Model for measure supply risk in supply chains: a SARS-CoV-2 crisis case study

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Abstract

This work presents a model for measuring supply risk based on the financial impact on the company caused by a supply-side disruption that will result in the non-delivery of a purchasing material. A research action methodology is used to develop the model and to illustrate its application on a real case company to manage the SARS-CoV-2 coronavirus supply chain disruption. The model allowed to quantify the potential impact of a disruption of individual purchasing parts and thus to correctly funnel and prioritize risk mitigation activities to overcome the possible disruptions.

Keywords
Supply Chain Risk, Supplier Risk, SARS-CoV-2

1. Introduction
Sourcing and manufacturing globally allow companies to take advantage of differences in cost of labor, cost of capital, infrastructure, the availability of skilled labor and raw materials as well as tax laws, among others. The internet makes it easy to share information worldwide and to find adequate suppliers in distant countries. Low shipping and logistic costs add to the attractiveness of sourcing globally. These factors contribute to the supply chains become more global but at the same time, more complex and have a higher level of risk than domestic supply chains (Manuj and Mentzer, 2008). While a global supply chain may have the benefit of the lowest overall cost, this comes with the disadvantage of increased individual supply risks derived from supplier failures or supply market occurrences (Zsidisin, 2003; Kırılmaz and Erol, 2017). There is a higher exposure to a diversity of political, regulatory, and geographic settings, as well as longer transportation routes. A breakage in any one of the added risk factors may lead to large disruptions and could cause the entire supply chain to fail. Thus, today's supply chain managers are in the challenging situation of having to find the right balance between risks and rewards (Chaudhuri et al., 2018) like the task of a financial portfolio manager.

Supply chain risk management aims to reduce risks and enhance the recovery time after such disruptions. In recent years this theme has been the subject of many studies. Rajagopal et al. (2017) reference 21 reviews in supply chain risk management. Fan and Stevenson (2018) in a systematic literature review mention a high growth rate of publication in this field, 68% of the papers their sample were published between 2011 and 2016. Bier et al. (2020) also notice a substantial increase in the number of publications related to supply chain risk management

Among the different definitions of supply chain risk management, the one proposed by Fan and Stevenson (2018) provides a holistic definition that intends to guide researchers towards solving a real business problem: "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".

Supply chain risk management is not only a patch for the negative effects of global supply chains. Rather, it must be seen as a source of competitive advantage in itself. If a supply chain disruption occurs that affects several competitors in a certain market at the same time, the one company with the best risk management is likely to be least affected or the fastest to recover. This situation can be used by the company to take market share and to gain a long-term advantage over its competitors. Additionally, companies with a strong risk management process can take well-calculated risks that other companies with weak risk management couldn't afford to take. The ISO31000 risk management framework prescribes that the process of risk identification, risk analysis, risk evaluation, and risk treatment is a cycle that must be repeated in proper time intervals. In this process, one of the most difficult tasks is the estimation of the consequences of a certain risk event, this is "If a risk event occurs, what are the consequences?". Kırılmaz and Erol (2017) stress the need to develop an assessment model of risks to support the decision-making process that can be easy to use.

There are numerous types of risks and in the literature different classifications can be found (e.g. Tang and Musa, 2011). While supply chain risk management considers risks along the whole supply chain, it is important to note that for this work, only the supplier-side risks are considered. Rajagopal et al. (2017) provides a classification of ten operational risks including the supply risk which they defined as the "risk from upstream operations associated with suppliers and their supply network, e.g., supplier base selection, long term versus short term contracts, supplier reliability, supply lead time/yield, supplier relationships, inability of supplier to adapt to technological/product design changes".

Despite the diversity of studies in supply chain risk management, there are still several research gaps that need to be addressed. Among them, the is needed to classify and prioritize risks and risk monitoring (Fan and Stevenson, 2018). Rajagopal et al. (2017) also stress the need to develop supply chain risk mitigation models based on robust measures such as value at risk (VaR) that can be used by supply and purchasing managers. Considering these gaps, this work pretends to present a model for risk assessment that measures the financial impact on the company caused by a supplier disruption that will have as a final consequence the non-delivery of purchased material.

This article is structured as follows. In the introduction, the theoretical background on the topic is presented. In section 2 the research methodology and methods used are presented. In section 3 the supply risk is modeled and in section 4 the model is applied in a real case example. Finally, in section 5 the main conclusions are drawn.

2. Materials and methods

This paper describes research done in a real case setting in which the main goal is to improve the supply chain risk management process at Sensirion Holding AG (www.sensirion.com). This company is a globally leading manufacturer of digital microsensors and systems. This company was selected because the electronics and semiconductor industries are one of the industries more affected by supply chain disruptions (Carvalho et al., 2014). Also, one of the researchers has a professional position in the purchasing department; in this way, the research team had the opportunity to be involved in the design and implementation of the solution that allows the company to identify which suppliers represent a higher risk. This is aligned to the need to develop research in purchasing and supply management topics which are based on real problems anchored in practice (Meehan et al., 2016). Considering this, from October 2019 to February 2020, a participatory action research methodology was used to collect and analyze data, and to develop and test a model to measure the risk of supplier disruption. In this paper, to ensure data protection and confidentiality, a factor was used to mask the real data.

One of the benefits of using action research methodology is to induce changes by the researcher and evaluate 'where the multiple parties will benefit'; this means that the research team departs from the traditional positivist research approach. Action research belongs to the critical interpretative paradigm of research in which researchers are seen to be a critical part of the research process and the perceptions and interpretations of the participants are central to understanding (Ticehurst & Veal, 2000). Action research is particularly useful when a study is seeking innovation, change, growth, and transformation of organizations and their leaders/managers (Wilson-Evered & Hartel 2001). It has been suggested that in-depth inductive innovation studies should be conducted to safeguard against the premature adoption of a rigid framework which may limit the scope of inquiry (Meehan et al., 2016). The iterative approach embodied in action research is particularly useful when many variables are not known at the commencement of the research and there is unlikely to be any way of controlling them. Moreover, action research provides flexibility and responsiveness to emerging data and understanding facilitates the refinement of a robust conceptual framework, and rigor and validity are enhanced through multiple approaches to data collection (triangulation) and the creation of opportunities for confirmation and disconfirmation (dialectical processes).

Sensirion, headquartered in Staefa, Switzerland, is a leading manufacturer of digital microsensors and systems. The company employed 783 people at the end of 2018 and earned revenue of roughly 175 million US dollars in 2018. The automotive market is an important market for Sensirion. It was accounting for 31% of the turnover in 2018. With roughly one-third of all cars produced worldwide containing at least one sensor from Sensirion, Sensirion is also an important player in the automotive supply chain. From 2008 to 2017 Sensirion was a tier 2, supplying sensor components to tier 1 companies that integrated the components into modules, which were then sold to the automotive OEMs. In 2017, Sensirion made a strategic acquisition of such a tier 1 module manufacturer, thereby becoming a tier 1 itself (forward integration). The acquisition added two manufacturing sites, one in China and one in Korea, which are also important for the company to stay globally competitive. Other manufacturing locations might follow in the future. In 2018 Sensirion went public through an IPO and is now listed on the Swiss stock exchange (ISIN: CH0406705126).

Both the added manufacturing locations and the increased supplier base due to the higher complexity and product variety of sensor modules make it necessary to review and optimize the current supply chain risk efforts. At the same time, the OEM car manufacturers, which are now direct customers of Sensirion, have recently increased their interest and efforts in supply chain risk management and are strongly encouraging their suppliers to increase efforts in this area as well.

Because Sensirion entered the automotive market already in 2008 and, in many cases, is a single-source supplier for its customers, supply chain risk management is already well established at Sensirion and many efforts are made to ensure an adequate supply of materials, parts, and components. Despite the former supply chain risk management processes implemented by Sensirion, several areas of improvement had been identified as follows:

- There was no established measure to evaluate the potential losses of disruption on purchasing materials in monetary terms. Such a measure is useful in ranking materials, suppliers, and risks and to be able to focus on the most critical ones.
- The risk assessment was often done on a non-regular basis. Yet risk factors can change and previous risk assessments can get outdated. A more continuous and automated risk assessment process was desirable.

At the time of publishing, the desired improvements have been implemented. Considering these managerial problems, the research team addressed the following research question:
RQ: "How could manufacturing companies measure the risk of a supply-side disruption?"
This research question contributes synergistically to a practical concern of the company under study but also contributes to addressing a research gap in the literature. Using this research design, it is possible to analyse this real case in detail and to develop a framework that could be replicable to other industrial settings.

In the first research phase, endeavors were taken to find out which could be the most appropriate way of measuring the impact of a certain risk. To the company under study, measuring the importance of a supplier or a purchasing material in terms of money spent, and to use the same measure as a proxy for its risk and potential impact is not a useful approach. The reason is because even a supplier that ranks very low in money spends can have a big impact on the business if the parts do not get delivered. Also, in a complex product, a low-value part can be just as important for the functioning of the product as the most high-value part. A much better measure for the impact is the "financial loss" that a certain part or supplier would cause if it or he was disrupted. This can be approximated by the loss of contribution margin that would be caused by lost sales if a product cannot be manufactured due to lack of one or more raw materials. It is much more common and easier to think in terms of loss of turnover since the contribution margin must first be calculated from the turnover by subtracting the variable costs. However, it is worth to use the loss of contribution margin for evaluating the impact of a risk, if the data is available. If a certain sales product was disrupted due to the non-availability of a purchasing material and thus could not be delivered on-time, the company would lose the turnover but also does not incur the variable costs associated with the production of the sales product. Hence, the real loss is the contribution margin that the sale would have generated. Using this measure also makes sure that products with a lower turnover but high gross-margin get valued fairly against products with a high turnover but a very low gross margin.

It is important to note that this measure (loss of contribution margin) is probably not good for assessing company internal operational risks. This is because internal production disruptions often lead to scrap material, and thus at least part of the variable material cost is incurred. Hence, the loss is not only the contribution margin but also the cost of the scrap material. In contrast, disruptions (such as quality deviations) that occur at a supplier can usually be charged back to the supplier who caused the problem. It is a common business practice that a supplier will take back bad parts for rework or send new defect-free replacement parts free of charge. Hence, the scrap cost is covered by the supplier. Therefore, in this research, the loss of contribution margin is assumed to be directly proportional to the loss of the company's production rate.

At this point, it is important to note that the non-fulfillment of customer orders can also have further negative consequences other than just the loss of contribution margin. For example, especially in today's internet-based markets, the reputation of a company can easily be damaged and cause the loss of future sales. Moreover, risk events may lead to lawsuits, environmental damages, or even endanger the health and lives of humans. For this work, however, only the financial impact caused by lost sales is considered.

3. Supply risk modeling

Each risk event is unique and the concrete impact is defined by the value of many variables at the time of the disruption, for example, whether the current stock level is high or low. The supplier might have to stop production completely or may still be able to do partial deliveries. Sometimes a risk event has a negative impact on the production rate since there will be not enough materials, parts, or components to sustain the planned production. Both the impact, as well as, recovery characteristic is unique for each event.

To properly model the risk events, this paper uses a generic type of risk event based on four variables (TTD, TTI, TTR and IF), as shown in Figure 1. This type of event allows to describe disruptions where the supplier will still be able to partially deliver the materials necessary to satisfy the demand. This is achieved through the introduction of a so-called "impact factor" (*IF*). This factor ranges from greater than zero to one and describes the percentage of the company's production that is disrupted by the risk event. For example, if the supplier can still deliver 80% of the materials necessary to satisfy the actual production demand, the impact factor is 0.2. On the other hand, if the impact factor is 0.8 this means that the supplier is only able to deliver 20% of the materials needed to comply with the actual production demand. Additionally, since some risk events may be detected in advance of the actual disruption, the "time-to-disruption" (*TTD*) is considered in the model. This allows the company to immediately initiate mitigation initiatives. The "time-to-recovery" (*TTR*) is the time between the detection of the risk and the successful recovery; this is the return to the previous performance in terms of production rate.

The safety stock, if available, provides a buffer between the disruption and the impact on the company production rate. This time buffer is called the "time-to-impact" (*TTI*). In this scenario, the financial loss is proportional to the shaded area in figure 1. A typical example of this type of disruption is for example a lack of human resources because of a strike or a raw material shortage on the supplier's supply-side.

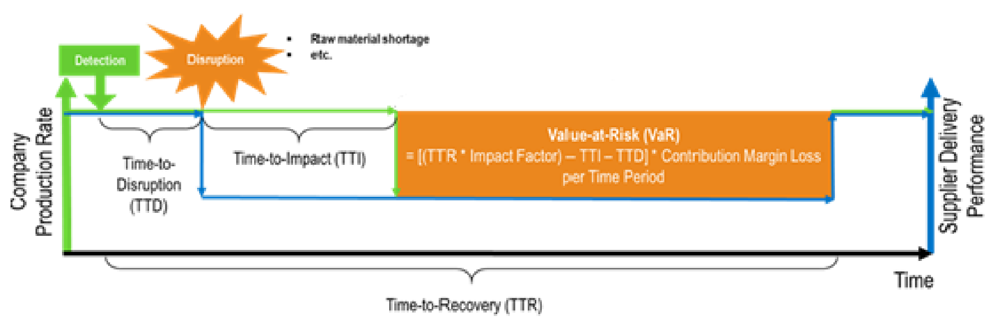

Figure 1. Supplier disruption modeling

In this paper, the "value-at-risk" (*VaR*) definition proposed by Sheffi (2018) is used. For a given period of time, the financial damage derived from a supplier disruption can be computed using data from the Bill of Materials (BOM) and Enterprise Resource Planning system to determine which products might be affected by a given supplier disruption. To compute the *VaR* the following steps are proposed:

Step 1 – For an appropriate future time period (for example the next month or quarter), based on the forecasted turnover and variable costs (mainly cost of goods sold), calculate the contribution margin for each product i (SP_i) by subtracting the variable costs from the projected turnover. Then express it as a percentage of the total contribution margin (TCM) of the company earned in the period of time under consideration. The result is denoted as the contribution margin impact percentage of the sales product i, $CMIP(SP_i)$. It indicates how many percent the sales of product i (SP_i) are contributing to the total contribution margin of the company.

Step 2 - Based on the BOM, is possible to assign the $CMIP(SP_i)$ to all the purchased materials j that are used in the production of product i. Often, the same purchasing material j is incorporated in more than one product. Therefore, it is necessary to consider the sum of all $CMIP(SP_i)$ where the purchased material j is incorporated during the production. This measure is denoted as the contribution margin impact percentage of the purchased material j, $CMIP(PMj)$. For example, if the purchased material Z is used to manufacture products A, B, and C, then the $CMIP(PM_z)$ is calculated as $CMIP(PM_z) = CMIP(SP_A)+CMIP(SP_B)+CMIP(SP_C)$.

Step 3 – If a supplier disruption occurs and the material j is not available, the estimated financial damage also named by the contribution margin loss (per period of time) will be given by $CMIP(PM_j) \times TCM$ x duration of the disruption.

Step 4 – When considering an impact factor (IF_j) that describes the percentage of material j that the supplier is not able to deliver under a disruption, a twofold effect occurs. Firstly, the financial damage (per period of time) will be affected by IF_j. Secondly, since the fraction $1 - IF_j$ of the demand for material j is still being deliverd, the safety stock will allow sustaining the normal production level during a longer period of time. For example, if the supplier can still deliver 75% of the actual production demand ($IF_j = 0.25$), the safety stock will last four times as long, or 1/0.25, compared to a complete disruption scenario. Under this assumption the equation 1 can be used to compute the VaR_j caused by a disruption in the supplier of material j:

$$VaR_j = \left(TTR_j - \frac{TTI_j+TTD_j}{IF_j}\right) \times CMIP\left(PM_j\right) \times TCM \times IF_j = \left(TTR_j \times IF_j - TTI_j + TTD_j\right) \times CMIP\left(PM_j\right) \times TCM \quad \text{(eq.1)}$$

It is important to notice the following assumption in the VaR_j formula:

- It assumes that if a delivery to the customer cannot be made as normal, the sale is lost and cannot be made up for with a delayed delivery. This is for example the case if the customer has a 1-to-1 replacement available, which may or may not be true.

Furthermore, because of this assumption, several issues can arise when applying the VaR in a real-case setting:

- Often missed delivery dates can be made up for with delayed deliveries and are not lost immediately. In this case, the turnover and contribution margin are not lost but just delayed.
- Usually, the customers keep some safety stock of the sales product (their purchasing material) in their warehouses. This delays the time by when the next delivery has to be made and a sale is actually lost. This is not considered in the VaR.
- The VaR presented here only considers the loss of contribution margin. It does not consider damages in reputation that inevitably come with major disruption and that causes lost future sales or higher costs of capital.
- The cost of recovery is not considered. The recovery efforts that are made cost both time and money and can reach a substantial level. Also, the opportunity costs are not considered (for example, engineers working on recovery e orts will lead to delays in other projects).

Most importantly, the VaR is not the risk itself for this event (the risk itself is an expected value), since it does not take into consideration the likelihood of the event. Rather, it is an approximation of the loss that would be caused if the risk event happened and the assumptions which were made held true. The risk can be derived from the VaR of the risk event by multiplying it with the likelihood.

5. Model application: the SARS-CoV-2 crisis

During the time span that the research was developed, a new type of virus (named SARS-CoV-2 by the World Health Organization) first occurred in the Hubei province of China (Wang et al., 2020). It spread rapidly among the local population, leading to an overstress in the hospital system. In order to contain further spreading, the Chinese authorities shut down airports, train stations, and regulated travels between cities and provinces. The regular Chinese New Year's holidays were extended by one week for all companies and even longer for others. Even after resuming operations, most companies struggled with finding operators. Since extensive travel restrictions were in effect inside China, many people could not return to their companies. Even if they could reach their company, they often had to stay in home quarantine for 14 days before they were allowed to show up at work. Deutsche Post and DHL stopped delivering packages to China. Several major airlines suspended their flights to and from China. As a result, many supply chains were disrupted (Paris, 2020).

Sensirion was at the time of this study (end of February 2020) affected by this situation. Several of its suppliers are located in China and other suppliers outside of China have sub-suppliers located in China. Apart from the suppliers, the subsidiary based in Shanghai also had to halt production for one additional week after Chinese New Year and could only partially resume production afterward. A task force was created to assess and handle the situation. On the supplier-side, the above-presented framework would help to continuously assess the supply situation and to manage the crisis. Generally, crisis response in supply chain risk management consists of five basic tasks (Sheffi, 2015) as illustrated in figure 2.

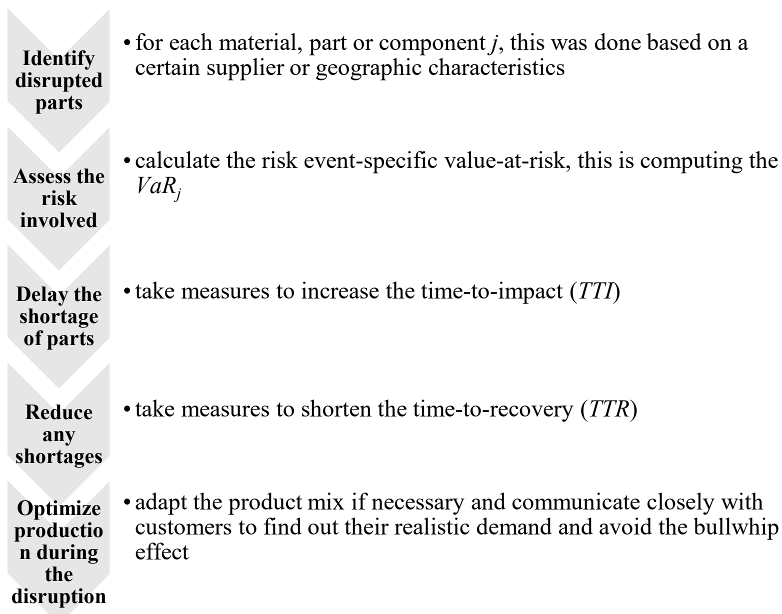

Figure 2. The 5 steps in the crisis response.

For the first step, to determine which materials could be affected, the purchasing materials were sorted by their country of origin (COO). Initially, all materials with COO China were selected. Additionally, all purchasing materials with China as a shipping location were selected. The resulting list contained 34 purchasing materials from 13 different suppliers. Considering the same risk event for all materials (same TTD, TTR and IF), and using equation 1, the materials could be easily ranked by their importance based on the *VaR* and the event. The material with the highest $CMIP(PM_j)$ of almost 50% was a very low value and low spent material. This fact shows the importance of measuring the contribution margin impact instead of ranking the materials only based on their purchase price. Only by knowing the real impact that a purchasing material can have on the contribution margin of the company allows for it to be treated as such and receive the necessary focus.

As a next step, the current *VaR* of the potentially affected materials was measured. Based on the current stock level and current demand outlook, the current TTI was calculated (also known as months inventory held)). The TTD was set to 0, as the event had already occurred. The TTR was estimated to be 4 months with an average IF_j of 50%. As a result, ten purchasing materials were found to have a financial impact and only 5 of them had a substantial impact (see figure 3). Mitigation actions were defined for all ten materials and their suppliers. They were contacted to track their specific situation closely and available material was secured by placing extra orders.

Corona Virus Crisis Evaluation + Tracking

Nr.	Top Risk	Risk Event	Affected Supplier	Affected Material Name	Affected Material Number	TTD	On Stock	Demand Forecast	TTI	TTR	Impact Factor (1-100%)	Current Value-at-Risk	Evaluation
1		Wuhan Virus Epidemic	Supplier 1	Purchasing Material 1	Number 1	0	3'465	846	4.1	4	50%	CHF -	No action needed
2		Wuhan Virus Epidemic	Supplier 2	Purchasing Material 2	Number 2	0	984'622	465'386	2.1	4	50%	CHF -	No action needed
3	1	Wuhan Virus Epidemic	Supplier 1	Purchasing Material 3	Number 3	0	1'459	1'151	1.3	4	50%	CHF 2'725'454	Action needed
4		Wuhan Virus Epidemic	Supplier 3	Purchasing Material 4	Number 4	0	488	214	2.3	4	50%	CHF -	No action needed
5		Wuhan Virus Epidemic	Supplier 4	Purchasing Material 5	Number 5	0	12'000	5'484	2.2	4	50%	CHF -	No action needed
6		Wuhan Virus Epidemic	Supplier 1	Purchasing Material 6	Number 6	0	580	163	3.6	4	50%	CHF -	No action needed
7		Wuhan Virus Epidemic	Supplier 5	Purchasing Material 7	Number 7	0	845	23	37.6	4	50%	CHF -	No action needed
8		Wuhan Virus Epidemic	Supplier 1	Purchasing Material 8	Number 8	0	6'938	1'134	6.1	4	50%	CHF -	No action needed
9		Wuhan Virus Epidemic	Supplier 6	Purchasing Material 9	Number 9	0	17'040	3'088	5.5	4	50%	CHF -	No action needed
10		Wuhan Virus Epidemic	Supplier 7	Purchasing Material 10	Number 10	0	46'308	11'931	3.9	4	50%	CHF -	No action needed
11	2	Wuhan Virus Epidemic	Supplier 1	Purchasing Material 11	Number 11	0	3'300	10'750	0.3	4	50%	CHF 789'107	Action needed
12		Wuhan Virus Epidemic	Supplier 3	Purchasing Material 12	Number 12	0	97	39	2.5	4	50%	CHF -	No action needed
13	3	Wuhan Virus Epidemic	Supplier 8	Purchasing Material 13	Number 13	0	49	48	1.0	4	50%	CHF 443'072	Action needed
14		Wuhan Virus Epidemic	Supplier 1	Purchasing Material 14	Number 14	0	938	101	9.3	4	50%	CHF -	No action needed
15		Wuhan Virus Epidemic	Supplier 3	Purchasing Material 15	Number 15	0	60	18	3.3	4	50%	CHF -	No action needed
16	4	Wuhan Virus Epidemic	Supplier 9	Purchasing Material 16	Number 16	0	-	252	-	4	50%	CHF 192'913	Action needed
17		Wuhan Virus Epidemic	Supplier 6	Purchasing Material 17	Number 17	0	21'849	4'589	4.8	4	50%	CHF -	No action needed
18		Wuhan Virus Epidemic	Supplier 10	Purchasing Material 18	Number 18	0	38'940	4'688	8.3	4	50%	CHF -	No action needed
19		Wuhan Virus Epidemic	Supplier 11	Purchasing Material 19	Number 19	0	69'057	4'589	15.0	4	50%	CHF -	No action needed
20		Wuhan Virus Epidemic	Supplier 11	Purchasing Material 20	Number 20	0	23'776	4'589	5.2	4	50%	CHF -	No action needed
21		Wuhan Virus Epidemic	Supplier 6	Purchasing Material 21	Number 21	0	20'669	4'586	4.5	4	50%	CHF -	No action needed
22		Wuhan Virus Epidemic	Supplier 6	Purchasing Material 22	Number 22	0	21'799	4'589	4.8	4	50%	CHF -	No action needed
23		Wuhan Virus Epidemic	Supplier 6	Purchasing Material 23	Number 23	0	22'382	4'590	4.9	4	50%	CHF -	No action needed
24		Wuhan Virus Epidemic	Supplier 6	Purchasing Material 24	Number 24	0	26'570	4'590	5.8	4	50%	CHF -	No action needed
25		Wuhan Virus Epidemic	Supplier 12	Purchasing Material 25	Number 25	0	12'844	4'586	2.8	4	50%	CHF -	No action needed
26	7	Wuhan Virus Epidemic	Supplier 13	Purchasing Material 26	Number 26	0	10	437	-	4	50%	CHF 49'745	Action needed
27	8	Wuhan Virus Epidemic	Supplier 13	Purchasing Material 27	Number 27	0	-	8'533	-	4	50%	CHF 43'295	Action needed
28	9	Wuhan Virus Epidemic	Supplier 11	Purchasing Material 28	Number 28	0	-	685	-	4	50%	CHF 35'987	Action needed
29	5	Wuhan Virus Epidemic	Supplier 11	Purchasing Material 29	Number 29	0	-	554	-	4	50%	CHF 131'135	Action needed
30	10	Wuhan Virus Epidemic	Supplier 11	Purchasing Material 30	Number 30	0	-	4'142	-	4	50%	CHF 35'922	Action needed
31		Wuhan Virus Epidemic	Supplier 11	Purchasing Material 31	Number 31	0	138'466	22'943	6.0	4	50%	CHF -	No action needed
32		Wuhan Virus Epidemic	Supplier 8	Purchasing Material 32	Number 32	0	42	18	2.3	4	50%	CHF -	No action needed
33	6	Wuhan Virus Epidemic	Supplier 6	Purchasing Material 33	Number 33	0	130'952	41'753	3.1	4	50%	CHF 62'726	Action needed
34		Wuhan Virus Epidemic	Supplier 6	Purchasing Material 34	Number 34	0	59'591	45'690	1.3	4	50%	CHF -	No action needed
											Sum of current VaR	CHF 4'509'356	

Figure 3. Screenshot of the spreadsheet used to evaluate the impact of the SARS-CoV-2 crisis. To ensure data protection and confidentiality, a factor was used to mask the real data.

As the crisis continued to become more and more severe, and the infections spread to other countries, the time-to-recovery for the general situation was increased to 6 months with an average impact factor of 80%. The spreadsheet easily allows to make such adjustments and to consider alternative scenarios. Purchasing materials with COO Hong Kong, South Korea, Japan, and Italy were added to the list. The resulting list now contained 65 purchasing materials from 25 different suppliers. From these materials, the combined current *VaR* of the first 6 materials was equal to that of the other 59 articles. Again, the analysis allowed us to focus on these materials and securing their supply chain. During a crisis, having this kind of information and being able to focus on the highest impact materials is of very high value. When resources are limited, which is almost always the case during crisis management, the right focus allows companies to reduce the total impact to a minimum and to recover sooner than other companies; which can be a source of competitive advantage.

Not only were the mitigation actions being tracked, but also their cost and the resulting benefit was analyzed (see figure 4). The most common mitigation action was to increase the safety stock level. In these cases of increased safety stocks, the cost was estimated based on the cost of capital and storage space needed for the additional stock. The benefit of these or other mitigation actions was measured by either the increase in the *TTI* or the decrease in the *TTR*. Both lead to a lowered *VaR*. This reduction is compared with the cost of the mitigation action (by calculating the ratio of the *VaR* reduction over the cost). A ratio greater than one is overall beneficial for the assumed disruption scenario. Luckily, in a specific situation, it turned out that the purchasing materials with the highest impact were low-cost materials. Therefore, a very large reduction in the *VaR* could be achieved at a very low cost.

				COST							BENEFIT		
Course of Action	Mitigation Actions	Status	Price/Piece	Approx. Cost	Prob. (1-5)	TTD	TTI	TTR	Impact Factor (0-100%)	VaR After Mitigation	VaR Reduction	Likelihood Reduction	**Cost/Benefit**
Mitigate	Sample Action 1	Done	CHF 64.90	CHF 2'776	5	0	5.8	6	80%	CHF -	CHF 4'527'745	0	**1631**
Mitigate	Sample Action 2	Ongoing	CHF 44.33	CHF 1'218	5	0	5.8	6	80%	CHF -	CHF 4'333'519	0	**3559**
Mitigate	Sample Action 3	Ongoing	CHF 2.57	CHF 9'065	5	0	5.8	6	80%	CHF -	CHF 2'303'586	0	**254**
Mitigate	Sample Action 4	Done	CHF 0.81	CHF 717	5	0	4.9	6	80%	CHF -	CHF 2'049'273	0	**2858**
Mitigate	Sample Action 5	Ongoing	CHF 43.03	CHF 903	5	0	6	6	80%	CHF -	CHF 970'902	0	**1075**
Mitigate	Sample Action 6	Ongoing	CHF 2.60	CHF 7'280	5	0	5.8	6	80%	CHF -	CHF 365'528	0	**50**

Figure 4. Screenshot of the spreadsheet used to track the mitigation actions, their cost, and their benefit. To ensure data protection and confidentiality, a factor was used to mask the real data.

As a further step, all the remaining purchasing materials which were not on the current tracking list and which had a $CMIP(PM_j)$ greater than 10% were checked for their status. These were 58 materials, out of a total of 727 purchasing materials. They were checked because of their high impact in case they were also affected. For example, it could be that some raw materials for these parts were coming from affected regions. This cannot be seen just by looking at the country of origin. Also, this step allowed the company to focus on the most critical items.

In addition to analyzing the desired outcome of the mitigation actions by the new *VaR* after their completion, the evolution of the current *VaR* towards the desired state was also being tracked. This was done by calculating and documenting the sum of the current *VaR* over all affected purchasing materials on a daily basis. It allowed us to see any progress made by implementing the mitigation actions.

Note that taking the sum of the current *VaR* only yields the correct result for the total contribution margin impact if all the purchasing materials on the list go into different sales products. If two materials are used in the same sales product *i*, then the $CMIP(SP_i)$ is counted twice and the sum of the current *VaR* is overestimated. Nevertheless, this value can be used as a KPI to see if the risk exposure is growing or shrinking and where the company is standing on the way towards the desired state.

6. Conclusions

The growing complexity and globalization of supply chains make them more vulnerable to disruptions. This leads to a substantial increase in risk and makes it mandatory for companies to have an effective supply chain risk management system. At the same time, resources for risk mitigation and crisis management are limited. Hence, on the supply-side, a system is needed to focus the available resources on the most important purchasing materials and risks. A common approach is to use the amount spend on the material as an indicator of its importance. It has been argued that this approach is flawed, and a better solution is needed. In this paper, a quantitative model for assessing supply-side risks has been developed and implemented at Sensirion Holding AG and successfully tested during the SARS-CoV-2 pandemic. The model allowed the company to quantify the potential impact of a disruption of individual purchasing parts and thus to correctly funnel and prioritize risk mitigation activities. Especially during crisis management, the ability to prioritize and focus is essential. Based on the same model, a process to assess the effectiveness of proposed mitigation actions and to track their progress during the implementation has been presented. A cost-benefit analysis shows its financial viability. The model has been described in a general way so that it can also be implemented and used by other companies.

This research has been limited to describe supply-side risks. For a complete supply chain risk management, also company internal risks and customer-side risks need to be considered. Most notably, the calculation of the potential impact of a purchasing material disruption is based on the sales forecast. However, sales forecasts are inherently inaccurate. The model could be developed further to account for such customer-side risks present in the sales forecast and, for example, consider several sales forecast scenarios.

Moreover, the model to describe risk events was intentionally kept simple and thus assumptions were made that might not hold true. A more enhanced model could be used to better describe the realistic course of a disruption. Specifically, the time-to-disruption and the impact factor are probably dependent on each other. A model could be developed to describe this dependency. Lastly, a quantitative approach to assess the probability of certain risk events is desirable because human judgment is prone to heuristics in decision making which regularly leads to misjudgments.

While it's undoubtedly necessary and beneficial to know what the major risks are and how to handle them in case needed, some risks are not foreseeable. Fires, for example, occur frequently and it would be foolish not to prepare for such a scenario beforehand. At the same time, probably no risk manager reasonably imagined a scenario like the 2011 Japan earthquake and consequent tsunami that would cause a nuclear meltdown and almost lead to the evacuation of Tokyo, until it happened. Luckily, the response to a disturbance mostly follows the same basic principles and processes. This idea is also what the concept of supply chain resilience is based on. Hence, it is not necessary to foresee all risks and to prepare for each one specifically. Rather, by building the supply chain on the principles of flexibility and redundancy, a company can greatly enhance its ability to recover from any kind of disruption in a short time. Thus, to further enhance the long-term stability of the company Sensirion Holding AG, several additional adequate resilience practices are currently being implemented.

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Biography

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