Inbound Supply Chain Resilience Analysis Based on Key Resilience Areas

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ABSTRACT

Supply chain resilience has moved up the corporate agenda in recent years, not least because of the number of crisis events that have caused supply chain disruptions. The aim of this paper is to shed light on the inbound supply chain and its strategic resilience status, using the resources already available to decision-makers within the organization. To do this, we translate a holistic set of previously developed Key Resilience Areas (KRAs) into concrete analytical steps to reveal weaknesses in the network in terms of vulnerable suppliers and materials. We illustrate our thinking with an example that focuses on the inbound side of a fictitious manufacturing company based in Hamburg, Germany.

INTRODUCTION

A resilient supply chain reflects an organization's capability to anticipate, prepare for and respond to supply chain disruptions. The issue has gained momentum in recent years, due to major crises that have affected global supply (e.g., Covid-19 pandemic, Suez Canal disruption). There are several reasons why supply chain resilience is a business enabler (for a comprehensive review of supply chain resilience, see Blackhurst et al. 2005; Rao and Goldsby 2009; Ghadge et al. 2013, Yang et al. 2021):

- By being resilient to disruption, companies can minimize the impact of unexpected events on their operations and bottom line.
- The ability to respond quickly and effectively to disruptions can help companies avoid costly shutdowns or delays.
- Companies with resilient supply chains are better able to adapt to changing market conditions and maintain their competitive edge.
- Supply chain resilience ensures that the company can continue to operate under adverse conditions, enabling companies to minimize the risk of long-term damage and to ensure business continuity.
- Companies that can maintain business continuity during a crisis can protect their brand reputation, which is particularly important to customers and stakeholders.

Although supply chain managers are aware of the importance of this issue, it has rarely been addressed and translated into a structured process within companies - as the primary focus has been on efficient supply chains. This is where our research comes in. Our aim is to develop a practical approach that proactively guides decision-makers in logistics to design a resilient supply chain. Our research follows three premises. 1) The topic of resilience has rarely been considered by companies in recent years, accompanied by a lack of knowledge and ability to even estimate the current resilience status of their network. 2) Time is a critical factor in business today. Decision-makers need cost-effective and pragmatic support rather than comprehensive models for detailed resilience analysis, e.g., using complex optimization models. (3) All the ingredients for such resilience analyses are actually available in the company and can be used directly, but guidance is lacking, and application-oriented research should support decision-makers in this regard.
We have taken the first steps to support decision-makers and presented our ideas in previous publications (Schätter, Morelli & Haas 2022, Schätter, Haas & Morelli 2022). In what follows, we build directly on these ideas to show how our proposed concept of Key Resilience Areas (KRAs) can be translated into concrete steps for analyzing inbound supply chain resilience. The rest of this paper is structured as follows. In the next chapter, we describe the concept of KRAs in terms of the different process links within a supply chain. We then shift the focus to inbound supply chain resilience analysis and present simulation sequences that should be conducted in this regard. To illustrate our considerations, we apply the sequences directly to a fictitious manufacturing company in Hamburg, Germany.

ANALYSIS OF KEY RESILIENCE AREAS

The aim of our previous research using KRAs was to identify vulnerable parts of the supply chain in terms of entities, materials and transport relations based on a limited set of transactional data highlighting historical delivery items (Schätter, Morelli & Haas 2022, Schätter, Haas & Morelli 2022). Therefore, we have developed 8

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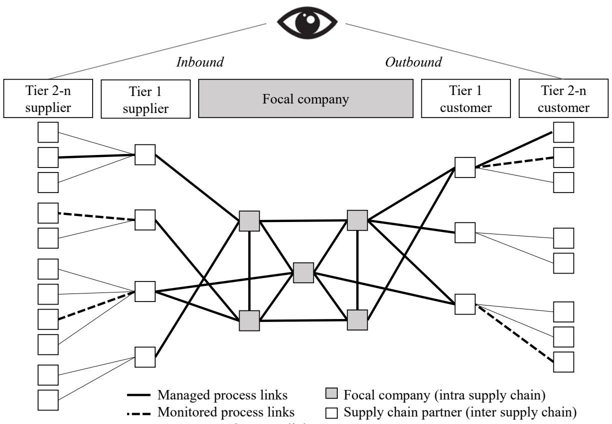
KRAs (KRA$_{1-8}$) covering different aspects of the supply chain that may be critical with respect to disruptions: the geographic distribution of entities (KRA$_1$), the sourcing strategy of materials (KRA$_2$), warehouse materials (KRA$_3$), average storage times (KRA$_4$), transport delays (KRA$_5$), consolidations of deliveries (KRA$_6$), transport distances (KRA$_7$), and intra-logistics processes (KRA$_8$). The KRAs can be directly analyzed within data available in the data warehouses of the companies. Rather than setting up and applying overly analytical approaches that are time consuming and costly, we believe it is more valuable to use the resources already available in an organization - namely transactional and master data - to provide a rough but quick initial indication of the strategic resilience status of the supply chain. The KRA grid provides a framework for this purpose. In this way, we help decision-makers take a first step into the complex issue of strategic supply chain resilience and enable them to answer the question: how strategically resilient is our network?

In the following sections, we describe the focus of resilience analysis using the KRAs for the different parts of a supply chain. We then describe how the analysis can be extended to the entire supply chain.

Focus of the KRA analysis

The focus of the KRA-based resilience analysis is not on the entire supply chain, but on the process links that are under the direct control of a focal company. Figure 1 shows an abstract representation of a supply chain from n-tier supplier to n-tier customer and the corresponding process links (adapted from Lambert et al. 1998).

Figure 1: Process links and focus of supply chain resilience measurement



It is clear that a distinction is made between the *intra supply chain*, which includes all entities (e.g., warehouses supplying production sites) of the focal company itself, and the *inter supply chain*, which includes the interactions with the inbound and outbound tier 1 partners, as well as the interactions between the other partners involved in the further stages of the value chain. The focus of the KRA analysis is on all *managed process links*, as these are under the direct control of the focal company, including availability of required transactional and master data: process links in the intra-supply chain and with the inbound and outbound tier 1 partners, as well as some process links between other partners on the tier 2 to tier n level (e.g., due to joint ventures). The other process links, which are *monitored process links* and *non-monitored process links*, are excluded from the KRA analysis since the associated data is not directly accessible. Possibilities to extend the analysis to those parts is discussed below.

The KRA analysis of managed process links refers to the physical movement of materials either between companies (inbound, outbound) or between units of the focal company (intralogistics). Therefore, different KRAs can be used for different sides of the supply chain:

- *Resilience of direct inbound process links:* On the inbound side of the supply chain, resilience is determined by the geographical distribution of entities (KRA$_1$), e.g., whether there are large aggregations of suppliers in certain areas that could be at risk - and which could be compared with external information such as country risk indices e.g., Operations Risk Index, Political Risk Index. Secondly, the sourcing strategy (KRA$_2$) is essential to determine the number of suppliers per material number delivered to the focal companies' warehouses and/or factories and required within the Bill of Materials (BOM), highlighting redundancies in the network (of course, a supplier may supply different material numbers to the focal company, which is reflected in a number of delivery items.). Another option to identify alternatives are substitute references if they are already maintained in the master data on material number level. It should be a further scope to analyze where transport delays have occurred in the past (KRA$_5$), which may be the case if the transport infrastructure does not provide sufficient redundancy in terms of alternative transport channels. Related to this is the analysis of transport distance (KRA$_7$), which may be more susceptible to disruptions for long-distance deliveries from distant suppliers. Finally, transactional data can be used to examine how shipments are consolidated (KRA$_6$) in order to see the frequencies of supplies.
- *Resilience of direct outbound process links:* On the outbound side of the supply chain, the geographical distribution of entities is also relevant, with a focus on customer clusters describing large sales areas or individual customers with a history of high demand (KRA$_1$). These clusters could also be compared with country risk indices as described in the previous paragraph. All transport-related KRAs are also relevant to measuring the resilience of the outbound network. They provide information on transport delays (KRA$_5$), which is relevant as delays are associated with loss of reputation and probably market position. Even if no delays have occurred,

transport distances should be examined to identify possible future difficulties with long-distance customers (KRA_7). Finally, the frequency of past deliveries to the customers is important and is directly related to how well they have been consolidated in the past (KRA_6).

- *Resilience of direct intra supply chain process links*: Transactional data can also highlight supplies between and within entities of the same company. For example, the intra supply chain includes factories and warehouses, and insight into the resilience of the underlying material flows is also important. The transport-related KRAs are relevant again: the geographical distribution of the company's own entities (KRA_1), transport delays of material flows through these units (KRA_5), transport distances (KRA_7) and frequency of deliveries within the intra supply chain (KRA_7). In addition, an important aspect is the stockpiling of materials, as there are buffers of certain materials (KRA_4). For example, the frequency and quantities of materials entering and leaving the company's warehouses can be used to determine whether there is sufficient stock of a material to bridge a supply disruption. Other aspects such as replacement time and durability of materials should be a focus of the analysis. Finally, intra-logistics processes, such as the handling of incoming and outgoing materials at the focal company entities, should be examined (KRA_8) when exploring the intra supply chain resilience status.

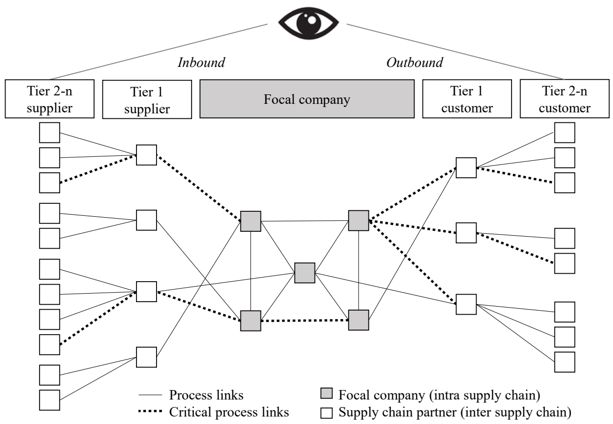
The result should be lists of vulnerable entities, materials, and transport relations in the supply chain. Thus, based on the results of the KRA analysis, the focal company will get a concrete indication of the status quo, e.g. by examining the share of vulnerable materials in the whole network. This is useful in two ways: firstly, to examine the past and identify bottlenecks in the supply chain that may be critical and could be controlled; and secondly, to look into the future, for example, by developing the BOM for future projects and simulating what proportion of these products could lead to severe disruptions in this regard. In this way, our analysis provides a kind of traffic light system to show where something critical might happen in the future supply chain application.

Extension of the KRA analysis

As mentioned above, the concept of KRA analysis could also be extended to the process links in the supply chain that are not under the direct control of the focal company, i.e., *monitored process links* and *non-managed process links* (see Figure 1). The main obstacle is that the focal company does not have direct access to the transactional data of the supply chain partners. However, to extend the KRA simulation to tiers 2 to n, it would be possible to work with several tier 1 parts that are considered critical to the resilience status from the perspective of the focal company. A partner's willingness to cooperate can in itself be seen as an aspect of that partner's resilience.

For example, if an inbound tier 1 supplier delivers a material that is considered critical to the focal company based on the initial resilience analysis and puts its own production processes at risk, there is an opportunity to obtain more in-depth information from the tier 1 supplier. One possibility would be to conduct a further KRA analysis of the focal company's own network of tier 1 suppliers - and in this context gain insight into further vulnerabilities of the identified critical material. For example, it may be that the components of this product are regionally sourced and therefore stable, so that the risk of a disruption spreading through the network is limited.
By extending the KRA analysis to these further process links, a holistic assessment of resilience status can be achieved. This can be done at all stages of the supply chain to identify the critical paths within the supply chain under consideration. Figure 2 illustrates the idea of identifying critical paths in the supply chain.

Figure 2: Identification of critical paths in the network



INBOUND RESILIENCE ANALYSIS

In this section, we focus on the concrete steps that should be taken to analyze inbound resilience based on the KRAs. To illustrate our reasoning, we will immediately provide an example focusing on the tier 1 inbound supply chain of a focal company with a production warehouse located in Hamburg, Germany.

Steps of inbound supply chain resilience analysis

A prerequisite for determining the resilience status is the transactional data on the delivery items of a focal company regarding its tier 1 inbound supply chain. In a nutshell, the inbound delivery items provide information about material-specific and (historical) deliveries from a supplier to the entities of the focal company. Data sets contained in the data table have been described in Schätter, Morelli & Haas (2022) and refer to unique identifiers (sender ID, receiver ID, material ID), geographical information (e.g. longitude and latitude of sender and receiver locations), material specifications (material numbers), transport specifications (quantities, distances) and time information (time stamp of delivery and receipt). In the context of the use case (illustrative example, see below), a dataset of transaction data with 62,461 delivery items is used. This contains fictitious company data.

In the previous section we described that five KRAs are relevant for determining the state of resilience in the inbound: KRA_1 (geographic distribution of entities), KRA_2 (sourcing strategy), KRA_5 (transport delays), KRA_6 (consolidation of shipments), and KRA_7 (transport distances). Based on these areas, the objective is to carry out a series of analyses to identify critical parts in terms of suppliers and materials in the inbound network to explore the supply chain's inbound vulnerabilities. Therefore, we propose to apply the KRAs either individually or in combination, and consequently use two analysis steps to do so: first, the five inbound-related KRAs are examined individually to get an initial overview of potentially critical parts of the network; second, a given combinatorial analysis of two KRAs allows a systematic examination of the vulnerabilities in greater depth.

In step 1, each of the five KRAs is examined separately to answer a series of questions quantitatively, as summarized in Table 1.

Table 1: Questions on resilience to be answered in step 1

KRA	Resilience-related questions
KRA_1	Are there large geographical clusters (number of suppliers, volumes supplied)?
KRA_2	Which deliveries follow a single sourcing strategy?
KRA_5	How many deliveries experienced a significant delay (deviation from target lead times) in deliveries to the focal company?
KRA_6	How well are the suppliers' deliveries bundled, what do the delivery frequencies look like?
KRA_7	What are the transport distances?

In principle, there are 120 combinations of the five KRAs (= 5!). We suggest always combining two KRAs. In this way, the effects remain understandable from their causes. In this regard, we have prioritized six combinations (out of ten combinations) that we consider very important to deepen the corresponding knowledge of vulnerabilities. We do not exclude the analysis of other combinations, but we consider the proposed ones as typical priorities. The resilience questions answered in this context are summarized in Table 2.

Table 2: Questions on resilience to be answered in step 2

KRA	Resilience-related questions
KRA_1, KRA_2	Are there geographical clusters of single source deliveries in the network?
KRA_2, KRA_5	Are there single source deliveries that have experienced significant transport delays in the past?
KRA_2, KRA_6	How has consolidation progressed and what can we say about the delivery frequencies following a single sourcing strategy?
KRA_2, KRA_7	Are there long-distance deliveries following a single sourcing strategy?
KRA_5, KRA_7	Are there any late deliveries in long-distance transport?
KRA_5, KRA_6	Is there an overlap of late deliveries and high frequencies?

The analysis can be understood as a filter that leads to the most vulnerable deliveries as well as the associated suppliers and materials that can then be defined as vulnerable. In this respect, we see whether there are suppliers and corresponding delivered materials in the inbound supply chain that appear in various results of the KRA analysis in steps 1 and 2. These should then be monitored by the focal company, or the chosen strategies have to be questioned and possibly adjusted in order to hedge against potential disruptions in the network.

In this context, the extension of the KRA simulation described in the previous section becomes relevant. Indeed, the filtered suppliers and materials could be used to determine which parts of the tier 2 network should be investigated further. For example, there might be a cooperation with a vulnerable supplier to improve its resilience status. It should be the goal of the focal company to obtain successive transparency in the critical paths of the entire inbound supply chain.

An illustrative example

We now illustrate the two analysis steps by considering the tier 1 inbound network of a manufacturing company whose production warehouse is located in Hamburg, Germany (focal company). It is assumed that all incoming materials are taken to the production warehouse in Hamburg before being shipped to the actual production sites. The transactional data contains 62,461 delivery items in the previous year with 256 shipping dates. The delivery items represent deliveries between 3,783 suppliers (ID: E1 to E3783) across Europe in 3,755 cities and 21 countries and the warehouse in Hamburg. There are 5,865 material numbers to be shipped. The total shipment weight last year was 8,550 tons, with an average weight per shipment of 136 kg. Figure 3 shows the inbound supply chain network.

Figure 3: Overview of tier 1 supplier network

Step 1: Individual KRA analysis

- KRA$_1$: The top three supplier countries are Germany (42%), France (24%) and the Czech Republic (7%). Although there are only 273 suppliers in the Czech Republic, this country accounts for 51% of the delivery items and 48% of the delivered weight, indicating a high sourcing cluster. On the other hand, although France has almost a quarter of the suppliers in absolute terms, it accounts for only 6% of the delivery items and 6% of the delivered weight (Germany: 22% of the delivery items, 38% of the delivered weight).
- KRA$_2$: 2,195 suppliers are managed on a single source basis, representing 58% of all suppliers (who have delivered in the previous year). Single source suppliers accounted for 66% of the delivery items and 65% of the weight delivered. 49% of all single source suppliers are located in Germany, 17% in France and 12% in the Czech Republic. In the latter country, all suppliers are single source.
- KRA$_5$: 371 suppliers had an average delivery time variance of more than 7 days across all delivery items. However, the corresponding weight was only 0.97% of the total weight of deliveries within the timeframe considered. This looks good, but when having a look at individual deliveries, 53% of all suppliers had at least one delivery with a delay of more than 7 days, which represents 23% of the total weight delivered within the year. Of this, 68% of the weight came from suppliers in the Czech Republic.
- KRA$_6$: There are 45,018 shipments consisting of multiple delivery items from the same supplier on the same day. It can be seen that 9% of the suppliers deliver to Hamburg at least once a week. The average weight per shipment is 193 kg. The suppliers with the highest frequency deliver 56% of the total weight. In the Czech Republic 231 of the 273 suppliers deliver highly frequent, whereas in Germany only a very small percentage.
- KRA$_7$: The average distance from the suppliers to the warehouse in Hamburg across all delivery items is 790 km, which corresponds to a travel time of 10.9 hours by truck. The furthest suppliers are located in Spain, E144 in Arrecife with 4417 km and E2649 in Puerto del Rosario with 4328 km distance. In contrast, there are also German regional suppliers such as E1326 in Hamburg and E298 in Barsbüttel with a distance of 13 km. 2% of the total weight is delivered from suppliers which are in a distance to Hamburg of 2,000 km or more.

Step 2: Combination of KRAs

- KRA$_1$ & KRA$_2$: All 273 suppliers from the Czech Republic are single source (49% of total weight) while 67% of all suppliers from Germany were single source suppliers last year. They account for 23% of the total weight. The three most important (ranked by delivered weight) single source suppliers for critical materials (e.g., those classified as A materials) are E1646 in Kojetin, CZ (618 kg per delivery item), E2434 in Opava, CZ (620 kg per delivery item) and E2273 in Neratovice, CZ.
- KRA$_2$ & KRA$_5$: There are 156 suppliers (out of 371) with a critical lead time of more than 7 days on average that follow a single source strategy. It is important to note that only 1 supplier is located in the Czech Republic, while 72 are located in France, 36 in Germany and 10 in Italy. 150 of the 156 suppliers deliver critical materials. The top 3 suppliers of critical materials are E1833 in Leganes, Spain, E1240 in Granadilla de Abona, Spain and E2326 in Nice, France.
- KRA$_2$ & KRA$_6$: The analysis shows that 169 of the 323 weekly suppliers are single source. 29 of them supply a critical material and all are located in the Czech Republic. The top three (again by weight) are E2434 in Opava, E2273 in Neratovice and E1646 in Kojetin.
- KRA$_2$ & KRA$_7$: The average distance of single source suppliers to Hamburg is 802 km. Seven of the most distant single source suppliers of critical materials are located in Spain and three in Italy. The most important single suppliers of critical materials with a distance of more than 2,000 km are E3114 in Siracusa, Italy with 2,513 km, E1833 in Leganes, Spain with 2,178 km and E3491 in Vigo, Spain with 2,459 km.
- KRA$_5$ & KRA$_7$: Of the top 10 suppliers (by weight delivered) with a delivery time variance of more than 7 days, six are in France, two in Romania and one each in Poland and Spain. The top three are E3302 in Timisoara, Romania, E470 in Brasov, Romania

and E1969 in Lublin, Poland. 176 suppliers with an average lead time deviation of more than 7 days supply a critical material. The top 3 by distance are E3409 in Utera, Spain (2,659 km from Hamburg), E575 in Italy (2,520 km) and E2509 in Paterno, Italy (2,466 km).

- KRA_5 & KRA_6: There is no overlap between the 371 suppliers with an average lead-time variance of more than 7 days and the 323 suppliers with a high frequency (at least once a week). However, all 371 suppliers have experienced at least one lead-time variance of more than 7 days in the last year.

Findings

Based on the KRA analysis, the following key findings on the state of resilience of the focal company can be summarized. The focal company

- has an inbound network that relies heavily on single sourcing. Last year, 65% of the weight was supplied by single source suppliers.
- should be aware that there is a cluster of single source suppliers in the Czech Republic, 85% of which have a high delivery frequency (at least one delivery to Hamburg per week).
- experienced at least one delivery delay of more than 7 days in last year for all suppliers in the Czech Republic. This could be a critical region in the event of a disruption.
- needs to understand that despite the supplier clusters in Germany and the Czech Republic, the most critical individual suppliers are not located in these countries; the ten most critical single source suppliers with significant delays for critical materials in the previous year are located in Spain, France and Italy.
- has a logistics structure with a central warehouse, but its weakness is the distance to its suppliers. The average distance of 802 km to individual suppliers is high and increases the risk of serious disruptions, as a significant proportion (29%) of suppliers are even further than 1,000 km from Hamburg.

Figure 4 shows the most vulnerable suppliers based on the KRA analysis. These are the top 10 (by weight) long-distance single source suppliers (> 1,000 km from Hamburg) of critical materials that were additionally affected by an average delay of more than 7 days in the previous year.

Figure 4: Top 10 critical tier 1 supplier

CONCLUSION AND OUTLOOK

In this paper we have described how a systematic analysis of the resilience-relevant parts of the inbound supply chain from the perspective of a focal company can be carried out. We first summarized the concept of KRAs and then described how different subsets of them can be used to analyze the resilience of different parts of the inter and intra supply chain of a focal company. We identified a number of priority analyses that should be carried out, particularly for the inbound network of the inter supply chain and illustrated our proposal with an illustrative example. In addition, we discussed that the resilience analysis should initially focus on the managed process links in the network, as the relevant shipment data is directly accessible. Based on a resilience analysis of these links, an extension to monitored and non-monitored process links should be considered in cooperation with the critical supply chain partners.

With our approach, we have created the basis for logistics decision-makers to use a pragmatic and applicable procedure in an area that was previously not part of their core capabilities: resilience management instead of efficiency management. Our aim is to provide decision-makers with a process that allows them to make a rough estimation of "how resilient is our supply chain" by providing them with the most vulnerable parts of the supply chain such as suppliers, materials, and relations. Our proposal is resource efficient as it uses historical transactional data that can be easily captured from the company's data warehouse and / or transactional systems. Working within a supply chain is a complex undertaking because there are so many relationships within the value chain that one does not even suspect, e.g. relationships at tier 2 or higher. Our research has shown that the direct and first step to take is to look at the managed process links (and corresponding data) that are already available to decision-makers. These are the managed process links in the supply chain. We believe that once decision-makers understand the vulnerabilities within these process links, further steps can be taken to address the critical pathways throughout the supply chain from the perspective of the focal company. For example, by identifying a vulnerable supplier, it is possible to mitigate associated risks if this company is willing to have its own tier 1 network resilience tested. In this way, vulnerabilities are revealed one by one.

There are several pieces of work that are next in our research. 1) The analyses presented in this paper should be extended to the outbound network and the intra supply chain. Further case studies in collaboration with companies are needed to further develop and verify our approach. 2) To support decision-makers, the results of the KRA analysis should be visualized in a dashboard to be used at a strategic level. 3) The approach should be coupled with an operational tool that intervenes directly in the processes, e.g., in the selection of a single source strategy. In this respect, process mining is a promising option, see Schätter, Haas & Morelli (2022). Understanding the processes and automating them in terms of decision making to avoid disruptions directly strengthens the functionality and resilience of the supply chain. Furthermore, a strategic supply chain analysis such as the one conducted in this paper should be based on event logs collected over the year and show through dashboards how the resilience statistics of the supply chain design have changed at different intervals (e.g. quarterly). This will provide decision-makers with a strategic monitoring system in addition to operational decision support.

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