# A Case Study Concept for Supply Chain Resilience Analysis

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*Abstract* — **In times of crisis, the strong characteristic of a supply chain to be resilient is an important success factor. However, logistics structures are complex, and it is difficult for companies to assess where the vulnerable and, thus, critical parts of the supply chain are located. To provide an applicable and easy-to-use method, a two-step approach of resilience analysis was developed. This paper introduces a case study illustrating the different steps of this approach and gives an outlook with a focus on process mining.**

***Keywords - supply chain resilience; supply chain data modelling and simulation; key resilience areas; process mining.***

## I. INTRODUCTION

Supply chain resilience analysis is one of the most important success factors and trends of supply chain management in today's world, e.g., see [1]. Recent events, not least the Ukraine war, have shown like a burning glass how vulnerable supply chains are when hit by external crisis events. But the challenges for companies in dealing with such events are complex. Many companies felt the negative impacts in the form of disruptions to material flows throughout the supply chain. In many cases, the situation was even further exacerbated by an unexpected growth in the company's own business - as it was the case in the construction industry during the coronavirus pandemic.

One challenge that has arisen repeatedly in recent years is that logistics managers often know little about the state of resilience of their own supply chain. In this context, resilience can be defined by the so-called triangle, which highlights the ability of structures to cope with the maximum negative impact of a disruption and the duration of the disruption [2]. The triangle that emerges between these two dimensions characterizes the extent of the current state of resilience. Companies need to define measures to reduce the net negative impact of a disruption with respect to these two dimensions.

This is exactly where our research comes in. Due to the limited knowledge of logistics managers regarding the state of resilience, we propose an easy-to-use procedure to preventively increase the transparency in the network and to simulate possible management decisions to improve the state of resilience. We aim at positive impacts on the dimensions of the resilience triangle by limiting either the maximum loss or the time of disruption, e.g., by storing critical materials in warehouses or by applying a multi-sourcing strategy. In our earlier research, see [3,4], we concentrated on the process that a supply chain resilience analysis should go through. In this paper, we present a case study to illustrate our earlier thinking.

The methodology used to operationalize our approach is case study research for qualitative data collection. The objective of case study research is to adequately represent reality. Case studies are based on empirical investigations that analyze a currently relevant issue in a practical context. Holism, empiricism, interpretation, and empathy can be named as the central parameters for this method [5]. Their use proves to be particularly suitable when the boundary between observation and context is not clearly evident. Therefore, the framework conditions of the phenomenon to be observed must also be included. Related studies analyze relationships and processes and join different methods and data sources [6]. Moreover, the use of a well-defined theoretical basis is particularly important to ensure generalizability of results [7].

The remainder of this paper is organized as follows. In the next section, we briefly summarize our two-stage approach for supply chain resilience analysis, then we present a case study and show how the two stages can be translated into reality. This paper also provides insights into initial analytical results; the next step is to further detail, apply, and discuss the case study with practitioners and to move forward with a process mining application. Concrete initiatives in this regard are summarized in the concluding section.

## II. TWO-STAGE APPROACH OF SUPPLY CHAIN RESILIENCE ANALYSIS

Supply chain resilience analysis should be data-driven by applying the data that is directly available to companies: transactional data, which represents the physical flows in the chain and can be easily captured by Enterprise Resource Planning (ERP) systems, and event logs, which can be used to understand the actual management processes. Based on these two data sets, we have developed an approach that provides a guideline for logistics managers to easily assess both the current state of strategic resilience of the supply chain and the potentials within the actual processes that led to this state [4].

The first stage of our approach relates to the *data-based modeling of material flows* in the supply chain. In this way, a company's network becomes transparent in terms of its incoming and outgoing material flows from internal and external suppliers to internal and external customers. It must be mentioned that a supply chain is actually a very complex

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structure when considering the entire value creation process. Inbound involves suppliers up to the provision of raw materials (tier 1-n); outbound involves customers' customers establishing their own relationships and forming large, interconnected networks. Rather than claiming to be able to model this entire network (which is a challenging, if not impossible, undertaking), we focus explicitly on the direct links in the supply chain from a company's perspective that can be influenced by its own decisions and collaboration initiatives. We have defined the relevant data sets (e.g., columns) to be included in a model sufficient to assess the strategic state of resilience in the enterprise [4]. These data roughly refer to delivery items highlighting the sender and receiver locations (e.g., cities, IDs) of a single material flow, the date and time of delivery, the quantity of material, and relevant metrics such as weight, volume, and landed cost.

We also introduced a set of eight so-called "Key Resilience Areas" (KRAs) that can be focused on to assess the current state of supply chain resilience, which can be derived from the data-based supply chain model [4]. These KRAs provide insights into critical parts of the supply chain. First, there are *vulnerable entities* due to the geographic distribution of included companies (KRA1), suppliers sourced from with a risky single-sourcing strategy (KRA2), the consolidation of different materials within shipments (KRA6), and factories and warehouses that could be critical for valuable materials due to high volumes (KRA8). Second, *vulnerable transport relations* can be revealed in terms of frequent transportation delays of certain relations between senders and receivers (KRA5) or relationships at risk due to long distances (KRA7). A third category of analyses refers to *vulnerable materials* in the sense of an analysis of materials that are currently (not) stored in warehouses (KRA3). In addition, the average storage duration of critical materials (KRA4) shows the total quantity of a stored material in relation to demand.

The use of KRAs can be understood as a strategic assessment of the current structure in terms of its vulnerability, which is an important first step in understanding the state of resilience. Although such transparency of vulnerability is indeed important when implementing long-term strategies to assess the benefits of resilience and efficiency in the supply chain, a deep understanding of the decisions and processes behind this state is essential. Therefore, we propose a second analytical stage that focuses on the actual management decisions related to the processes within the supply chain. *Process mining* has become an important approach in this regard.

One of the biggest challenges in using process mining is the overwhelming amount of event log data available in companies. This is exactly where our approach comes in. To ensure that the highly relevant event log data can be used to uncover real opportunities to improve the state of resilience of a supply chain, the first stage of strategic resilience analysis is used as a filter: the collected event log data should be analyzed with a particular focus on the identified vulnerable entities, transportation relations, and materials. The reason for this is that these parts within the supply chain are responsible for potentially weak resilience and should therefore be assessed and possibly changed.

## III. CONCEPTION OF A CASE STUDY

In this section, we present the concept and initial analytical results of a case study to illustrate the application of the two stages of our approach. We focus on a manufacturing company whose production warehouse is in Hamburg, Germany. The resilience analysis should focus on the inbound material flows from the tier 1 suppliers. It is assumed that all incoming materials are brought to the production warehouse in Hamburg before being shipped to the actual production sites. The company follows a European strategy, which means that all suppliers are located in the European Economic Area, including the United Kingdom.

### *A. Stage 1: Strategic resilience analysis by using a data-based supply chain model*

Stage 1 proposes to develop a data-based model of the supply chain to analyze and simulate vulnerabilities in the network. For the case study, this model represents all inbound material flows from suppliers to the warehouse. In the following, the relevant aspects in the creation of the model and the application of KRAs for strategic resilience analysis are presented and discussed.

<u>Data-based supply chain model</u>

Logistics managers are provided with a complete list of transaction datasets required for the inbound material flow modeling, see [4]. The case study therefore considers delivery items from the last 12 months obtained from the company's ERP system. Here, a delivery item is defined as a single material-specific flow from a supplier to the production warehouse in Hamburg. The data-based supply chain model, thus, comprises the following data sets:

- A sender ID as a unique identifier of the supplier; the ID is assigned in the ERP system, a total of 3,783 suppliers are considered in the case study (E1 to E3783).
- The receiver ID as a unique identifier of the recipient. In the case study, the production warehouse is defined by the receiver ID 'WH1'.
- The country and city where the supply chain entities are located. If they are not included in the transaction data, other location master data should be used. In total, the 3,783 suppliers are in 3,755 cities and 21 countries; WH1 is located in Hamburg, Germany.
- Sending date and receiving date as timestamps which shows the lead time of the delivery item directly; in the case study, we focus on historic shipments from 2021. In total, the data includes 256 dates of shipment and receipt. Furthermore, the defined to-be lead times are available within the data.

- A unique material number that defines the actual shipment; in the case study, we look at 5,865 material numbers (M1 to M5865).
- The quantity of material in the shipment; in the case study, all quantities are expressed as the number of individual parts (not packages).
- The corresponding total weight of the delivery item in the unit kg. If this is not included in the transaction data, it can be calculated simply by multiplying the weight of an individual part specified in the material master data by the quantity.
- Geographic information about the sender and the receiver such as latitude and longitude of all locations. If this information is not available in the company's location master data, it must be calculated; there are various open access tools for this purpose available. We have used the "Log-hub supply chain apps" for this purpose.

The data includes a total of 62,461 delivery items with a total weight of 8,550 tons delivered within 12 months. This corresponds to an average weight per delivery item of 136 kg. Fig. 1 illustrates the inbound supply chain, with each line referring to a specific transport link in the supply network.


Figure 1. Illustration of inbound material flows in the supply chain

We propose a series of KRAs to analyze the current state of strategic supply chain resilience. In the case study, we focus on inbound tier 1 material flows and, thus, on the strengths and weaknesses of the current sourcing structure chosen by the company. To gain a better understanding in this regard, the following KRAs are considered relevant to the case study: the geographic distribution of locations (KRA1), materials sourcing strategies (KRA2), lead time deviations (KRA5), and the transport distances and durations (KRA7).

<u>*State of resilience: KRA1 & KRA2*</u>

With respect to KRA2, 64.7% of the supplied weight [kg] and 75.6% of the material numbers [#] refer to a single-sourcing approach - or at least to a strategy where the incoming material flows were mainly ordered from only one supplier within the last 12 months. Table I provides an overview of the top 10 single-sourcing material IDs by total weight. We see that the corresponding suppliers (out of 2,195 suppliers) account for 21.6% of the total single-sourcing material flow. This is an important aspect of resilience because if one of these suppliers was to fail, there would be significant disruption to the company's production facilities.

TABLE I. TOP 10 SINGLE-SOURCING SUPPLIERS BY WEIGHT [KG]

| Material ID | Sender ID | Sender City & Country | Weight [kg] | Avg. del. weight [kg] | Weight share [%] |
|---|---|---|---|---|---|
| M2537 | E1646 | Kojetin, CZ | 381.016 | 809 | 6,89% |
| M2868 | E2434 | Opava, CZ | 183.688 | 633 | 3,32% |
| M441 | E3184 | Steinfurt, DE | 93.462 | 1.507 | 1,69% |
| M2250 | E3429 | Vaterstetten, DE | 86.219 | 713 | 1,56% |
| M4723 | E2273 | Neratovice, CZ | 79.114 | 977 | 1,43% |
| M3417 | E878 | Duchcov, CZ | 66.762 | 514 | 1,21% |
| M985 | E1002 | Ettlingen, DE | 62.622 | 963 | 1,13% |
| M930 | E2666 | Radebeul, DE | 62.554 | 2.406 | 1,13% |
| M5097 | E2677 | Rakovnik, CZ | 61.434 | 407 | 1,11% |
| M444 | E1509 | Idstein, DE | 59.701 | 1.456 | 1,08% |
| M2126 | E3184 | Steinfurt, DE | 58.996 | 1.054 | 1,07% |

Based on the bills of materials of the company under consideration, an indicator was added to the material master to indicate whether a material ID should be considered as critical or not (e.g., referring to the ABC/XYZ classification per material ID). The inbound data shows that 822 single-sourcing suppliers (from 2,195) refer to a material ID that can be classified as critical. Table II provides an overview of the geographic clusters of these suppliers in relation to the top 5 countries, the number of critical suppliers in each country, and the weight.

TABLE II. CRITICAL SUPPLIERS PER COUNTRY (TOP 5)

| Country | Suppliers [#] | Weight [kg] | Weight [%] |
|---|---|---|---|
| DE | 281 | 132,903 | 23.47% |
| CZ | 271 | 397,199 | 70.15% |
| SK | 116 | 1,430 | 0.25% |
| FR | 68 | 10,717 | 1.89% |
| IT | 41 | 6,933 | 1.22% |

It becomes clear that Germany and the Czech Republic represent a geographical cluster of single-sourcing suppliers for critical materials (KRA1). In particular, the Czech Republic appears to be a very important region, as 70.15% of incoming material flows by weight [kg] are shipped from there. Hence, although most of these suppliers are in Germany (282), the functioning of shipments from the Czech Republic is of great importance for a functioning supply chain. In addition, a comparison of the top ten individual suppliers of critical materials and the top ten individual suppliers overall (see Table I) shows an overlap of six suppliers (E1646, E2434, E3184, E2273, E878, E2666, E3184). Thereby, five of these suppliers are in the Czech Republic, which underlines the criticality of the region. Fig. 2 summarizes the findings from the KRA1 analysis in terms of the top 30 suppliers of critical materials by shipping weight [kg].

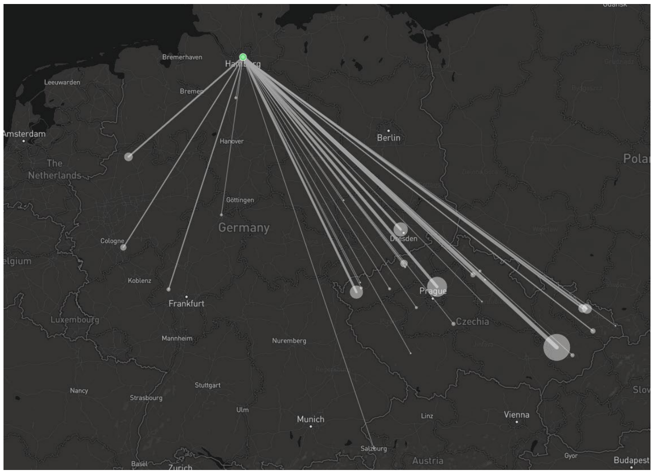


Figure 2. The top 30 single-sourcing suppliers of critical materials

*State of resilience: KRA5 & KRA7*

A deeper understanding of the resilience state of inbound material flows can be gained by examining the lead times experienced by suppliers in the past (here: 12 months). Second, the geographic locations of the suppliers provide direct insight into the actual transportation time and distance to the recipient - the longer this time and distance, the more susceptible the relation is to disruption (KRA7).

In the model, we can see target lead times of 7 days (Germany) and 20 days (e.g., Finland) defined by the companies. In addition, the actual lead time can be calculated based on the available sending and receiving time stamps. Since there are usually multiple shipments available per supplier within the considered time frame, we analyze the average lead time per supplier by comparing this time with the defined target lead time. The results show that in 2021, 371 suppliers (9.9%) had an average lead time deviation of more than 7 days. The corresponding shipping weight of these suppliers was relatively low (0.97%) and only 673 delivery items were affected.

While this suggests a relatively robust structure and, thus, resilience of the current network, there is still a risk that those suppliers could cause significant supply chain disruptions. This is particularly true for 151 suppliers that are in addition single-sourcing suppliers, and even more specifically for 20 of these single-sourcing suppliers who are delivering critical materials. It is imperative that decision makers should continue to monitor these suppliers, develop strategies to improve their delivery times, and avoid supply chain disruptions.

Finally, KRA7 refers to those suppliers characterized by long transport distances and/or times. In particular, single-sourcing suppliers identified in KRA5 that also supply critical materials face an increased risk of disruption if they are located at a great distance. The KRA analysis shows that 8 of these 20 suppliers are long-distance suppliers. Fig. 3 summarizes the results with respect to the 20 single-sourcing suppliers of critical materials; the 8 long-distance suppliers - which by definition are more than 1,200 km away from the warehouse - are highlighted in white.


Figure 3. Critical single-sourcing suppliers regarding KRA5 & KRA7

*B. Stage 2: Process mining of procurement strategy*

In stage 2 of our approach, we suggest using process mining to precisely examine delivery items which are classified as critical in stage 1 in a more detailed analysis regarding root causes. Process mining offers the advantage of identifying the as-is process with its variants as it actually runs in the company. In this way, all foreseen and especially non-foreseen deviations become transparent.

*Introduction to event-log based process mining*

The process mining approach subsumes methods for analyzing business processes based on digital traces that instances leave in the system during their execution [8]. Process mining is based on various data sources that are collected based on events in an event log. On the one hand, the preparation of event logs must focus on the relevant data in the sense of simplicity according to Occam's razor; on the other hand, the loss of information must be minimized so that the event log is valid [9]. To conduct process mining, it is necessary to store additional data elements (e.g., attributes of resources) to leverage information about resources and organizational perspective. Process steps that were not previously recorded in terms of data can be considered as part of process mining. However, they must be added to the event log so that they can be considered within the current model. Since such manual processing usually proves to be time-consuming and uneconomical in operational practice, corresponding data has rarely been generated or used to date [10]. However, the event log must contain the relevant data for the considered process.

*Process mining with focus on the procurement process*

In the case study, we focus on the procurement process of the company under consideration. The application of process

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mining requires the execution of three steps. Step 1 is the collection of all events in an event log that include all relevant actions taken by the planner. The order line item should be used to uniquely identify the events. In step 2, the to-be process model is generated. All actions to reveal the standard procurement process are being plotted. Fig. 4 illustrates the process model regarding the procurement process as the result of step 2; the flashes show where the process can be interrupted.

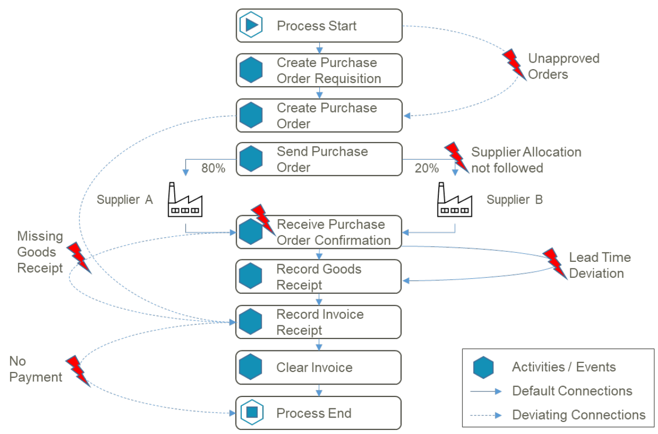


Figure 4. Generation of the process model using the example of a procurement process (step 2)

Step 3 finally focuses on the process analysis and improvements: the process starts with the creation of a purchase order requisition. If the first visible event is the created purchase order, it becomes transparent that an approval in the form of a purchase requisition is possibly missing. The next event that should be logged is that the purchase order has been sent to the supplier and confirmed. If the setting provides that orders should be allocated between more than one supplier, e.g., the setup follows a dual or even multiple procurement strategy, but the event log shows that purchase order confirmations are only received by one supplier. This immediately points to a possible shortfall in the process with an immediate negative impact on a company's state of resilience for this material. Also, if the event log shows that no purchase order confirmation has been received (although the supplier is maybe delivering), we can assume a lack in the process that negatively impacts the company's ability to act well in advance before a shortage becomes apparent because the material is actually missing.

Moreover, by the event goods receipt, a deviation in lead time from what has been agreed with the supplier can be detected. A permanently increased lead-time exposes the company to additional risks. Often forgotten is payment as the last step in the procurement process. The acceptance of an invoice for material that might not even been received is a financial risk. This - from a supply chain perspective more critical step - occurs if the invoice is properly cleared. Missing on-time payment can not only lead to a discontinued supply but also harm the company's reputation amongst its suppliers which negatively impacts the company's state in terms of preferred delivery in a bottleneck situation.

The provided examples underline the power of process mining. In fact, the purchasing process generally being followed becomes transparent as well as - even more important - unforeseen and unknown deviations from the standard. Now we are using the findings from stage 1 to focus our analysis in a targeted manner on precisely those materials and suppliers that were previously classified as critical. In this way, our approach allows us to reduce the extent of the order lines to be analyzed in a way that makes it manageable in practice. Immediate measures directly addressing the weaknesses identified by the event logs can be simulated and followed through.

Further advantages of the suggested two-step approach of a supply chain resilience analysis providing insights on the eight KRAs followed by implementation of measures derived from process mining in a very cost-effective way can be further illustrated using the procurement process. Decisions taken in the Source-to-Contract phase that expose the company to an increased supply risks can be identified by a combination of KRA2 (sourcing strategy of materials), KRA5 (transport delays), and KRA7 (transport distance). This allows to increase the resilience of a company's supply chain also from a strategic perspective, e.g., by increasing the number of suppliers, located at least domestically or even globally. Strategic decisions in terms of sourcing amongst others could also be to move supply from direct to indirect sources, to use bigger suppliers and to invest in long-term relationships.

Given the strategy has been adjusted to address weaknesses in the eight KRAs the second step assures that the strategy is also followed through the whole organization. Process mining relentlessly logs every operational decision as an event and, thus, every deviation becomes transparent and can be addressed by managerial action.

## IV. CONCLUSION AND FUTURE WORK

Our research is based on real-world experience of past global crises which have shown that, first, a resilient supply chain design can be a success factor and, second, the current state of resilience is often not transparently available to logistics managers. Therefore, we developed a two-stage approach that sequentially uses data analytics and process mining to capture and improve the state of resilience within the supply chain. In this paper, we presented the concept of a case study focusing on the inbound material flows of a company whose warehouse is in Hamburg, Germany.

According to the first stage of our approach, we developed a data-based supply chain model that summarizes the shipments of materials from suppliers to warehouses. Using this model, we identified and analyzed elements in the supply chain that could be at risk, such as vulnerable locations or materials, via so-called KRAs. In the second stage of the approach, we showed how process mining of current procurement event logs can provide further insight into the decisions made by the company in the past and highlight measures to improve the current state of resilience. Thus, possible future configurations of the supply chain can be simulated and, thus, provide strategic decision support for logistics managers. It must be mentioned that this second stage is a work in progress concept which has not yet been verified with real data in the form of event logs. However, the case study illustrated the applicability of transaction data in terms of assessing the strategic state of resilience of a supply chain.

Hence, the next step required for the continuation of the approach presented is to choose a business case to gather the data elements. The following guiding principles, based on the "Process Mining Manifesto" are of particular importance here [11]. First, significant events need to be identified and evaluated. By looking at an example of a procurement process that follows a fixed procedure also for compliance reasons, we assume that the quality criteria as defined by Peters et al. can be met [10]. The next principle that needs to be considered for the continued research is the amount and condition of data that is being used. It proves to be purposeful to adjust the quantity and the quality of the data to one's own requirements. The level of detail or granularity of the selected attributes plays an important role for the event log data. Looking at a procurement process, it makes sense to be able to trace the document flow for individual purchase order items or lines (and not just purchase orders). For this, attributes such as the ID (identification number) of the purchase order items, the purchase order number or the material number are required [10]. Also, the question must be clarified which data should be analyzed to avoid "noise" in the sense of taking irrelevant data into account [11]. From our view, the presented case study results already show at this point that the two-step approach to supply chain resilience analysis with the KRAs concept is suitable for this purpose.

A limitation of contemporary process mining techniques can be seen in the fact that they tend to focus on distinct process instances and not on the multi-case setting of business process simulation. An event log with a unique and consistent case ID is available for this purpose. To utilize a multi-case context in supply chain resilience management, approaches, such as the multi-event-log and the execution management system from Celonis or the object-centered process mining of van der Aalst et al. can be applied [13,14,15]. Their goal is to provide multiple event logs that allow process correlations to be analyzed without having an overarching case ID. For the above-mentioned reasons, we intend to continue our research on the example of the procurement process. The KRA developed in stage 1 refer, however, also still to a whole set of other supply chain related processes of a company's operational performance. As things stand today, these must be analyzed individually by means of process mining, analogous to the procedure described for the example of the procurement process in stage 2. Here, a still more extensive linkage and recognition of the continuity would be desirable. We see the chance to even create an overarching case ID, for example, by linking the purchase order item with the transport order in the future. In the complex field of supply chain resilience management, this fact proves to be of central importance.

## ACKNOWLEDGMENT

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