# Ensuring Supply for Emergency Services – Modeling Supply Chains with Incomplete Sets of Data

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**Abstract.** Supply chain simulation could be used to identify the risk of bottlenecks due to disruptions in global supply chains and to improve the availability of products and materials for emergency services. However, these stakeholders do not have the capabilities and in-house know-how about their supply chains required for reliable simulation results. To overcome this issue, this manuscript provides a method to enable the modeling of supply chains without a comprehensive knowledge of all process parameters and nodes. It consists of generic data containers, each representing typical nodes within a supply chain with plausible generic process parameters, boundaries, and distributed values. We present the conceptual feasibility of the approach through a case study and demonstrate the methodology for modeling a supply chain for detailed bottleneck analysis and automated risk assessment of a public health and safety supply chain.

## Introduction

Societies around the world have been confronted with numerous challenges during the last years, which have been further intensified in the context of recent crises like the COVID-19 pandemic and the Ukraine war. These crises occurred in rapid succession and across several economic areas.

Manufacturing companies and wholesalers in particular were faced with the challenge of maintaining their globally interconnected supply chains. With highly dynamic demand and interrupted productions, process variables such as transportation times and costs were also greatly affected [10]. This did not only have consequences for the manufacturing industry. Additionally, sectors that previously deemed supply chains as secondary, such as public health, safety services, and healthcare, were also impacted by these disruptions. In addition to drugs [4], shortages were reported for numerous products necessary for patient care or the protection of personnel [13]. Thus, in addition to the prevailing shortage of personnel, the limited availability of supplies, consumables, and drugs also jeopardized the security of supply in critical infrastructures. The need for resilient supply chains and the possibility of identifying impending supply bottlenecks at an early stage were thus impressively illustrated.

An established method for analyzing the impact of disruptions on supply chains is supply chain simulation. It allows the impact of disruptions on the entire supply chain to be examined on a scenario basis and bottlenecks to be identified [12]. Cope et al. (2007) and Hermes (2011) describe different methods using model building blocks to facilitate supply chain modeling and the transfer of models into a simulation environment [6, 11].

Supply chain simulations are primarily used by manufacturing companies, which have in-depth knowledge about their supply chain - even beyond 1st-tier suppliers [17]. When this information is accessible, it enables the meaningful and reliable analysis of processes [2].

However, in the sectors of public health and safety services, such information is often unavailable due to the procurement practices involving wholesalers. To facilitate the use of supply chain simulation within public health and safety services, it is imperative to address the challenge of incomplete supply chain data.

## 1 Related Work

The issue of incomplete data is recognized in the literature as a topic relevant to practice and has been addressed through scientific research [9]. The emphasis is placed on methodologies designed to handle missing quantitative data, as discussed in [20]. Oliver et al. (2022) address this issue with a modeling study of national supply chains in the United States in the context of natural disasters [18]. They use stochastic methods to describe key parameters such as order quantities and transportation times at an aggregated product class level (e.g., "package meal").

To conduct a supply chain simulation, it is essential to model both quantitative and qualitative data. This paper presents a methodology that supports filling data gaps and enables the application of supply chain simulation.

## 2 Case Study

Within the context of this use case, we consider the supply chain of an emergency medical service for two essential products: syringes and the medical ingredient Acetylsalicylic Acid (ASA). This scenario involves a multi-stage supply chain, as depicted in Figure 1. This supply chain model acknowledges the potential risks associated with overseas shipments between producers and wholesalers, a factor that is critical to the reliability and efficiency of emergency medical services [15].

The emergency service's demand for syringes and ASA is met by a wholesaler, who procures syringes from two different producers. These producers, in turn, are supplied with necessary raw materials by a variety of suppliers. On the other hand, ASA is sourced from a single producer, which similarly depends on several suppliers for its raw materials. This structure highlights the complexity and interconnected nature of supply chains in the healthcare sector, emphasizing the importance of robust and risk-aware supply chain management.

## 3 Methodology

Each relevant object of a supply chain is represented by a node in the simulation model. Each node is characterized by its type – such as a producer, transport route, or warehouse – and its corresponding process parameters, which might include transport time or warehouse capacity. By specifying successor nodes, these individual nodes are interconnected to form a network that represents the specific structure of the supply chain.

This results in certain information requirements that are necessary for producing meaningful outcomes of the simulation. Although the overall structure of the supply chain can be examined at an abstract level with relative ease, acquiring detailed process parameters for the individual nodes is either impossible or requires significant effort. For example, it can be assumed that the active ingredient ASA is produced in Asia and shipped to Europe, where it is further distributed through road transportation [15]. However, product-specific transport times, production capacities, or suppliers are usually unknown.

To address the challenge of incomplete data, a strategy of modularized abstraction for sub-processes is adopted. This approach involves generalizing processes, such as transportation from the country of manufacture to the country of consumption, to a higher, generic level. These generalized processes are then described in broad terms within a "data container," allowing for a more flexible and adaptable simulation framework that can accommodate the gaps in specific data points. The description is based on publicly available data sources, expert estimates within the domain, and analogous cases. The resulting process parameters of the simulation nodes are finally made available as data containers. For instance, there may be a data container for shipping from Southeast Asia to Europe that contains common transportation times and capacities. A supply chain under investigation can thus be modeled and simulated within a modular framework, utilizing both existing real data and generic data containers. The assumptions embedded within these data containers can be revised or substituted with more appropriate data containers at any point, ensuring the model's adaptability and accuracy.

To evaluate the resilience of the supply chain against disruptions, the process parameters are enhanced with plausibility limits, including minimum and maximum values, alongside a distribution, in addition to the default values.

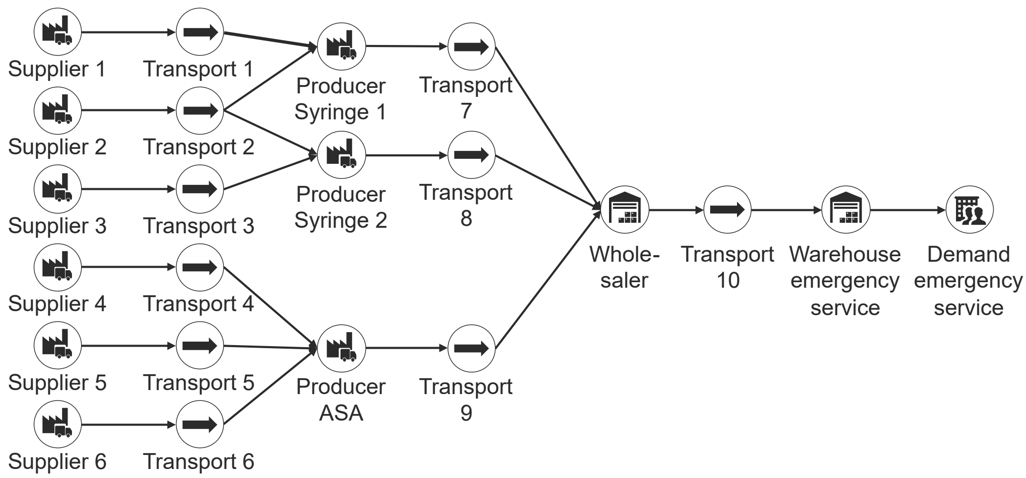


**Figure 1:** Simplified sample supply chain for an essential device (syringes) and a medical ingredient (ASA) for an emergency medical service.

Using this data, the supply chain can be simulated manually or automatically with different configurations in order to examine the effects on the entire supply chain. During an acute crisis, the simulation can be adjusted to reflect disruptions, allowing for an investigation of their effects on the resilience of supply and to assess potential mitigation strategies and their effectiveness.

## 4 Results and Discussion

The case study serves as an illustration to demonstrate the methodology for developing generic data containers to facilitate the modeling of a supply chain. Additionally, it simulates and evaluates the impact of disruptions on supply-related metrics, thus demonstrating and confirming the methodology's applicability.

This approach underscores the importance of a resilient supply chain structure in enhancing the robustness against potential disruptions, and - in consequence - leading to a more consistent and reliable supply chain performance.

### 4.1 Introducing Generic Data Containers for Supply Chains

The development of data containers is exemplified through the use case of the medical active ingredient ASA.

It is chosen from a comprehensive inventory of 569 products, including 68 medical active ingredients, provided by an emergency medical service in Germany. This methodology is similarly applicable to describing the process parameters for consumable material.

ASA is a widely used active ingredient in preclinical emergency medicine, adhering to current guidelines for its anti-inflammatory, analgesic, and antipyretic effects, in particular in the prevention of heart attacks, ischemic strokes, and blood clots [1, 14]. The active ingredient is no longer patented. This results in its availability under various brands such as Ascriptin, Aspergum, and Aspirin. In Germany, only the commercial product 'Aspirin i.V. 500 mg' from the manufacturer Bayer Vital AG is approved for intravenous use. The Federal Institute for Drugs and Medical Devices (BfArM) reported a persistent shortage of this specific product throughout 2023 [3]. To mitigate this, the importation of Aspégic, which is an alternative product available in France, was permitted under §73 AMG. Although the shortage was resolved at the beginning of 2024, this highlights the vulnerability associated with reliance on single manufacturers.

First, the locations of production sites are approximated using the addresses of the holders of the Certificates of Suitability (CEP) issued by the European Pharmacopoeia [7]. A valid certificate is a critical element in the approval procedures for pharmaceuticals within the European Economic Area [8].

Specifically for the active ingredient acetylsalicylic acid, four valid certificates authorize its marketing in the European Economic Area. The holders of these certificates, located in La Felguera (Spain), Zibo (PR China), Tanuku (India), and Ecully (France), are highlighted with square markers in Figure 2, indicating their potential roles as production sites for suppliers of the active ingredient *ASA*.

Second, a distance matrix was employed to calculate the times needed. For road transport routes originating from the production site in La Felguera (ES) and Ecully (FR), the calculations were based on driving and rest times according to German legislation assuming an average of six daily driving periods of nine hours each. This model does not account for special circumstances such as occasional extensions of driving times or reductions in rest periods over weekends. For sea transport, transportation times were estimated for shipments in less-than-container (LCL) mode from the ports closest to the production sites in Zibo (CN) and Mumbai (IN).

The effort to approximate the production characteristics for syringes is fraught with uncertainties compared to pharmaceuticals. While the marketing of pharmaceuticals is regulated at the European level, allowing for possible production sites to be identified through publicly available databases, syringe bodies, as medical devices, are governed by national regulations.

BfArM oversees marketing authorization for medical devices and offers a national database (DMIDS), which is subject to a fee, for searching manufacturers of medical devices [5]. In addition, in a hypothetical crisis scenario, the production of plunger syringes, as defined by the DIN EN ISO standard 7886-1 and using polyolefin granules, could be undertaken by numerous manufacturers equipped with the necessary molding technology, scale printing, and thermoforming along with the means for subsequent sterilization.

To generate a global view of production sites for syringes, data "Healthcare" and "Chemicals" sectors published by the Open Supply Hub initiative were used[19]. This led to the hypothesis that syringe manufacturing could be predominantly situated in Bangladesh, the USA, or Eastern China. The data sources used for node parameterization are detailed in the Additional Materials section.

### 4.2 Simulation Results

To validate the data containers, that were previously developed, the simulation tool OTD NETWORK ("Order-To-Delivery-Network") was used. OTD NETWORK, which was developed by Fraunhofer IML, is a discrete-event simulation environment designed for modeling, simulation, and analysis of supply chains. Its abstract, object-oriented architecture allows for versatile applications across various industries and a wide range of specific issues [16].

The simplified supply chain, as shown in Figure 1, was modeled. This model includes a scenario where the sea route between the ASA producer and the wholesaler (identified as Transport 9) experienced a disruption. The simulation also integrated data that the emergency medical service has from its supply agreements with the wholesaler. The inventory management for both the wholesaler and the emergency medical service was designed around the minimum stock levels and the range of stock specified in these contracts, in addition to the standard procurement times. Figure 3 presents a selection of the simplified supply chain model, how it was parameterized, and an indication of the sources of the data used.

Various simulation trials were conducted with different parameter settings using this supply chain model. The disruption led to significant delays in sea shipments from the ASA producer to the wholesaler serving the medical service, causing a critical bottleneck. This issue is depicted in the left section of Figure 4. As a result of these delays, the ASA inventory at the wholesaler progressively decreases, eventually dropping below the agreed-upon minimum stock level and depleting entirely for ten days. Subsequently, the emergency medical service's warehouse, which maintains a smaller reserve stock, also experiences a stock out, lasting for two days, albeit with a slight delay.

This predictive analysis enables the initiation of measures to enhance resilience in advance. For instance, identifying alternative suppliers could facilitate immediate replacement shipments to bridge the bottleneck. The inventory projection depicted in the right section of Figure 4 shows that the bottleneck could be circumvented by engaging an alternative ASA supplier based in France.

Additionally, it is possible to use a scenario-based variation of the parameters (e.g. duration of disruption) to investigate the inventory strategy's limits and facilitate adjustments to the inventory parameters as needed.

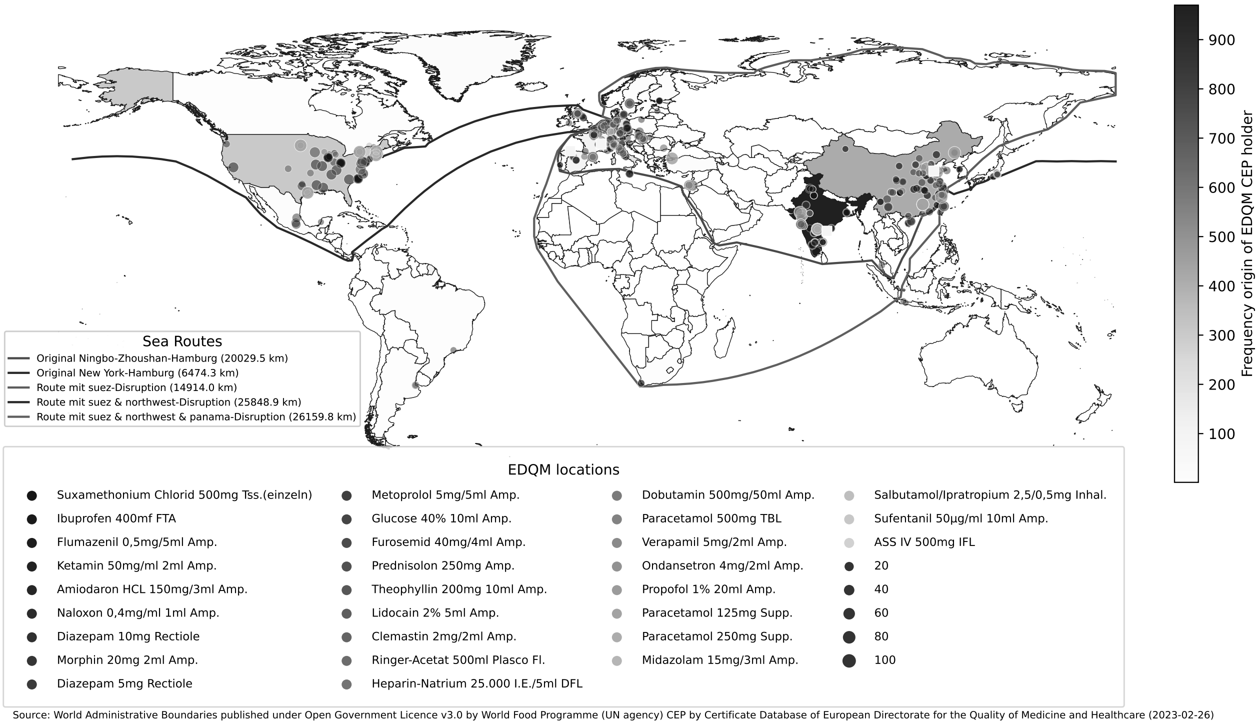


**Figure 2:** The Distribution of certificate holders, serving as a proxy for production sites of each active ingredient within the product portfolio, is visualized through a cumulative sum for each country. The size of each scatter point corresponds to the number of Certificate of Suitability(CEP) holders. Additionally, approximated sea routes are mapped out, highlighting potential bottlenecks from New York (USA) and Ningbo-Zhoushan (PRC) to Hamburg (GER), providing a geographical context to the supply chain's vulnerability. Data: [7]

Trends in inventory levels, influenced by varying durations of transportation delays, can be explored in the Additional Materials section.

The simulation results for the different scenarios outlined above align with the anticipated behavior of the supply chain, considering the established minimum stock level. The previously developed data containers have successfully facilitated the incorporation of detailed supply chain information, which is typically not a feature enabled for emergency services, into the model. This integration has enabled a credible inventory forecast and bottleneck analysis, demonstrating the practical utility of the data containers in enhancing supply chain modeling and analysis.

## 4.3 Transfer to Application

The service for evaluating supply security (EvaVe), developed within the scope of the ResKriVer research project, exemplifies how data containers can be applied to applications (Figure 5).

This service is designed to assess the impact of disruptions on supply chains. If bottlenecks occur, it presents crucial key performance indicators on a dashboard. Moreover, it employs artificial intelligence to recommend parameter adjustments to users, aiming to prevent or mitigate the anticipated bottleneck scenarios. This approach enhances decision-making by providing actionable insights based on simulated supply chain dynamics.

On the left-hand side of the dashboard, the service displays analyzed supply chain events, in particular disruptions, along with their consequences and effects. It also shows the simulation period and the various nodes within the supply chain. At the top of the dashboard, a visualization of the inventory trend for the analyzed product is provided. This section also provides a summary of delivery reliability and features a traffic light system to quickly indicate the presence of any bottlenecks. The lower part of the dashboard is dedicated to showcasing solutions proposed by AI.

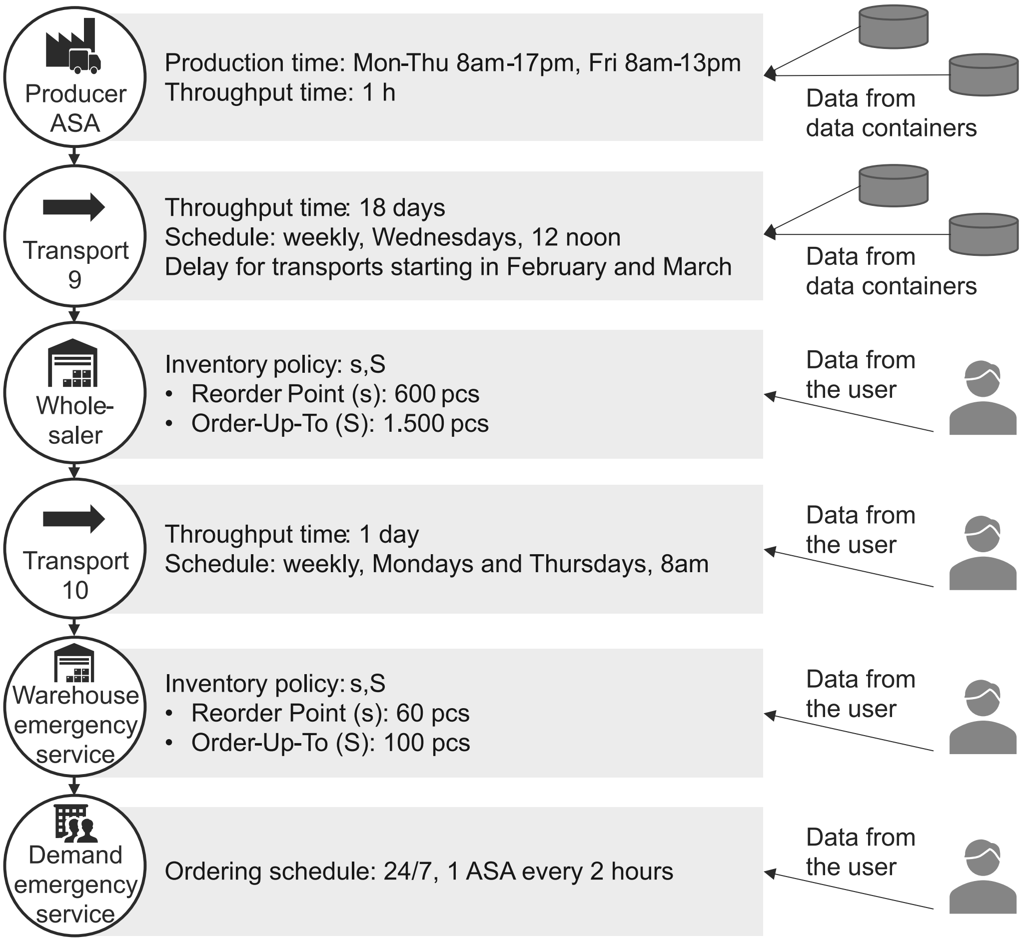


**Figure 3:** Selection of process parameters.

For each suggested solution, a forecast of the inventory trend and a summary of delivery reliability are presented, offering a comprehensive view of potential outcomes following the implementation of these solutions. This service exemplifies simulation-based services that require comprehensive data for effective utilization, a need that the data container methodology adeptly supports.

### 4.4 Limitations

The quality of simulation outcomes generated by OTD NETWORK is significantly influenced by the precision of the model parameterization. This intrinsic limitation underscores the necessity for careful evaluation and validation of simulation results, especially those derived from data containers, which are a composite of numerous assumptions and generalizations.

Thus, at the cost of precision, information gaps are closed with approximations. Plausibility cannot be guaranteed without the involvement of domain experts.

In addition, creating data containers demands considerable research effort and, often, extensive domain expertise, presenting a balance between generalization and specificity. While data containers need to be detailed enough to yield relevant results, they must also maintain a level of generality to be applicable across various scenarios and usecases.

Simulations offer the flexibility to vary parameters, enabling the investigation of various scenarios. Due to the emergent nature of complex systems, structural changes in the model may affect all nodes and edges. It is therefore advisable to integrate alternative paths already in the modeling stage in close coordination with domain experts and to characterize them with additional data containers if necessary.

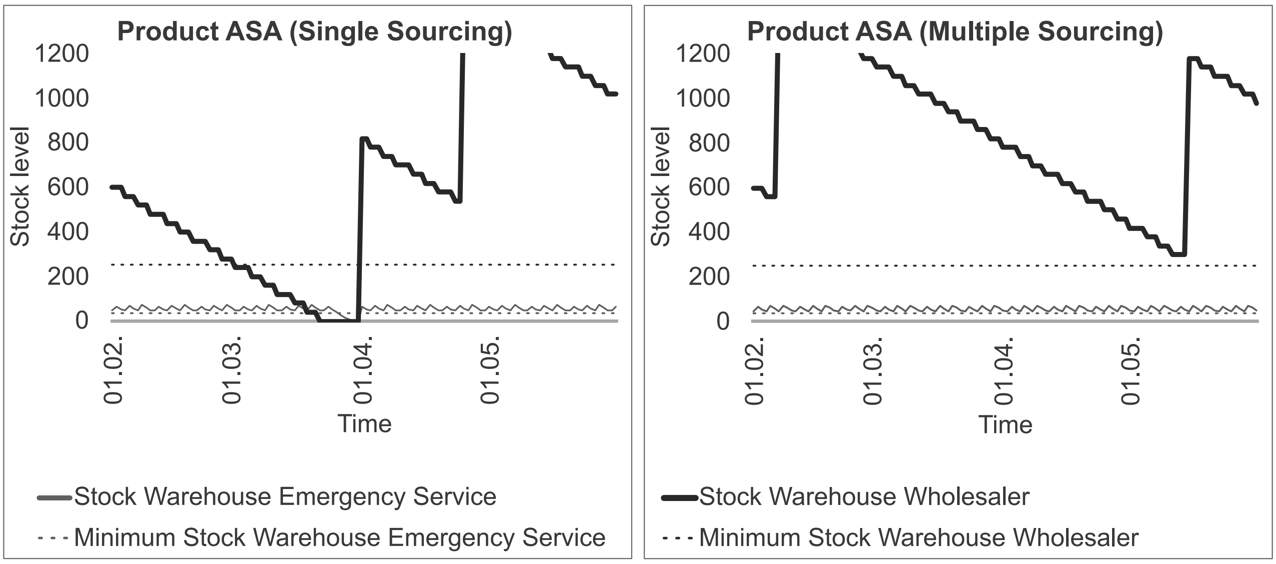


**Figure 4:** Inventory development as a function of time for the active ingredient ASA depending on the selected sourcing strategy, single sourcing (left) and multi-sourcing (right).

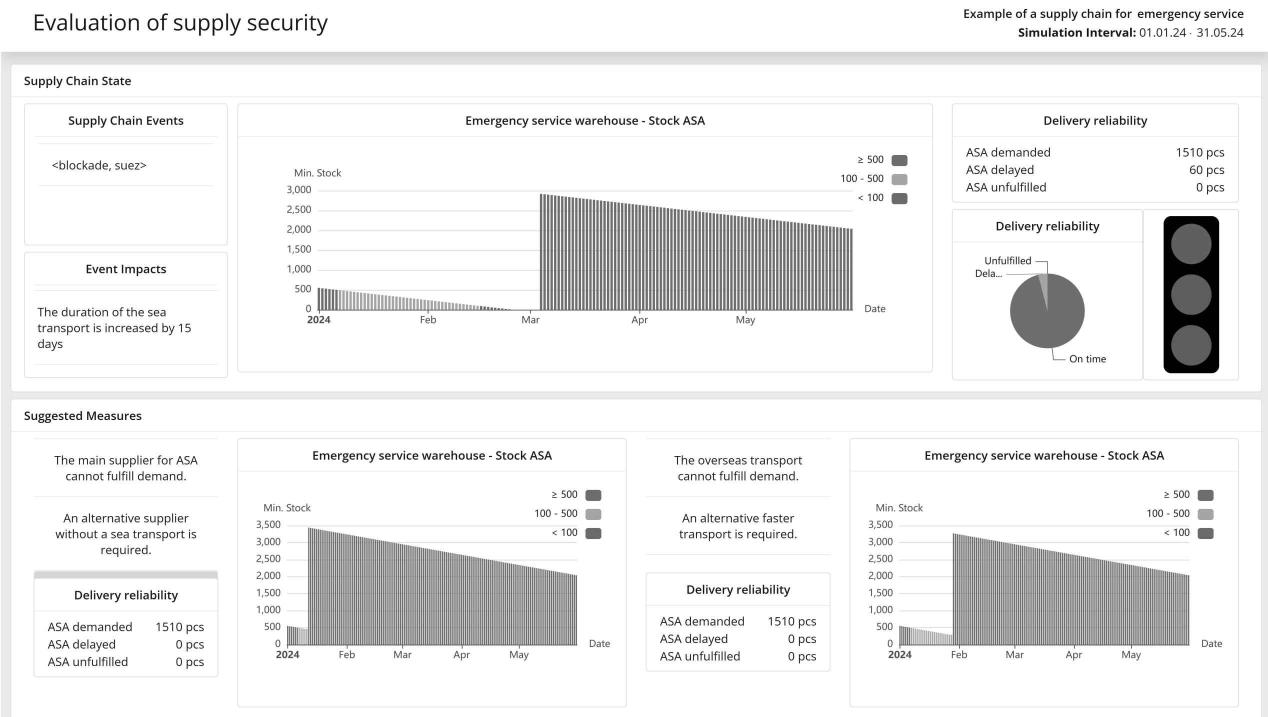


**Figure 5:** Dashboard from the service for evaluating supply security (Evave).

# 5 Conclusion

Internationally interconnected supply chains are complex systems characterized by numerous attributes and interdependencies, making the prediction of disruption impacts on supply resilience challenging.

Scenario-based supply chain simulation offers a methodological approach to examine these interdependencies systematically and mitigate disruption impacts immediately.

A fundamental requirement for modeling and simulating supply chains is a comprehensive understanding of their structure and process parameters. This knowledge is often lacking in emergency services due to their reliance on wholesaler procurement.

The data container methodology presented in this paper enables the substitution of absent supply chain information with generic, preliminary assumptions.

Using these generic build blocks, users with incomplete data are empowered to identify the impacts of disruptions on the supply security of their organizations and to initiate countermeasures. Furthermore, they can evaluate scenario-based preventive approaches for increasing supply chain resilience. Thus, the developed methodology contributes to the reduction of dependencies on regional actors in the German healthcare sector and the emergency services on international supply chains.

However, the considerable effort and domain expertise required to create high-quality data containers are notable limitations of this methodology. A potential solution could be the establishment of a (open-access) platform for data container exchange, facilitating the creation and sharing of a library of data containers across various fields.

Integrating these data containers directly into existing simulation software could further streamline their use. Achieving this would necessitate standardizing the structure for data containers.

### Additional Material

Further information, the model parameters used for the simulation as well as the data containers used for parameterization are made available permanently and freely under CC BY 4.0 license under the doi 10.5281/zenodo.10809378

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