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ACCURATE

Simulation and optimization model for supply chain management and stress test

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Accurate

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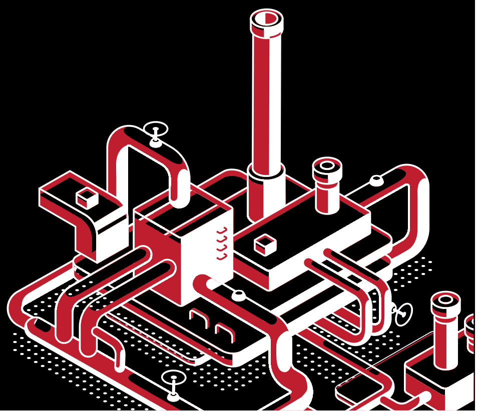

DELIVERABLE FACTSHEET

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Dissemination level	
x	PU = Public
	PP = Restricted to other programme participants (including the EC)
	RE = Restricted to a group of the consortium (including the EC)
	CO = Confidential, only members of the consortium (including the EC)

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Terms and abbreviations

ABM	Agent-Based Modeling
AOI	Automatic Optical Inspection
BANI	Brittle, Anxious, Nonlinear, and Incomprehensible
BoM	Bill of Materials
DC	Distribution Center
DES	Discrete-Event Simulation
DSS	Decision Support System
EBIT	Earning Before Interest and Taxes
ELT	Expected Lead Time
ERP	Enterprise Resources Planning
ICT	In-line Testing
IT	Information Technology
KPI	Key Performance Indicator
MOQ	Minimum Order Quantity
MRO	Maintenance, Repair and Operations
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
Q	Replenishment quantity
ROP	Reorder Point
SCM	Supply Chain Management
SL	Service Level
WMS	Warehouse Management System
WP	Work Package

Public Summary

Resilience is one of the key components for the long-term success of our industrial partners in the ACCURATE project. Resilience is the capability to maintain, execute, and adapt to an unprecedented changing environment. The risks we identify come from known-known, known-unknown, and unknown-unknown uncertainty. Among them, material shortages are typical for material flows while climate change and geopolitical disruptions are long-term crises. We develop a low-data latency simulation architecture that mimics a physical supply chain and integrates several decision-support tools.

Regarding the use case of Airbus Atlantic, we are working on a simulation model that captures three levels of materials, comprising more than 800 parts. We use Anylogistix software to develop the supply chain simulation model. End-users can use the tool to identify the performance impact of disruptions and analyze recovery strategies. We also developed a tool to visualize the Tier-1 network of Airbus Atlantic and aim to build an interface between the Tier-1 network in Airbus Atlantic and the deep-tier aerospace supply chain network to be more informed on unknown risks.

In the use case of Continental, we develop a simulation model. While Airbus Atlantic uses a make-to-order strategy, Continental’s model is based on make-to-stock. Supply chain policies are, therefore, different. The complexity of the Continental supply chain is not less than that of Airbus Atlantic. In our model, a typical product comprises up to 300 electronics parts and 60 mechanical parts sourced from 60 global suppliers.

To address the business problems in Tronico, we develop a multi-layer simulation integrating the shop floor level and supply chain level using AnyLogic and Python. Tronico operates under high-mix, low-volume settings, and our project includes 19 products from five business segments. The simulation model is a part of the decision-support ecosystem of ACCURATE. We aim to offer a tool for a better material management process in business as usual and a better comprehensive approach when dealing with disruptions.

The digital-twin-based supply chain stress-test models that we developed in Tasks 4.1-4.2 can serve as a tool to monitor disruptions and enable informed decisions under time-pressure situations. We plan to further develop the solution and pilot it in other tasks in WP4 and WP7 of the project, and our pilot use cases are diverse, covering the aerospace, automotive, and electronics industries. The results are, therefore, promising to boost the resilience of EU manufacturing.

1 Introduction

1.1. About this deliverable

The deliverable D4.1 report aims to present the initial stress-test scenarios and results from simulation model development for Tasks 4.1 and 4.2 in Work Package 4 (WP4). This report intends to enhance the understanding and transparency of the analyzed supply chains to facilitate the next steps of the ACCURATE project. Based on the data instances, we offer insights into supply chain management and outline how digital supply chain twin technology can be utilized to stress-test supply chains in the use cases of three industrial partners involved in the ACCURATE project.

In the first stage, we collected primary data for modeling and developed the initial model. Supply chain modeling is an iterative process that continuously improves through verification. We utilized historical data and insights from partners during bi-weekly use case meetings to gather qualitative and quantitative data. Subsequently, we applied statistical analyses to build the supply chain network and processes. The first version of simulations was developed using anyLogistix, AnyLogic, and Python. Based on literature and contributions from industrial partners, we defined various disruption scenarios, including lead-time changes, supplier disruptions, route modifications, and natural disasters.

The stress-test scenarios can be classified into four categories: known disruption reasons affecting material flows (e.g., supplier disruptions), known disruption reasons affecting non-material flows (e.g., energy shortages), unknown disruption reasons (e.g., hidden suppliers), and long-term supply chain crises (e.g., the COVID-19 pandemic or the semiconductor crisis). Each of these stress tests will be analyzed with different possible mitigation and recovery strategies in mind, such as risk mitigation inventory, reconfiguration of the supplier base through multiple sourcing, capacity flexibility and scalability, product substitution, and integration with the supply chains of other industries (i.e., re-purposing).

We use discrete-event simulation to assess the impact of disruptions and the ripple effects on supply chain performance. This model allows us to develop a better understanding and more transparent view of the analyzed supply chain. We deploy a standard indicator SL (service level) to illustrate our approach. Further steps may consider financial indicators to discuss the results better.

Finally, based on the collected data instance, we provide recommendations to enhance supply chain resilience and identify some vulnerable suppliers in the process. A more systematic approach to designing experiments is necessary. In the following steps, we will refine the supply chain simulation model and outline an optimization approach, which is a critical component of our solution. A simulation-based digital twin will integrate various data sources from external systems, optimization models, and performance analyses as a comprehensive solution for stress-testing supply chains.

1.2. Document structure

To structure the results obtained, the content in the following subsections of each section will be uniform and correspond to individual use cases. Each subsection has a specific purpose and addresses a particular aspect of the solution.

The introduction and motivation section (Sections 2.1, 3.1, and 4.1) describes the company, provides relevant context for the supply chain, and explains existing problems. It is essential to establish targets for the supply chain and operations management view and possible examples of Key Performance Indicators (KPIs) to measure performance. During this stage, in addition to analyzing the company's supply chain, relevant information can be gathered from the internal report of the ACCURATE Project and public data.

The use case description (Sections 2.2, 3.2, and 4.2) details each use case and defines the relevant user story. For Airbus Atlantic, two use cases will include supply chain disruption monitoring and hidden critical supplier/material analysis. For Continental, the case will focus on a supply chain stress test, while for Tronico, the use case will involve inventory replenishment. The information provided is based on joint discussions and interviews with partners during Tasks 4.1-4.2, as well as insights from the internal report of the ACCURATE Project and the Project proposal, supported by scientific literature analysis.

The modeling approach (Sections 2.3, 3.3, and 4.3) explains the choice of specific software (AnyLogic, AnyLogistix) and provides information on how this modeling approach addresses the defined problems within the organization. Data sources for model building must be established at this stage, and relevant assumptions will also be described. Sources for formalizing this part include the same ones mentioned previously: the internal report of the ACCURATE Project, the Project proposal, and the literature review.

The simulation conceptualization section (Sections 2.4, 3.4, and 4.4) describes the various policies of the analyzed supply chains, such as production, inventory, and transportation policies. This part will also cover general approaches and how key supply chain policies—mainly sourcing, making, delivering, planning, ordering processes, and inventory management—function. Some assumptions regarding these policies will also be made at this stage.

The data section (Sections 2.5, 3.5, and 4.5) outlines the collected dataset for supply chain modeling and presents a primary analysis. The analyzed dataset should include information about the demand from the organization's customers and data from the inbound, process, and outbound stages. Key details concerning products, suppliers, production sites, warehouses, customers, and transportation routes will be considered.

The stress-test scenarios section (Sections 2.6, 3.6, and 4.6) identifies 3-4 disruption scenarios: known disruption causes in material flows (e.g., supplier disruptions), known disruption causes in non-material flows (e.g., energy shortages), unknown disruption causes (e.g., hidden suppliers), and long-term supply chain crises (e.g., the COVID-19 pandemic or semiconductor crisis). This section will describe the modeling process for these scenarios, including the context behind each scenario. We will also consider the modeling experience of similar scenarios documented by other researchers. At this stage, indicators for measuring supply chain performance during stress testing will be introduced.

The stress test results section (Sections 2.7 and 3.7) presents the initial findings. The defined indicators will be analyzed, and key insights from the experiments will be provided. Additionally, findings and key results will be compared with those reported by other researchers, where possible. For the Tronico stress tests, the report includes an outlook on the stress-test results.

We propose several recommendations in Sections 2.8 and 3.8 based on the initial findings and the literature analysis. These recommendations aim to address each organization's problems and increase its supply chain resilience.

The outlook for optimization section (Sections 2.9, 3.9, and 4.7) highlights the main levers that will be applied further to enhance the performance of the studied supply systems. This section will provide a plan and vision for optimization and decision-making support tools that could be integrated into the developing solution.

In the following steps, we will leverage this report to facilitate discussions and further validate the developing solutions. This work will continue in Tasks 4.3-4.6 of the ACCURATE Project. We appreciate the joint efforts in data collection within the ACCURATE Project, which have contributed significantly to achieving the current results.

2 Supply chain stress-testing for the use cases of Airbus Atlantic

2.1 Introduction and motivation

Airbus is a European aerospace corporation that is engaged not only in the development and production of commercial aircraft but also helicopters. Today, Airbus is a leader in the aircraft manufacturing industry. The first A300 aircraft was produced in 1972, the next A310 model was launched in 1982. Over the next 4 decades, the production portfolio of commercial airliners was enriched with 6 more models - A320, A330, A340, A350, A380 and A220 (Airbus Official Website, 2024[1]). In this report, we focus on part S14A, managed by Airbus Atlantic. The current supply chain configuration for this specific section is illustrated in Figure 2.1.

Airbus Atlantic operates primarily under a Build-to-Order or Make-to-Order model, where parts are manufactured based on specific customer orders. Its supply chain is exposed to high supply chain complexity with more than 2,000 general procurement products sourced from over 500 global suppliers. Specific supplier nodes, such as South Korea and North Africa, pose significant risks to the operational stability of the company. Some suppliers are dedicated due to technical requirements, and the product qualification requires significant time and effort. When multiple-source is applicable, the choice of supplier is driven by cost, exacerbating system uncertainty. Deployed Build to Order model, product changes occur often, and some late changes may take up to 3 months. One of the major reasons is the lack of a co-development approach, the long lead time of jigs and tools, and the long engineering lead time constraint by overall capacity. Missing materials is not an uncommon problem. Disruption events, such as flooding in the Atlantic region due to climate change, further increase vulnerabilities that Airbus Atlantic needs to manage.

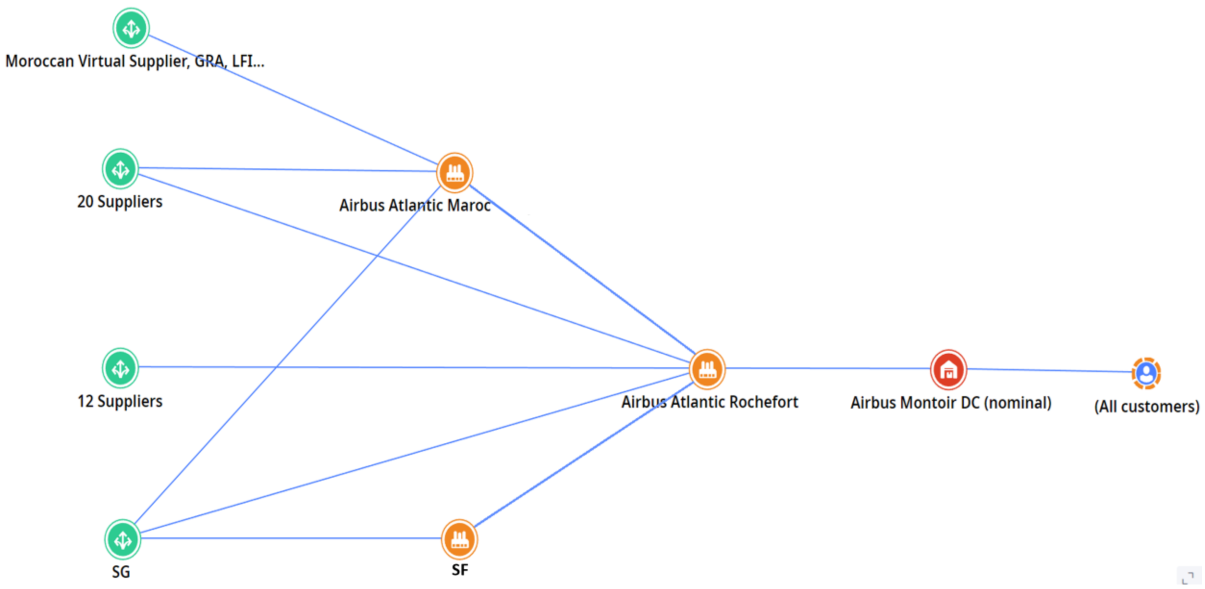

Figure 2-1. Supply Chain of Airbus Atlantic for the European market.

The flow diagram presented illustrates the manufacturing supply chain of the model studied in this research. All suppliers responsible for supplying the enterprises are represented in green color. The grouping of suppliers is based on the similarity of relationships - a particular group supplies a particular enterprise or set

[1] https://www.airbus.com/en/about-us/our-history

of production sites. As previously described, there are three facilities involved in production activities, represented in yellow color on the diagram. These companies are responsible for the production of certain parts according to the BoM. After final assembly at the Airbus Atlantic Rochefort facility, the finished product is delivered to the customer at Montoir. For the model to function, a nominal finished goods warehouse is located in Montoir and marked in red in the flow diagram. This warehouse regulates the demand information from the customer, represented by the blue color in the flow diagram.

Such an extensive supply chain supplying manufacturing plants around the world needs to be carefully managed to avoid delays in deliveries and stock shortages for production activities. Reactive supply chain management techniques are simply not enough, with the major crises of the last decade - the COVID-19 pandemic and the semiconductor crisis - increasing the demand for proactive risk management tools (Kähkönen et al., 2021). It is hard to imagine a more relevant and frequently used proactive management method in supply chain management than scenario modeling. SC stress test not only provides a real-world assessment of the company's current situation but also suggests potential solutions to current problems and provides recommendations to strengthen the operability of the supply chain.

Building a digital twin is a huge analytical effort that considers the activities of the organization and the company's external environment. A full-fledged digital twin requires data sets proportional to the size of the company and its supply chain. In addition, a crucial factor of the digital twin is the frequency of synchronization with internal company data to improve the relevance of forecasts and adjust the solutions provided (Tan et al., 2023). In this regard and the scope of WP4, we develop a supply chain simulation model, a core module in the digital twin, based on a specific dataset, which has not enabled the real-time processing of current data through automatic data updates.

2.2 Use-case description

Stress testing with a simulation-based digital twin can enhance Airbus Atlantic's proactive management capabilities. Preparing for potentially disruptive events strengthens the company's preparedness for unpredictable events, ensuring supply chain resilience (Hezam et al., 2024). By conducting a series of tests on real data for the company, critical suppliers will be identified, and aspects of dealing with them will be explored.

The proposed possible scenarios, based on the literature and news sources studied, allow the company to assess the extent to which supplier groups influence the supply chain as a whole. Such scenarios assess the geographical supply regions in which these suppliers are located rather than the dependence on specific suppliers. The results of this testing can help a company realign its inventory management priorities in favor of creating safety stocks for products with the longest transport times.

Individualized tests based on disruptive events for each supplier can assess the degree of impact of a particular supplier on the entire supply chain. This method can indicate gaps or inefficiencies in the current inventory management system for a particular supplier's products.

Individual tests based on the extension of transport time for each supplier can determine the degree of inventory dependence on transport time and assess the sensitivity to changes in the supply chain. The results of these tests can help the company to understand in more detail the degree of dependence of suppliers on transport time. Analyzing this data can help prioritize suppliers whose volatility to external events can leave the most significant impact on the company's operations. This data can help prioritize suppliers whose volatility to external events can leave the most significant impact on the company's operations.

Using these techniques will not only allow the company to identify critical suppliers by determining their dependence on external events and the extent to which the entire supply chain is dependent on them but will also help to strengthen the resilience of the supply chain. The systematic use of the digital twin can help the company to implement elements of continuous improvement, which in today's economy is the basis of competitive advantage (Li et al., 2023).

2.3 Modelling approach

The following approach aims to develop a platform for experimentation without suffering severe consequences on physical systems and entities. The suggested platform can not only assess the actual situation of the company but also provide potential improvements for both operational and strategic management. In this report, the model serves as a tool to assess the situation of the company, highlight the most vulnerable nodes of its supply chain, and test its resilience under major disruptive events and capabilities of recovery to pre-disruptive levels of KPIs. As part of the construction of the model, a major step is to identify the components and participants, which will immediately determine the extent to which the digital twin is applicable in the future. The object of this study is the production network of part S14A for the European market. The key participants in this network are 37 suppliers from Africa, America, Asia, and Europe, production facilities in France, Morocco, and South Korea, and a facility in Montoir, considered as the internal customer, which is subsequently responsible for the nose and forward fuselage. In terms of physical flows, the supply of components to the manufacturing plants, production processes, and demand coverage will be considered. SL, average inventory level turnover by component category, recovery time, and transport time will be considered as key KPIs. The data used during the development of this simulation-based digital twin was provided by Airbus Atlantic by offloading current inventory, transport, and production data from Enterprise Resource Planning (ERP) and Warehouse Management System (WMS). Some of the data was taken from academic sources, company reports, and other publicly available materials.

This data was then transferred into AnyLogistix software, a simulation modeling tool. The software is designed for the design, optimization, and analysis of supply chain networks, including inventory management techniques, production plants, and transport. Since the software uses Excel datasets as input data, the simulation and modeling processes run quickly due to the low required load on the computing power of the device. The most important feature of the software in the context of the study is the ability to use proactive management techniques - predictive analytics. AnyLogistix provides an opportunity to stress test various risk scenarios that affect the operability of the supply chain. Thus, this application acts not just as a tool for simulating current processes within the supply chain, but also as a tool for tactical and strategic management of the supply chain network.

The baseline model will serve as a template for comparing the ideal situation with disruptive events, based on which the impact of an event on the supply chain can be assessed. The model, although it will be based primarily on clear data carefully provided by Airbus Atlantic representatives, will involve a certain level of abstraction and assumptions. Once the baseline model has been developed, a series of tests from two groups will be conducted. The first group is responsible for discrete events related to real-world political, socio-economic, and natural events that we consider most likely to occur and impact the supply chain. The second group represents stress testing of individual suppliers for a fixed period to identify critical suppliers of components. The results of these tests will be analyzed to identify the most vulnerable parts of the supply chain, their impact will be quantified, and then strategies will be proposed to mitigate these risks.

This work is of immense value to address the identified use cases. The presented simulation models, together with the test results and recommendations, will help the company to strengthen its vulnerabilities and introduce additional proactive management techniques into its arsenal of anti-disruption measures (Psarommatis et al., 2022).

2.4 Simulation conceptualization

The first step in the conceptualization of the simulation model was to identify the position of individual suppliers and manufacturing plants within the supply chain and their geographical location. Based on the supplier location data provided by the company and publicly available reports, the location of the suppliers was determined to a specific address. The location of suppliers can be represented in the map format shown in Figures 2.2 – 2.3.

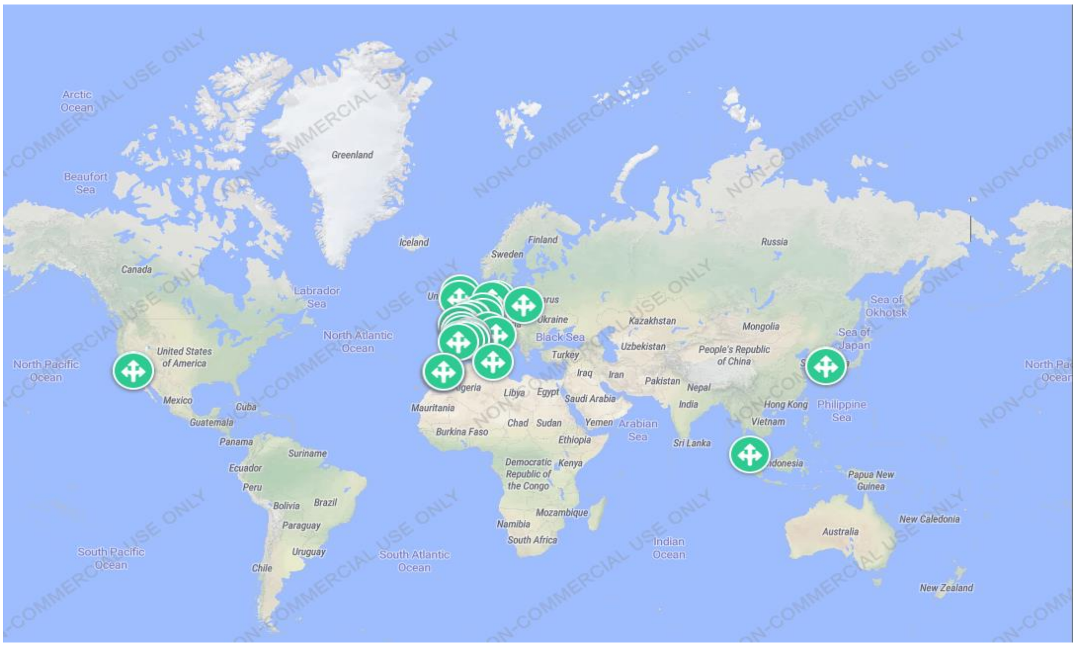

Figure 2-2. Map of geographical location of suppliers of Airbus Atlantic.

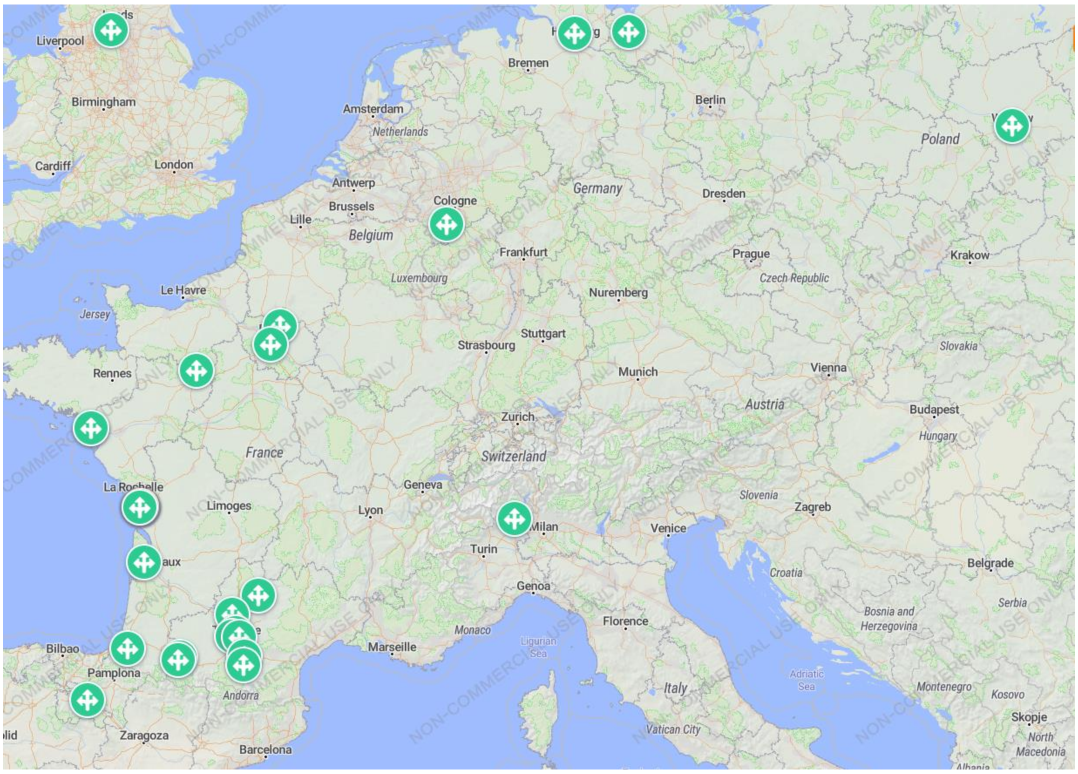

Figure 2-3. Map of geographical location of suppliers of Airbus Atlantic in European region.

After studying the material flows, it was decided to partially simplify the logistics network. In particular, the production plants in Morocco and South Korea are regarded as regular suppliers. This was done in order to make the model less cumbersome and to speed up the computational processes in stress testing. In addition, the Rochefort manufacturing facility has been split into 5 workshops, each responsible for producing a certain level of components. In addition, a virtual supplier for parts with missing information, called 'French virtual supplier', was added for the model to function. In addition, a nominal finished goods warehouse was created for the model, whose location coincides with the customer's location. This warehouse is solely necessary in order to build a logical link between the client and the production plant. From a geographical point of view, the definition of the location was achieved through data provided by the company and publicly available reports on the company's suppliers. The collected location data was entered into a 'locations' table and presented in the format of 'agent name,' 'latitude,' and 'longitude.'

The second step was to copy all product and component names into the appropriate 'products' tab. In addition, the products were grouped into groups based on the supplier and their relationship to the standard/special/WP parts group.

The third step was to determine the demand, its frequency and magnitude of demand on a weekly basis from historical data. A simplified model was chosen with an order frequency of every three days, with an order value of three final products. All of the following parameters are set on the 'demand' tab, as well as an expected lead time of 14 days.

The fourth step was to identify the characteristics of the production activity - the location of production, components, and suppliers for the production activity. The BOM for each part (except for level four parts) was filled in according to the data provided by the company and entered into the appropriate "Production" and ' 'BoM' tabs. The 'sourcing' tab was used to set up the flows between all parties involved, allowing for the setting of origin, destination, and product points.

The fifth step was to set up the flows in terms of transport in the 'paths' and 'shipping' tabs. However, before working with them, two types of transport were created in the 'vehicles' tab - ship and truck. As mentioned earlier - ships are responsible for intercontinental transportation, while trucks are reserved for regional supply. All of this information is reflected in the 'shipping' tab together with the lead times. The lead times of ships are equal to 90, and the lead time of trucks equals 15 days with the exception of the 'French virtual supplier', for whom the lead time equals 1 day. We set the lead time for the "French virtual supplier" to one day, as it represents suppliers delivering parts without specified sources in the current data. We acknowledge that virtual suppliers are not the primary focus and may adhere to the assumption of standard parts with infinite capacity.

The final step before launching the model was the customization of the storage parameters for spare parts and finished goods at the Rochefort production facility. It is worth mentioning that based on the data studied and information provided by the company representatives, it was concluded that the focus of the model should be on inventory management for specific parts. This conclusion was made on the basis of the volume and frequency of purchase of standard parts, as a consequence of which the inventory management policy for this category for each of the components is set to the parameter 'infinite stocks'. A min-max model was used to calculate the required stocks for the remaining components. In calculating the Reorder Point (ROP) for specific parts, the consumption rate of the specific component in the manufacturing activity was used, which was then multiplied by the lead time.

Based on all the previously mentioned simplifications and assumptions presented earlier in the paper, the flow diagram is in simplified form, as Figure 2.4 shows.

This state of the model allows us to consider the Rochefort production plant as a factory consisting of five workshops responsible for the production of a certain level of components - so the fourth workshop is responsible for the production of components of the third level, the third workshop for the production of components of the second level and so up to the workshop 'FP', which is responsible for the assembly of finished products.

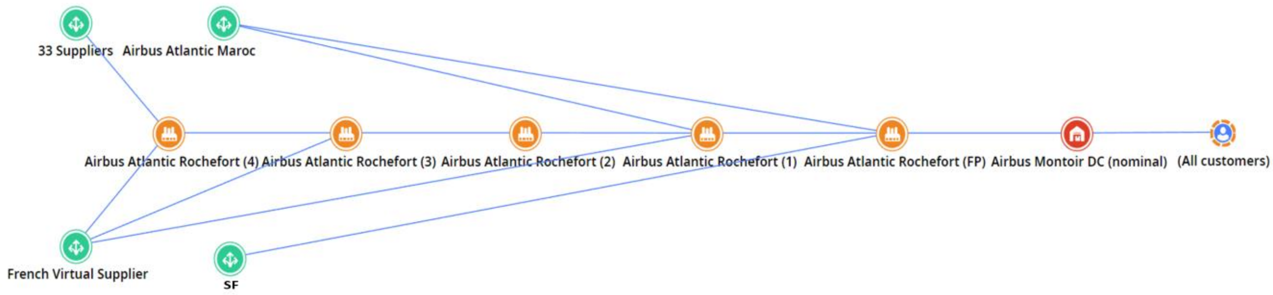

Figure 2-4. Simplified version of supply chain of Airbus Atlantic within the model.

Manufacturing plants in Morocco and South Korea, on the other hand, are seen as suppliers of pre-equipped and already assembled work packages, which simplifies the model considerably. After creating a baseline simulation model, a test run was performed to calibrate the SL and Expected Lead Time (ELT) SL values. Both values were equal to one after the test run, indicating that all material flows, production processes, and warehouse inventory management techniques were working as intended.

2.5 Data

The data on which the framework of the model was built was obtained by representatives of Airbus Atlantic. This data represents a detailed supply chain of components for the production of part S14A for European customers. The company provided historical data on the construction of the final product from the period December 2023 to August 2024, where the Montoir facility is the focal customer. The final product transport data shows the transport price between the final assembly facility at Rochefort and the Montoir facility. In addition to this information, data on inbound transport of components to the plants by sea is also provided. Based on this information, it was assumed that intercontinental transport uses sea transport, while regional transport (within the same graphic region on the scale of a part of the world) predominantly uses land transport.

The S14A manufacturing process is quite complex - it consists of a five-level assembly process, where at the last level the S14A is assembled from 6 main groups of components called work packages. These work packages are predominantly assembled at the French facility, but three of the four work packages produced require pre-assembly at the facility in Morocco. The remaining two parts are produced entirely at the facilities in Morocco and South Korea. The production of each of the work packages requires a four-level assembly of components, divided into unique and universal parts. In total, production activities take place in 3 plants, supplied by 37 suppliers from all over the world, most of which are in Europe.

In addition to this information, the company has provided data on the production of individual units, focusing on the labor and resource intensity of individual processes. However, due to the nature of this study, the proposed data was not fully incorporated into the model, as it assumes an agent-based approach, whereas this study primarily assumes a discrete event approach. Nevertheless, data on the cost of the final product and the number of components were also included in the model.

In fact, if we categorize the data obtained, it can be categorized into the following groups:

- Geographic data of suppliers, component assembly manufacturing facilities, and final assembly site
- Material requirements for part production, including suppliers of components
- Demand data on a weekly basis
- Historical data on cost and frequency of shipments
- Current inventories of parts at manufacturing plants
- Production and realization costs

It is important to note that the data obtained from the perspective of the author of the study is sufficient for stress testing but cannot be used in the construction of a complete simulation model, as it operates on several assumptions which are listed below:

- The simulation model is developed for focused part S14A.
- Production plants in Asia and Northern Africa are considered as suppliers (to accelerate calculation capabilities)
- Products with a lack of sources are assigned to a 'French virtual supplier' (due to lack of information)
- Lead time is fixed – 15 days for trucks and 90 days for shipping (to calculate inventory)
- Demand is set for 3 products, with an order cycle of 3 days (to decrease simulation time)
- Inventory is calculated according to lead times to ensure the synergy of all required materials based on BoM data.
- Locations of suppliers pin-pointed to addresses mentioned in public reports

The listed types of data were taken from the company's report and supplemented with data that was published by the company in the public domain. In particular, the company provided the abbreviated name of suppliers and cities of location but based on the analysis of the 2023 suppliers' report, their location was determined with street and building accuracy. Academic sources helped manually establish theoretically correct inventory levels for spare parts at the facilities according to a min-max inventory management model for all spare parts and components. Demand data, on the other hand, was adjusted to historical data to equalize demand and material flows.

2.6 Stress-test scenarios

In this part, scenarios will be considered and further analyzed using the developed AnyLogistix model described in the previous part of the paper. During the development of scenarios for stress testing, emphasis was placed on the location of suppliers and enterprises. Their geographical location, combined with the political situation in the state where they were located, as well as a set of socio-economic factors and environmental features, became the basis for selecting a series of the most likely scenarios. The scenarios analyzed, their duration, and the actors involved in supply chain disruption are summarized in Table 2.1.

These scenarios represent a set of disruptive events in specific parts of supply chains and can indicate the geographical regions with the highest dependence. However, it is worth remembering that in some cases, it is the nature of these tests that the data will be averaged over the number of nodes where a disruptive event occurs. In the context of this study, a disruptive event at a large supplier of standard products may be less significant than the same event at a smaller supplier of specific products. The study does not prioritize suppliers of standard parts, and as a consequence, stocks in this category are infinite. In this case, disruptive events related to temporary plant closures or longer transport times with these suppliers will not lead to any changes in the SL.

Scenario Code	Scenario Description	Scenario Type	Affected Nodes
Asia1	Political instability, curfew	Political	SF, SG
Asia2	Storm in Moluccas Straits	Environmental	SF, SG, UASB
Morocco1	Workers Strike	Socio-Economic	Airbus Atlantic Maroc, AAM, CA, Moroccan Virtual Supplier
France1	Earthquakes in Southern region of France	Environmental	LAF, AA, ADA, REA, GAM, AHG, BDS, MET, GRA, WAE
France2	Floods in areas surrounding Rochefort	Environmental	Airbus Atlantic Rochefort (1/2/3/4/FP), SSA, UC, French virtual supplier

Table 2-1. Scenarios for stress testing.

In terms of specific parts, these changes will have a strong impact on the SL, as this indicator directly depends on the efficiency of the inventory management policy, which in turn is based on the transport time.

This means that in order to identify critical suppliers, it is necessary to conduct not only stress tests according to the scenarios presented in Table 2.1 but also single tests of each supplier using two methods. The first method involves conducting tests of 30-, 60-, and 90-day duration, where each of the suppliers will successively fail, and the simulation data will be recorded in the corresponding cell of the table. The second method involves increasing the transport time by 10, 25, 50, and 100% for each of the suppliers, where the comparison will also be made on a SL basis. Based on the tests conducted, the most vulnerable node in the supply chain with the proposed inventory management policy will be identified by the weighted estimation method.

Thus, the next chapter of the research work will reveal the technical features of the stress test settings, offer an interpretation of the test results, and identify the most significant suppliers in the current logistics network configuration.

2.7 Stress-test results

In this part of the study, stress tests will be conducted on the three main categories for which data were laid out in the ‘events’ and ‘paths’ tabs. The purpose of the tests is to identify critical nodes in the supply chain and to verify the reliability of the proposed inventory management parameters. In the ‘Events’ tab, paired events were created for each of the suppliers supplying the Rochefort manufacturing facility, which includes two manufacturing facilities in Morocco and South Korea. The first event triggers a disruptive event; the second event counts a set number of days before stopping the disruption. By default, the time of each of the disruptive events is set to 0, which means that the start and stop of the event coincide, i.e., the disruptive event does not occur.

Scenario Code	Scenario Description	SL			
	Weeks of disruption	1	2	3	4
Asia1	Political instability, curfew	99,2%	97,5%	95,9%	93,4%
Asia2	Storm in the Moluccas Straits	99,2%	97,5%	95,9%	93,4%
Morocco1	Workers Strike	99,2%	97,5%	94,3%	89,3%
France1	Earthquakes in the Southern region of France	100,0%	100,0%	100,0%	100,0%
France2	Floods in areas surrounding Rochefort	20,5%	18,9%	0,8%	0,8%

Table 2-2. Results of stress test scenarios.

In the case of the first set of stress tests dedicated to modeling specific scenarios, the time for each mentioned vendor was changed in turn, first from 0 days to 7 days, then from 7 days to 14 days, then from 14 days to 21 days and finally from 21 days to 28 days. The results of the vendor tests in the four proposed regions were presented in service-level equivalents in Table 2.2.

Supplier	Months of disruption, SL		
	1	2	3
AA	100,0%	100,0%	100,0%
AAC	100,0%	100,0%	100,0%
AAM	100,0%	91,8%	83,6%
AASN	95,9%	87,7%	79,5%
AAT	100,0%	91,8%	83,6%
ADA	100,0%	100,0%	100,0%
AFIA	100,0%	100,0%	100,0%
AGM	100,0%	100,0%	100,0%
AHG	100,0%	100,0%	100,0%
AII	100,0%	100,0%	100,0%
BDS	100,0%	100,0%	100,0%
BI	100,0%	100,0%	100,0%
CA	95,9%	87,7%	79,5%
DEG	100,0%	100,0%	100,0%
FAGA	100,0%	91,8%	83,6%
French virtual supplier	95,1%	86,9%	78,7%
GAM	100,0%	91,8%	83,6%
HFS	100,0%	100,0%	100,0%
LA	100,0%	100,0%	100,0%
LAF	100,0%	91,8%	83,6%
MAA	100,0%	91,8%	83,6%
MET	100,0%	91,8%	83,6%
MGA	100,0%	91,8%	83,6%
PA	100,0%	100,0%	100,0%
PAS	100,0%	100,0%	100,0%
REA	100,0%	91,8%	83,6%
RS	100,0%	91,8%	83,6%
SEF	100,0%	100,0%	100,0%
SG	100,0%	91,8%	83,6%
SF	93,4%	85,2%	77%
SSA	100,0%	91,8%	83,6%
UASB	100,0%	91,8%	83,6%
UC	100,0%	91,8%	83,6%
WAE	100,0%	91,8%	83,6%
WAEL	100,0%	100,0%	100,0%
Airbus Atlantic Maroc	93,4%	85,2%	77%

Table 2-3. Results of individual disruption for every supplier.

The comparison metric for the conducted scenario modeling is the SL. The term "service level" means the share of orders executed in the right quantity, in the right product quality, at the right time, to the right customer at the right price from the total number of orders placed by the customer. This indicator demonstrates how well the supply chain meets customer demand. As can be seen, some of the data from the tests are very similar in structure, and some demonstrate absolute indifference to change. The most significant blow to the SL comes from the France2 scenario. The results are not surprising, as the scenario disrupts the main internal Airbus Atlantic production as well as the supply chain, from which, even after the start of production activities, the company cannot recover until the end of the simulation period. The Asia1 and Asia2 scenarios are not distinguished from each other because the UASB provider shows no indication of sensitivity to disruptive events of less than a month's duration. In the case of France1, SL does not reduce - while suppliers of standard parts with infinite inventories, suppliers of specific parts in the scope of this scenario do not pose significant risks. In essence, the findings provide insight into the feasibility of certain experiments. Since some suppliers supply only standard parts, the stock of which is infinite under the conditions of the model, disruptive events related to these suppliers will not affect the SL. For suppliers of specific parts, however, disruptive events starting at the same disruption time and severity produce the same results. To validate this argument, individual stress tests were conducted for each of the suppliers; the duration of the experiments was 30, 60, and 90 days. The results of the 108 tests are presented in Table 2.3.

The test results clearly reveal the suppliers of standard parts, and the hypothesis of their indifference to disruptive events is thus confirmed. Based on the obtained information, it is possible to group suppliers into four types, as presented in Table 2.4.

Supplier Group ID		**SL**		
	Months of disruption	1	2	3
1	AA, AAC, ADA, AFIA, AGM, AHG, AII, BDS, BI, DEG, HFS, LA, PA, PAS, SEF, WAEL	100,0%	100,0%	100,0%
2	AAM, AAT, FAGA, GAM, LAF, MAA, MET, MGA, REA, RS, SG, SSA, UASB, UC, WAE	100,0%	91,8%	83,6%
3	AASN, CA	95,9%	87,7%	79,5%
4	French virtual supplier	95,1%	86,9%	78,7%
5	SF, Airbus Atlantic Maroc	93,4%	85,2%	77,0%

Table 2-4. Supplier groups after individual disruption.

All members of the first group are suppliers of exclusively standard parts, as evidenced by the lack of variation in SL. In order to reduce the number of unneeded repetitive results, the vendors of standard parts will not participate in the following tests. The members of the second group are mainly suppliers of specific parts, which can be seen in the decreasing SL. In contrast to the members of the third group, at the time of the triggering of the disruptive events, they had sufficient stocks to cover the demand for some time. The members of the third group are thus representatives of the group whose parts in the company's warehouses were not replenished at the time of the triggering of the disruptive event on day 10 of the simulation, which is why their performance differs from the second group. The fourth group followed the same logic yet was put in another bracket only for numerical reasons. Additionally, it's worth noting that this supplier, in addition to Level 4 parts, also supplies Level 3 and Level 1 parts to the Rochefort production facility, which makes the SL dynamics different under the same conditions of the disruptive event for all suppliers. Finally, the fifth group consists of two production plants that supply the final workshop with essential products for the manufacturing activity. In this regard, the dynamics of the SL of these companies coincide because, in addition to having the same impact on the supply chain, they also have the same component consumption rate and lead time according to the current model conditions. However, ELT for Airbus Atlantic Maroc is two weeks, and ELT for SF is 26 weeks. In the next version of our model and experiment design, we will reset the ELT assumption and may expect different SL when there is disruption in Airbus Atlantic Maroc and SF.

As the findings do not sufficiently rank suppliers by highlighting the most influential ones, a second round of tests was conducted, this time exclusively for suppliers of specific parts. These experiments aim to test the sensitivity of the supply chain to changes in lead time. From a technical point of view, AnyLogistix does not allow temporary changes in the lead time on specific destinations via the 'events' tab. Therefore, the 'paths' tab was used. The simulation results are presented in Table 2.5.

Supplier	**Lead time multiplier, SL**			
	1,1	1,25	1,5	2
AAM	100,0%	100,0%	100,0%	100,0%
AASN	100,0%	100,0%	100,0%	9,0%
AAT	100,0%	100,0%	100,0%	100,0%
CA	100,0%	100,0%	100,0%	9,0%
FAGA	100,0%	100,0%	100,0%	13,1%
French virtual supplier	100,0%	100,0%	100,0%	100,0%
GAM	100,0%	100,0%	100,0%	100,0%
LAF	100,0%	100,0%	100,0%	100,0%
MAA	100,0%	100,0%	100,0%	100,0%
MET	100,0%	100,0%	100,0%	100,0%
MGA	100,0%	100,0%	100,0%	100,0%
REA	100,0%	100,0%	100,0%	100,0%
RS	100,0%	100,0%	100,0%	100,0%
SG	100,0%	100,0%	33,6%	33,6%
SF	27,0%	27,0%	27,0%	27,0%
SSA	100,0%	100,0%	100,0%	100,0%
UASB	100,0%	100,0%	33,6%	33,6%
UC	100,0%	100,0%	100,0%	100,0%
WAE	100,0%	100,0%	100,0%	100,0%
Airbus Atlantic Maroc	27,0%	27,0%	27,0%	27,0%

Table 2-5. Results of lead time stress tests for every supplier.

The results obtained can also be grouped and presented in Table 2.6.

Group	**Suppliers**	**Lead time multiplier, SL**			
		x1,1	x1,25	x1,5	x2
1	AAM, AAT, French virtual supplier, GAM, LAF, MAA, MET, MGA, REA, RS, SSA, UC, WAE	100,0%	100,0%	100,0%	100,0%
2	AASN, CA	100,0%	100,0%	100,0%	9,0%
3	FAGA	100,0%	100,0%	100,0%	13,1%
4	SG, UASB	100,0%	100,0%	33,6%	33,6%
5	SF Airbus Atlantic Maroc	27,0%	27,0%	27,0%	27,0%

Table 2-6. Supplier groups after lead time stress tests.

The first group, predominantly consisting of suppliers with a transport time of 15 days, did not demonstrate sensitivity to changes in delivery time, indicating the sustainability of the supply chain under the proposed parameters of the inventory management technique. The second and third groups consist of suppliers most susceptible to longer delivery times, indicating that improvements in inventory management techniques are needed for these suppliers' products. The fourth group demonstrated the dependence on delivery time already at the stage of multiplier increase by 1.5 times. This can be easily explained by a rather long basic transport time of 90 days to these parts of the supply chain. A similar logic of explanation applies to the fifth group, which consists of suppliers of key components. Suppliers in this group respond with a 10% change in delivery time, which indicates the extreme dependence of the supply chain on these suppliers.

Based on the 204 stress tests conducted, the next part of the research work is dedicated to the results of the study; it presents the critical suppliers and proposes practical recommendations to improve the logistics KPIs for Airbus Atlantic.

2.8 Recommended mitigation and recovery practices

Since one of the objectives of this study is to identify critical suppliers, it is time to summarize the results of the stress tests conducted and present the most vulnerable nodes in the current supply chain configuration and the proposed inventory management parameters. The results obtained are a synthesis of scenario stress testing and two methods of individual testing of each supplier. The condition for selecting critical suppliers was the demonstration of special results in both pairs of unique stress tests for each supplier. The list of the most important suppliers, as well as the reasoning, is presented in Table 2.7.

Supplier	Reasoning
AASN **CA** **FAGA**	These suppliers do not differ from other suppliers of specific parts under the model conditions in their transport times and inventory management logic, but they demonstrated both significant sensitivity to disruptive events and to changes in transport times. The presented dynamics in SL indicate that the proposed inventory management parameters should be revised in order to strengthen the resilience of the supply chain.
SG **UASB**	The suppliers represented are distinguished from other suppliers of specific parts by their long shipping time of 90 days. Therefore, in the event of a disruptive event, the supply chain requires more time to resume production activities, and in the event of persistent delivery delays, the production chain loses a significant amount of efficiency. Suppliers in this category should be offered additional measures to protect against out-of-stock situations, and inventory management parameters should be reviewed.
SF **Airbus Atlantic Maroc**	These manufacturing facilities for key components to produce the final product were destined to be among the most critical component suppliers. This is not primarily due to the long lead times and sensitive inventory management parameters but to the position of these companies in the production chain. Since the products of these companies are used in the production of the final product, the slightest fluctuations in a no-fault environment can lead to a significant reduction in financial and logistical KPIs.

Table 2-7. Critical suppliers and reason of selection.

2.9 Outlook for optimization

Manufacturing operations management and Supply Chain Management (SCM) are critical levers that drive organizational efficiency and competitiveness. These fields focus on optimizing internal processes and coordinating external activities. The interplay between manufacturing operations and SCM has become

increasingly evident, especially in light of disruptions, more and more frequent in our BANI (Brittle, Anxious, Nonlinear, and Incomprehensible) world, where consumers, manufacturers, businesses, and governments are more uncertain than they have ever been.
Key factors to strengthen the SCM in the aerospace industry (Koblen and Nizníková, 2013) include the improvement of the flow management between OEM and suppliers in all stages of the product/system life cycle, development of the supplier portfolio, improvement of the supply chain design, supply chain coordination and risk management.
In addition to the design and simulation of the supply chain, three main directions have been chosen jointly with Airbus Atlantic further to enhance its performance, responsiveness, and resilience as follows:

- *Demand management and lot sizing*: Demand management is a major, complex, and time-consuming activity that controls and avoids the bullwhip effect from final assembly lines to suppliers.

  The material demand forecast is built from historical data. This is based on a statistical approach based on past consumptions to determine future demands while taking into account the aircraft rate variations. To do so, the average past consumption per program needs to be identified to apply the right production rate. The data are finally aggregated in one single forecast, which is visible in the material master data. The adjusted consumption profile is calculated monthly.

  Minimum order quantity is defined contractually (based on economic lot sizing) and adjusted with rate evolution. There is no forecast collaboration, only for purchase orders that are done daily.

- *Supply chain coordination and risk management*: One of the main disruptions in the aerospace supply chain is highly relevant to supply chain risk management for practitioners, including resource constraints, communication issues, supplier-solvency, environmental impact, and product quality. The majority of the disruptions occur upstream in the supply chain outside the focal company's direct control (Treuner et al., 2014).

  The aerospace industry focused on outsourcing many non-value processes, which led to a risk-sharing partnership with T1 suppliers. However, this interdependence makes it more vulnerable to disruptions since OEMs become more dependent on their suppliers. Raw materials can become unavailable or have very high prices, and competition can affect future contracts and sales.

- *Integration of external and internal supply chains:* For tractability reasons, the management of manufacturing decisions is generally decomposed according to the time horizon granularity, namely: long-term (strategic), mid-term (tactical), and short-term (operational). Generally, decisions are made independently of the decision level. This decision process can lead to inconsistent or unfeasible decisions even under normal operating conditions (Barhebwa-Mushamuka et al., 2023; Asmussen et al., 2018). To enable a swift adaptation of supply chains subject to disruptions and minimize the impact of disruption propagation, particular attention will be paid to ensure the consistency between strategic and tactical decisions.

The supply chain management tool currently applied at Airbus Atlantic is MRP, and the company is working to accelerate the Demand-Driven MRP. These models are static and not linked to ERP or MES, thus creating a discontinuity of the data. Manual entry of data available in several data sources, such as ERP, MES, resources, skills, and assets, is implied.

To address data and decision fragmentation, data-centric models and decision-support approaches will be developed to deliver a consistent source of truth for the needed data and a harmonized definition of each parameter, decision, or criterion.

Development and operational processes need to be optimized. To define the critical paths of the value stream mapping, an approach based on business process modeling will be considered and integrated. Manufacturing engineering experts certify the criteria for sizing the industrial system in accordance with the overall objectives. The architect can thus make the right decision during the development phase. For operations, the manufacturing leader will be assisted in adapting the production plan, supplier orders, and resource-efficient assignment based on data post-processed through simulation-based digital twin and MaaS.

3 Supply chain stress-testing for the use cases of Continental

3.1 Introduction and motivation

Continental’s factory in Romania operates within a highly complex supply chain and production planning environment, requiring robust strategies to maintain operational efficiency and adapt to fluctuating customer demands. Several interrelated factors contribute to this intricate supply chain, presenting significant challenges that highlight the need for advanced supply chain simulation and stress testing. These measures are essential to optimize performance and enhance resilience against potential disruptions.

Continental's production and supplier network is notably diverse, encompassing a wide range of suppliers that vary significantly in size, type, and geographic location. A typical product requires up to 300 electronic components, 60 mechanical parts, and nine chemicals sourced from 65 global suppliers. Most electronic components are sourced from Asia, while mechanical parts come from specialized facilities across Europe. This diversity complicates supplier coordination and heightens vulnerability to regional disruptions, adding layers of complexity to supply chain management. Furthermore, the involvement of multi-tier suppliers across various regions further complicates the effective management and monitoring of supply chain activities.

The production process at Continental is highly intricate, involving multiple stages, including PCB production, testing, final assembly, and packaging. Each stage presents potential points of failure, requiring meticulous coordination to ensure smooth, uninterrupted operations. Additionally, a typical product undergoes sub-assembly across nine independent lines before proceeding to final assembly. The factory operates continuously, 24/7, at high utilization capacity. This level of operation demands robust production planning and rapid adjustments to optimize capacity utilization and prevent disruptions, ensuring production consistently meets demand.

Long lead times for electronic components, especially due to a preference for sea transportation, represent a significant vulnerability in the supply chain. Extended lead times of 60 to 90 days emphasize the importance of stress testing to anticipate and mitigate potential delays and disruptions. Frequent disruptions, particularly in the current business environment where suppliers struggle to meet volume demands, draw attention to the necessity for effective recovery strategies that can be rigorously tested and validated. Continental’s ability to quickly switch transportation modes or identify alternate suppliers in response to local and global disruptions is critical for maintaining supply chain resilience.

High variability and fluctuations in demand further complicate the supply chain landscape. The factory faces significant variability in production yield, process duration, and capacity, especially when introducing new products. This underscores the necessity for stress-testing production planning processes to ensure adaptability to rapid changes and maintain operational stability. Fluctuating customer demands, along with limitations in adjusting demand forecasts, emphasize the need for robust inventory and demand planning systems that can accommodate variability and ensure supply continuity.

Continental's planning systems must effectively manage backlogs caused by missing components, requiring recovery strategies that consider both production capacity and raw material availability. Robust planning systems are essential to enabling rapid recovery from disruptions and minimizing their impact on production schedules. Supplier disruptions, particularly in the aftermath of COVID-19, have intensified the challenge of maintaining consistent supply volumes, making effective contingency measures crucial.

The introduction of new products often leads to variability in production yield and process duration, which can destabilize production planning. Planning systems must be designed to accommodate these variations to ensure smooth transitions and stable operations. Additionally, managing fluctuating customer demands, which can result in increased volume requests, requires maintaining minimum stock levels as a buffer against variability. Effective planning is essential to ensure that inventory levels align with anticipated demand, supporting the factory's continuous operation.

The Global Supply Chain Concept of Continental can be found at the following link: https://www.continental-automotive.com/en-gl/Passenger-Cars/Company/Supplier-Information/Supplier-Logistics

3.2 Use-case description

Supply chain stress test simulations could facilitate the modeling of Continental’s extensive supplier network, including multi-tier relationships and geographic dispersion. By simulating various disruption scenarios, such as supplier delays or regional disruptions, these simulations provide valuable insights into potential vulnerabilities within the network. This would enable Continental to develop strategies for improved coordination and risk mitigation, ultimately ensuring a more resilient and reliable supply chain.

By simulating lead time variability and exploring transportation options, a supply chain stress test can offer Continental valuable insights into the effects of prolonged lead times on overall supply chain performance. This approach allows for testing different strategies, such as alternative sourcing or transportation methods, to mitigate risks associated with extended lead times. Valuable insights can support the development of more resilient logistics strategies, enabling adaptation to shifting lead time demands and minimizing the risk of delays.

Analyzing different inventory management strategies for critical materials could facilitate the development of contingency plans to mitigate risks associated with sole-supplier dependencies. This would help ensure a more reliable supply chain and reduce the risk of inventory-related disruptions.

By incorporating such analyses, Continental can better understand the interdependencies within its network and identify critical nodes that require prioritization in risk mitigation strategies. This holistic view enables the development of a rapid reaction strategy to disruptions, which shortens the recovery period. Through continuous refinement of these models, the company can also adapt to emerging trends and challenges, such as shifts in geopolitical landscapes or evolving environmental regulations, ensuring a forward-looking and sustainable approach to supply chain management.

Taking into account the fact that Continental operates a significantly complex supply chain, it is essential to develop the most useful disruption mitigation strategies for various cases in advance. This can save a significant amount of time and resources in case of disruption occurrence. In the present volatile world, being prepared for disruptions is an important competitive advantage that will enable a company to survive not only short disruptions but also long disruptions.

3.3 Modelling approach

The objective of this modeling approach is to develop a simulation model using AnyLogistix software to assess the resilience and robustness of Continental's supply chain in the face of disruptions. Model-based simulation is a valuable tool that replicates real-world systems in a virtual environment, enabling researchers to analyze and predict behaviors without affecting the actual systems. The model will be used to simulate various disruption scenarios, analyze their impacts, and evaluate potential mitigation strategies.

An essential part of the modeling approach is defining supply chain components. In the case of Continental, this will include suppliers, production sites, customers, transportation networks, and products. Modeling can be performed through such techniques as discrete-event simulation (DES), agent-based modeling (ABM), or hybrid methods based on their specific advantages. ABM focuses on modeling systems as collections of autonomous elements called agents. Each agent has distinct characteristics, behaviors, and decision-making capabilities, often driven by simple rules. DES models systems as sequences of discrete events that occur at specific points in time. Data, which is used for modeling, is collected from industry reports, academic sources, internal reports of the company, ERP, WMS and other systems, historical data, and media. The main KPIs to measure the performance of the simulation model in disruption scenarios are: Lead Time, Capacity Utilization, Service Level, and Inventory Turnover.

AnyLogistix was chosen as the primary simulation platform due to its specialization in supply chain modeling and optimization. AnyLogistix offers a user-friendly interface and robust features tailored for supply chains. Its ability to develop detailed digital twins and conduct side-by-side comparisons of disruption scenarios makes it ideal for this research. AnyLogistix mainly uses ABM with a combination of DES.

The central idea of the modeling approach is the development of the baseline scenario. The baseline scenario reflects the actual supply chain as a reference point. Correct creation of a baseline scenario is crucial for further supply chain stress testing, as all further results depend on its accuracy. At the base scenario creation stage, it is necessary to make sure that the required data is correct and up-to-date, and it is essential to define certain assumptions. The modeling approach assumes that the input data accurately reflects the real-world supply chain structure, including supplier relationships, transportation networks, production processes, and inventory levels. Certain parameters, such as lead time, production capacity, and primary demand, are assumed to remain constant. Supplier and production behaviors are assumed to remain consistent throughout the simulation period. Stress-testing scenarios, such as supplier shutdowns or transportation blockages, are then introduced to assess the supply chain's capacity to recover from disruptions. These scenarios reveal system resilience and help to find optimal disruption mitigation strategies.

Development of the simulation model in AnyLogistix addresses the increasing complexity of the particular network, as well as disruption risks in global supply chains, as highlighted in the motivation, by providing a virtual environment to simulate and analyze Continental's supply chain under various scenarios. It allows the capture of interactions within the network, enables the identification of vulnerabilities, and tests various strategies to overcome disruption. The modeling approach supports the use case by offering actionable insights into supplier network risks, production inefficiencies, lead time variability, demand fluctuations, and inventory management.

3.4 Simulation conceptualization

Supply chain modeling for product P001 begins by entering the necessary data on supply chain elements and transportation, inventory management, and supply policies. The elements entered into the model in the AnyLogistix environment are: BOM, Customers, DCs and Factories, Demand, Events, Inventory, Locations, Paths, Periods, Production, Products, Shipping, Sourcing, Suppliers, Unit Conversation, Vehicle types. A supply chain consisting of suppliers, production, and customers, modeled in the AnyLogistix environment, is shown in Figure 3.1.

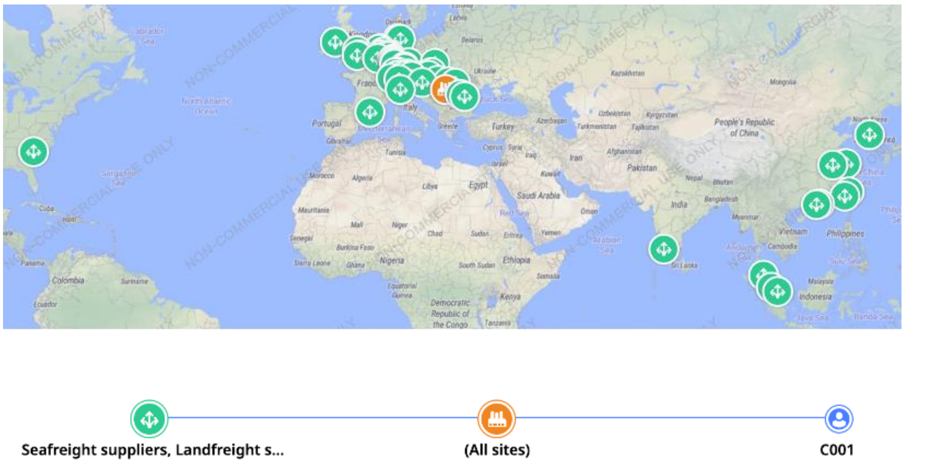

Figure 3-1. Supply chain network (Baseline scenario) of Continental.

An important assumption of the model refers to the specifics of the transportation of products and raw materials. The model uses only two types of transportation, Seafright and Landfreight. Landfreight is taken as one truck with a volume of 80 m3 and speed of 50 km/h; lead time is calculated based on the speed of the vehicle and the distance calculated by road networks. Seafright is taken as a straight fixed route; delivery time is 14 days. This information in the form of AnyLogistix input is presented in Tables 3.1 and 3.2.

Seafreight	80	m^3	30	km/h
Landfreight	80	m^3	50	km/h

Table 3-1. Transport vehicle information.

From	To	Cost calculation	Transportation time	Time unit	Straight	Vehicle type
[Seafreight suppliers]	Timisoara Location	Fixed delivery	20	day	TRUE	Seafreight
[Landfreight suppliers]	Timisoara Location	Product&distance based		day	FALSE	Landfreight

Table 3-2. Transportation information.

The "Sourcing" table in Anylogistix is used to define the rules and constraints related to how products are sourced from various suppliers, production facilities, or distribution centers. It defines the relationship between suppliers and other facilities of the supply chain through understanding which products in which quantity can be supplied to particular facilities from certain suppliers. The base model assumes that each facility sources products from the nearest supplier, adhering to a “Closest (Fixed source)” policy. It is assumed that one product can be sourced only from one supplier. This policy can be formulated using the following logic:

```
FOR each product at the facility:
  FIND the nearest supplier with stock availability
  PLACE order with lead time constraints
```

The “Inventory” table in Anylogistix is used to define and analyze how inventory is handled at various locations, such as warehouses or distribution centers. In the “Inventory” table, one has to define such parameters as Facility, Product, Policy Type, Policy Parameters, Initial Stock, Period, and others. Anylogistix provides a set of standard inventory policies, which are Min-max policy, Min-max policy with safety stock, RQ policy, Unlimited inventory, Order on demand, Material requirements planning, Regular policy, Regular policy with safety stock, No replenishment, and Cross-dock policy. In Min-max policy, the order is placed when the inventory level falls below a fixed replenishment point (s). The ordered quantity is set to such a value that the resulting inventory quantity equals the desired maximum inventory capacity (S). For the Min-max policy with safety stock, respectively, an order is placed when the inventory level falls below a fixed replenishment point (s + safety stock). RQ policy represents the situation where the fixed replenishment quantity (Q) is ordered when the inventory level falls below a fixed replenishment point (R). Unlimited inventory is a default policy for Anylogistix, and it assumes that inventory is always available. Order on-demand policy assumes that no inventory is stored and the required quantity is ordered after receiving an order from a customer/factory or other DC. Material requirements planning schedules inventory replenishment based on safety stock level. Once the policy detects possible safety stock violations, it estimates the required amount of products and defines the date on which the order must be placed to replenish the inventory in a timely manner. Regular policy, as well as Regular policy with safety stock, estimates that products are ordered every specified period (considering safety stock in a second case). With no replenishment, inventory won’t be replenished, and in a Cross-dock policy, the facility does not have inventory; it only transfers products from one type of transport to another.

In the Continental simulation model, it is assumed that Inventory is managed using a "Min-Max" strategy, with periodic checks every 7 days. A periodic check is an Anylogistix parameter, which allows inventory to be checked every specified period; if this parameter is enabled, inventory will not be checked on every single product shipment. In this case, inventory policy can be described by the following logic:

```
FOR each periodic check:
  IF stock level < Min:
    Order replenishment to Max level
  ENDIF
```

Facility	Product	Policy type	Policy parameters	Initial stock
Timisoara	P0001	Min-max policy	s=3500, S=4000	2000
Timisoara	[Landfreight products]	Min-max policy	s=200, S=700	200
Timisoara	[Seafreight products]	Min-max policy	s=2500, S=3000	1500

Table 3-3. Inventory information.

Table 3.3 represents inventory policies for products at the Timisoara facility in AnyLogistix, all using a Min-Max policy. For P0001, the thresholds are s=3500 and S=4000, with an initial stock of 2000 units. Land freight and sea freight-supplied raw materials have s=200, S=700, and s=2500, S=3000, respectively, with initial stocks of 200 units for land freight materials and 1500 units for sea freight materials.

The shipping table outlines shipping policies from the Seafreight and Landfreight suppliers to Timisoara for various products using Seafreight or Lanfreight as vehicle type. Shipping policies in Anylogistix include FTL, FTL with periodic check, LTL, LTL with periodic check, Pending orders, Push: schedule, Push: uniform, and Prohibited. The current model uses the LTL (Less than truckload) policy, where the truck does not need to be necessarily fully loaded, and any ordered amount can be shipped. Types of shipment prioritization that are available at Anylogistix are FIFO, ELT, and Big First. In FIFO (First In, First Out) prioritization, orders are sent in order of how they were received. In ELT prioritization, an order with the least possible lead time receives the first prioritization. In the “Big First” prioritization type, the order with the biggest volume of products demanded is the highest priority. In the current model, the FIFO policy is used.

The “Products” table includes information about all raw materials from M001 to M0367, as well as information about the product P001, a total of 368 products. Units of measurement for all products are pcs, kg, and liter. For raw materials, the column “Cost” is listed, which represents the cost of purchasing product units. For the final product, the column “Selling price” is defined, which represents the cost for the customer. P001 has a selling price of 317,64 EUR. The currency used for cost and selling price is EUR.

The “Production” table provides information about the only production site in Timisoara for product P001. AnyLogistix, while designing SIM experiments, supports a “Simple make” or “Partial production” policy. With the “Simple make” policy, products that are required by the Inventory policy are produced. With the “Partial production” policy, the percentage required by the Inventory policy quantity is set to produce. In this model, “Partial production” is set, with 100,0% required by Inventory policy. As it requires 322 minutes to make 100 pcs of P001 product, for one pcs, the production time of 3,22 minutes is set. Detailed production time calculations are presented in the "Data" section. For the production of P001, the BOM P001 is used. The “BOM” table represents BOM data from the company data.

Period	Requirements
10/2024	4954
11/2024	6272
12/2024	1760
1/2025	5072
2/2025	4870
3/2025	4969

Table 3-4. Demand information.

The “Demand” table represents the requirements of customer C001 of product P001 and is based on the demand information from Table 3-4. Anylogistix allows for the following types of demand: periodic demand, periodic demand with the first occurrence, and historical demand. Periodic demand represents the situation when a certain number of products is ordered regularly after a certain amount of time. Periodic demand with the first occurrence represents the same approach but defines the date of the first requirement occurrence. Historic demand represents the exact demand data from the company's previous periods. The current model assumes that demand is set as periodic demand, with an order interval of 7 days and a quantity of 1037 pcs. The lines of the table represent the demand of client C001 from October 2024 to September 2025. As former demand data included only 6 months of demand information, a year was taken into account for extended analysis and missing information was assumed based on existing data and average numbers.

The "Period" table represents the time frame of analysis. As mentioned, although demand data is only given for 6 months, a year will be considered for a more complete analysis. The "Events" table will be considered in Session 3.6 to perform disruption scenario experiments. "Customers," "DCs and Factories," and "Suppliers" tables represent key information about the Continental network, and table "Locations" defines the exact location of every element. The "Unit Conversation" table ensures compatibility of all elements through relationship definition.

Steps which were taken to develop a baseline model are listed below:

1. Defining network elements (Suppliers, Factories, Customers) and their locations.
2. Defining demand for the analyzed period.
3. Defining sourcing policies, paths, and transportation.
4. Defining inventory and production policies.
5. Running the experiment and analyzing key performance metrics.
6. Calibrating the Model

Results of an experiment run with a baseline model for 15 and 24 months are presented in Figures 3.2 and 3.3. The difference between 15 and 24 months is shown to show the difference in service levels over time. In addition, in future stress testing, it will be possible to observe how quickly the model recovers from a failure.

#	Statistics	Value	Unit
	filter	filter	filter
1	Service Level by Orders	0.97	Ratio
2	Service Level by Products	0.97	Ratio
3	Lead Time	13.733	day
4	Mean Lead Time	1.099	day
5	Production Utilization	0.327	Ratio

Figure 3-2. Baseline model 15 months.

#	Statistics	Value	Unit
	filter	filter	filter
1	Service Level by Orders	0.981	Ratio
2	Service Level by Products	0.981	Ratio
3	Lead Time	21.972	day
4	Mean Lead Time	1.031	day
5	Production Utilization	0.328	Ratio

Figure 3-3. Baseline model 24 months.

The developed model of the Continental supply chain network includes all provided data and allows performing the assessment of key supply chain parameters. This will allow the creation of reliable stress-test scenarios and the following performance analysis.

3.5 Data

The data used to build the model is supply chain data for a single Continental product. A BOM of 367 components sourced from 65 suppliers is used to produce this product (P001). The dataset provides data on a single production facility located in Timisoara, which is the production site for the specified product. Demand data is presented as demand per customer for the period October 2024 through March 2025 (6 months). The only customer is located in Wackersdorf. Transportation information can be divided into two large groups: Landfreight and Seafreight.

Analyzed product P001 is Instrument Cluster RHD G6x, production of which is difficult in terms of supplier diversity. Twelve suppliers are located in Asia, which makes their supply exposed to environmental disasters and maritime transportation disruptions; 1 supplier is located in the US, which also means maritime transportation risks and the remaining suppliers are located in Europe. The rest of the suppliers are located in various locations across Europe. For most products supplied, the unit of measure is PCS, but for some products, the units of measure are also ML and G. For the convenience of model building, components with units ML and G are translated into L and KG, respectively. BOM is given per 100 units of finished product. Of all the components required to produce P001, only 8.17% (30 components) exceed €1 in value. At the same time, seven components exceed €5 in value, which is 1.36% of all components. These components are: M0007 thermal transf compou GF1500 for 166,29 euros (supplied by S023 of Düsseldorf, Germany), M0233 DISPLAY,PANEL,TFT (IPS),+/-,FPC for 51,98 euros (supplied by S010 of Eschborn, Germany), M0237 glass cover BMW RHD NCAP for 45,47 euros (supplied by S011 of Taichung City, Taiwan), M0231 DISPLAY,PANEL,TFT (IPS), +/-,FPC for €34.02 (supplied by S010 of Eschborn, Germany), M0018 covering RHD G6X for €17.10 (supplied by S014 of New Taipei City, Taiwan), M0004 hot melt TECHNOMELT PUR 4663 for €16.66 (supplied by S009 of Bucuresti, Romania), M0347 illumination housing RHD for €11.13 (supplied by S014 of New Taipei City, Taiwan).

The company's production process begins with the receipt and inspection of components, which are booked into the ERP system and stored in designated warehouses. Materials are transferred to an internal warehouse, where components are picked based on production orders. The assembly process starts with surface-mounted components for the top and bottom sides, followed by automatic optical inspection (AOI), depanelling, and in-line testing (ICT). Functional testing ensures the assembled parts meet performance standards before moving to automated bottom assembly, PCBA, and cover assembly, culminating in optical bonding.

After assembly, finished products are transferred to the warehouse and prepared for delivery based on customer requests. The process is tightly controlled, with structured workflows, automated quality checks, and efficient material management to ensure high-quality products are delivered promptly. For all the assembly process (per 100 parts) of P001 it takes production: 0,83 minutes for components receipt, 0,41 minutes for components inspection, 1,66 minutes for external warehousing, 1,66 minutes for internal warehousing, 2,29 minutes for components picking, 16,67 minutes for SMT Top, 16,67 minutes for SMT Bottom, 16,67 minutes for AOI, 26,67 minutes for depanelling, 18,33 minutes for ICT 1, 58,33 minutes for FCT, 28,33 minutes for Automatic Bottom Assembly, 50,00 minutes for Automatic PCBA&Cover Assembly, 78,33 minutes for Optical Bonding, 2,29 minutes for Warehouse transfer, 1,00 minute for delivery creation, 1,66 minutes for Final shipping. Thus, it took 322 minutes for the entire process to produce the P001 product for 100 pcs.

With working 24/7 and having 4 hours of maintenance weekly and 14 hours of shift changes weekly, the production line can work 150 hours a week. This is 9000 minutes. If the production line operates only on P001 production, it can produce 2795 pcs of P001 a week. However, through considering the stock reports, on average, 2259 pcs of P001 are made per month, which means around 565 pcs a week. Based on this information, it can be concluded that the production of product P001 takes up 25% of the production capacity of the given production line. Also, the production line information states that the average utilization of the production line is 85% capacity. In this case, the maximum line capacity for product P001 will be 665 pcs per week, which is 29,4% of the capacity of the entire production line.

Information about demand is provided by Continental's ERP system in the "Requirements" column in Table 3.4. In addition to information on all elements of the supply chain, the file includes information on historical failures and their impact on the specific supply chain. Thus, from 23/03/2021 to 29/03/2021, there was a Suez Canal blockage, which meant for the product P001, there was no supply of materials from Asian suppliers. This information will be used in the future to build supply chain failure scenarios. In addition to the scenario modeling of the Suez Canal blockage and its impact on the P001 product, other scenarios related to major disruptions in global supply chains in recent years will be used.

All listed data and data analysis was done based on the files 4_Acc raw stock evolution.xlsx and 5_Data template WP4_Conti.xlsx, as well as on the Internal report of the ACCURATE project. In addition to internal company and project files, the work utilizes academic sources, particularly to create the most realistic and relevant failure scenarios for stress testing. Global supply chain disruptions, such as the COVID-19 pandemic and the Suez Canal blockage, have highlighted the vulnerabilities in interconnected supply networks. Glas et al. (2021) discuss how the pandemic exposed critical weaknesses, leading to strategies such as redundancy and enhanced flexibility to build resilience. Similarly, Xiong et al. (2024) analyze the semiconductor supply chain's disruptions, proposing mitigation strategies like supplier diversification and flexible production systems.

The analysis of product P001 data highlights the complexities and challenges of modern supply chain management, particularly in addressing supplier diversity, transportation risks, and production capacity constraints. The data underscores the critical need for resilience-building strategies and the need for flexibility to mitigate the impact of global supply chain disruptions.

3.6 Stress-test scenarios

The events required for baseline model stress-testing in AnyLogistix are selected to simulate significant disruptions in the global supply chain. Examples include high-impact global events such as COVID-19, the semiconductor crisis, and the Suez Canal blockage, which have become increasingly common in recent years. These disruptions lead to serious consequences for global businesses, requiring companies to continuously adapt their supply chains to remain competitive. The selected cases involve the Suez Canal blockage and the semiconductor crisis. These cases have been chosen because they allow for analysis of supply chain issues at both the company and global levels. Internally, they address challenges such as managing complex supplier networks, while externally, they explore global factors like increased delivery times caused by the Suez Canal blockage. By analyzing these disruptions individually and comparatively, the cases provide insights into the impact of global events on supply chains and the corresponding strategies companies employ to respond and recover. This approach offers a comprehensive understanding of both organizational challenges and global supply chain dynamics.

The first scenario analyzed is the Suez Canal Blockage. The Suez Canal Blockage occurred on 23 March 2021 and ended on 29 March 2021 and was caused by an EverGreen container ship running aground. An accident got the massive attention of the mass media and had a significant influence on the global supply chain. The main reason for this is that the Suez Canal is one of the world's most vital waterways, connecting the Mediterranean Sea to the Red Sea; up to 12% of global trade passes through the canal. Blockage of the canal forced some container ships to take the western route, bypassing West Africa, which increased the traveling time by 15 days on average (Lee & Wong, 2021). The Suez Canal Blockage cost world trade $400 million per hour or $9.6 billion per day. By March 29, more than 450 different vessels had gathered in line to pass through the canal.

To model this scenario in Anylogistix, two events, which are presented in Table 3.5, were created ("Events" table). The first event represents the actual blockage of the canal, while the second event represents the re-opening of the canal. Dates are chosen randomly in the middle of the analyzed period. The total taken period is 14 days, as although the blockage of the canal ended on 29 March, the queue was resolved only around 3 April 2023. Alternatively, while the path "Sea Suez Canal" is temporarily closed, the path with extended delivery time can be used, increasing the fixed delivery time from 20 to 38 days.

Event 1 Scenario 1	Path state	Path: Sea Suez Canal, New state: Temporarily closed	Date	5/13/24 12:00 AM
Event 2 Scenario 2	Path state	Path: Sea Suez Canal, New state: Open	Date	5/27/24 12:00 AM

Table 3-5. Events for Suez Canal blockage scenario.

The majority of suppliers affected by the Suez Canal Blockage were Asian suppliers that were shipping their goods to Europe. In the case of the Continental supply chain, these are suppliers S006, S013, S012, S014, S029, S007, S001, S021, S061, S011, S050, S030, S016, a total of 13 suppliers. The majority of these suppliers provide electronic components for Timisoara production. These suppliers don't have alternatives, which means disruption in their supply or transportation processes can cause significant problems for all networks. The second modeled scenario is Supplier disruption. The base of this scenario is connected to the causes of the semiconductor crisis. The semiconductor crisis occurred in 2020-2022, with demand for integrated circuits exceeding supply. This crisis affected many areas, including automotive, consumer electronics, and industrial equipment. The semiconductor crisis highlighted the fragility of global supply chains and reminded us about the importance of resilience, capacity planning, and technological self-reliance development. Specifically for the automotive sphere, the semiconductor crisis caused the loss of revenue of approximately $210 billion in 2021 (around 11.3 million vehicles were not produced as planned) and $100 billion in 2022 (3 million vehicles were delayed or not produced) (AlixPartners, 2021). The semiconductor crisis had several serious causes that ultimately led to the supply shortage. First, COVID-19 led to an increase in demand for computers, consumer electronics, medical equipment, and household electronics. The pandemic also led to factory closures in key semiconductor manufacturing regions in Asia because of the epidemiology situation. Another reason for the semiconductor crisis occurrence is the fires in October 2020 at the Asahi Kasei Microsystems (AKM) audio chip factory and on March 19, 2021, at Renesas Electronics' factory, which influenced the supply of semiconductors for the automotive industry (Frieske & Stieler, 2022). Besides that, climate and ecological crises are important reasons for the semiconductor cruise. The semiconductor supply chain faced severe environmental challenges in early 2021, disrupting production at key manufacturing hubs. In Taiwan, the chip production process relies heavily on a consistent water supply for wafer fabrication. However, by May 2021, reservoirs supporting TSMC and other semiconductor facilities were operating at critically low levels, with water storage capacity reduced to just 11-23% due to the island's worst drought in 56 years (Narvaez et al., 2022b). Record low rainfall during April and May had compounded the crisis, raising concerns about the continuity of chip fabrication processes. While heavy rains in June alleviated the drought, the deluge brought new risks of flooding, threatening factory operations. Simultaneously, in February 2021, extreme winter storms in Texas caused widespread power outages, directly impacting Samsung's Austin semiconductor plant and NXP's production facilities. Ecological crises, which had a significant impact in previous years, play a pivotal role in exacerbating semiconductor shortages, as the production of chips relies on resource-intensive processes highly sensitive to environmental conditions. Another reason is US restrictions on Chinese tech companies, which lowered the supply and created uncertainty in the semiconductor industry. The semiconductor crisis shows the importance of analyzing the possible supplier disruptions.

Scenario 2 S001 close	Facility state	Object: S001, New state: Temporarily closed	Date	06.02.2024 00:00
Scenario 2 S011 close	Facility state	Object: S011, New state: Temporarily closed	Date	06.02.2024 00:00
Scenario 2 S012 close	Facility state	Object: S012, New state: Temporarily closed	Date	06.02.2024 00:00
Scenario 2 S014 close	Facility state	Object: S014, New state: Temporarily closed	Date	06.02.2024 00:00
Scenario 2 S050 close	Facility state	Object: S050, New state: Temporarily closed	Date	06.02.2024 00:00
Scenario 2 S001 open	Facility state	Object: S001, New state: Open	Date	7/14/24 12:00 AM
Scenario 2 S011 open	Facility state	Object: S011, New state: Open	Date	7/14/24 12:00 AM
Scenario 2 S012 open	Facility state	Object: S012, New state: Open	Date	7/14/24 12:00 AM
Scenario 2 S014 open	Facility state	Object: S014, New state: Open	Date	7/14/24 12:00 AM
Scenario 2 S050 open	Facility state	Object: S050, New state: Open	Date	7/14/24 12:00 AM

Table 3-6. Events for Supplier Disruption Scenario

To model such a scenario in Anylogistix, 10 events, presented in Table 3.6, were created. Half of them represent the closure of several supplier facilities, and the remaining half represent their re-opening. The closure of suppliers' facilities is modeled for 6 weeks. Affected suppliers are Asian suppliers: S001, S011, S012, S050. These suppliers don’t have alternatives, which means that with long-lasting supplier disruption, Continental can face serious challenges in production.

The third modeled scenario is a Material shortage. Semiconductor cruise also became an example of a shortage of supply to EU productions, as suppliers couldn’t provide more than a certain amount of goods. Similar cases were observed during the pandemic due to the epidemiologic situation and outbreaks among production employees. For example, COVID-19 slowed steel production globally, and the Russia-Ukraine war disrupted steel exports from Ukraine, a major global supplier, which became a major challenge to many automotive companies. As well, rising energy costs in Europe, driven by the Russia-Ukraine war, curtailed aluminum smelting operations. China also reduced aluminum production to meet energy and emission targets. Automakers have faced delays in delivering vehicles, as aluminum is essential for lightweight components. These shortages highlight the importance of researching material shortages for companies.

To model this in Anylogistix, eight events, presented in Table 3.7 were created. In this scenario, the disruption of certain Landfreight suppliers for 5 weeks is studied. Affected suppliers are S010, S047, S008 and S020.

Each of the designed scenarios sheds light on different challenges, from transportation bottlenecks and supplier dependencies to resource scarcity and ecological impacts, all of which have far-reaching consequences for production and delivery systems. By simulating such events in AnyLogistix, Continental can identify vulnerabilities, evaluate alternative strategies, and strengthen resilience against future disruptions. Detailed results of running the presented scenarios will be presented in the "Stress-test results" section.

Scenario 3 S010 close	Facility state	Object: S010, New state: Temporarily closed	Date	5/12/24 12:00 AM
Scenario 3 S010 open	Facility state	Object: S010, New state: Open	Date	6/16/24 12:00 AM
Scenario 3 S047 close	Facility state	Object: S047, New state: Temporarily closed	Date	5/12/24 12:00 AM
Scenario 3 S047 open	Facility state	Object: S047, New state: Open	Date	6/16/24 12:00 AM
Scenario 3 S008 close	Facility state	Object: S008, New state: Temporarily closed	Date	5/12/24 12:00 AM
Scenario 3 S008 open	Facility state	Object: S008, New state: Open	Date	6/16/24 12:00 AM
Scenario 3 S020 close	Facility state	Object: S020, New state: Temporarily closed	Date	5/12/24 12:00 AM
Scenario 3 S020 open	Facility state	Object: S020, New state: Open	Date	6/16/24 12:00 AM

Table 3-7. Events for Material shortage scenario.

3.7 Stress-test results

All designed experiments are aimed at addressing Continental's ability to provide the same level of service in case of significant disruptions from the external environment.

The first scenario, the Suez Canal blockage results with analysis for 15 months, are presented in Figures 3.4 and 3.5. The results show that the Continental supply chain model is achieving a high service level of 0.909 for both orders and products. This suggests that the company is consistently meeting customer demands and fulfilling orders on time. The production utilization is 0.327. This highlights that the Continental production line is currently utilizing only 32.9% of its production capacity for product P001. However, as it was calculated in the "Data" part, the average production capacity for this product is ~30%, which means that to fulfill demand, production must operate at full capacity.

#	Statistics	Value	Unit
	filter	filter	filter
1	Service Level by Orders	0.909	Ratio
2	Service Level by Products	0.909	Ratio
3	Lead Time	22.955	day
4	Mean Lead Time	1.567	day
5	Production Utilization	0.327	Ratio

Figure 3-4. Suez Canal blockage scenario results (15 months).

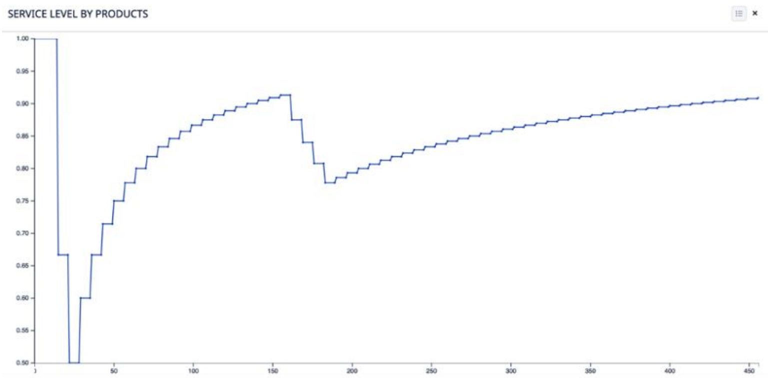

Figure 3-5. Suez Canal blockage scenario results (15 months) - Service level.

In a scenario with an analysis of 24 months with Suez Canal blockage, the service level resulted in 0.943, which is presented in Figure 3.6, meaning that the supply chain is continuing to recover after disruption.

#	Statistics	Value	Unit
	filter	filter	filter
1	Service Level by Orders	0.943	Ratio
2	Service Level by Products	0.943	Ratio
3	Lead Time	31.195	day
4	Mean Lead Time	1.325	day
5	Production Utilization	0.328	Ratio

Figure 3-6. Suez Canal blockage scenario results (24 months).

The second scenario, supplier disruption with analysis for 15 months, shows that the service level in this case is dropping to 0.848. Since the suppliers subjected to the failure cannot be replaced, production is forced to stop for a certain period of time; this can be seen in Figures 3.7 and 3.8.

#	Statistics	Value	Unit
	filter	filter	filter
1	Service Level by Orders	0.848	Ratio
2	Service Level by Products	0.848	Ratio
3	Lead Time	12.817	day
4	Mean Lead Time	3.389	day
5	Production Utilization	0.327	Ratio

Figure 3-7. Supplier disruption scenario (15 months).

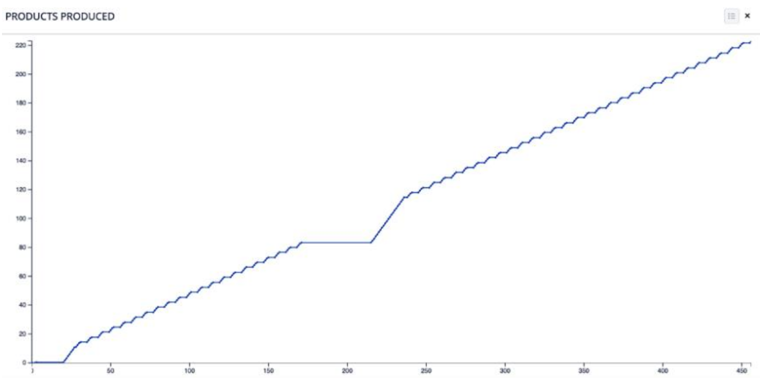

Figure 3-8. Supplier disruption scenario (15 months) - Products produced.

In the case of supplier disruption in a period of 24 months, the service level continues to recover and results in 0.905. This is presented in Figure 3.9.

#	Statistics	Value	Unit
	filter	filter	filter
1	Service Level by Orders	0.905	Ratio
2	Service Level by Products	0.905	Ratio
3	Lead Time	21.057	day
4	Mean Lead Time	2.47	day
5	Production Utilization	0.328	Ratio

Figure 3-9. Supplier disruption scenario (24 months).

The third scenario, material shortage with an analysis of 15 months, is presented in Figure 3.10. In the case of material shortage, the service level drops to 0.909. The same is true in the case of supplier disruption, as there is no alternative supplier, and there is no supply of certain materials. The inventory level of this material is illustrated in Figure 3.11.

#	Statistics	Value	Unit
	filter	filter	filter
1	Service Level by Orders	0.909	Ratio
2	Service Level by Products	0.909	Ratio
3	Lead Time	14.476	day
4	Mean Lead Time	1.572	day
5	Production Utilization	0.327	Ratio

Figure 3-10. Material shortage scenario (15 months).

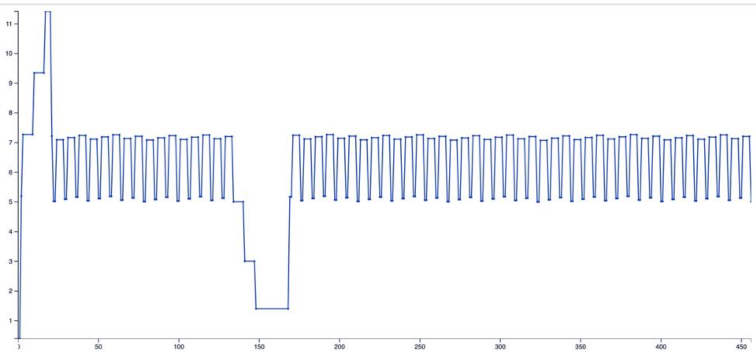

Figure 3-11. Material shortage – M0231 Inventory.

The results of the third scenario, material shortage, with an analysis of 24 months, are presented in Figure 3.12. The service level result is 0.943, showing that the supply chain continues to recover after the disruption.

#	Statistics	Value	Unit
	filter	filter	filter
1	Service Level by Orders	0.943	Ratio
2	Service Level by Products	0.943	Ratio
3	Lead Time	22.716	day
4	Mean Lead Time	1.328	day
5	Production Utilization	0.328	Ratio

Figure 3-12. Material shortage scenario (24 months).

All performed stress-testing experiments show that the presented service level of the supply chain falls significantly when the supply chain is facing disruption. In two out of three experiments, the model shows that production can't function properly in a case of supplier disruption or material shortage, as each raw material component is sourced from only one supplier, and there are no supply alternatives. Short-term disruptions, like the Suez Canal blockage, have less impact on service levels when considering a period of 15 months or 24 months than disruptions affecting multiple materials at once over a long period of time, such as in the supplier failure scenario. Each of the scenarios performs better in terms of service levels at the 24-month review period than at the 15-month review period, demonstrating that the supply chain recovers from disruptions.

3.8 Recommended mitigation and recovery practices

The results of Anylogistix experiments have shown that service level, as well as other KPIs, dropped after disruption occurrence. It shows that the currently modeled supply chain has a significant lack of mitigation possibilities. A main cause for this is that based on existing data in a current model, every component is supplied only from one supplier. Also, there is a lack of backup delivery routes. To prevent major negative implications of such crises in the future, the company should consider implementing certain recovery strategies based on its own and global experience.

The Suez Canal serves as a critical maritime route for global trade, including essential automotive components. A blockage of the Suez Canal resulted in significant supply chain delays and dropped service levels. To mitigate and recover from such an event, automotive companies should consider the implementation of certain ideas: diversification of delivery routes and suppliers, adjustments to inventory management, and collaborative planning. For the diversification of delivery routes, the company can try to establish alternative routes, such as airfreight for key components, and partner with logistics providers that specialize in route flexibility. Geographical diversification of suppliers (with components that can possibly be supplied from different sources) can give a significant competitive advantage. Adjustments, which can be considered in the inventory management system, are the implementation of the safety stock for key components. Besides safety stock, investments in predictive analytics will allow us to anticipate potential bottlenecks. Collaboration with suppliers and logistic providers allows the creation of contingency plans. Through such cooperation, performing a risk assessment will also be beneficial to all parties. As a recovery practice for the occurred disruption, in the case of the Suez Canal, the usage of air freight for critical materials can be considered. Establishing a crisis communication team to maintain constant contact with affected parties, as well as keeping stakeholders informed about shipment delays and recovery timelines, can help to maintain trusted relationships with parties. Documentation of disruptions and their effect, as well as recovery and mitigation strategies and achieved results, will allow for the improvement of future responses.

Turning to supplier disruption experiment results, environmental concerns can disrupt automotive supply chains, especially for critical raw materials and components sourced from ecologically sensitive regions. A failure of even one single supplier can seriously affect the whole supply chain if there is a high reliance on this exact supplier. To mitigate supplier disruption situations, one should take into account supplier diversification, supplier sourcing agreements, supplier audits and monitoring, and research and development investments. For supplier diversification, it is reasonable to establish secondary suppliers in less ecologically vulnerable areas for components for which it is possible. Sustainable agreements with key suppliers will allow the establishment of long-term cooperation and clear communication. In this case, the company will receive priority in supplied components and will have clear expectations about lead time. Supplier auditing and monitoring, in turn, will help to identify the level of possible reliance on suppliers and reveal challenging situations or any need for necessary changes in suppliers' management policy. Research and development investments can allow us to find alternative solutions for certain materials and technologies. This allows us to reduce the dependence on single suppliers and high-risk suppliers. Besides that, through investments in its own technologies, the company can implement recycling technologies, contributing to the circular economy and reducing waste. As a recovery practice for already occurred disruptions, one may take into account suppliers' collaboration and clear communication, agility in manufacturing, and optimized onboarding of new suppliers. Clear communication, in this case, will allow us to receive timely information and have an opportunity to estimate risks accordingly. Also, collaborative communication with other stakeholders, such as local governments, industry associations, and environmental organizations, allows us to navigate regulatory hurdles and ensure compliance and continuity.

Results of material shortage experiments have proven that such disruption can seriously affect automotive production timelines and service levels. Material shortages are usually driven by demand fluctuations, various disruptions, and geopolitical or ecological reasons. To mitigate material shortages, organizations can implement strategic inventory management, material sourcing diversification, advanced demand forecasting techniques, and/or vertical integration. Strategic inventory management techniques not only optimize inventory levels but also assist in minimizing risks by maintaining buffer stocks for critical materials. Material sourcing diversification or alternative material searching allows the identification of alternative components from alternative suppliers to minimize risks. In this case, a clear collaboration with the research and development department is required to accurately estimate the quality of alternative materials and to integrate alternative materials into the system without impacting the quality of the final product. This can become challenging in the automotive industry and will require a significant source and additional research due to the high level of complexity of the product, but if it is implemented successfully, it can become a significant competitive advantage. Advanced demand forecasting techniques allow the precise alignment of materials availability and production schedules. Historical demand and machine learning tools can be implemented to predict possible material shortages in advance. Vertical integration allows us to gain greater control over material supply through upstream operations. One of the possibilities as well is to create a joint venture with key material suppliers. To recover from the disruption, the company can implement cross-industry partnerships, implement supplier collaboration, and prioritize allocation. Cross-industry partnerships will allow partners with other industries to share resources and mitigate shortages in cooperation. In this case, a partnership can help share materials and/or supply them together to increase supply chain resilience. Through supplier collaboration, one can negotiate flexible terms to secure emergency supplies during shortages. In this case, it is also possible to track supply accurately. Prioritized allocation allows the use of a tiered approach to production planning to maximize output and to spread out scarce materials to high-margin or high-priority product lines.

These recommendations are based not only on theoretical approaches but also on practical flights that have occurred in the automotive industry recently. One example is the case with the Toyota plant in Mexico in February and March of 2024 (Reuters, 2024). Toyota was forced to repeatedly halt production in Tijuana after local labor shortages snarled output at suppliers. Besides supplier labor shortages, technical issues at the plant challenged the situation even more. Toyota used collaboration with suppliers as a main strategy to solve the disruption that occurred disruption.

Another example is the case of Tesla, when it had to suspend vehicle production at the Gigafactory Berlin-Brandenburg between 29 January and 11 February 2024 due to a lack of components (DW, 2024). Components shortage was caused by geopolitical crises in the Red Sea and associated shifts in transport routes between Europe and Asia via the Cape of Good Hope. Crise in the Red Sea caused big shipping companies such as Maersk and Hapag-Lloyd to send their vessels on longer, more expensive journeys around South Africa's Cape of Good Hope, avoiding the Suez Canal. This costs about 10 days on a journey from Asia to northern Europe and about $1 million (€910 000) in extra fuel. Besides Tesla, Geely, China's second-largest automaker by sales, and Swedish home furnishing company Ikea, have warned of delays in deliveries.

The latest McKinsey Global Supply Chain Leader Survey suggests that disruption problems like these remain the norm, not the exception, with nine in ten respondents saying they have encountered supply chain challenges in 2024 (McKinsey & Company, 2024). More worrying is that the survey results identify considerable gaps in the ability of organizations to identify and mitigate supply chain risks, with few new initiatives aimed at addressing those weaknesses. It is highlighted that only 30% of companies report their boards have a deep understanding of supply chain risks. Alarmingly, regular discussions on these risks at the senior management level have decreased from nearly 50% to 25%, with many organizations reverting to ad hoc reporting in response to disruptions. This decline in proactive risk management underscores the need for companies to ensure that supply chain vulnerabilities are consistently addressed at the highest organizational levels.

3.9 Outlook for optimization

As a key player in the automotive industry, Continental's factory in Romania operates within a highly complex supply chain and production planning environment, requiring smart decision-support tools to maintain operational efficiency and adapt to disturbances and/or disruptions.

In order to ensure the cost-efficiency, resilience, and robustness of procurement/production/distribution paths, two main optimization levers will be considered:

- ***Optimization of material flow along the supply chain:*** To ensure the necessary data exchange, Continental uses the Electronic Data Interchange (EDI) standard. The suppliers are supposed to accept the EDI standard, i.e., to communicate the following information: Delivery Schedule, Inventory Report, Invoices/Self-Billing Invoices for Evaluated Receipt Settlement system in consignment stock, Advanced Shipping Notification/ Delivery and Transport Data/ Planned Deliveries (source: https://www.continental-automotive.com/en/company/supplier-information/supplier-logistics.html).

  Prescriptive models dedicated to optimizing the circulation of material along the supply chain will be proposed in terms of the quantities to order/produce/distribute for different time horizons, while (i) *external performance*: minimizing materials stock (particular attention will be paid to obsolete materials), (ii) *internal performance*: maximizing the customer satisfaction, minimizing the associated logistic costs and the number of special freights.

- ***Integration of production planning with production control:*** At the production line (i.e., machine group) level, we will deal explicitly with the following decisions:
  - *Sequencing Decision*: Determine the best order of jobs on a production line to maximize on-time delivery rates while minimizing logistics costs. This problem is addressed on a weekly basis, with a focus on reducing the number of changeovers and their associated impact.
  - *Assignment Decisions*: Allocate operations and jobs to machines and operators efficiently.
  - *Dispatching Decisions (currently done manually)*: Prioritize jobs in a queue by assigning a priority for processing on a machine by operators. This problem is resolved daily.

At the shop floor level, our focus will be on integrating and ensuring consistency between production planning and production control and demonstrating an approach to addressing suboptimal production performances.

4 Supply chain stress-testing for the use cases of Tronico

4.1 Introduction and motivation

Tronico, a prominent company in the electronics manufacturing sector, specializes in the production, testing, and assembly of electronic boards. Its processes include the receipt and testing of electronic components, tinning, wave soldering for through-hole components, and Surface Mounted Device soldering for surface-mounted devices. One of Tronico's key challenges is managing a highly complex and diverse product mix comprising approximately 40,000 unique component references sourced from 350 different component manufacturers and over 600 material suppliers. The company's warehouses handle 60,000 component batches, representing over 50 million individual parts.

Tronico's supply chain is supported by multiple sourcing channels, including direct customer supplies, component manufacturers, and brokers. However, this value chain is frequently disrupted by component shortages, the risk of counterfeit parts, and last-minute specification changes due to component unavailability. These challenges are further compounded by the disparity between the typical 4–5-year lifecycle of components and the significantly longer product lifecycles—up to 40 years—in critical sectors like nuclear, defense, and aerospace.

Tronico currently manages certain supply chain processes manually, underscoring the need for digital models to support decision-making across its supply and internal value chains. This manual approach limits visibility into the broader impacts of disruptions and does not provide alternative solutions, leading to inefficiencies and an incomplete understanding of how these disruptions may affect key performance indicators. Key challenges include issues with component availability, where late deliveries and shortages disrupt production schedules, and component obsolescence, which requires identifying alternatives that always necessitate customer approval. Demand fluctuations pose difficulties in maintaining optimal inventory levels, which has a negative impact on cash flow due to excess inventory and waste generation due to perishable or obsolete stock.

The electronics manufacturing environment under study is characterized by:

- *Low to medium volume with high mix or even ultra-high mix production* (including more than 40,000 references): Electronic product lifespans are becoming increasingly shorter, while businesses today demand a growing variety of product types and greater customization options. This implies a higher quantity of production lots, smaller lot sizes, and more series changes.
- *Customer-oriented production planning process:* Once a customer order is entered into the ERP system, a person responsible for its manufacturing is assigned. He/she determines an appropriate production window and a commitment time based on the delivery targets (expedition or storage).
- *Fragmented production control:* The shop floor is divided into several functional machining groups called workshops. Dispatching and scheduling decisions are taken by the heads of the workshop based on slack times.

At the shopfloor level, Tronico faces some challenges in managing work-in-process (WIP) and optimizing production scheduling. The company's rapid growth in electronic product development and rising demand require improvements in cycle time, throughput, and on-time delivery. However, the current manual approach to lot prioritization and WIP management, along with the absence of a robust system to address multi-resource constraints and waiting times, creates inefficiencies. Given the nature of low volume-high mix, these issues lead to production bottlenecks, suboptimal production performance, and high production change-overs.

4.2 Use-case description

A supply chain stress test simulation provides a comprehensive solution for optimizing Tronico's inventory replenishment management. Through simulation of various disruption scenarios, such as supplier delays or component shortages, the tool offers Tronico valuable insights into how these disruptions can impact the entire supply chain. This allows the company to identify vulnerabilities within its supplier network and develop risk mitigation strategies. This will subsequently enhance the overall reliability and efficiency of the supply chain.

Additionally, the simulation tool assists in analyzing current replenishment policies by modeling the cost implications, production KPIs, and waste generation associated with different inventory management strategies. This enables Tronico to assess the effectiveness of existing policies and identify areas for improvement. Continuous improvement leads to reduced stock immobilization time, minimized waste from perishable goods, and improved cash flow management.

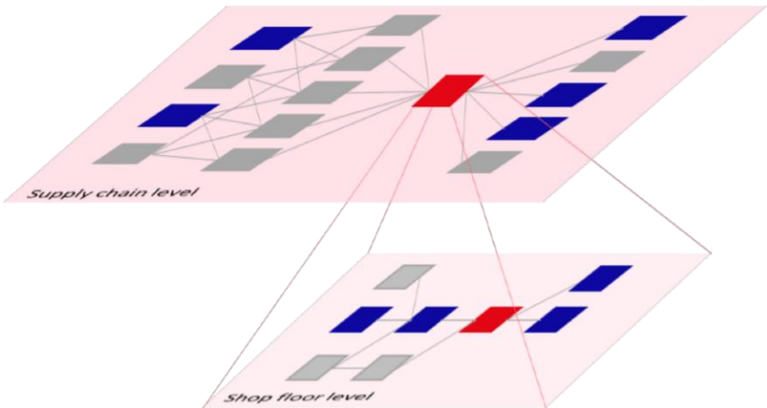

Figure 4-1. Illustration of two-layer simulation model.

Through automating and optimizing inventory replenishment, the presented simulation tool can optimize Tronico’s operations through reduction of reliance on manual decision-making and enhancement of the efficiency of inventory management. This leads to better alignment between inventory levels and production requirements as it ensures the timely availability of components while minimizing the risks of stockouts and excess inventory.

In this stress-test model, our objective is to develop a two-layer simulation model that encompasses both the supply chain level and the shop floor level, as depicted in Figure 4.1. At the supply chain level, the model will incorporate suppliers and customers, taking into account current inventory policies, sourcing policies, and ordering processes to simulate the flow of the supply chain. At the shop floor level, our focus will be on modeling the high-level production flow, with an emphasis on bottleneck operations and demonstrating an approach to addressing suboptimal production performances and high production change-overs, considering the dynamics of the Tronico supply chain.

4.3 Modelling approach

To cover all the features needed, we design our solution with five major modules, including a data integration layer, analytic layer, simulation engine, optimizer, and interfaces. Each module plays a vital role in ensuring comprehensive functionality and integration within the ACCURATE ecosystem. Figure 4.2 captures the overview of the interaction among five major modules.

Data Integration Layer. This module is responsible for collecting, processing, and integrating data from various sources and formats. It ensures that data from different systems are harmonized and made accessible for further optimization and simulation. The data integration layer acts as the foundation, providing clean and consistent to the other modules inside the software.

Analytic Layer. The analytic layer focuses on analyzing the integrated data to extract meaningful insights and patterns. It employs analytics techniques, including statistical analysis and descriptive and predictive analytics. This layer enables the identification of demand and supply patterns, the detection of anomalies, and the input generation for simulation and optimization modules.

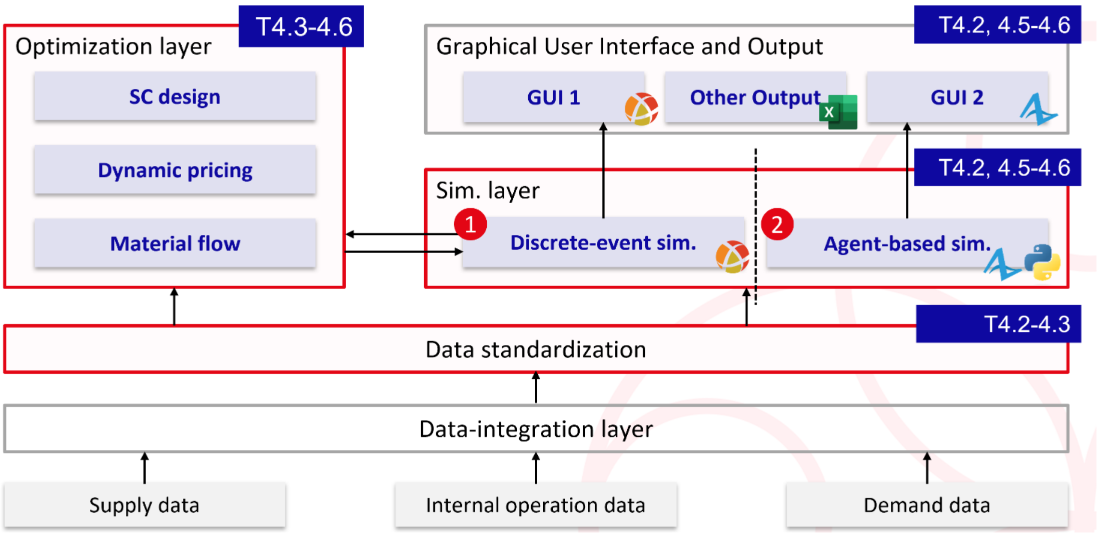

Figure 4-2. High-level architecture of supply chain model (version 1).

Simulation module. The simulation engine allows for the modeling and simulation of various scenarios within the supply chain. Creating digital replicas of physical processes enables the testing and evaluation of different strategies and the prediction of outcomes. Inside this module, we design two simulators. First, we use discrete event simulation and its connection with optimization to address known-unknown uncertainties. Second, we use agent-based simulation to leverage limited amount of data to address unknown-unknown uncertainties. To ensure the novelty of our work, we aim to develop intelligent agents and perform online optimization, in which we optimize the supply chain at every discrete time. It is different from the first simulator, which is used to simulate the optimized solution (prescriptive analytics) and use the simulation results to enhance the optimization algorithms.

Optimization module. The optimizer focuses on finding the best possible solutions to complex supply chain challenges. It uses optimization algorithms to determine the most efficient and effective ways to allocate resources, material flow, and dynamic pricing.

Interfaces. The interfaces module provides the means for interaction between this software and users, as well as other systems. For end users, we aim to develop performance visualization to show the focal indicators and offer the data that users can perform ad-hoc analysis. In the broader context, we also consider the connections between the WP4 software and other software developed within the ACCURATE project and its ecosystem. It includes communication tools (e.g., data files, APIs) that facilitate the exchange of information. For example, we can agree upon the requirements of input of WP3 software and develop an extract engine to generate input for WP3. Similarly, the same approach can also be deployed for the ACCURATE project ecosystem. This module ensures that the system is user-friendly, accessible, and able to integrate with other software and systems within the ACCURATE project ecosystem.

We grounded our solution to the perspective that the supply chain is a complex adaptive system. From this view, the developing solution is an advanced approach that integrates high-granularity simulation with decision-making processes and enables the coevolution of decisions (strategies) and the environment (modeled supply chain) (see Figure 4.3). The feedback loops between agents and their environment provide insights into the dynamic behaviors of supply chains, which traditional models fail to capture Choi et al.(2001). By simulating the complex interactions, the proposed solution offers an understanding of how strategic decisions and environmental factors co-evolve. The technology allows us to collect data on resilience performance and find the optimal combination of resilience strategies.

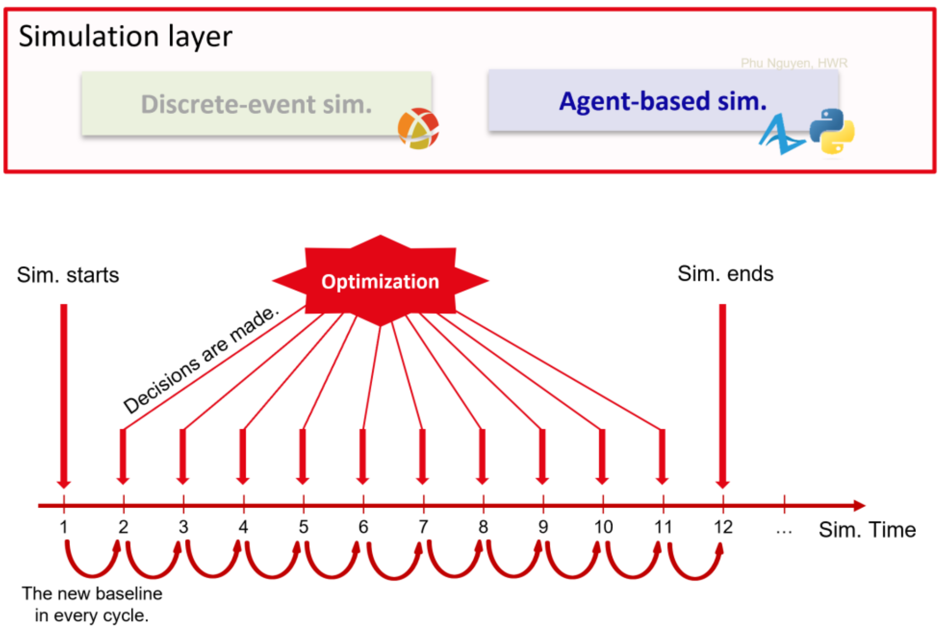

Figure 4-3. An illustration of the complex adaptive system approach.

Figure 4.4 captures the initial data model. The current model consists of 10 data tables, covering demand, production, and supply perspectives. Customer and product data are used to formulate demand. In the prototype, demand data is generated using empirical distributions based on historical information. The model allows users to input their scheduling agreements or demand data at varying levels of time granularity, which is essential for our stress-testing processes.

On the supply side, we incorporate information from the BoM and potential sources of supply. For high-complexity stress tests, which consider different BOM levels, it is important to classify parts into categories such as standard parts or assembled parts. All possible suppliers need to be identified and mapped to their respective components, allowing us better visibility of the supply chain network.

Once the solution is scaled up, we could integrate the actual production schedule and material receive schedule. Additionally, to enable an integrated two-layer simulation model, we also need new data tables to capture production flow and required resources (machines).

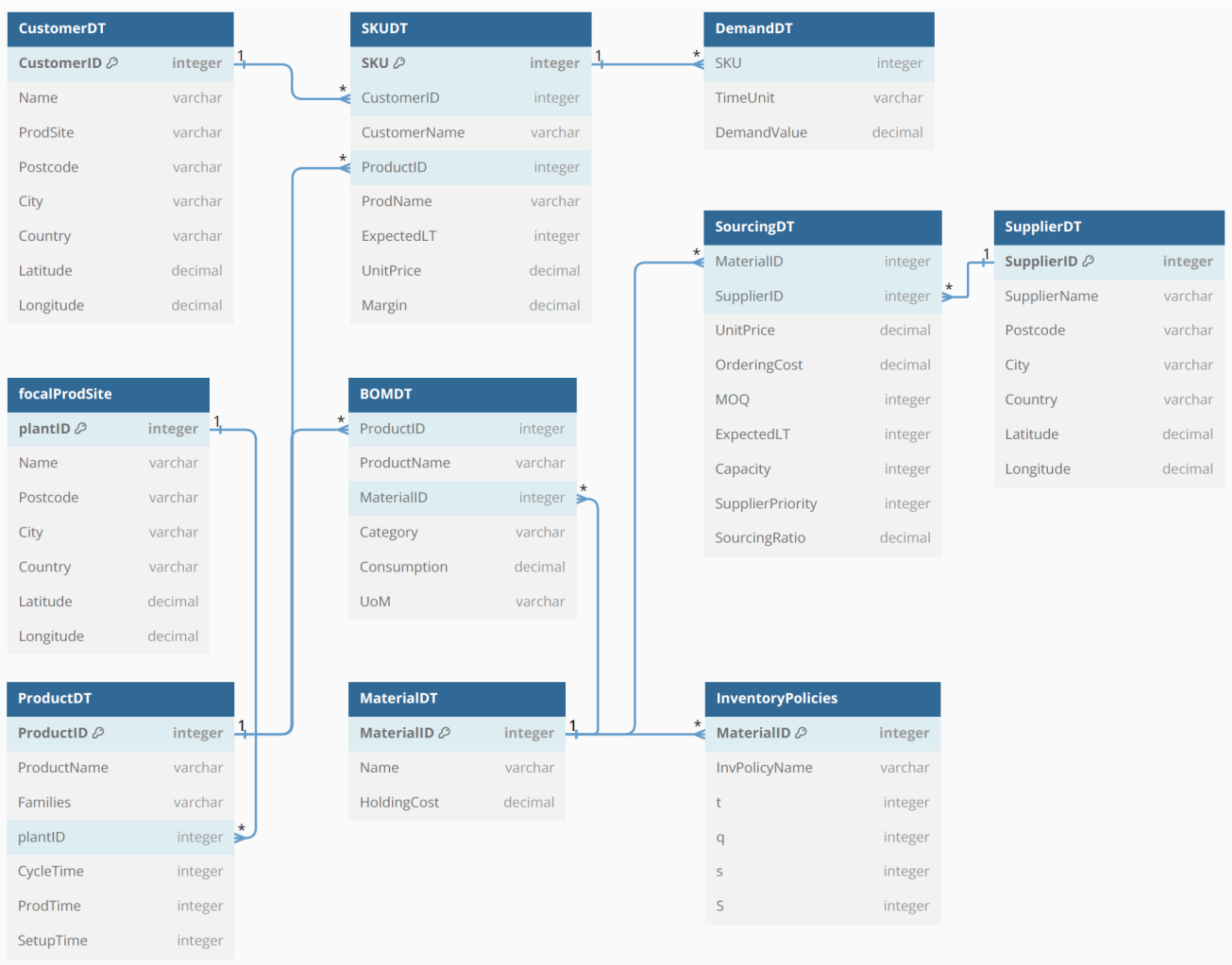

Figure 4-4. Supply chain data model (version 1).

4.4 Simulation conceptualization

Supply chain policies are critical in this study. To model these, we initially focus on sourcing and inventory management policies. While other policies, such as transportation and production policies, are also important, we begin by mapping the key policies necessary for understanding complex supply chain networks. In this first iteration, we link sourcing policies to regulate material flow between potential suppliers, stress-testing the model to identify hidden critical suppliers. Given that one identified use case is inventory replenishment policies, we focus on inventory management policy starting with the ordering process.

First, for sourcing policies, based on the BoM data and inbound logistics, we identify possible sources for each material. There are two possible scenarios, as Figure 4.5 captures: single source and multiple source. For a single source, the material can only be from one supplier. Supplier for single source material is, therefore, a single point of failure, and disruption in that supplier may pose significant consequences to the operations. For multiple sources, we need to quantify the sourcing ratio. The sourcing ratio is the probability that the order is released to a supplier. For example, material 1 can be sourced from two suppliers: supplier A, with a sourcing ratio of 80%, and supplier B, with a sourcing ratio of 20%. Once an order is released, the probability that supplier A will receive an order is 80%, while the probability that supplier B will receive an order is only 20%. We can adapt these policies based on real-world data with accurate time stamps. In some commercial software, sourcing from the highest available inventory or the lowest price can be selected. We could also adapt the solution based on the needs of users.

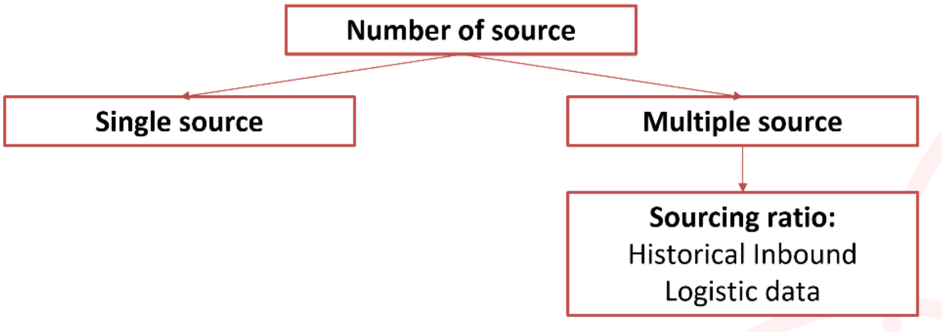

Figure 4-5. Illustration of the conceptual sourcing policies.

Second, for the inventory management policy, we start with the material ordering process, as captured in Figure 4.6. We apply the min-Max inventory policy as the baseline policy. The order quantity is calculated based on the projected material requirements and inventory on hand. We start with product demand and use the BoM data to calculate the material requirements. The material requirement is checked with the stock on hand and stock in transit. The shortage quantity is then compared with the minimum order quantity (MOQ). If the shortage quantity is less than the MOQ, we will release another supplier with the quantity as MOQ. Otherwise, the purchase request with the shortage volume is sent to selected suppliers. Once the order is released, we will adjust the inventory in transit. After the supplier lead time, the inventory on hand is updated with the order quantity. At every discrete time, the inventory level is updated based on actual consumption.

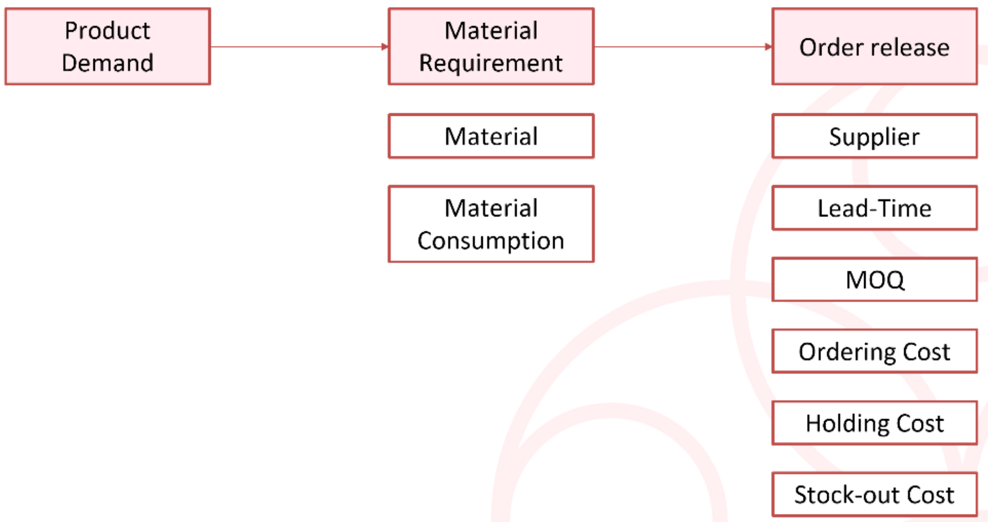

Figure 4-6. Illustration of the order release process.

4.5 Data

Primary data for Tronico's future model include data on Inbound logistics, BoM, outbound logistics, production flow, and resources. All collected data will be examined and analyzed using Python. In particular, BoM data will be examined in terms of products, materials, and definitions of consumption rate. Suppliers will be examined in terms of possible suppliers' definitions and analysis of the ordering process. MOQ, lead time, and costs will also be examined by a range of suppliers. In the customer block, exact customers will be defined, and demand will be examined. At the same time, the delivery process for all customers will be defined. In the floor block, the production path is going to be defined. Bottlenecks of machines used will be defined, and total capacity will be analyzed. After the analysis, this data will be used for modeling using Python and Anylogic. Figure 4.7 captures the data pipeline of our current solution.

During the data transformation stage of BoM, 25 products from aeronautics, defense, spatial, energies, and medical were analyzed. As a focused product, XPF0001202 (Defence, customer: 324) was chosen. Through analysis of the BoM dataset, it was defined that the outbound logistic dataset (extraction-CC.xlsx) misses four products, which are 00A105558A, 098-F1560411, 098-F1600526, and XPF0004200. It was also defined that the Inbound logistic dataset has no “Delivered” materials for two products: XPF0001205 and XPF0007330. In total, BoM data consists of 1068 lines of material. From 1068 lines of material, there are 627 unique materials for 19 products (if not to consider products 00A105558A, 098-F1560411, 098-F1600526, XPF0004200, XPF0001205 and XPF0007330 in analysis) or 961 unique materials for 25 products. BoM data in terms of Consumption rate, Supplier number, MO

Q, Expected lead-time, Durée de contrôle, and Ordering cost are presented in Figure 4.8. Also, a comparison between full BoM data and filled BoM data for products that have demand data is presented in Figure 4.9.

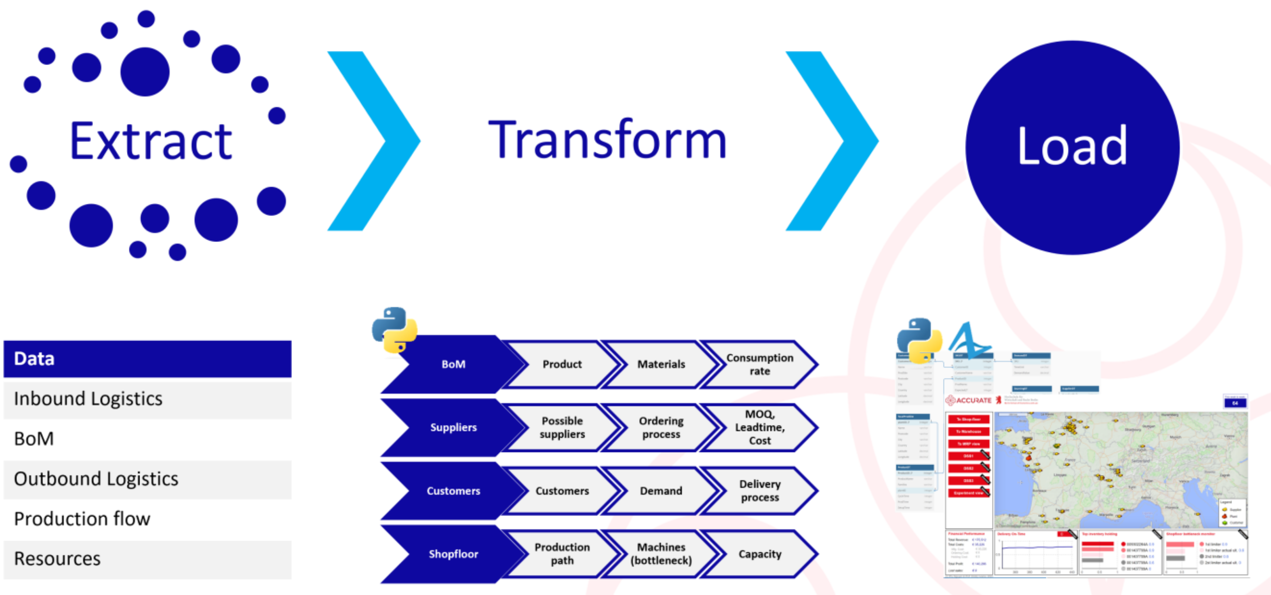

Figure 4-7. Data pipeline.

	Consumption rate	Supplier number	MOQ	Expected Lead-time	Durée de contrôle	Ordering cost
count	1068.00	1051.00	982.00	1051.00	1051.00	1068.00
mean	6.12	3517.83	7887.37	140.24	16.76	27.77
std	19.33	7863.01	15019.12	234.20	22.42	604.74
min	0.00	4.00	1.00	5.00	2.00	0.00
25%	1.00	542.00	500.00	50.00	2.00	0.01
50%	2.00	542.00	4000.00	80.00	2.00	0.09
75%	6.00	3926.00	10000.00	100.00	25.00	0.89
max	460.00	48857.00	240000.00	999.00	90.00	19642.36

Figure 4-8. BoM data.

	Product	Full BOM	Filled BOM
0	XPF0001202	190	164.00
1	069-E49678AAA	229	141.00
2	069-E49677AAA	156	95.00
3	XPF0004999	124	95.00
4	XPF0004175	44	38.00
5	XPF0004943	32	25.00
6	597-1557LC001-TEST	38	19.00
7	00A105548A	32	16.00
8	XPF0007423	21	14.00
9	XPF0003198	19	12.00
10	XPF0006595	11	9.00
11	XPF0003892	13	7.00
12	XPF0005904	15	7.00
13	XPF0006968	20	7.00
14	XPF0000932	18	5.00
15	XPF0003586	9	4.00
16	XPF0000991	18	4.00
17	143-E18529AA	10	4.00
18	003-100376110	12	3.00
19	XPF0001205	2	NaN
20	XPF0007330	3	NaN

Figure 4-9. Full BoM data and filled BoM data for products have demand data.

During the transformation stage of Supplier data, 627 unique materials were mapped with possible sources. It appeared that 60% of materials, 375 materials in total, are single sources. At the same time, 168 materials have two sources; 64 materials have three sources; 2 materials, which are DA008629828 and 00140A712A, have five sources; 2 materials, which are DA007548435 and DA008629852, have six sources. The full distribution of unique materials with possible sources can be seen in Figure 4.10. The main idea of the sourcing policy, which is taken into account, is that in the case of multiple sources, the sourcing ratio is based on historical inbound logistic data. There is an opportunity for improvement in dynamic sourcing based on selected KPIs that can be implemented.

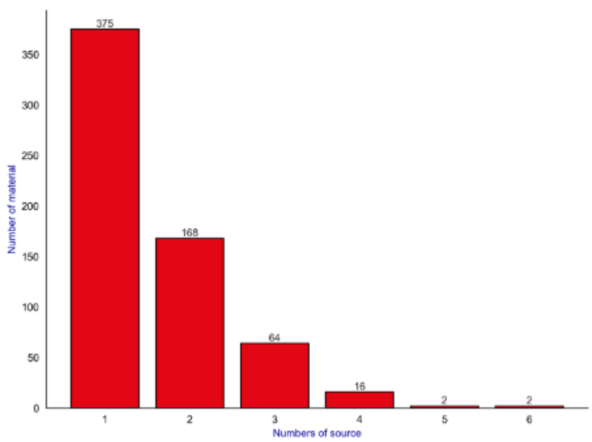

Figure 4-10. Unique materials with possible sources.

During the transformation stage of MRP data, the flow of the ordering process was defined. Everything starts with product demand, which is transforming further into material requirements. In the material requirement stage, the data is divided into material data and material consumption data. Material requirement data is transforming further in order to release. At this stage, data of supplier, lead-time, MOQ, ordering cost, holding cost, and stock-out cost is defined.

During the transformation stage of customer data, date data was turned into week number, as it was decided to go with a granularity of week. Synthesis demand data for simulation is developed from historical demand data. The empirical distribution of historical demand by week can be observed in Figure 4.11.

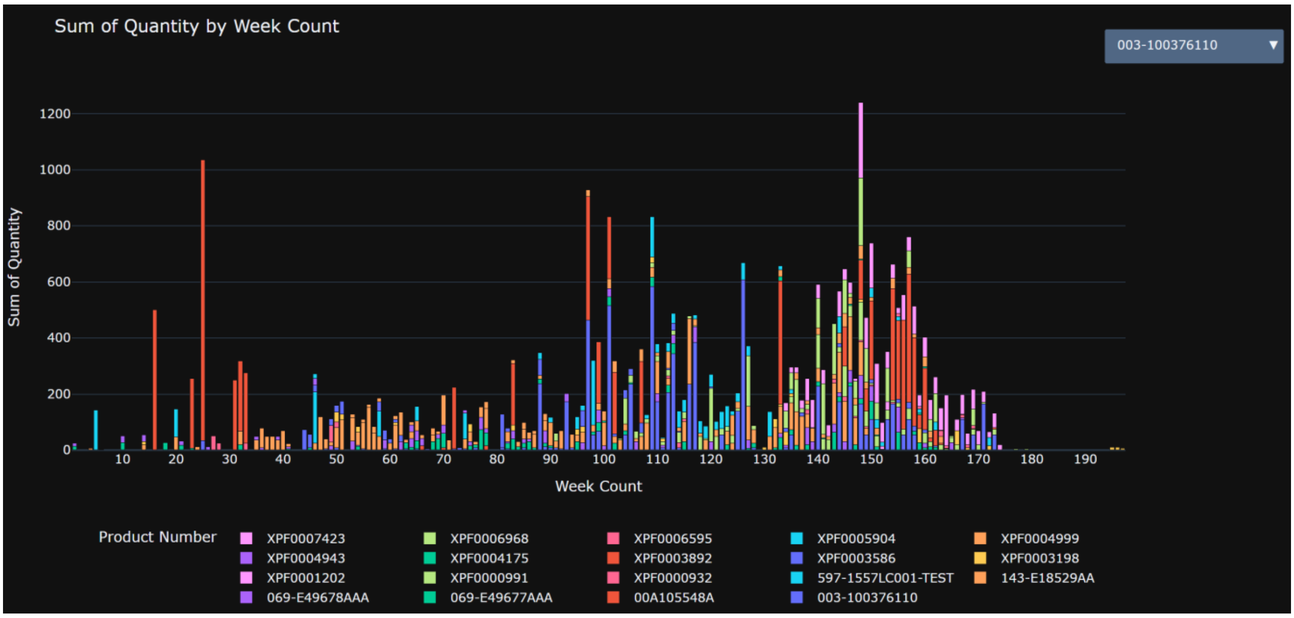

Figure 4-11. Empirical distribution of historical demand by week.

ID	Vulnerability	Impact	Probability	Impact	Estimated duration of impact
1	Item obsolescence	Unusable items	High	Strong	Undetermined duration (Component supply)
2	Tension in the components market (increased lead times, prices, pandemic, etc.)	Disruption in the logistics flow (delay, cost, logistics problem)	High	Significant	<3 months
3	IT risk (breakdown, attack, disaster, theft)	Computer system paralysis	High	Significant	Depending on the intensity and severity of the attack suffered
4	Suppliers in risk areas (natural disasters, geopolitics)	Supplier can no longer meet our needs or is uncertain	Medium	Medium	<3 months
5	Carrier IT platform more accessible and/or functional	No more tracking of ongoing deliveries	Medium	Significant	< 12 hours
6	Breakage in the product workshop with long lead times for components	Damage or scrap of affected components and production delay	Medium	Significant	Undetermined duration (Component supply)
7	Financial dispute, late payment	Supply interrupted	Medium	Strong	Supply disruption or overstocking

Table 4-1. Identified disruption scenario.

4.6 Plan for supply chain stress-test

The project team is working on developing the simulation model for the Tronico use case. We have done to capture the supply network and two supply chain policies. Figure 4.12 captures the snapshot of the current model. We also succeeded in defining a disruption scenario related to Tronico, as Table 4.1 describes. It is clear that supply chain disruption poses many risks to the operation of Tronico. We aim to address vulnerabilities 1-2, 4, 6-7 using the developing solution. In each vulnerability, we plan to identify the list of suppliers and materials that have a higher risk than the others and develop the pilot scenario. For undetermined durations, we will develop three scenarios: short (4 weeks), medium (12 weeks), and long (36 weeks).

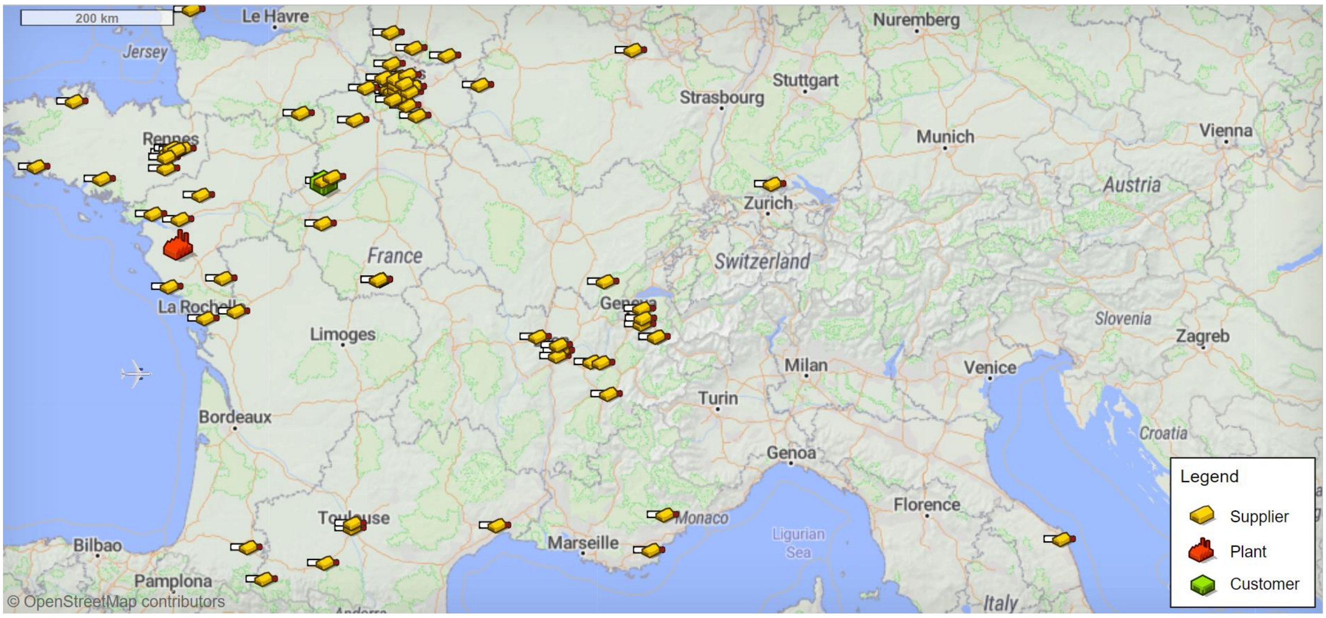

Figure 4-12. A snapshot of the supply chain model (version 1).

Our work aims to develop a two-layer simulation model that integrates supply chain dynamics with shop floor operations while fostering high interaction between optimization (decision-making processes) and simulation. The current model captures key elements of the supply chain, including suppliers, customers, and the focal plant. At present, we are verifying the supply chain layer to ensure its accuracy and robustness.

To enable two-layer simulation, we require a digital model of the shop floor layer, which is currently under development. This layer will allow us to capture both actual and potential production bottlenecks. To achieve this, we are leveraging process mining techniques in collaboration with our academic partner, IMT Atlantique, and partners in WP3. The integration of these two layers introduces a novel aspect to our project, as it enhances insight generation by facilitating interaction between supply chain and shopfloor dynamics. Furthermore, it enables decision-making at various levels, including supply chain planners, supply chain managers, and factory managers.

However, this ambitious approach presents significant challenges. The complexity of integrating both layers has delayed the supply chain stress test results. Despite these challenges, we remain committed to advancing this work within the scope of Tasks 4.3 and 4.6.

Moving forward, we will continue refining our supply chain policies, enhancing the data model, and integrating the shop floor layer. Additionally, we aim to develop features that enable capturing new dataset instances. A key priority is strengthening the interface between supply chain and shopfloor operations by leveraging process analysis to identify potential bottlenecks in Tronico's manufacturing processes. At the shopfloor level, our focus will be on capturing only critical bottleneck operations.

To assess the resilience of Tronico's supply chain, we will employ key performance indicators, including service level, on-time delivery, financial metrics (such as revenue, profit, and lost sales), and stock-out probability. These metrics will provide a comprehensive evaluation of the supply chain's robustness and responsiveness under various conditions.

4.7 Outlook for optimization

As in other domains concerning a wide range of operations management problems, production planning and control problems in PCB assembly are generally decomposed according to the time horizon granularity, namely: long-term (strategic), mid-term (tactical), and short-term (operational) (Crama et al., 2002). Generally, for tractability reasons, decisions are made independently per decision level, even if they are not purely serial or hierarchical (McGinnis et al., 1992).

Multiple hierarchical schemes exist in the PCB assembly literature. The interested reader can refer, e.g., to McGinnis et al. (1992), Ahmadi (1993), Croci and Perono (2000), Smed (2002), and Ellis et al. (2003). As pointed out by Crama et al. (2002), the relevance of a given decision hierarchization depends on multiple aspects, including:

- *Product mix*: Diversity of PCB types, batch sizes, etc.
- *Equipment*: Layout, number of machines, details of the operating mode, etc.
- *Managerial practices*.

In ACCURATE and as generally done in the related literature (Ellis et al., 2003), we distinguish the decisions related to process management from those related to production planning and control. Process management decisions refer to the machine optimization and lead to the specification of the numerical control programs guiding the assembly operations for each particular PCB type (Van Laarhoven and Zijm, 1993; Crama et al., 2002), and include feeder arrangement, component placement sequencing, component retrieval, and motion control specification. These decisions are taken while minimizing the time to place components on a particular card for a given arrangement of assembly machines (Ellis et al., 2003).

Production control refers to short-term decisions and includes scheduling and dispatching capabilities (Mönch et al., 2012). Production planning refers to mid-term decisions and provides the quantities and points of time for releasing orders.

Based on the works of McGinnis et al. (1992), Smed et al. (2000), Crama et al. (2002), and Mönch et al. (2012), let us consider the hierarchy of production planning and control illustrated in Figure 2 decomposed on the left side according to decision time horizon (from minutes to year), and on the right side according to the resource grouping (from machine level to shop level). Again, the decisions illustrated in Figure 4.9.1 are not independent, and they all contribute to the assembly performance.

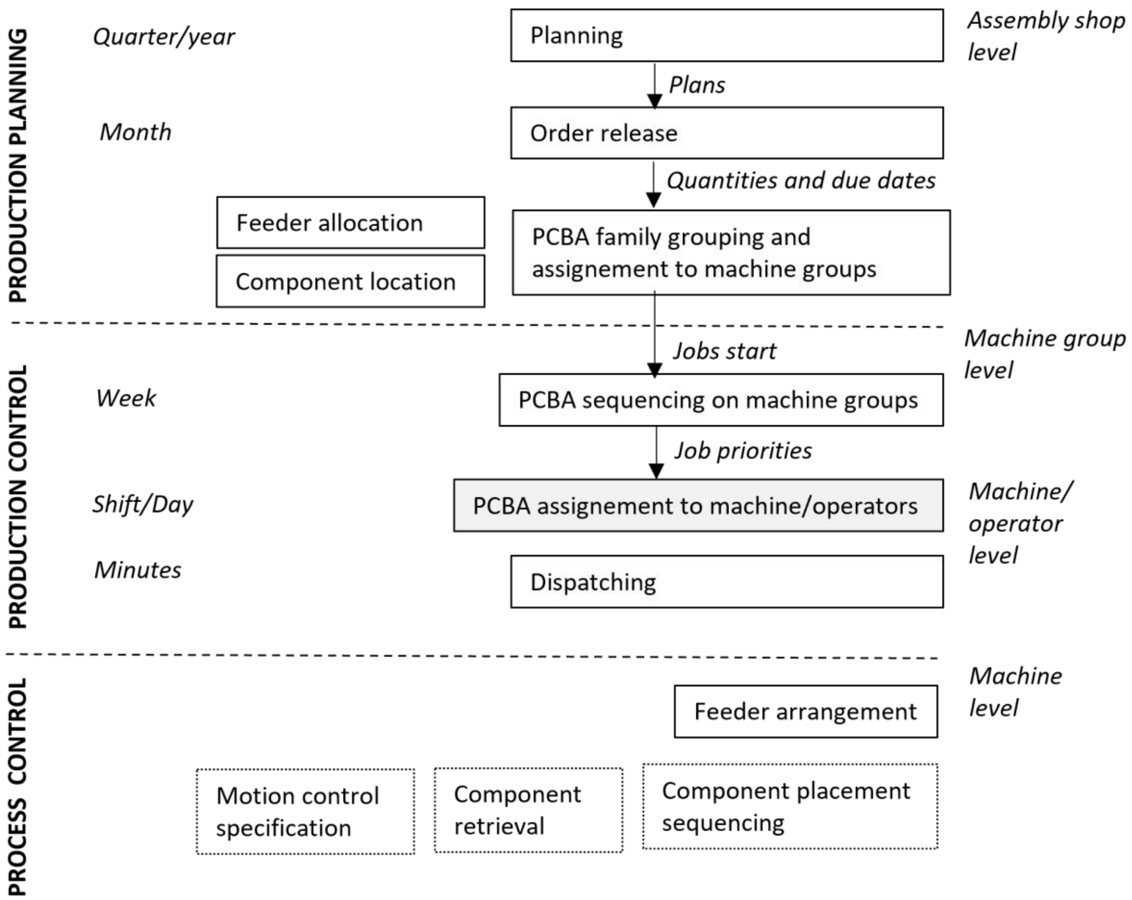

Figure 4-13. Production planning, production control, and process control in PCB assembly.

Like many other factories, Tronico is pressed by competition to improve shop floor flexibility and performance. The rate of OTD and performance-to-schedule are critical Key Performance Indicators (KPI) for the efficiency of manufacturing operations management.

Through discussions with Tronico's decision-makers, three critical focus areas have been identified for driving performance improvements:

1. *Production Control Level:* Currently, the production process lacks lot traceability, creating challenges in monitoring and optimizing workflows. To address this, we will leverage data collected through the recently deployed human resources software, Octime (https://www.octime.com/), to implement a robust lot-tracking system. This system will enable us to:

- Monitor the movement and progress of production lots in real-time,
- Identify critical parameters within the production system,
- Detect bottlenecks that hinder operational efficiency and reduce waiting times on the shop floor, which can achieve significant values (see, e.g., Figure 4.9.1).

By utilizing Octime data, we can refine scheduling and dispatching decisions and improve the accuracy of planned release dates. The integration of lot traceability will provide a clear view of production dynamics, leading to more informed decision-making and improved overall performance.

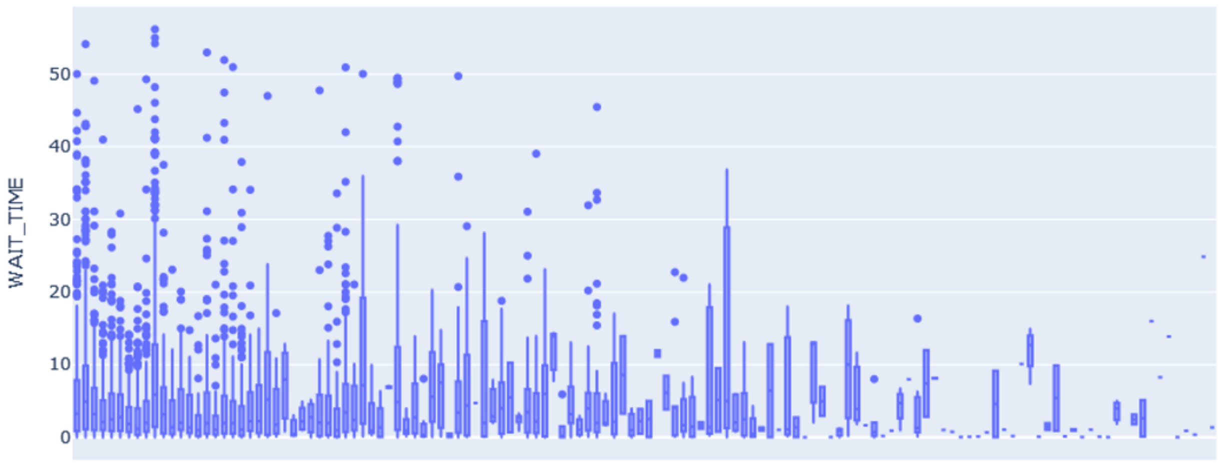

Figure 4-14. Examples of waiting times between two workshops (in days) of the Tronico shop floor in 2023-2024. Each barplot corresponds to a specific pair of workshops.

2. *Supply Chain Management Level:* To enhance the efficiency of Tronico's supply chain, we will develop a comprehensive approach to characterize and model demand forecast fluctuations that can exhibit significant variability (see Figure 4.9.2- Figure 4.9.3) not only in a long-term perspective but also after the order closing. This initiative will involve:

- Conducting detailed analyses of historical demand patterns,
- Identifying trends and variability in demand forecasts,
- Implementing predictive models to improve forecast accuracy.

These insights will serve as the foundation for better control over demand fluctuations, leading to optimized decision-making in areas such as procurement and production planning. By aligning material flow with actual demand, we aim to minimize delays, reduce inventory costs, and ensure timely availability of resources.

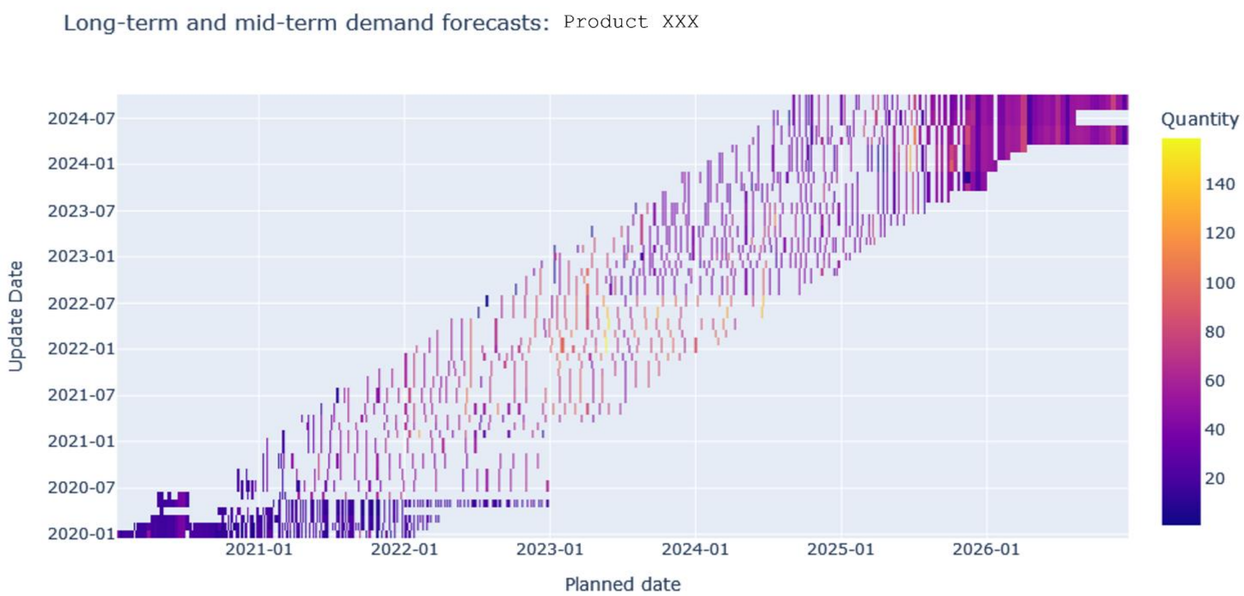

Figure 4-15. Example of demand forecast fluctuations for a given product.

Figure 4-16. Error-bars associated with the demand forecast fluctuations for forecast horizons.

3. *Vertical Integration of Decisions:* As a complementary focus area, we will establish feedback loops between supply chain management, production planning, and production control. This integration will ensure vertical decision consistency by:

- Tracking the effectiveness of implemented strategies,
- Collecting data to refine models and processes,
- Enabling iterative adjustments based on real-world outcomes.

This integrated approach is expected to drive long-term improvements in operational efficiency and customer satisfaction, as well as to increase the automation level in the case of Tronico.

5 Conclusion

The presented report analyzed the supply chains of three companies: Airbus Atlantic, Continental, and Tronico. All companies represent different fields, but they are united by the fact that each of them has a highly complex supply chain caused by the generally advanced products they produce. Each of the analyzed supply chains has a large number of suppliers (37 from Airbus Atlantic, more than 65 from Continental, and more than 600 from Tronico), which further complicates the transparent understanding and management of supply chains. Each of the companies has its own challenges, which, however, overlap with each other. Most of these problems and issues have become especially important due to the general instability of the environment. To find a solution to these problems, we developed three supply chain stress test models.

AnyLogistix, Anylogic, and Python were used to develop a simulation model for Airbus Atlantic. A simplified model of the supply chain of the S14A part, which is part of the A320 production, was created for correct analysis. AnyLogistix was used to create a simulation model for Airbus Atlantic and Continental. In the case of Continental, a simulation model is simplified and built for one product, P001. Python and Anylogic were used to create a simulation model for Tronico. For Tronico use cases, the goal was to develop a two-level simulation model covering both the supply chain and shopfloor levels. The data for building supply chain stress test models in each case was provided by the company. This is the main limitation of the conducted research: the data in the models are not updated automatically, and it is challenging to have full data for all aspects of the supply chain, incomplete in one or more areas.

In the case of Airbus Atlantic, the main task of the created simulation models was to analyze the reliability of suppliers in various conditions. During the stress testing experiments, the suppliers' performance in the events of political disruptions, environmental disruptions, and strikes were analyzed. The main modeling methods included stopping suppliers and extending delivery times. The results of the stress testing experiments of individual suppliers made it possible to divide suppliers into several groups. One group of suppliers demonstrated significant sensitivity to both operational failures and changes in transportation time. The other group, due to the initially long lead time, requires more time to recover from failures, which leads to a loss of efficiency. The third group, which includes some of the most important component suppliers, can significantly reduce financial and logistical performance in the event of the slightest disruption. Operations management processes must be continuously improved to strengthen the reliability of the supply chain. Thus, the key factors for strengthening SCM in the aerospace industry include improving flow management by OEMs and suppliers at all stages, developing a supplier portfolio, improving supply chain design, supply chain coordination, and risk management (Koblen and Nizníková, 2013). To further improve performance, responsiveness, and resilience, the following areas were selected together with Airbus Atlantic: demand management and lot sizing, supply chain coordination and risk management, and integration of external and internal supply chains.

For the Continental supply chain stress test model, the developed simulation model's primary goal was to assess its supply chain's resilience and robustness under various disruption scenarios. The main modeling methods involved simulating supplier shutdowns, extending delivery lead times, and introducing transportation blockages. The results of these experiments enabled the identification of vulnerabilities in critical areas. Key factors for enhancing supply chain resilience in Continental's case included diversifying supplier bases and delivery routes, adopting robust inventory management practices, and leveraging advanced predictive analytics for demand and disruption forecasting. Additionally, improvements in supply chain design, enhanced collaboration with suppliers, and integration of internal and external supply chain processes were identified as critical priorities. To further enhance performance, Continental should focus on developing contingency plans for sole-supplier dependence situations and exploring alternative sourcing and transportation options. These measures ensure greater adaptability to shifting supply chain dynamics, allowing the company to maintain service levels during disruptions and build long-term resilience.

In the case of Tronico, the supply chain is often disrupted by component shortages, the risk of counterfeit parts, and last-minute changes to specifications due to component shortages. Besides that, Tronico manages supply chain processes manually, which limits visibility into disruptions' broader impacts. The main problems of the supply chain under consideration are component availability, component obsolescence, and fluctuating demand. As mentioned, this stress testing model was developed as a two-level model. The model includes suppliers and customers at the supply chain level, considering inventory policies and supplier search. At the shop floor level, the model includes a high-level production process, focusing on operations with bottlenecks and demonstrating an approach to solving problems related to suboptimal production performance. Production control and production planning were considered to address supply chain disruptions. At the same time, production control refers to short-term solutions and includes planning and dispatching capabilities. Production planning, in turn, refers to a medium-term solution and determines the volume and timing of orders. After discussions with Tronico decision makers, three critical areas for efficiency improvement were identified: production control and planning, supply chain management, and vertical integration of solutions.

Despite the valuable insights provided by the stress testing models both for companies and research, there are several limitations that could be addressed in the future. First, as stated during the development stages of models, the simplified dataset for the models may not fully capture the complex dynamics and interdependencies in the supply chains. As well we also presented a standalone simulation model that lacks data-connected interfaces. To better manage rapidly changing environments, we will work with other partners in the project to integrate our stress-test model into the ecosystem. Another limitation is that the models were built for specific products within each company, which may not reflect broader organizational supply chain challenges. This can lead to incomplete insights, as in the decision-making stage, challenges in organizational structure and processes can be overlooked.

Future research can estimate possibilities in enhancing the granularity and scope of the models, incorporating real-time data integration through IoT and AI technologies, and expanding the simulations to include multi-product or company-wide analyses. This would provide a deeper understanding of the supply chain dynamics and allow us to stress-test the supply chain under more complex disruptions. Additionally, further studies could develop predictive tools for proactive risk management. Research can also explore methods of enhancing transparency and traceability of the required data and improving strategies for decision-making processes. Finally, cross-industry comparative analyses of obtained results can provide insights into the usage of best practices and mitigation strategies, allowing the adaptation of strategies from industries with similar supply chain complexities.5

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Apendix A Data collection template

Sheet	Data category	Mandatory data	Desirable data
Product	Master data	- Product (assembled products) in scope - Production lead-time - Production capacity - Production cost	- Data about stage in product life cycle (e.g., introduction, growth, maturity, decline)
BOM	Master data + reference data	- Bill-of-Material - Consumption rate - Possible sources (i.e., list of suppliers that can supply the materials), and their capacity (if any). - Sourcing policy (e.g., supplier allocation for multiple sources) - Ordering cost - Transportation cost	
Inbound logistics	Historical data	- Material - Supplier and supplier location (if multiple sites) - Purchasing volume (quantity, value) - Lead time (order release date, order delivery/receive date) - Other: batch size, modes of transportation (e.g., sea, land, air)	
Material inventory management	Historical data	- Snapshot of material inventory - Inventory holding cost	
Outbound logistics	Historical data	- Product - Customers - Delivered quantity - Lead time - Other: batch size, modes of transportation (e.g., sea, land, air)	- Lost sale and backorder penalty cost
Finish-good inventory management	Historical data	- Snapshot of product inventory '- Inventory holding cost	
KPIs	Historical data	- Snapshot of KPIs	
Sources of disruptions and Main mitigation levers	Expert judgement (+ historical data)	- Vulnerability - Likelihood - Impact - Disruption duration (best case, most probable case, worst case) - Mitigation levers	- Historical disruption events

Table A-1. Data collection template (launched in April 2024).

Apendix B Summary of the data collection effort

	AIRBUS	Continental	TRONICO (A member of AGON ELECTRONICS)
SC Characteristics	- Make-To-Order	- Assemble-To-Order - Scheduling agreement, with days on hand inventory	- Assemble-To-Order, - High Mix – Low volume
Data collection	- Focus in part S14A - Done 3 collection rounds	- Focus on 1 product - Done 2 collection rounds	- **Include 25 prod. in 5 families** - Done 2 collection rounds
Data complexity	- **BOM: 902 unique parts at 4 BOM levels** - Mapping with 37 global suppliers (material – supplier mapping rate: 74%) - Mapping Tier-1 supplier network for all parts	- **BOM: 367 unique parts** - Successfully mapped all parts with 65 global suppliers	- **BOM: 961 unique parts** - Successfully mapped all parts with 105 global suppliers
	- We are working to identify potential back-up suppliers to build comprehensive SC network.		

Image source: Airbus SE (2024); Continental AG (2024), Tronico (2024)

Figure B-1. Summary of the data collection effort.

The data collection process is the joint effort of all partners in the project. We particularly appreciate the effort to collect data from our three industrial partners: Airbus Atlantic, Continental, and Tronico.