaps, the least studied in the literature, remaining a research gap (Blackhurst et al., 2008). Nevertheless, VW AE should invest in monitoring the SCRs associated with the semiconductor crisis, namely, the supply failure risk and the production failure risk. This monitoring process will allow VW AE to measure the efficacy that the already implemented measures are producing in containing the negative impact of the identified SCRs. In this way, a continuous check will facilitate the adjustment or modification of the measures, if they are not producing the desired effects. Besides, this process of permanent observation also fosters the SCRI stage because it is easier to identify new threats or risk factors that can originate future disruptions. The monitoring stage should also be done to assess the performance of semiconductor suppliers/sub-suppliers in delivering the supplies needed, in order to be conscious of the probability of occurring a supply failure.

4 Conclusion

This work contributed to performing a comprehensive study of VW AE´s semiconductor SC, in order to cope with the problem of semiconductor shortages. The SCRM applied permitted: 1) identifying the two most relevant risks (supply failure and production failure); 2) assessing the overall risk score of occurring a production failure; and 3) proposing new mitigation measures to decrease the probability of occurring a production failure and increase SCRES in VW AE´s SC. To the best of my knowledge, this work is a novelty since it is the first one that applied the SCRM process to the semiconductor crisis that the automotive industry is facing, contributing also to the literature on SCD, SCRM and SCRES fields.

In terms of future work, it would be important to develop SCRM processes that reflect not only the views of OEMs but also the insights of suppliers located in several upstream tiers since disruptions in OEMs are mainly caused by upstream disruptions in suppliers. This would enable the study of SCDs from different angles, which would enrich the study. Moreover, it would be important to study the dynamic evolution of micro-risks to macro-risks since, to the best of my knowledge, this is an under-researched topic in literature, remaining a research gap. Finally, regarding the stages of the SCRM process, it is critical to invest in studying SCR monitoring since it received little attention in this work and it is also the least studied process in the literature (Fan & Stevenson, 2018; Ho et al., 2015).

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