Hochschule für
Wirtschaft und Recht Berlin
Berlin School of Economics and Law

4th edition

Supply Chain Simulation and Optimization with anyLogistix

design | optimize | experiment | innovate

Decision-oriented teaching notes for model-based management decision making

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About the Author

Prof. Dr. Dr. habil. Dmitry Ivanov is professor of Supply Chain and Operations Management at Berlin School of Economics and Law (HWR Berlin), deputy director and executive board member of Institute for Logistics (IfL) at HWR Berlin, and faculty director of M.A. Global Supply Chain and Operations Management program at HWR Berlin.

He has been *teaching* classes for more than 20 years in operations management, supply chain management, logistics, management information systems, and strategic management at undergraduate, master's, PhD, and executive MBA levels at different universities worldwide in English, German, and Russian. He has given guest lectures, presented scholarly papers and has been a visiting professor at numerous universities in Asia, Europe and North America.

His *research* explores structural dynamics and control in complex networks, with applications to supply chain resilience, scheduling in Industry 4.0 systems, supply chain simulation, risk analytics and digital supply chain twins. He is co-author of structural dynamics control methods for supply chain management. He applies mathematical programming, simulation, control and fuzzy theoretic methods. Based upon triangle "process-model-technology", he investigates the dynamics of complex networks in production, logistics, and supply chains. Most of his courses and research focuses on the interface of supply chain management, operations research, industrial engineering, and digital technology.

His *academic* background includes industrial engineering and management, operations research, and applied control theory. He studied industrial engineering and production management in St. Petersburg and Chemnitz and graduated with honors. He gained his PhD (Dr.rer.pol.), Doctor of Science (ScD), and Habilitation (Dr. habil.) degrees in 2006 (TU Chemnitz), 2008 (FINEC St. Petersburg), and 2011 (TU Chemnitz) respectively. Prior to becoming an academic, he was mainly engaged in *industry and consulting*, especially for process optimization in manufacturing and logistics and ERP systems. His practical expertise includes numerous projects on the application of operations research and process optimization methods to operations design, logistics, scheduling and supply chain optimization. Prior to joining the Berlin School of Economics and Law, he was professor and acting chair of Operations Management at University of Hamburg.

His research record includes around 300 publications, with 70 papers in prestigious academic journals and the leading books "Global Supply Chain and Operations Management", „Structural Dynamics and Resilience in Supply Chain Risk Management“ and „Handbook of Ripple Effects in the Supply Chain“. Professor Ivanov's research has been published in various academic journals, including Annals of Operations Research, Annual Reviews in Control, Central European Journal of Operations Research, Computers and Industrial Engineering, European Journal of Operational Research, IEEE Transactions on Engineering Management, International Journal of Integrated Supply Management, International Journal of Inventory Research, International Journal of Production Research, International Journal of Production Economics, International Journal of Technology Management, International Journal of Systems Science, International Transactions in Operational Research, Journal of Scheduling, Omega, Transportation Research: Part E, etc. He is a recipient of German Chancellor Scholarship (2005-2006), Best Paper Awards of International Journal of Production Research (2018 and 2019), and Commended Paper Award at International Conference LogDynamics (2018). He is listed in WiWo ranking 2019 „The Best Reseachers in Business and Management“ in categories TOP 100 and Long-Term Stars.

He is leading working groups, tracks and sessions on the Digital Supply Chain, Supply Chain Risk Management and Resilience in global research communities. He is Editor of International Journal of Integrated Supply Management and an Associate Editor in International Journal of Production Research and International Journal of Systems Science. He is an editorial board member, associate and guest-editor in different journals, including Annals of Operations Research, International Journal of Production Economics, International Journal of Production Research, International Transactions in Operational Research, International Journal of Integrated Supply Management, International Journal of Information Management, International Journal of Inventory Research, International Journal of Physical Distribution & Logistics Management, International Journal of Systems Science, Production Journal, and Resources, Conservation and Recycling. He is Chairman of IFAC TC 5.2 "Manufacturing Modelling for Management and Control" and Co-Chairman of the IFAC TC 5.2 Working group "Supply Network Engineering". He has been member of numerous associations, including CSCMP, GOR, INFORMS, POMS, and VHB. He regularly presents his research results and has been chairman, IPC and Advisory Board member of many international conferences where he has organized numerous tracks and sessions (including IFAC MIM, INCOM, EURO, INFORMS, IFORS, OR, POMS, IFAC World Congress, IFIP PRO-VE, LDIC, to name a few). He is General Chair of IFAC MIM 2019 – one of the worldwide largest conferences in manufacturing, operations and supply chain management.

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Foreword

anyLogistix is an easy-to-understand tool students and professionals can use to address a wide range of supply chain management (SCM) problems. This guide explains how to use anyLogistix to create supply chain models, conduct experiments and analyze the results. By reducing technical complexity to a minimum, anyLogistix allows students to focus on management decision analysis and use KPIs for operational, customer and financial performance measurement and decision-making.

This guide groups the content into three parts regarding facility location planning using GFA (Greenfield analysis), network optimization and simulation that correspond to three basic process structures — two-stage, three-stage and four-stage supply chains — as well supply chain-based risk management. It presents simulation and optimization examples by describing how to develop and build models and evaluate KPI. It also discusses how to use these models and their simulation and optimization results to improve management decision-making.

Because this guide is focused on management issues, it uses simple terms to describe model developments. If you want to import sample models and use them to perform experiments, you can point to anyLogistix's **File** menu and then click **Import**.

Please excuse any errors in the text and formatting. This guide is a work in progress and we welcome any comments and suggestions that may help us improve it.

This guide's author has also co-authored the textbook "Global Supply Chain and Operations Management" by Springer (http://www.springer.com/us/book/9783319242156) and its companion web site *http://global-supply-chain-management.de* where additional AnyLogic and AnyLogistix models can be found. In addition, he has also authored the e-book "Operations and Supply Chain Simulation with AnyLogic" (http://www.anylogic.com/books).

The author deeply thanks the AnyLogic Company for their valuable feedback and improvement suggestions.

Introduction

How to use this book

The ALX book aims to provide an overview of how to use anyLogistix to solve practical problems in supply chain management (SCM) and logistics. In doing so, the ALX book:

- provides an overview of anyLogistix;
- explains how to develop anyLogistix models with different degrees of complexity degrees;
- suggests a set of practical problem settings in supply chain management and logistics that can be modelled using anyLogistix;
- describes step-by-step how to use anyLogistix for decision-making support in supply chain management and logistics problem settings;
- figures out some cases for further development using anyLogistix.

The ALX book can be used as a self-study guide or in the classroom for exemplifying different SCM and logistics topics or guiding students as they create their own models. The book is structured as follows (Table I-1).

Table I-1: ALX book structure

Section	Content	Scenario as Excel file	Corresponding chapter in the textbook Global Supply Chain and Operations Management	Complexity level
Introduction	Principles of anyLogistix Basics of technical work with anyLogistix Basics of applying simulation and optimization to supply chain management		Chapter 1 Chapter 3	Basic
Chapter 1	Greenfield Analysis Simple Simulation	Scenarios for Chapter 1	Chapter 7	Basic
Chapter 2	Network Optimization Advanced Simulation (Inventory Control and Shipment Policy) Vehicle Routing Optimization	Scenarios for Chapter 2	Chapter 8 Chapter 13 Chapter 14	Advanced I
Chapter 3	Advanced Simulation (Production and Sourcing Policies)	Scenarios for Chapter 3	Chapter 5 Chapter 12	Advanced I
Chapter 4	Risk Analysis in the Supply Chain (Bullwhip Effect and Ripple Effect)	Scenarios for Chapter 4	Chapter 15	Advanced II

	Variation and Comparison Experiments Risk Analysis Experiment			
Appendix 1	Examples of case-studies that can be developed using anyLogistix (without solutions)	Scenarios for App. 1		Advanced I-III
Appendix 2	Advanced examples of case-studies with simulation and optimization (with solutions)	Scenarios for App. 2		Advanced I-III

We recommend starting the ALX book by reading the **Introduction**. Next, the examples from Chapter 1 should be studied using the supplementary Excel files (cf Table I-1). How to import scenarios is explained in **Chapter 1** in the form of Excel files and follows step-by-step explanations in the ALX Handbook. At the same time, we also recommend watching the Webinar and educational videos provided by The AnyLogic Company as well as the standard model samples which come with anyLogistix software (you will find them in **Help**). In **Help – ALX Help**, you will find detailed explanations for all tables, parameters, and statistics used in anyLogistix. After completing Chapter 1, you will be able to perform Greenfield Analysis and some simple simulations on a basic level.

Chapter 2 introduces network optimization and transportation optimization. It also extends the Chapter 1 materials on simulation, and explains inventory control policies and shipment policies. After completing Chapter 2, you will be able to perform network optimization and advanced supply chain simulations.

Chapter 3 extends the materials of Chapter 2 on simulation and explains production and sourcing policies in the framework of a multi-echelon supply chain. After completing Chapter 3, you will be able to perform advanced supply chain simulations.

Chapter 4 focuses on supply chain risks and explains how anyLogistix can be used to analyze the bullwhip and ripple effects in the supply chain. It also introduces variation, comparison and risk analysis experiments. After completing Chapter 4, you will be able to perform risk analysis for supply chains.

Appendix 1 contains some example supply chain problems that can be solved using anyLogistix (without solutions). **Appendix 2** contains more advanced example problems and their corresponding simulation and optimization solutions.

The respective chapters of the textbook
Ivanov D., Tsipoulanidis, A., Schönberger, J. (2019) *Global Supply Chain and Operations Management: A decision-oriented introduction into the creation of value*, 2nd Edition, Springer Nature, Cham

are depicted in Table I-1. Short theoretical background information is given about the relevant problem settings in each chapter.

Theoretical Background and Principles of Decision-making Support in Supply Chain Management using anyLogistix

Supply Chain Management

A *supply chain* is a network of organizations and processes where enterprises (suppliers, manufacturers, distributors and retailers) cooperate and coordinate along the value chain to acquire raw materials, to convert these raw materials into products, and to deliver these products to customers (Ivanov et al. 2017).

Supply chain management (SCM) is a cross-department and cross-enterprise integration and coordination of material, information and financial flows to use the supply chain resources in the most rational way along the value chain, from raw material suppliers to customers (Ivanov et al. 2017).

Supply chain management integrates production and logistics processes at several levels. *Strategic* issues include decisions such as the size and location of manufacturing plants or distribution centers, the structure of service networks and designing the supply chain. *Tactical* issues include production, transportation and inventory planning. Finally, *operative* issues address production scheduling and control, inventory control and vehicle routing.

Model-based Decision-Making in Supply Chain Management

Decision-making in supply chain management implies the use of qualitative and quantitative methods. Quantitative methods are typically based on optimization or simulation.

Model-based decision-making process is shown in Figure I-1.

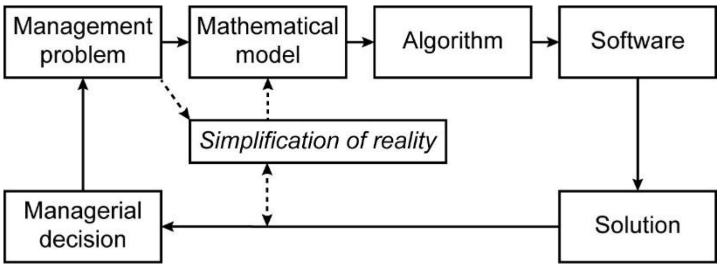


Figure I-1: Model-based decision-making process (Ivanov et al. 2017)

We can observe that a *real management problem* is the initial point of the decision-making process. For example, this could be a facility location problem where we are trying to decide where to locate the facilities and which quantities should be shipped from the facilities to the markets.

The next step is to transform the real problem into a *mathematical model*. For this transformation, we need to reduce the *complexity* of reality or in other words simplify the reality. For example, we aggregate demand into fixed quantities instead of considering fluctuations in demand.

The simplifications are necessary to represent the management problem as a mathematical model. This model can then be solved with the help of existing *algorithms* in a reasonable time. In our example, we formulate the facility location problem as a mixed-integer linear programming model that can be solved with the help of simplex and branch&bound algorithms.

For implementation of the mathematical model, *software* is needed. For example, the professional solver CPLEX is used in anyLogistix. Software will calculate the *solution*. In our example, the solution would include suggestions on where to open facility locations and which product quantities should be shipped from each opened facility to each of the markets so that total production and logistics costs are minimal.

However, it is important to consider whether this solution is automatically our *decision.* NO! This is a solution to the mathematical problem. Management expertise is needed to transfer this mathematical solution into managerial decisions. First, the simplifications of reality should be reviewed. Second, so called *soft facts* such as risks, flexibility, etc. should be included in the analysis. This need for managerial expertise is why we call these models *decision-supporting quantitative methods*.

To understand the application of quantitative methods to SCM in practice, SCM courses are often enhanced by decision-support software such as anyLogistix. Universities can use anyLogistix to support SCM, operations and logistics courses.

Principles of Supply Chain Simulation and Optimization in anyLogistix

anyLogistix makes it possible to develop real-life examples for many of the most important supply chain management domains, including:

- Facility Location Planning
  - ➢ Center-of-Gravity Method for Single and Multiple Locations
  - ➢ Network Optimization using Mixed-Linear Programming
- Capacity Planning of Distribution Centers
- Inventory Control Policies and Ordering Rules
- Sourcing Policies (Single and Multiple Sourcing)
- Transportation Policies (Full Truckload/FTL and Less-Than-Load/LTL)
- Batching in Transportation, Production, and Sales
- Bullwhip Effect and Ripple Effect Analysis in the supply chain

You can use KPI (key performance indicators) to assess the quality of your decisions in these areas as well as their impact on financial, operational and customer performance in the supply chain. The anyLogistix software can assess the impacts and interfaces of decisions and KPIs in all these domains to help you better answer the following questions:

- Where are the best locations for our warehouses, distribution centers and production sites?
- What are the best policies for replenishment, sourcing and transportation?
- How robust is our supply chain?
- What will happen if we change our inventory policy?
- What will happen if we increase a distribution center’s capacity?
- What will happen if demand changes?
- What will happen if we add a new product?
- What does an out-of-stock event cost?

You can model the supply chain in two ways (Figure I-2):

- Analytical modeling that uses optimization models to investigate the supply chain
- Simulation modeling that uses a set of objects and rules that describe their dynamic behavior and their interaction to represent the supply chain

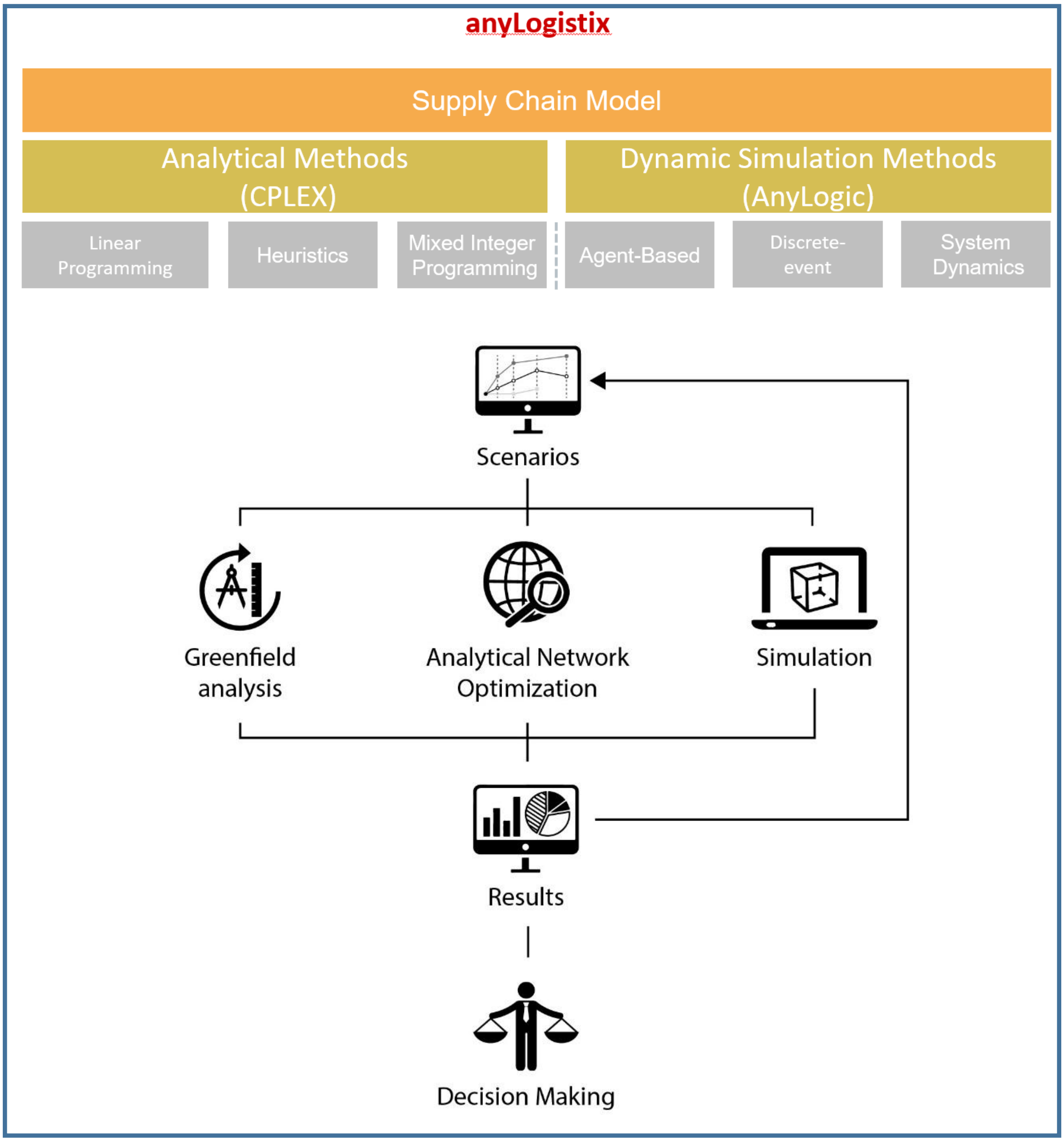


Figure I-2: Analytical and Simulation methods in anyLogistix

Simulation and Optimization for Decision-Making Support in Supply Chain Management

Both optimization and simulation have certain application areas, advantages and disadvantages. anyLogistix uses both and helps to understand differences and application issues. For example, you can optimize the supply chain's facility locations and then simulate their inventory control policies, transportation and sourcing rules (cf. Figure I-1 and I-2).

You'll usually start the *first stage* of a project (i.e., a scenario in anyLogistix) at the strategic level by using a green field analysis (GFA), sometimes called a center-of-gravity analysis, to define the optimal locations of distribution centers. At this stage, a high level of abstraction with a minimum number of details is used. Existing data, such as customer locations, demand per customer, the number and location of DCs, and/or service distances, are used as inputs to the analysis. The output of the analysis is an approximate, optimal location for a production or warehousing facility at which the cost of all in- and outbound transportation is minimized.

During the *second stage* – the NO (network optimization), you'll extend the problem setting by including feasible facility locations and use other parameters — such as fixed facility costs, inventory carrying costs, facility opening/closure costs, CO_2 emissions, many periods — and perform network optimizations. Network optimization is a decision-supporting quantitative model for supply chain management (SCM), which allows a supply chain manager to easily compare alternative network designs according to a customizable cost objective function. In contrast to the GFA, through an optimization analysis many alternative network designs and paths can be compared according to their impact on supply chain efficiency. The results also allow the maximal profitability of each potential alternative network design to be compared with one another. However, a real supply chain is complex and subject to uncertainty, and it is difficult to include many time-dependent, dynamic factors in optimization.

As your problem becomes more detailed, we extend the analysis in the *third stage* using simulations which provide an overview of the effects of different combinations of inventory control, sourcing, transportation, and production policies (Figure I-3).

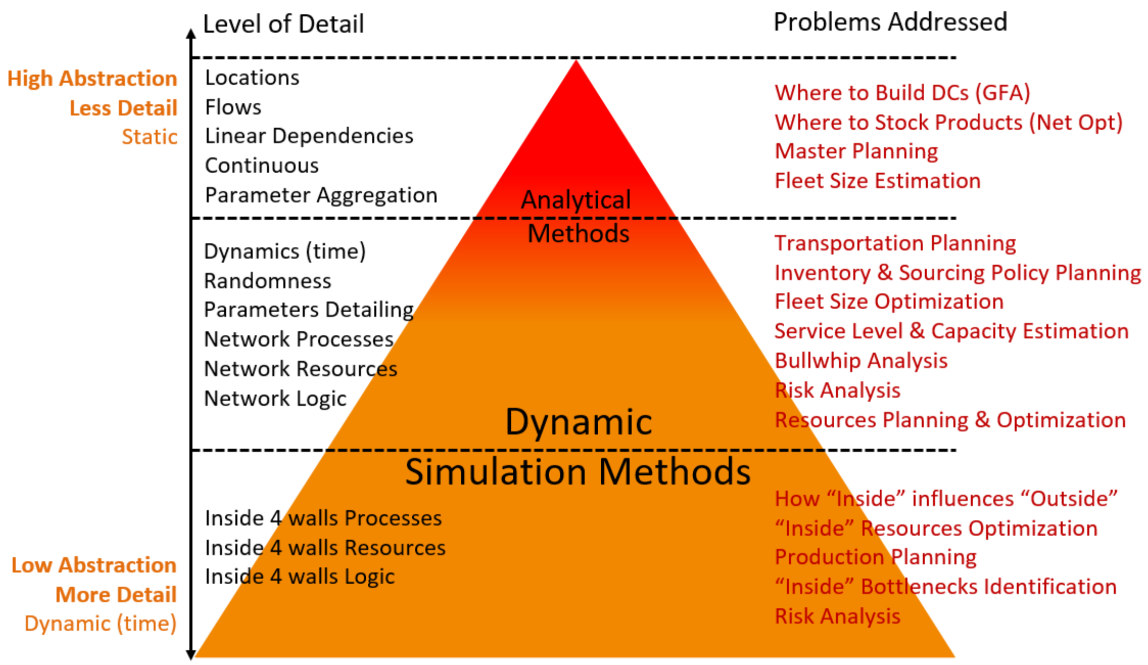


Figure I-3: A pyramid of supply chain design and analysis problems.

According to Ivanov et al. (2017, p.61), "Simulation is imitating the behavior of one system with another". In a simulation, supply chain processes in time can be observed and improved. By changing input parameters, the goal of the simulation is to understand the dynamics and material flow of the supply chain: "Simulation is an ideal tool for further analyzing the performance of a proposed design derived from an optimization model" (Ivanov et al. 2017, p. 61). To run a simulation, some critical data is needed, such as inventory control policy, sourcing policy, shipment policy, bills of material, production policy, etc. Supply chain simulation can be of strategic and operational support. Strategic support might include decisions concerning the number and location of facilities, stock levels, and transportation and supply planning. Operational support might include process control, predictions of developments in upcoming periods, trends detection, or decision support for choosing alternatives in unexpected situations such as operational risks of demand fluctuations (i.e., bullwhip effect) or disruption risks of facility breakdowns (i.e., ripple effect).

Finally, you will use the results of GFA, NO and Simulation for decision-making. In doing so, it will be important task to validate the results using sensitivity analysis and compare different scenarios subject to some KPIs. This will be done using Variation and Comparison analysis in anyLogistix. Conducting a sensitivity analysis with different iterations, a so called "variation" analysis, highlights the best result in the model and provides a check for robustness (Watson et al. 2013, p. 63-77). This can best be done by altering various key input parameters such as demand, inventory, or costs. The results then show whether any changes will have severe impacts on the network with regards to cost increases and savings decreases (Watson et al. 2013, p. 77).

How simulation and optimization are combined depends on the modeling objective. Three major combinations can be distinguished as follows (Figure I-3):

- Optimization as a starting point and simulation as an extended analysis method, e.g., for précising solutions obtained analytically using dynamic process analysis,
- Simulation as a starting point and optimization as an extended analysis method, e.g., for obtaining optimal parameters values in supply chain design, and
- Hybrid simulation-optimization techniques, e.g., simulation-based optimization, i.e., for iterative improvement of supply chain performance.

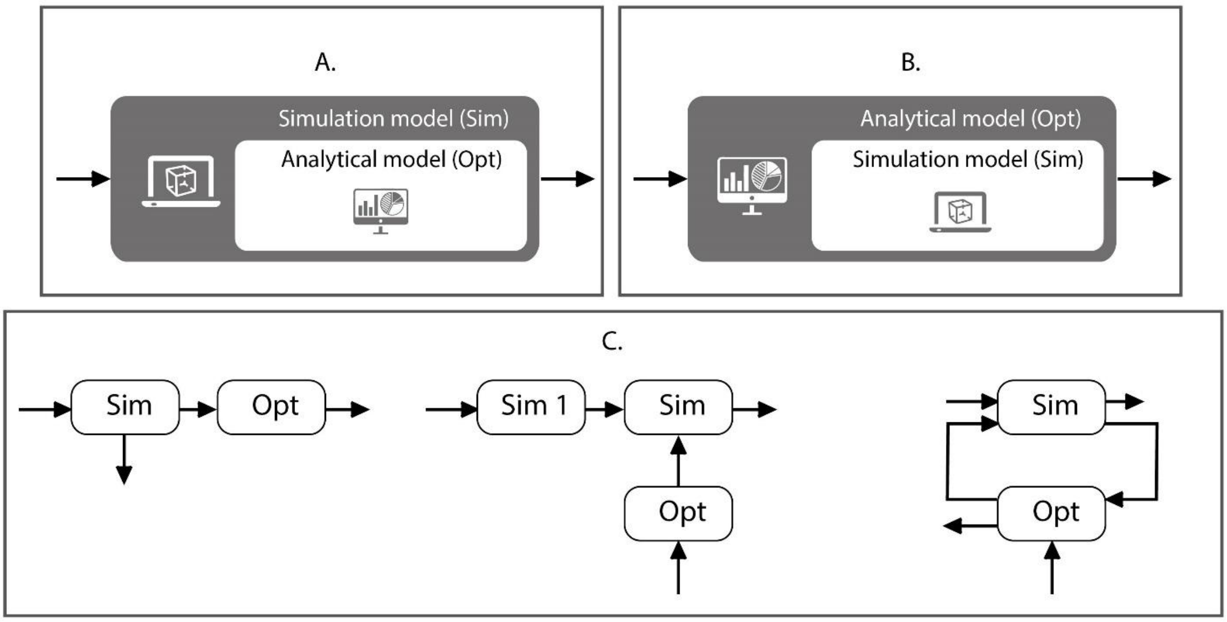


Figure I-3: Optimization and simulation combination variants

Optimization seeks the best solution for an operations or supply chain problem. It works by representing problem choices as decision variables and seeking values that extremized objective functions of the decision variables subject to constraints on variable values expressing the limits on possible decision choice. Optimization is an analysis method that determines the best possible option for solving a particular supply chain management problem. An optimization model comprises an objective function, a constraint system, and a set of decision variables and input parameters.

The drawback is the difficulty in developing a model with the detail to represent complexity and uncertainty that is also simple enough to be solved.

What's more, most optimization models are deterministic and static. Unless there are mitigating circumstances, optimization is the preferred approach. However, most supply chain and operations problems are dynamic. Their mutually dependent parameters and variables are difficult to restrict to an optimization model.

Simulation imitates the dynamic behavior of one system with another. By changing the simulated supply chain, one expects to better understand the physical supply chain's dynamics. Rather than deriving a mathematical solution, you experiment by changing the system's parameters and studying the results. Another advantage of simulation is to visualize the processes and structures.

However, since simulation works on the "what happens if..?" principle, the questions of result extremity, completeness and consistency remain open. That's why simulation can be an ideal tool for analyzing the performance of a proposed supply chain design you derive from an optimization model. Optimization-based simulation is a promising area to support supply chain and operations managers.

An optimal decision is the best decision which can be made according to some goal, criteria or objectives.

Note: The drawback of using optimization is the difficulty in developing a model that is sufficiently detailed and accurate in representing the complexity and uncertainty of the SCM, while keeping the model simple enough to be solved. Optimal decisions are "fragile" and presume certain problem dimensionality, fullness, and certainty of the model. In addition, the optimal solutions are usually very sensitive to deviations. Moreover, decision-making is tightly interconnected with dynamics and should be considered as an adaptive tuning process and not as a "one-way" optimization.

Optimization can also be applied as a validation tool for simulation models which can be run using the optimization results. Analytical optimization methods are used to define the supply chain design with aggregate parameters such as annual capacities, demands, etc. Using a number of parameters such as transportation costs, real routes, and feasible facility locations, it becomes possible to perform network optimization.

By reducing the aggregation and abstraction level, we extend the analytical network optimization models through simulation. In comparison to analytical closed form analysis, simulation has the advantage that it can handle complex problem settings with situational behavior changes in the system over time. The simulations in anyLogistix can be run using the optimization results and include additional, time-dependent inventory, production, transportation, and sourcing control policies which are difficult to implement at the network optimization level.

In addition to the standard functionality you'll find in anyLogistix, you can use AnyLogic to extend a policy or structural object (Figure I-4).

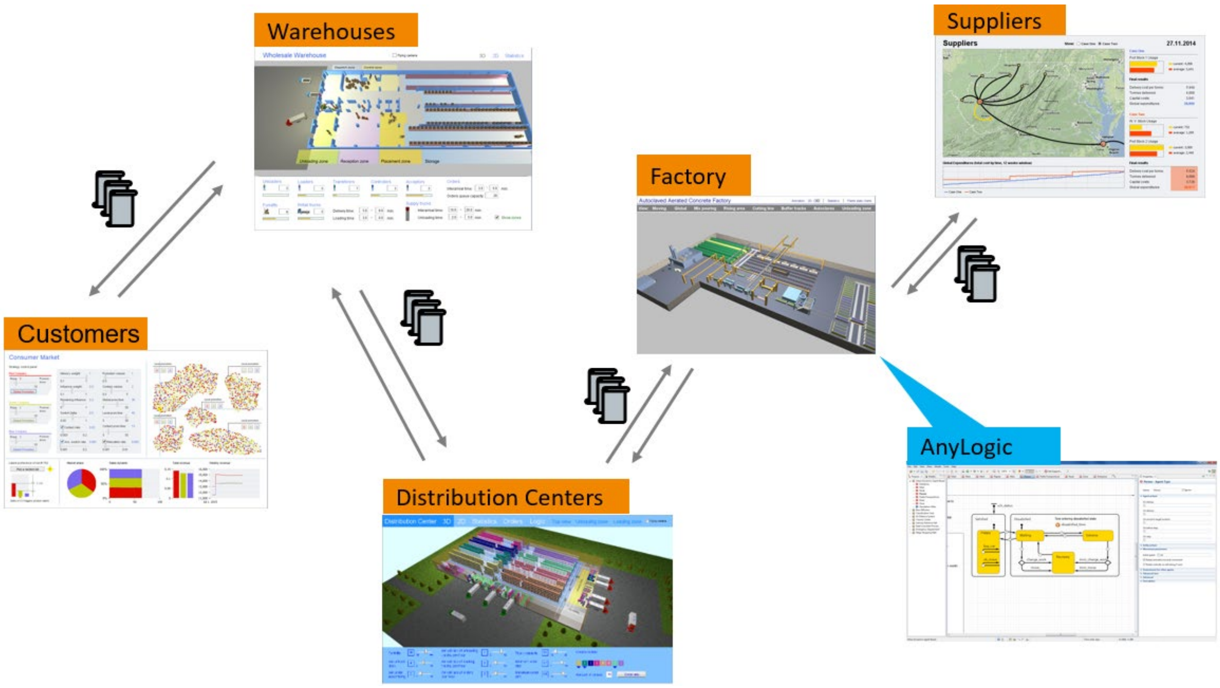


Figure I-4: An AnyLogic extension helps improve anyLogistix's supply chain modeling.

You can use AnyLogic's agent-based, discrete-event and system dynamics simulation models to customize inventory control, sourcing, transportation and production policies as well as distribution centers, customers and suppliers.

As an example, you might decide to <u>not</u> define a distribution center's processing time as a fixed time. Instead, you could embed a simulated distribution center you built in AnyLogic that uses details such as forklift capacities, real layouts and loading and unloading times.

We think you will find working with anyLogistix to be intuitive, and you'll find helpful descriptions of the program's features throughout this book.

Enjoy your supply chain simulation and optimization with anyLogistix!

Introducing anyLogistix

Understanding Projects

The anyLogistix software uses projects to organize data and experiments. Each project can include any number of scenarios and experiments. When you create a project, anyLogistix creates a dedicated database to store your project information.

Note: You can only work on one anyLogistix project at a time.

Understanding Scenarios

Your simulation and optimization starts when you create a scenario or import one from a Microsoft Excel workbook. A scenario is made up of the supply chain's:

- Design structure
- Sourcing, transportation, inventory control and production policies
- Parameters of the structural elements and policies

After you've created or imported a scenario, you can perform the following experiments (Figure I-5):

- Supply Chain Optimization: Green Field Analysis (GFA) and Network Optimization
- Supply Chain Analysis: Optimization-based simulation, simulation, variation, and comparison

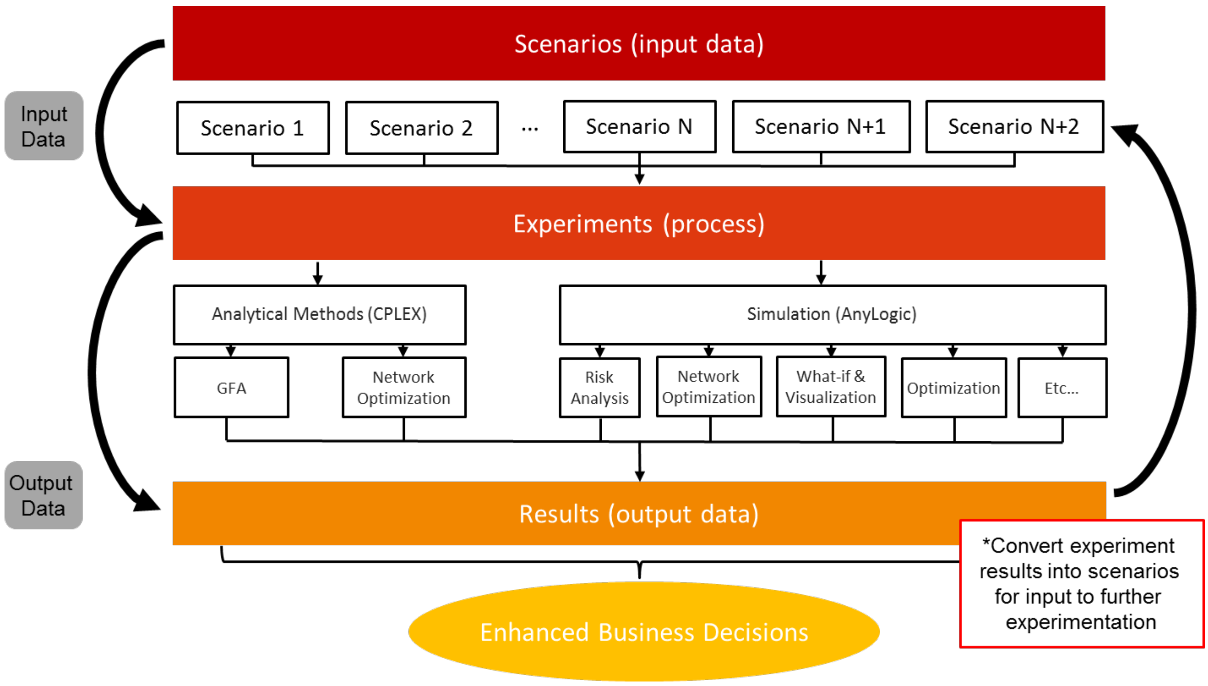


Figure I-5: An overview of the anyLogistix process that starts when you create a scenario and ends with your experiment's results.

The following illustrations introduce you to anyLogistix's user interface and show you how to create new project. If you're using the program for the first time, the **Projects** dialog box will open automatically. To open it at any other time, point to the **File** menu and click **Select Project**.

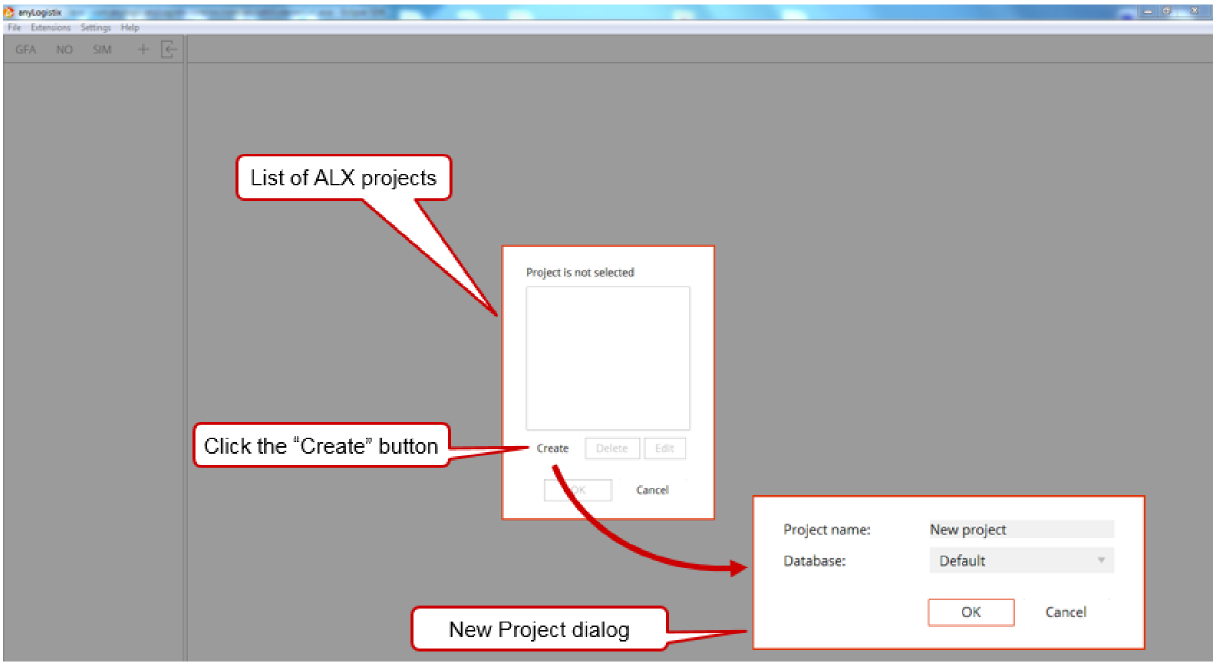


Figure I-6: Using anyLogistix's **Projects** Menu.

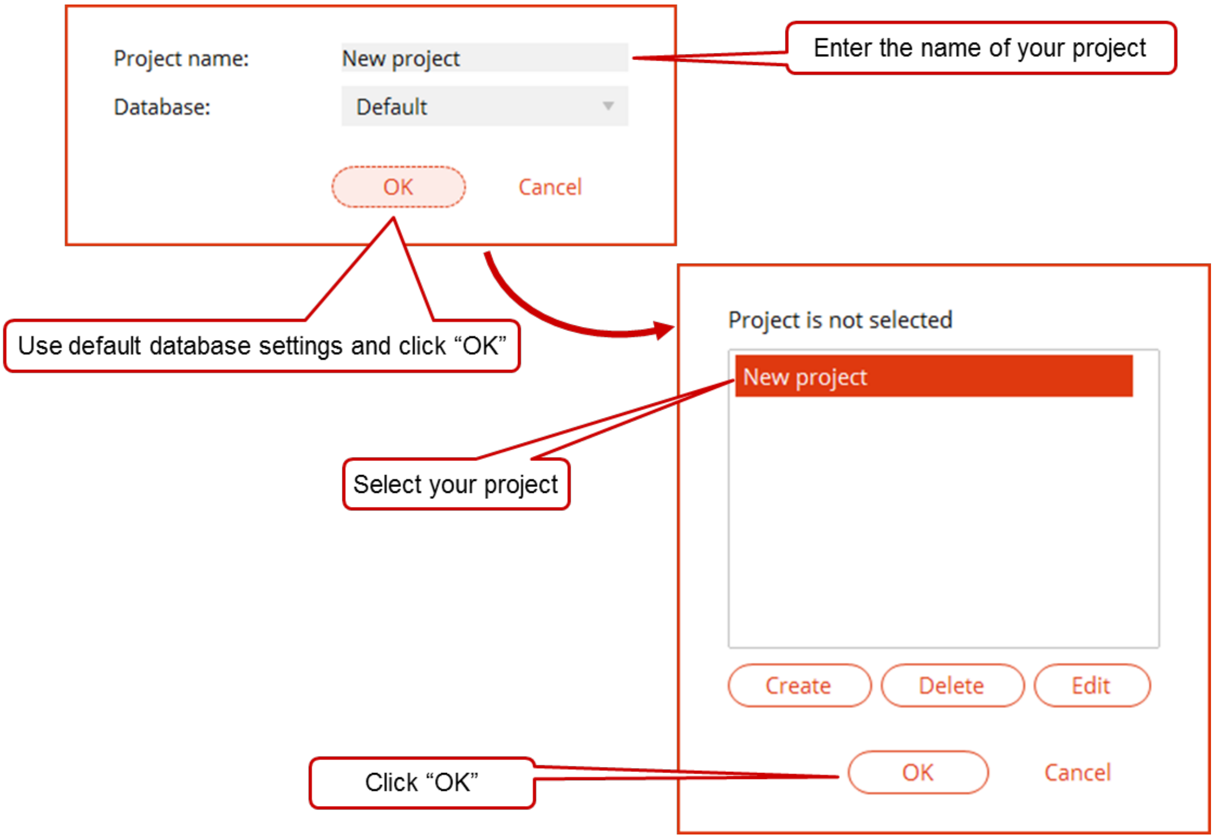


Figure I-7: Creating a project in anyLogistix.

Figure I-8 shows the basic steps you'll use to log on to anyLogistix's project database. If you haven't created a user account, the program will prompt you to set up a username and password.

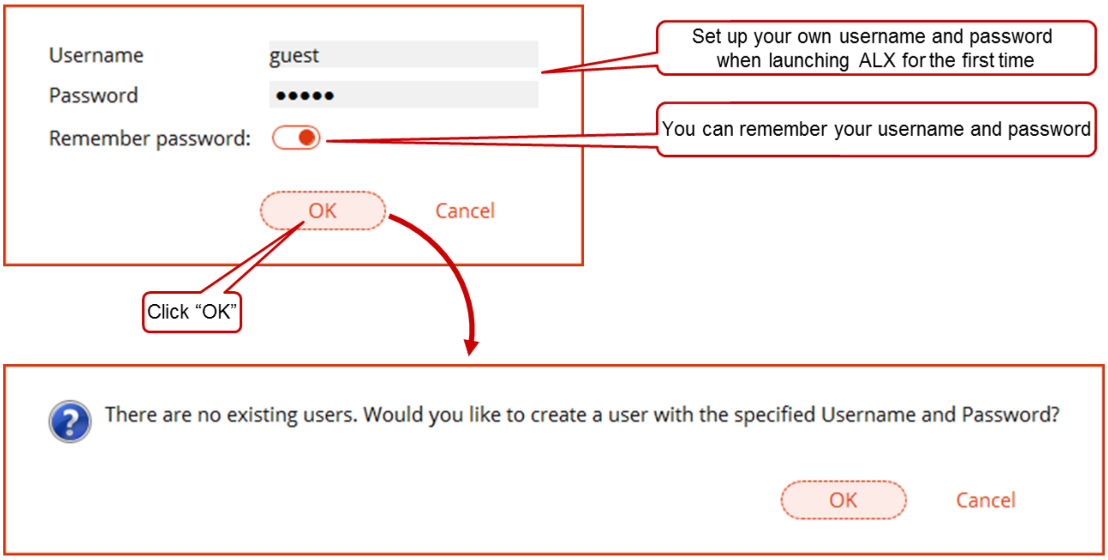


Figure I-8: Logging on to anyLogistix's project database.

As you've seen, your anyLogistix project contains scenarios that describe the supply chain. Figure I-9 shows the basic steps you'll need to perform to create a scenario.

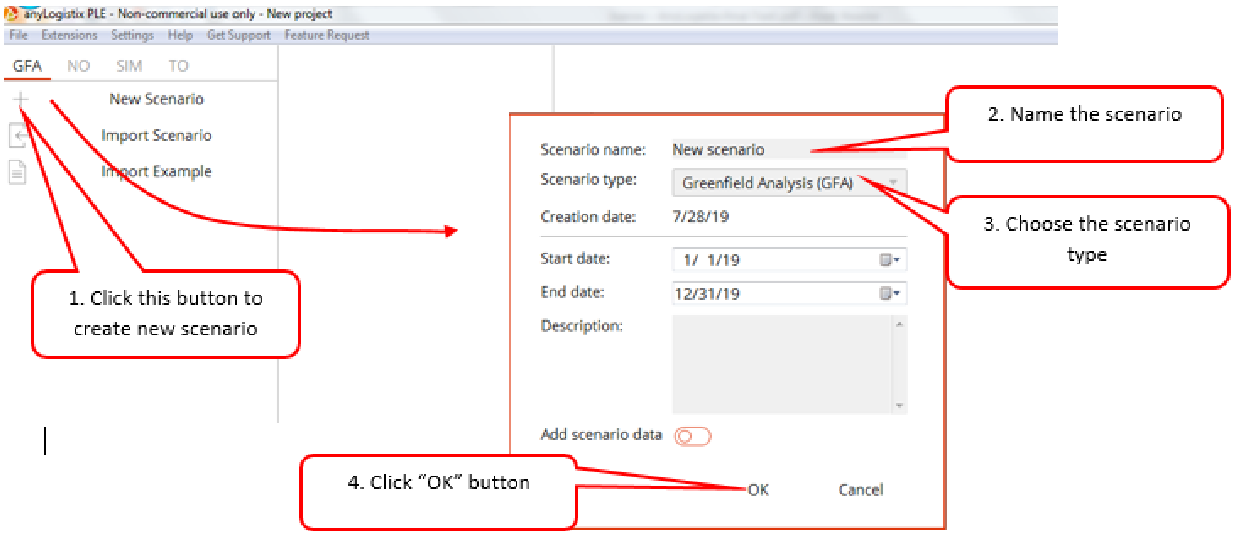


Figure I-9: Creating a scenario.

After you select a scenario from the list that displays on the left part of your screen (Figure I-10), you'll see a list of options for that scenario. For example, you may see options such as **Scenario Data** and **Experiment Settings**.

If you click **Data** for the selected scenario, a map with your supply chain objects will display in the right part of your screen. You can use the toolbar on top of the map to add objects to your supply chain, show or hide sourcing paths and show or hide object names. At the bottom of the screen, you'll see a list of tables you'll use to set up the supply chain.

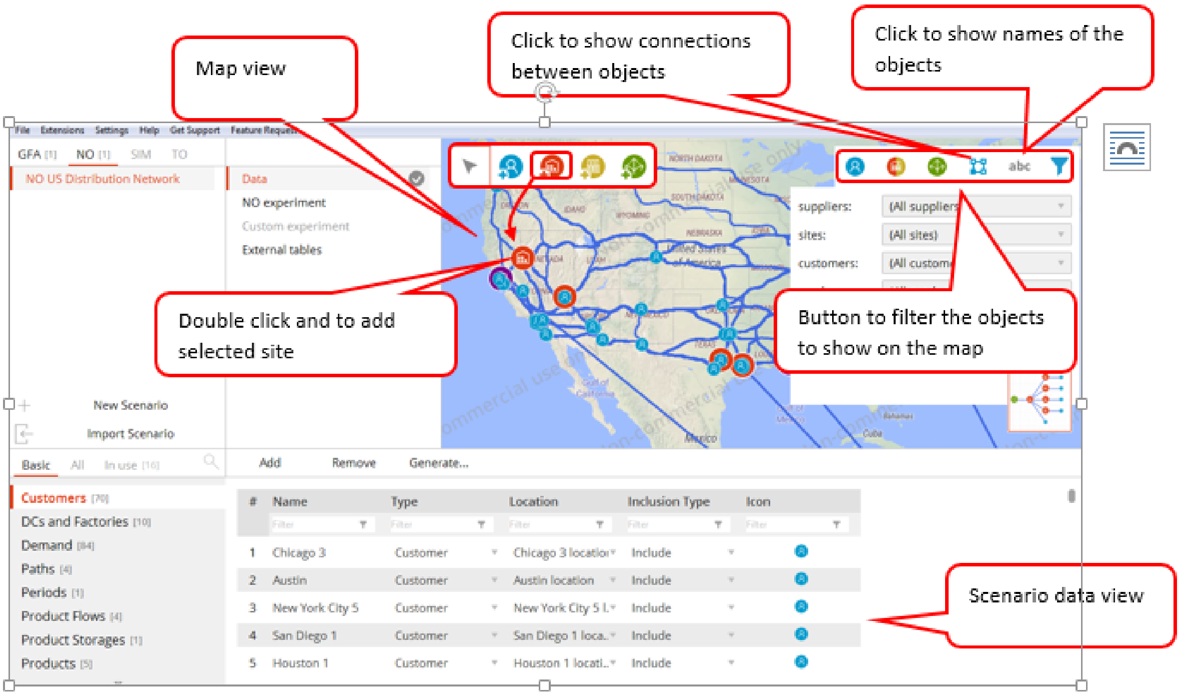


Figure I-10: A sample of anyLogistix's graphical user interface.

Figure I-11 shows how you can change scenario data.

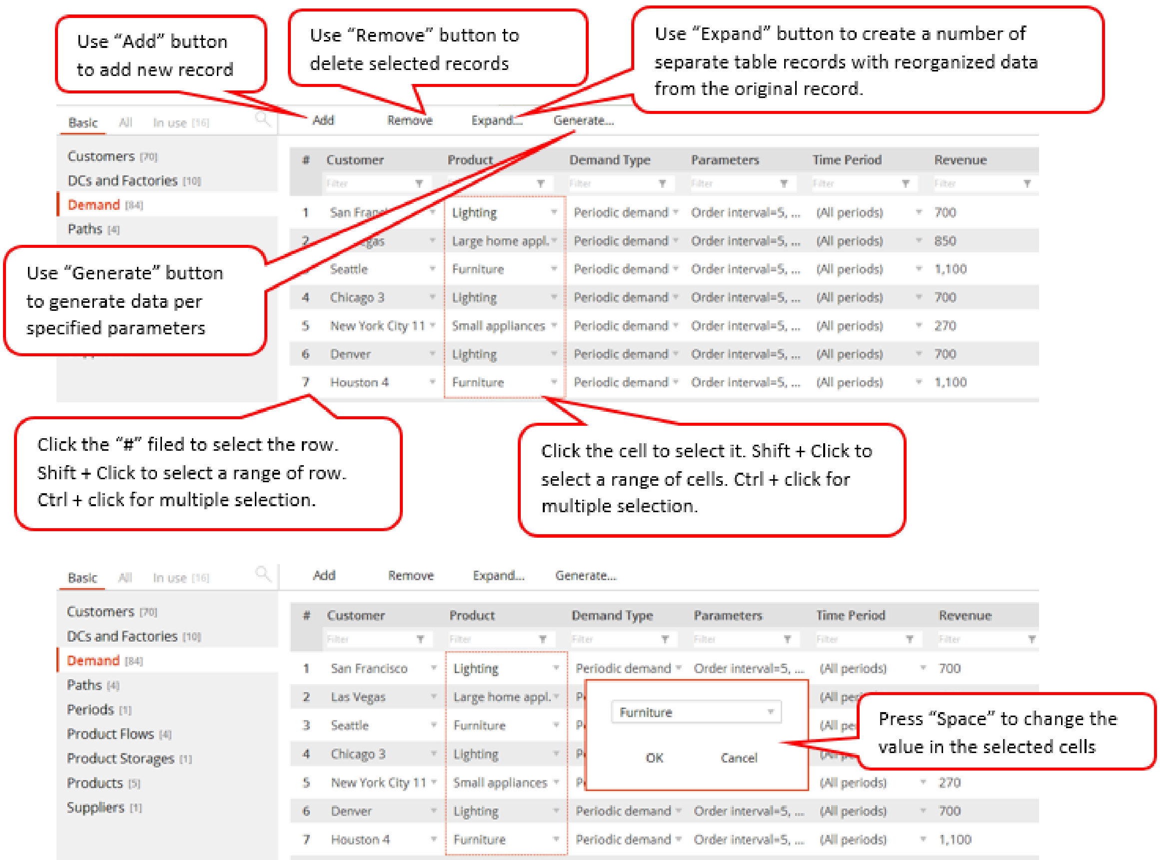


Figure I-11: A detailed look at anyLogistix's scenario data view.

Figure I-12 helps you understand anyLogistix's navigation menus.

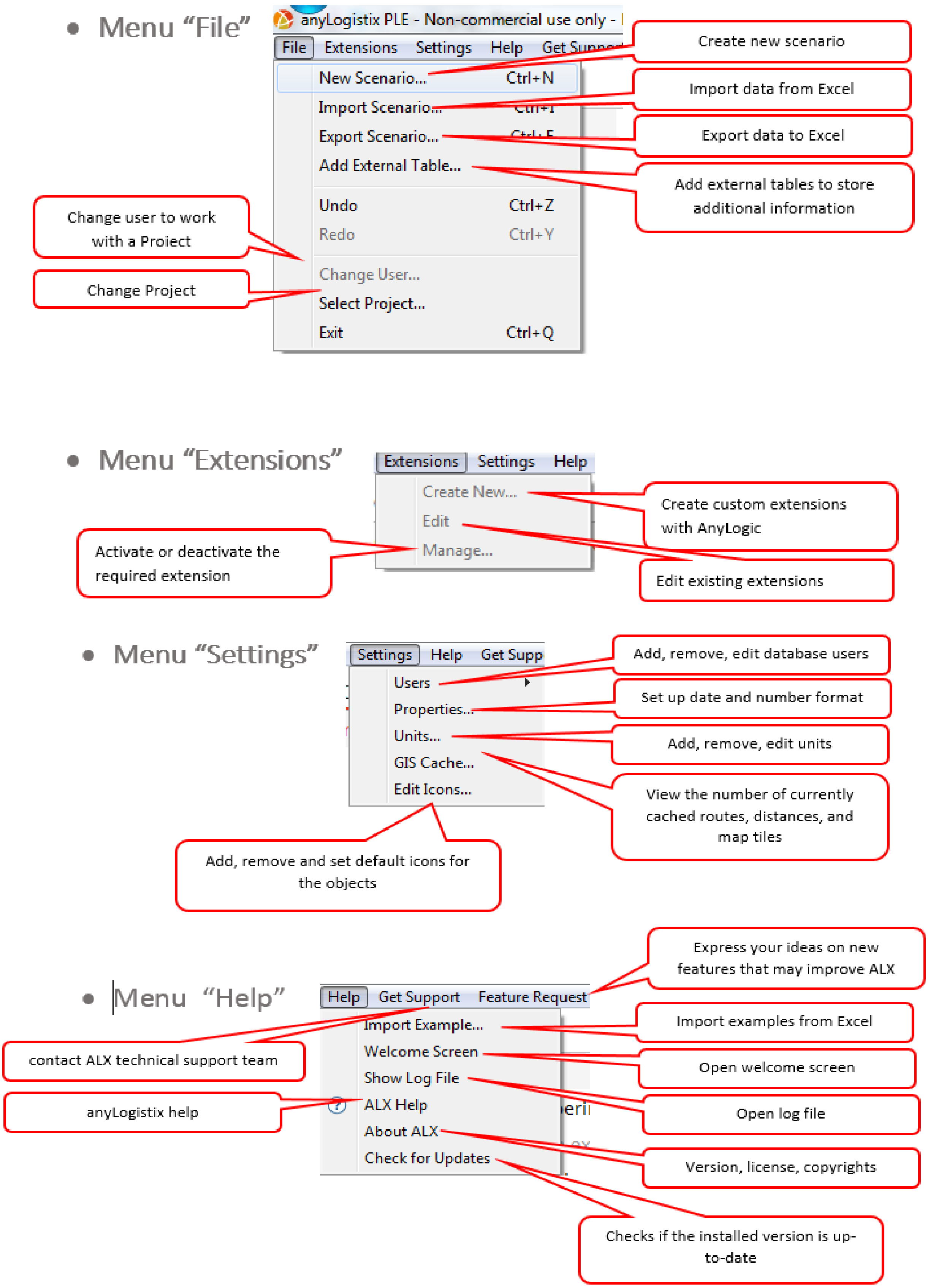


Figure I-12: An overview of anyLogistix's menus.

Option 1: Setting Up a Green Field Analysis Experiment

The image below (Figure I-13) shows you how to prepare a green field analysis (GFA) experiment. In anyLogistix's left pane, click the **GFA** heading, click **Simple GFA**, and then click **GFA experiment**. Afterward, you'll need to select your experiment's settings.

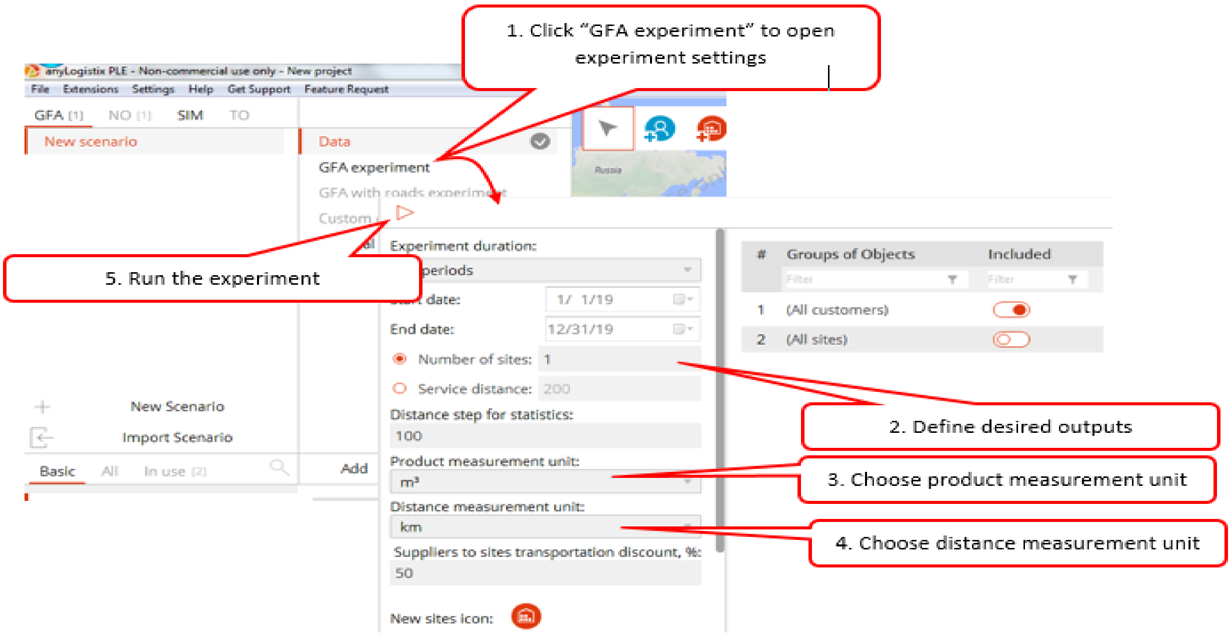


Figure I-13: A green field analysis (GFA) experiment's settings.

Option 2: Setting Up a Network Optimization Experiment

The following image (Figure I-14) shows you how to set up a network optimization experiment. In anyLogistix's left pane, click the **NO** heading, click **Simple NO** to select the network optimization scenario, and then click **NO experiment**.

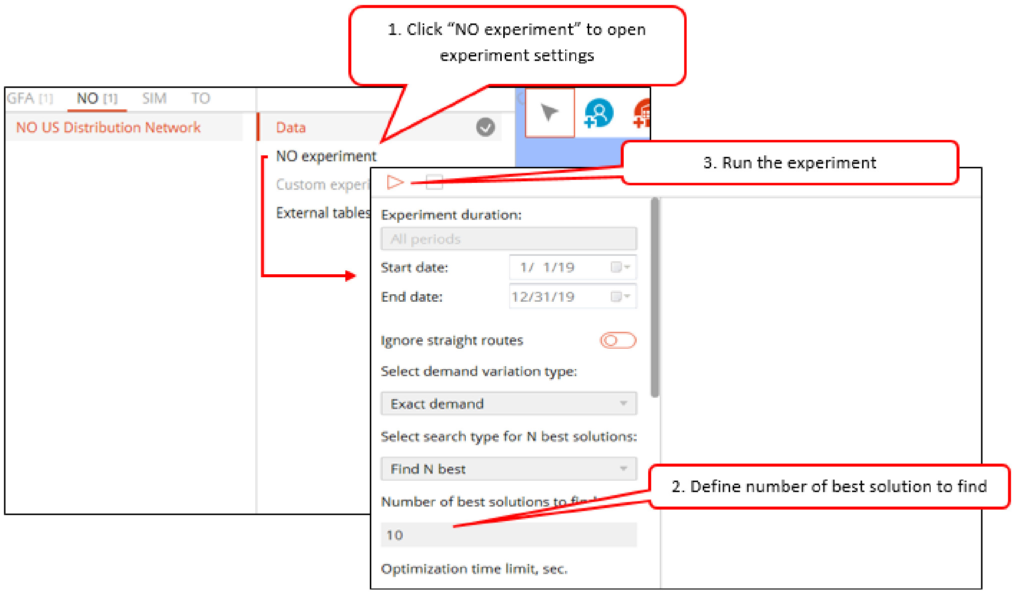


Figure I-14: Network optimization experiment settings.

Option 3: Setting Up a Simulation Experiment

The image below (Figure I-15) shows you how to set up a simulation experiment. In anyLogistix's left pane, click the **SIM** heading, click **Simulation Experiment** and then decide which statistics you want AnyLogistix to collect during the experiment.

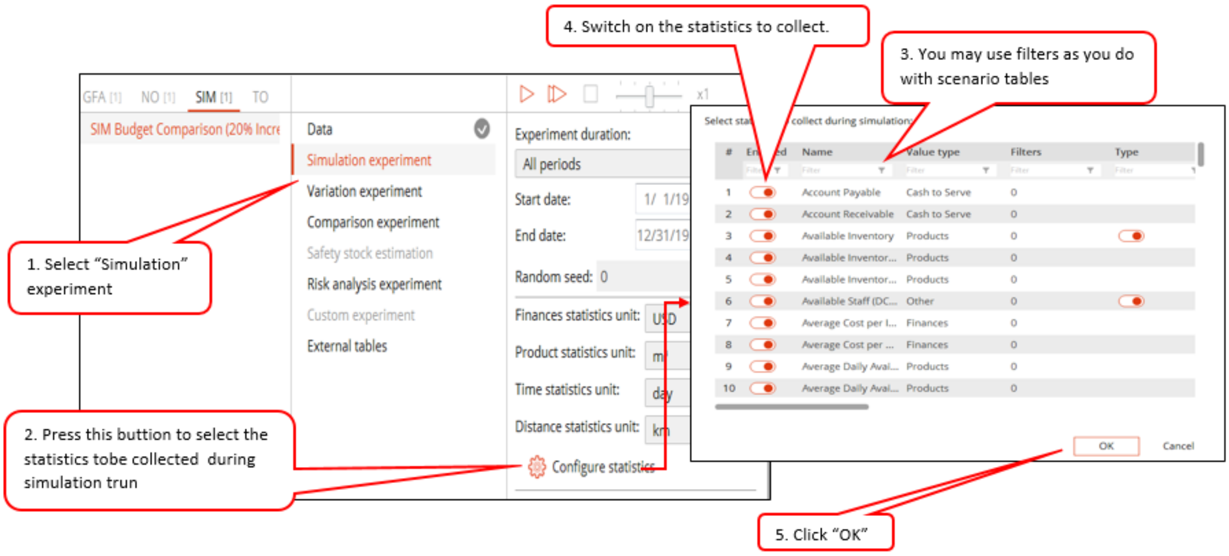


Figure I-15: Simulation experiment settings.

Figures I-16 and I-17 show you how to work with anyLogistix's dashboard. You'll use this dashboard—which may include one or many pages—to display the statistics the program collects during your experiment.

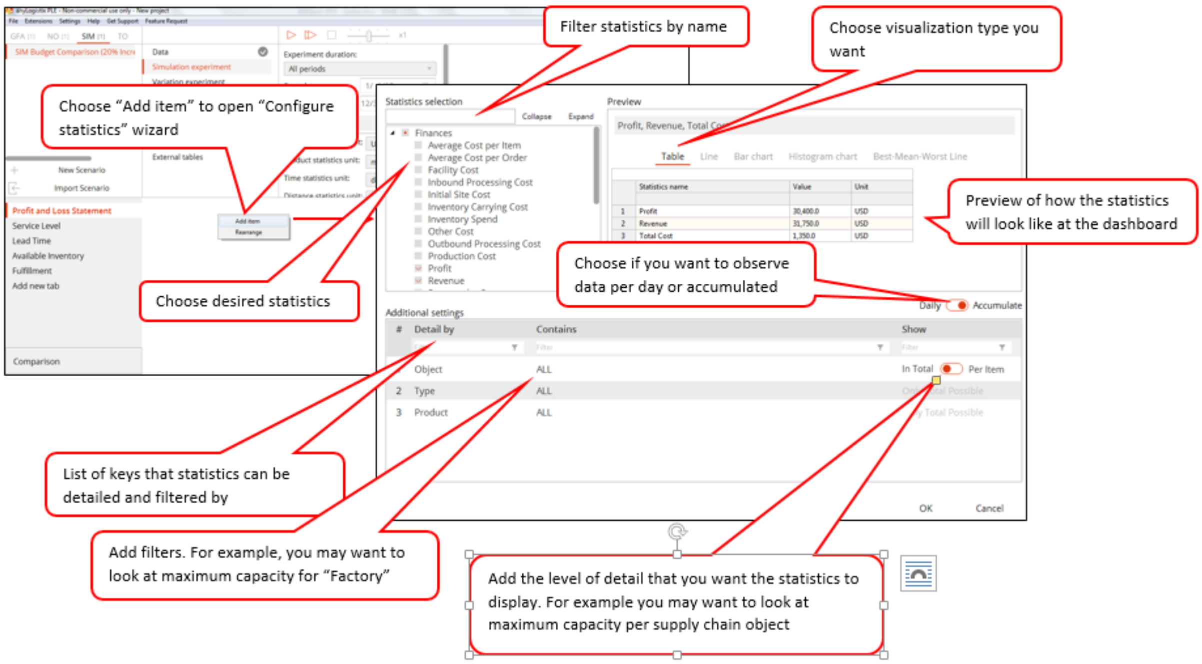


Figure I-16: Simulation experiment settings: dashboard (1 of 2).

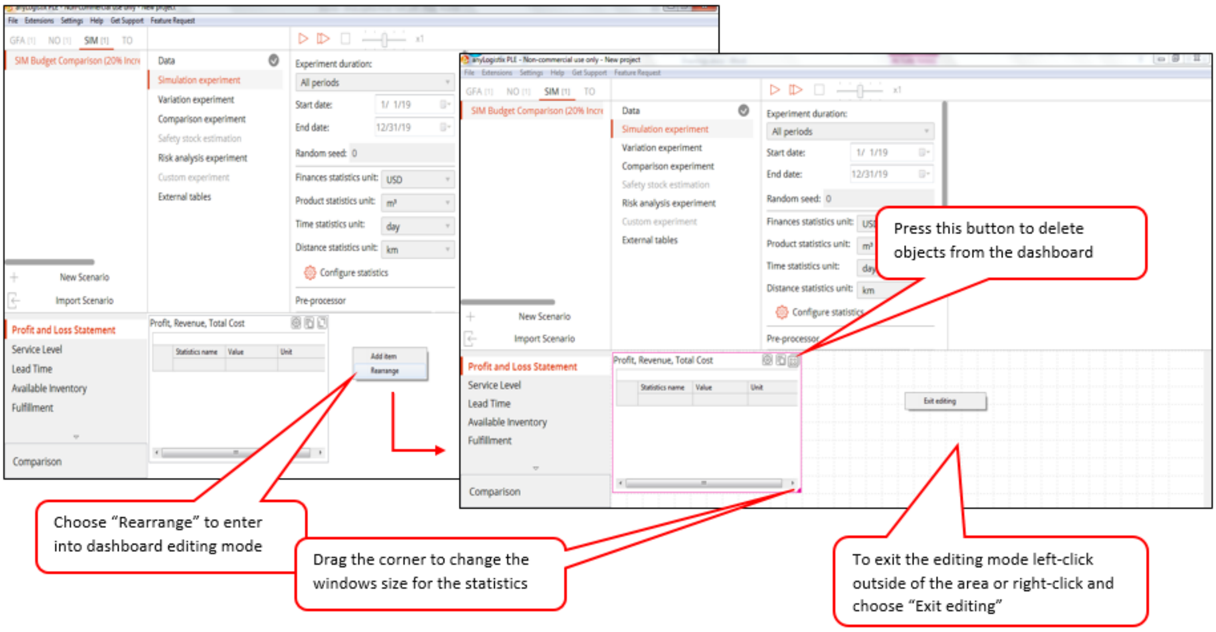


Figure I-17: Simulation experiment settings: dashboard (image 2 of 2).

Figure I-18 shows you the steps you need to complete to set up a variation experiment. You'll start by navigating to the right to the experiments tree and clicking **Variation experiment**. Afterward, you must select the scenario you want, define the variations and then select the statistics you want anyLogistix to collect.

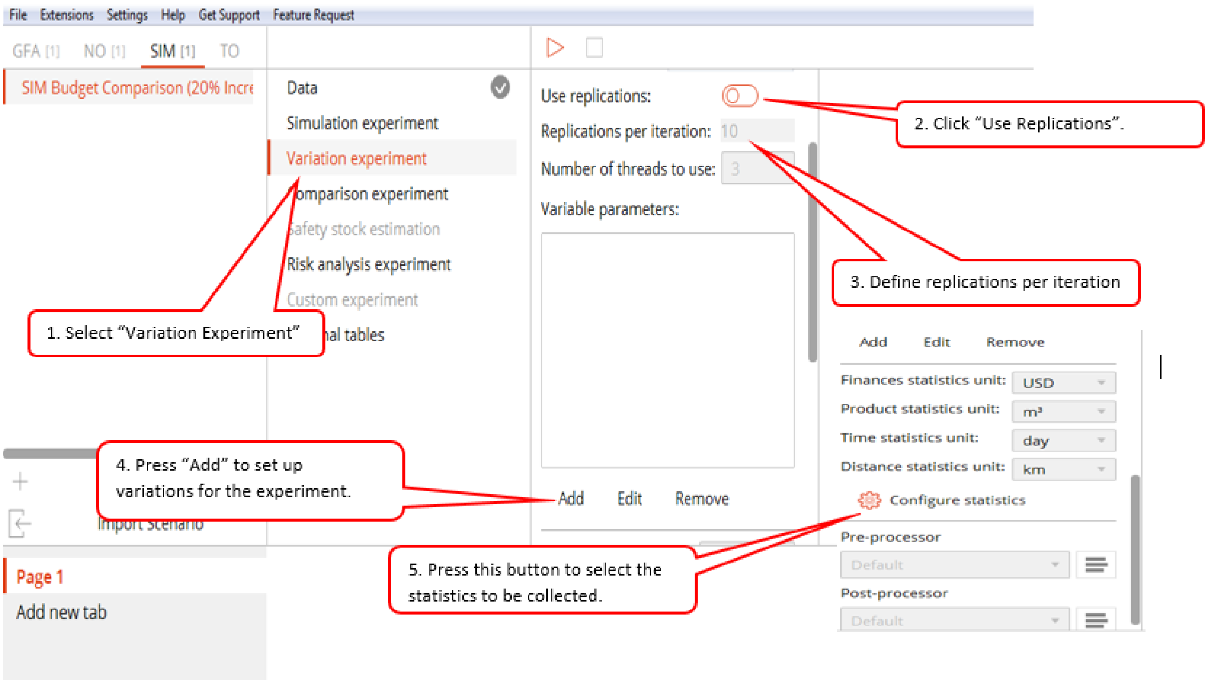


Figure I-18: Variation experiment settings.

If you want more information about anyLogistix's user interface, you can open the program's Help feature by pointing to the **Help** menu and clicking **anyLogistix Help**.

Chapter 1: Green Field Analysis and Basics of Simulation for Two-stage Supply Chain

Our Learning Objectives

1. Develop the analytical and management skills to use the center-of-gravity method and simulation to select the optimal locations for your company's facilities
2. Develop the technical skills you need to use anyLogistix to create two-stage supply chain models, perform experiments and measure performance
3. Understand the major trade-offs in facility location planning that affect the number of sites, lead time and demand uncertainty
4. Understand the areas of simulation and optimization

Theoretical background

The theoretical background described in this and further chapters is based on the textbook Ivanov D., Tsipoulanidis, A., Schönberger, J. (2019) Global Supply Chain and Operations Management: A decision-oriented introduction into the creation of value, Springer Nature, Cham.

The objective of the green field analysis (GFA) is to determine the best location for our distribution center. We want to find the location that allows us to fulfill our customer demands at the lowest total transportation cost.

GFA, also known as center-of-gravity analysis, is a common method for determining optimal locations for new facilities (Ivanov et al. 2019). The issues we need to consider during a green field analysis are our customers' locations, the distances from our warehouse(s) to our customers, and our customers' demands for our products.

The GFA is used to find the optimal location within a network to setup a new production facility or warehouse, while a "brown" field analysis, utilizing the same technique, can be used to adjust existing networks (Ivanov et al. 2019). Identifying the optimal location for a production or warehousing facility is determined by finding the point at which the sum of the distances from all suppliers to the factory (demand point), weighted by the volume of product flow between each supplier and the potential factory, is minimal. Likewise, to determine the optimal location for a warehouse, the distances from the customers to the warehouse, weighted by their respective demands, are calculated.

To conduct the GFA, a high level of abstraction with a minimum number of details is used. Existing data, such as customer locations, demand per customer, the number and location of DCs, and/or service distances, are used as inputs to the analysis. Program parameters for the GFA include how many possible results the program should calculate and whether the program should use real roads. The output of the analysis is an approximate, optimal location for a production or warehousing facility (Ivanov 2017). This optimal point is called the "center or gravity" (Ivanov et al. 2019). As explained, these so called "Gravity models" determine the location at which the cost of all in- and outbound transportation is minimized (Chopra and Meindl, 2016).

In technical terms, an ordered pair of (x;y)-coordinates represents each customer location. You can't change these data; they are input data or problem *parameters*.

By contrast, your new warehouse's (x;y)-coordinates (p_x;p_y) are variable. We will determine them after it calculates the data you provide in a way that matches the parameters you set. As a result, we say p_x and p_y are this scenario's *decision variables*.

We also assume our transportation cost is linearly proportional to the distance and the transportation volume (that is, the demand). We can see the total transportation costs will depend on the coordinates (p_x;p_y) of our prospective warehouses and distances. We assume the transportation costs from the prospective warehouse (p_x;p_y) to a customer location (x_i;y_i) is more or less equal to the distance and demand.

With that in mind, we need to determine the distances d((p_x;p_y); (x_i;y_i)) between the *i*-customer location and the warehouse to calculate transportation costs. To minimize the payments to the forwarding company, you must vary p_x as well as p_y as long as Z(p_x;p_y) becomes minimal.

Total costs Z(p_x;p_y) is a determinant in GFA since we seek to find optimal location of a warehouse subject to total costs minimization to serve all customer demands from the warehouse. We *assume* that the total transportation cost sum is proportional to the distance and the transportation volume (i.e., the demand). This leads us to the formulation of the *objective function,* as shown in Eq. (1.1):

$$Z\left(p_x;p_y\right)=\sum_{i-1}^{N} d\left((p_x,p_y);(x_i,y_i)\right)\cdot D\left(x_i,y_i\right)\rightarrow \min \tag{1.1}$$

We can observe that the total transportation costs depend on the coordinates p_x and p_y of the prospective warehouses and distances. We assume that total transportation cost sum from the prospective warehouse location (p_x;p_y) to a customer location (x_i;y_i) is more or less equivalent to the distance and demand. Therefore, the distance d((p_x;p_y); (x_i;y_i)) between the *i*-th customer location and the warehouse should be determined to calculate transportation costs.

To minimize the payments to the forwarding company, it is necessary to vary p_x as well as p_y as long as Z(p_x;p_y) becomes minimal.

The function Z is continuous and differentiable and the decision variables are unrestricted. Hence, we can determine the optimal point of Z by differential calculus. The following consecutive steps have to be executed in the given order. The first derivative Z′ of Z is determined and the zero of Z′ is determined. Then we have

$$\frac{dZ}{dp_x}=\frac{Np_x}{\sqrt{\left(x_i-p_x\right)^2+\left(y_i-p_y\right)^2}}-\sum_{i=1}^{N}\frac{x_i}{\sqrt{\left(x_i-p_x\right)^2+\left(y_i-p_y\right)^2}} \tag{1.2}$$

$$\frac{dZ}{dp_y}=\frac{Np_y}{\sqrt{\left(x_i-p_x\right)^2+\left(y_i-p_y\right)^2}}-\sum_{i=1}^{N}\frac{y_i}{\sqrt{\left(x_i-p_x\right)^2+\left(y_i-p_y\right)^2}} \tag{1.3}$$

The model (1.1) is called the *center-of-gravity model* of location analysis. Using demand data, formulas (1.4) and (1.5) are used to calculate optimal coordinates of the warehouse.

$$p_x = \frac{\sum_{j=1}^{N} \frac{D(x_j;y_j)\cdot x_j}{\sqrt{(p_x - x_j)^2 + (p_y - y_j)^2}}}{\sum_{j=1}^{N} \frac{D(x_j;y_j)}{\sqrt{(p_x - x_j)^2 + (p_y - y_j)^2}}} \tag{1.4}$$

$$p_y = \frac{\sum_{j=1}^{N} \frac{D(x_j;y_j)\cdot y_j}{\sqrt{(p_x - x_j)^2 + (p_y - y_j)^2}}}{\sum_{j=1}^{N} \frac{D(x_j;y_j)}{\sqrt{(p_x - x_j)^2 + (p_y - y_j)^2}}} \tag{1.5}$$

The determination of an optimal pair of coordinates for the warehouse again requires the determination of the directional derivatives. These two functions are then set equal to 0 and we get the expressions (1.4) and (1.5), respectively, to express p_x and p_y.

Note that the model (1.1)-(1.5) is valid for determining the location of a single warehouse's location. In anyLogistix, we can determine multiple locations and even the number of locations needed subject to a maximum service distance from warehouse to customer. This can be useful for comparing the costs of efficient vs responsive (short maximum distances to customers) supply chains.

In addition to the mathematical result of the GFA, supply chain managers should consider several other variables: a potential increase in production volume and future expansion needs; quality of the potential infrastructural network; qualifications of prospective employees; options for suppliers; and the regional availability of logistics service providers who could handle inbound and outbound transport. Certain taxation benefits provided by local government can also influence a company's decision about where to locate a facility (Ivanov et al. 2019).

Performing a Green Field Analysis (GFA) for a New Facility

Our Green Field Analysis Case Study: Facility Location Planning

Suresh, a supply chain manager at a German-based retail network, needs to decide where his company should build their new distribution centers and how many centers they need to open to minimize supply chain costs. The data he needs for his analysis are the company's:

- Customers and their geographical locations
- Products and measurement units
- Customer demand
- Per-kilometer transportation costs
- Distances in the supply network

He began gathering the data by asking sales and marketing managers to estimate the annual demand from customers in different regions and then grouping those regions into ten major markets. Afterward, Suresh asked the transportation manager to estimate the company's shipment costs.

In this case study, we'll use anyLogistix to help Suresh improve the distribution center network. The following steps will show you how to:

1. Create a scenario and define the supply chain's structure and parameters
2. Define the supply chain's customer demand, transportation and sourcing policies
3. Parametrize the sites and policies
4. Perform the Green Field Analysis experiment to determine the best locations for one or many warehouses
5. Create a KPI dashboard and collect statistics on supply chain performance
6. Simulate the supply chain design with the new greenfield locations and determine their impact

Creating a Scenario

The first step in building a decision-support model for facility location planning is to create a new scenario. Figure 1, below, shows you the basic steps you need to complete to create a scenario and make it available in anyLogistix's central panel. Each scenario has a supply chain structure and parameters you can use during your simulation and optimization experiments.

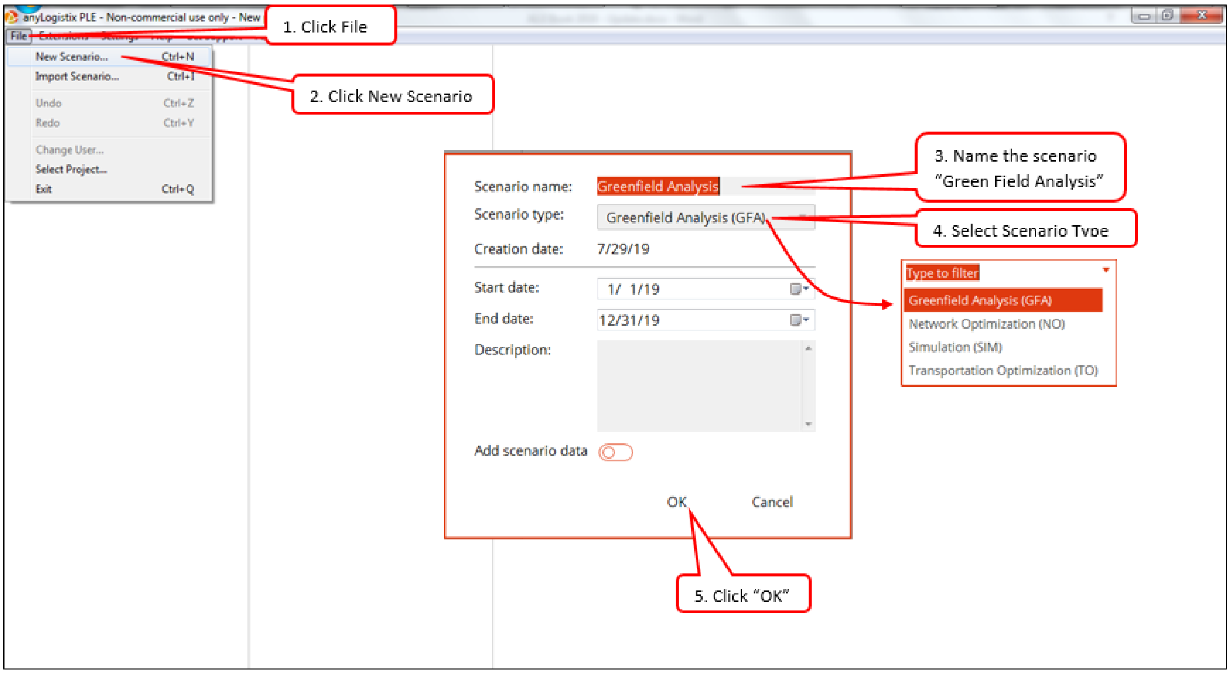


Figure 1: Creating a scenario.

You can modify a scenario's properties by right-clicking the scenario's name to open the context menu, and then clicking **Properties**. You can also import a scenario from a Microsoft Excel workbook and use it to perform an experiment.

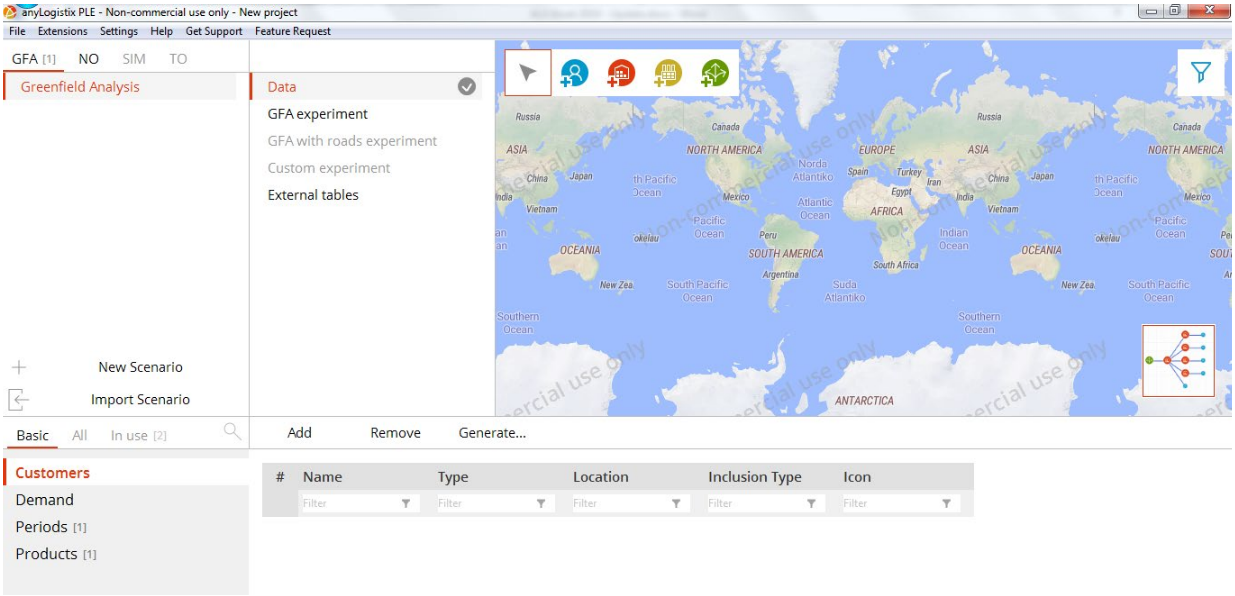


Figure 2: Using the Start window to prepare a new scenario.

We've named our new scenario **Green Field Analysis** (GFA), and it now displays in the program's list of scenarios. Our next step is to define the supply chain's structure and parameters.

Defining Supply Chain Structure and Parameters

Adding Customers and their Locations

Our first step in defining the supply chain's structure is to define our customer locations. To define a location, right-click on the map, click **Create Customer** and enter the required information (Figure 3). Afterward, anyLogistix adds the customer location and its latitude and longitude to the list of customers (Figure 4).

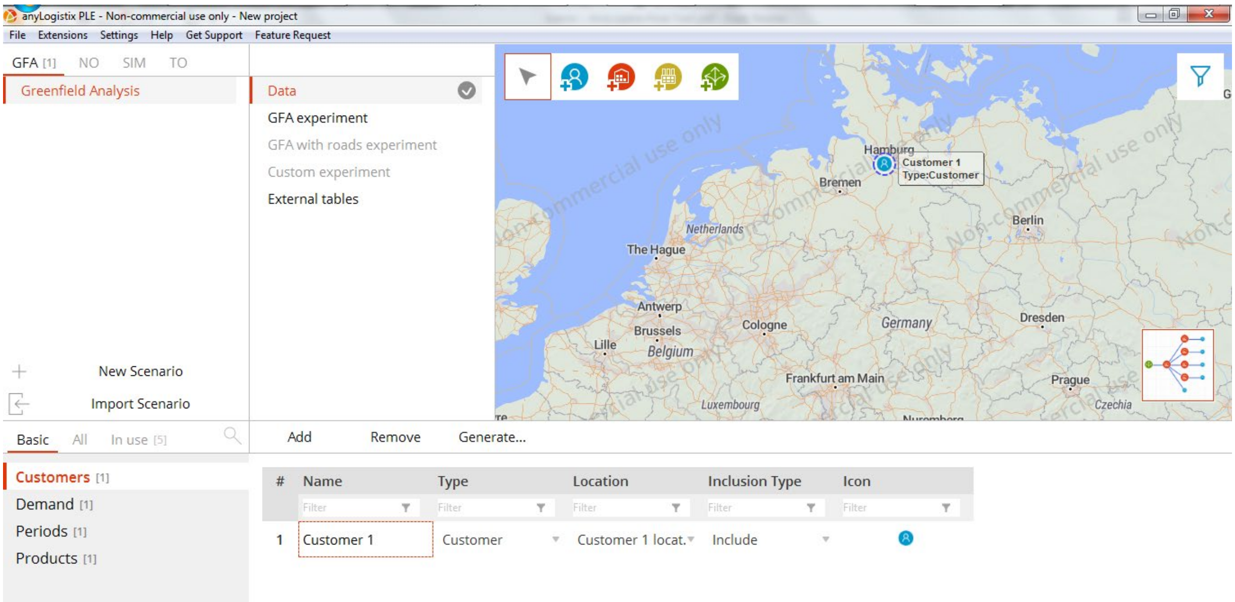


Figure 3: Defining a new customer.

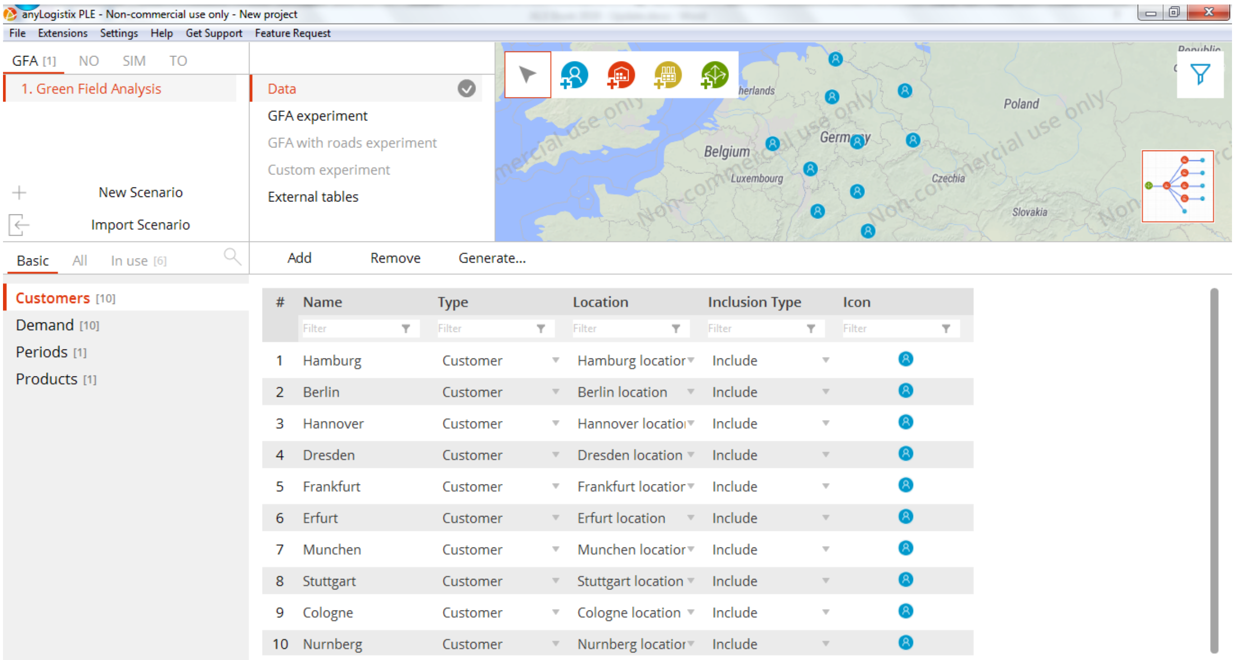


Figure 4: A view of anyLogistix's list of Customers.

Defining Products and Customer Demand

Before we define customer demand, we need to use the **Products** table to add and define the products we will ship to our customers. In our example, we'll define a new product (**Water**) by opening the **Products** table and clicking **Add** (Figure 5).

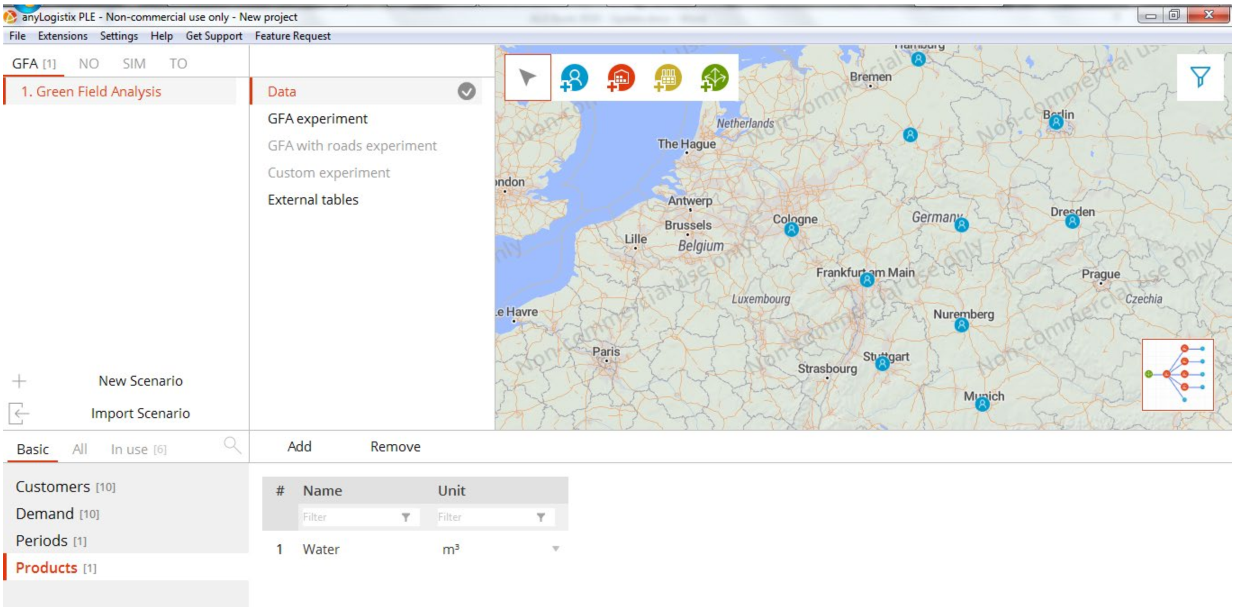


Figure 5: Adding and defining a product.

To set the product's demand parameters, click the **Demand** heading on the screen's left pane. The **Demand** table that opens lists our customers and allows us to select each customer's demand type and demand parameters. In time, anyLogistix will use these values to compute our service levels.

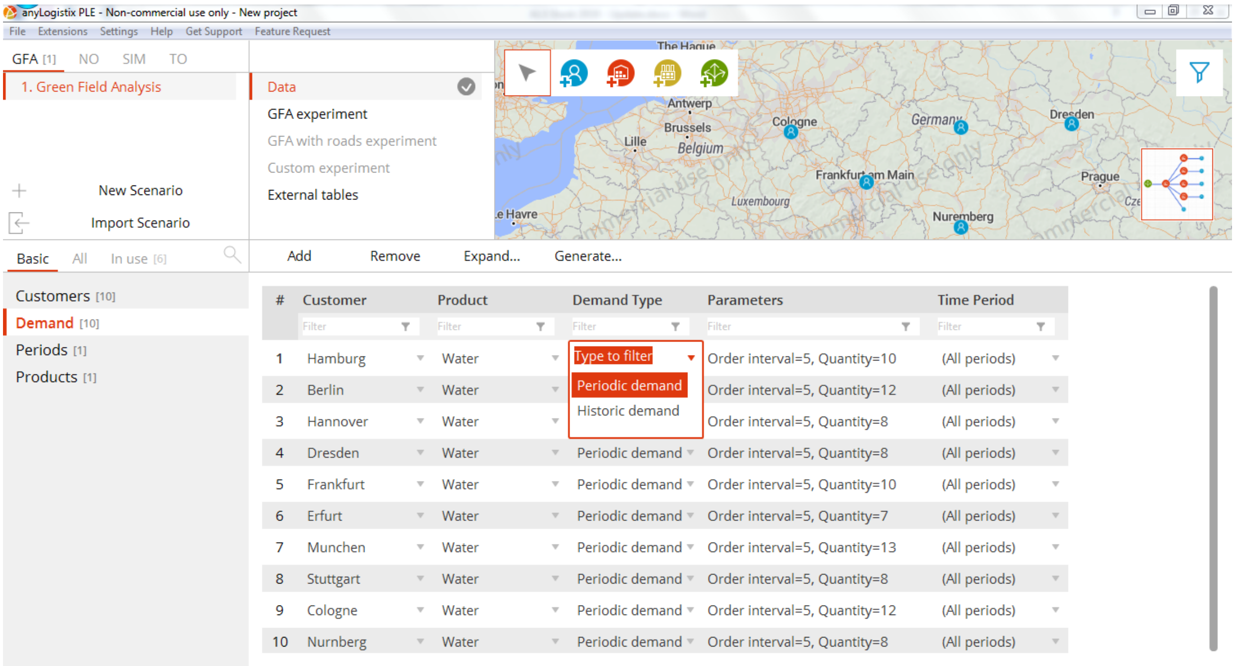


Figure 6: Selecting product demand data.

For now, we'll use two parameters—**Order Interval** and **Quantity**—to define customer periodic demand. By setting the **Order Interval** value to five days and the **Quantity** value to eight, we've ensured our simulated customers will send a new eight-unit order to the distribution center every five days.

You can set customer demand to be *deterministic* or *stochastic* by using the **Demand** table's **Demand Type** column to select **Periodic demand** or **Historic demand**.

You can use periodic demand if you know the sales quantity that takes place during a given period. In this example, we know we can expect to sell five water pallets within ten days. By contrast, historical demand assumes you use data about sales over a longer period such as the previous year. To define our historical data, we'll select the **Historic demand** option and click **Add** (Figure 7).

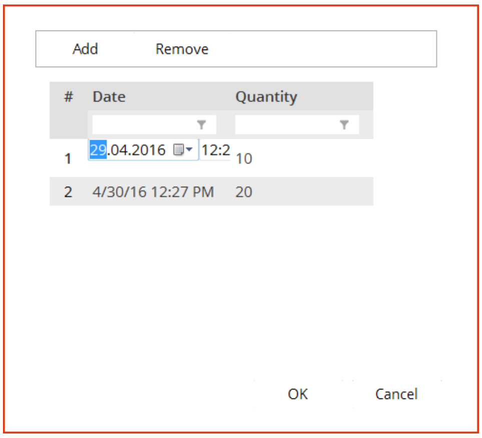


Figure 7: Setting up historical demand.

To define periodic demand data, we select the **Periodic demand** option and then define the customer's demand for a given period. For example, Figure 8 shows you how to set **Customer #1**'s demand for five water pallets over a ten-day period.

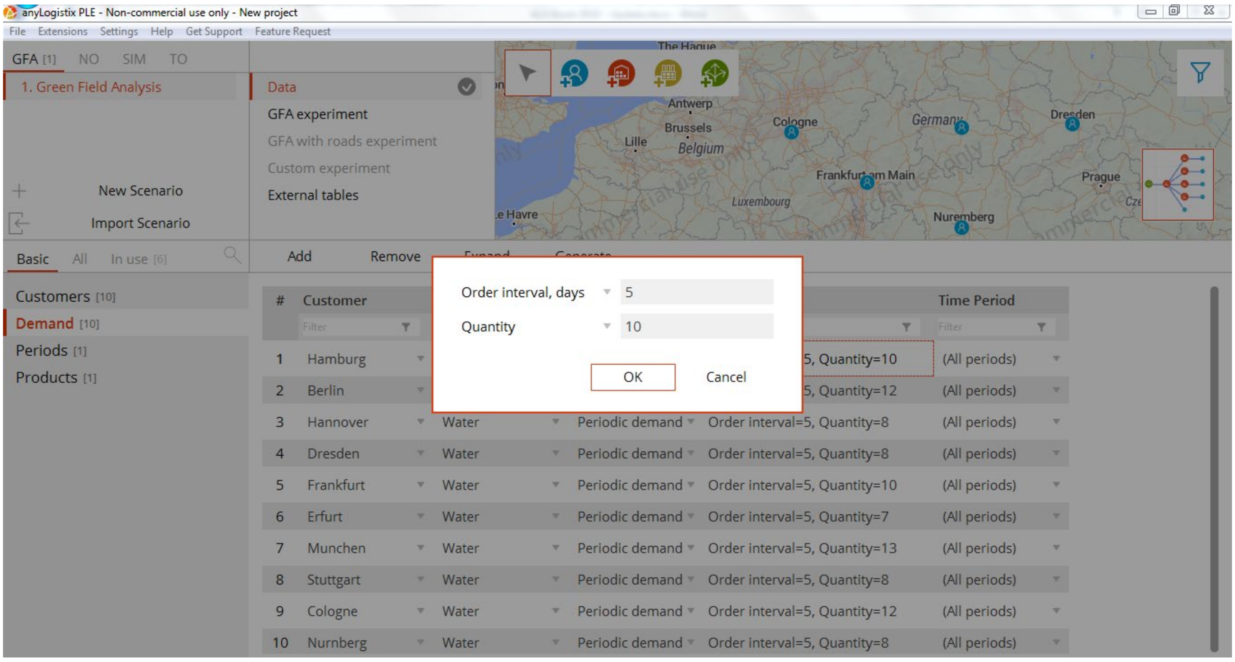


Figure 8: A Periodic demand setup.

To make our analysis more valuable, we'll change the default customer names—for example, **Customer 1** and **Customer 2**—to the names of the markets we serve such as Hamburg and Berlin. To do this, open the **Customer** table and change the **Name** values as needed.

Figure 9 below shows the results of our renaming process.

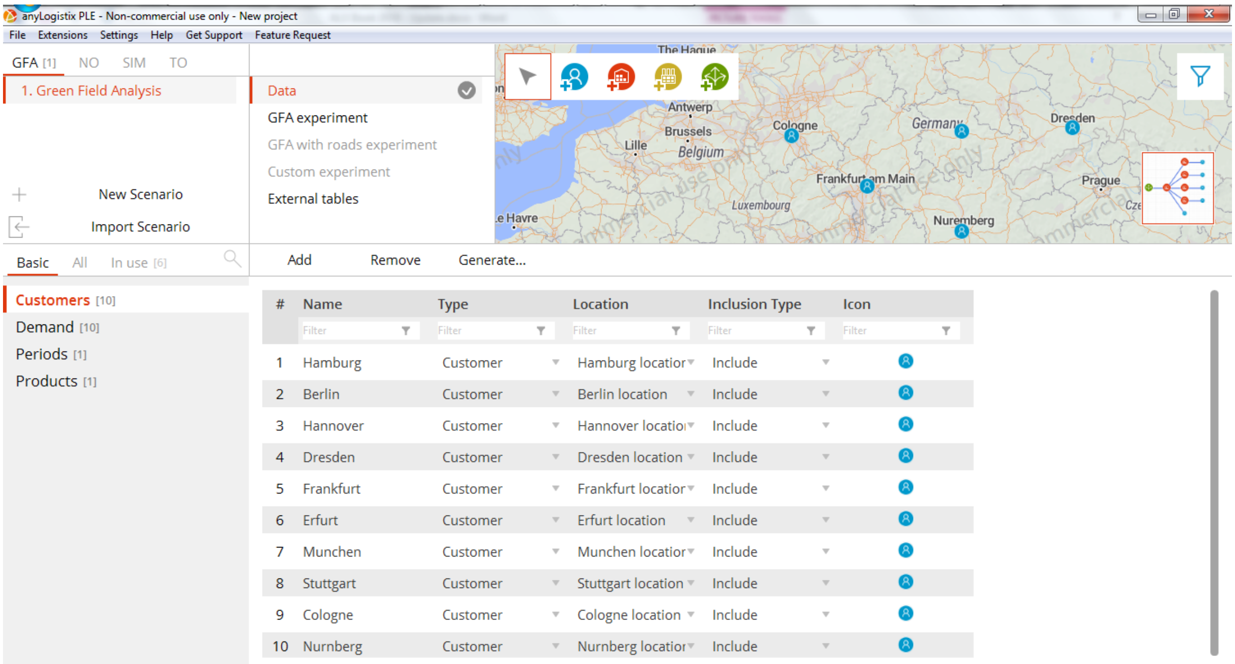


Figure 9: Renaming customers.

Now, we'll define the periodic demand for each customer (Figure 10).

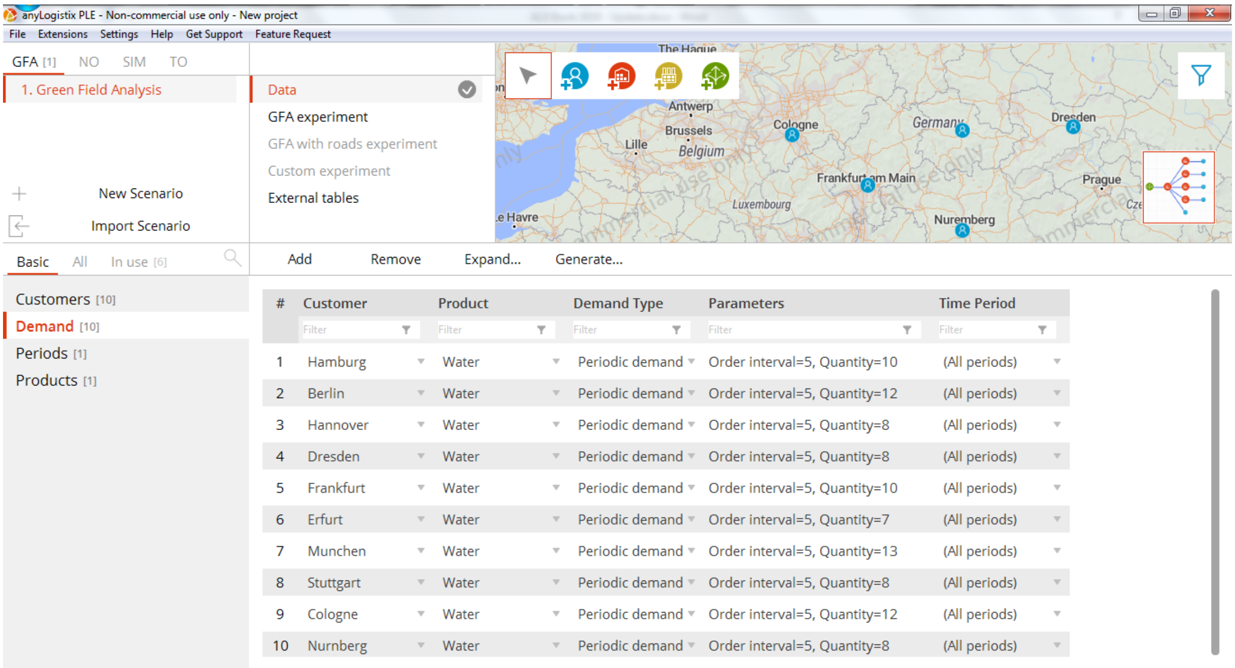
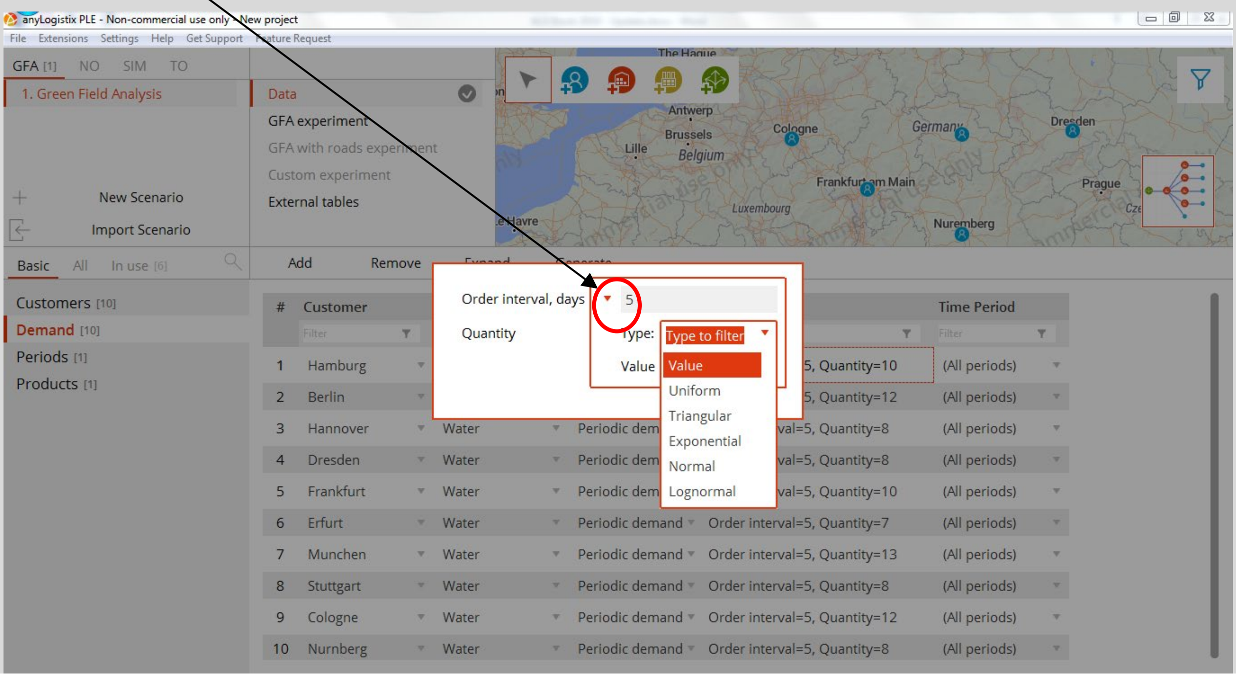


Figure 10: Setting the experiment's demand data.

Note: If you want a flexible approach to demand data, you can define **Time Periods** (for example, spring, summer, winter and fall) and use the **Demand Forecast** table to define demand coefficients (Figure 11).

→ You can define stochastic demand, we can select different types of distributions clicking the arrow in the respective parameter (that is, order interval or quantity):



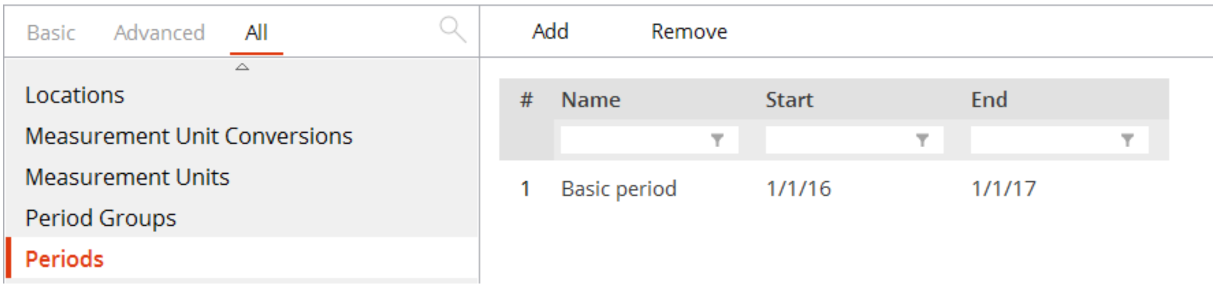


Figure 11: Defining Periods

> **Note:** Parameters Period (order interval) and Quantity will determine the customer ordering logic in our future simulation experiment. For example, in case of Period=5 and Quantity=10, the customer will order at a DC 10 units every 5 days.

Importing Data from Microsoft Excel workbooks

If you have a long list of customers and products or you want to avoid manually entering demand data, you can import this data from a Microsoft Excel workbook. To do so, point to the **File** menu and then click **Import**.

You can import sample ALX scenarios and your own scenarios with experiments. You can also accelerate the scenario creation process by using a Microsoft Excel workbook to create a scenario. After your scenario is complete, you can import it into anyLogistix.

Creating Groups

The problem in this example is simple, but other problems can be complex. To simplify your simulation modeling and experiments, you might want to group similar objects, such as distribution centers, customers or suppliers. You'll do this in the **Groups** table (Figure 12).

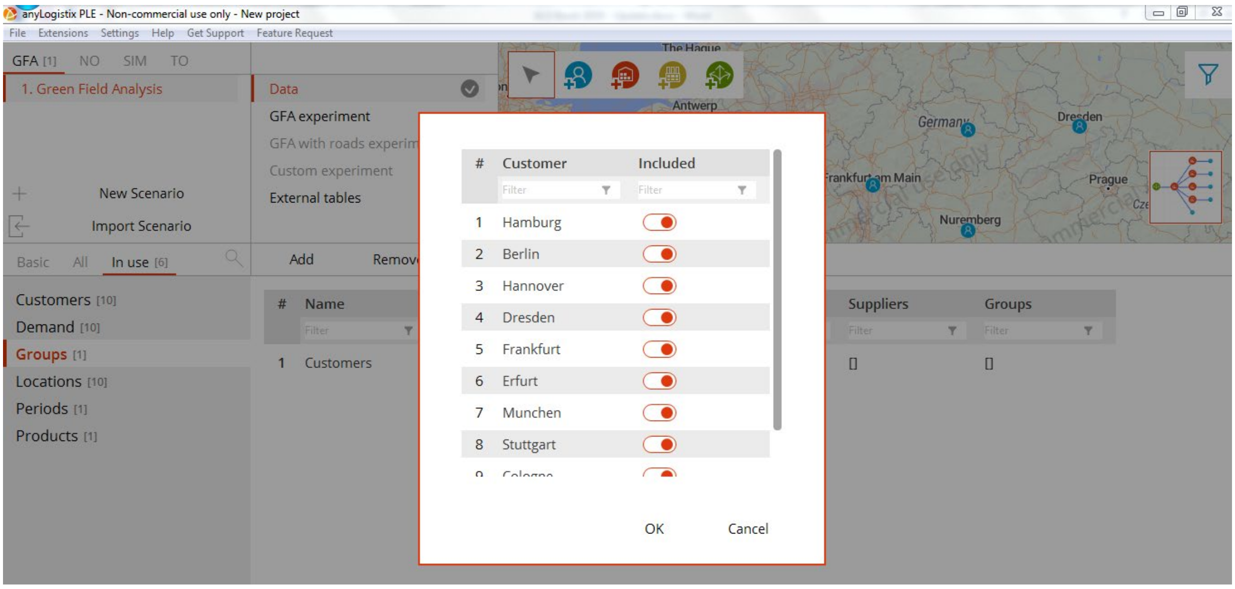


Figure 12: Creating a group.

To create a group, click **Add** and then enter the new group's name (for example, **Customers**). Second, we open the list of all customers in the new **Customers** table and activate those we need in the group. For distribution centers and factories, we activate objects in the **Sites** column. Supplier groups are created in the **Suppliers** column.

After you create your groups, you can use them in sourcing, transportation, inventory and production policy definitions instead of individual objects. In the **Product groups** table, you can group individual products in a similar way. This helps to *reduce modeling complexity and your time when setting up different sourcing and transportation policies in future*.

With our data set up, we are ready to perform our first experiment.

New GFA Experiment

Creating a New Experiment

In **Experiments**, we select Green Field Analysis. We select our new **Green Field Analysis** scenario (Figure 13).

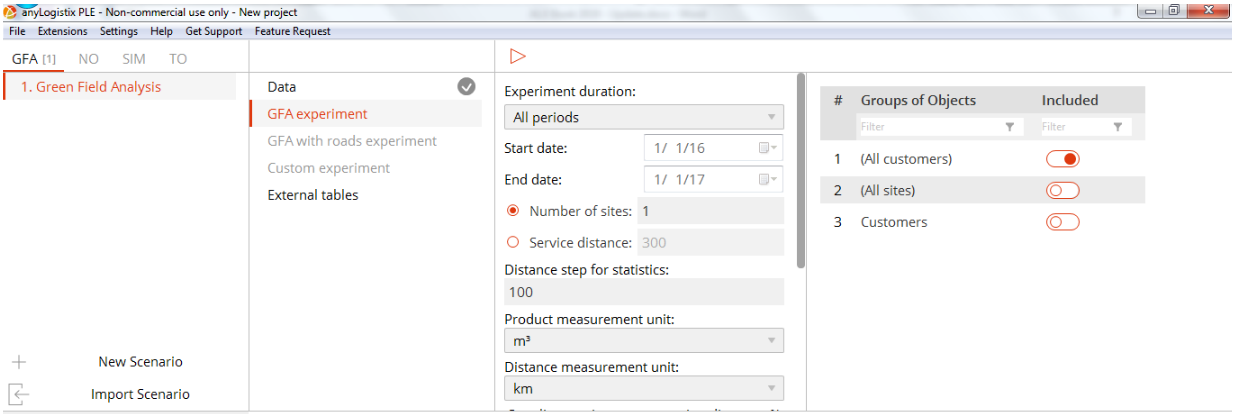


Figure 13: Setting data for a Green Field Analysis experiment.

We'll start by selecting the locations and customers we want to include in our analysis. In this example, we'll include all our customers. Second, we can perform the computation in two modes:

- Define optimal location for a single warehouse
- Define minimal number of warehouses and their locations subject to a maximum service distance.

Determining the Optimal Location for a Single Warehouse

In a Green Field Analysis experiment, the default value for the **Desired number of sites** parameter is **1**. While you can easily change the default value if you want to consider more than one location, we'll continue our work to determine the optimal location for a single warehouse (Figure 14).

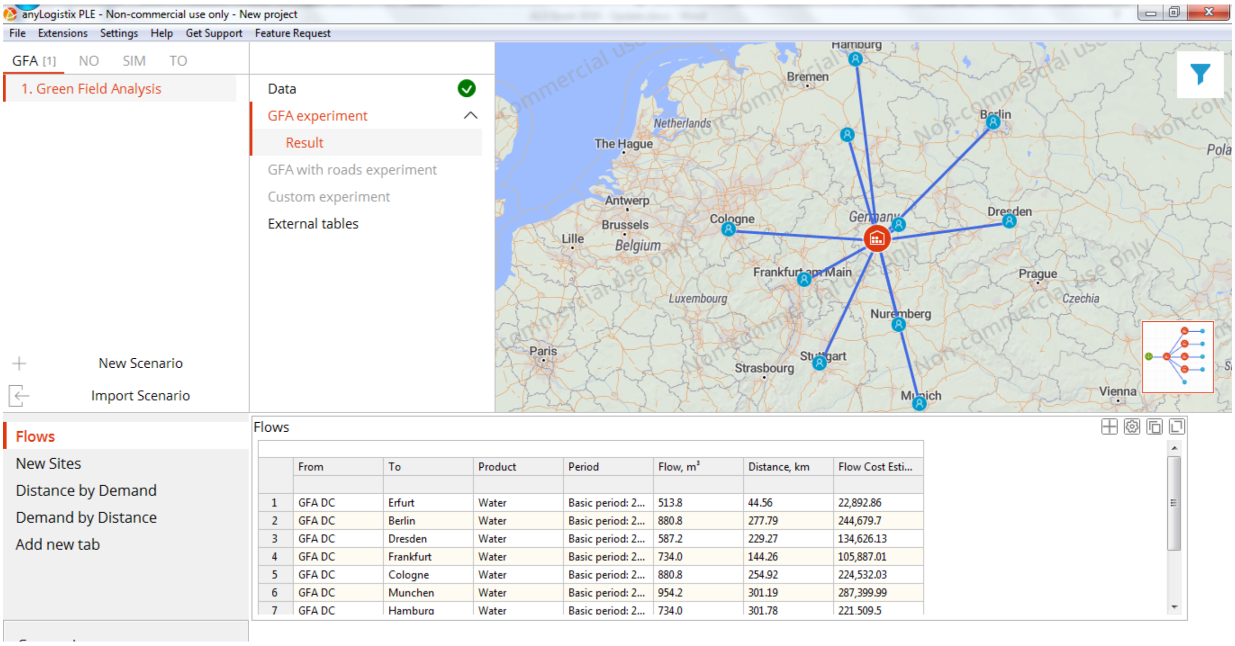


Figure 14: Computed optimal location for single warehouse.

Determining the Minimal Number of Warehouses and their Locations

In our experiment, we select the **Service distance** option and enter a value in the box. In this example (Figure 15), the maximum service distance is 300 kilometers.

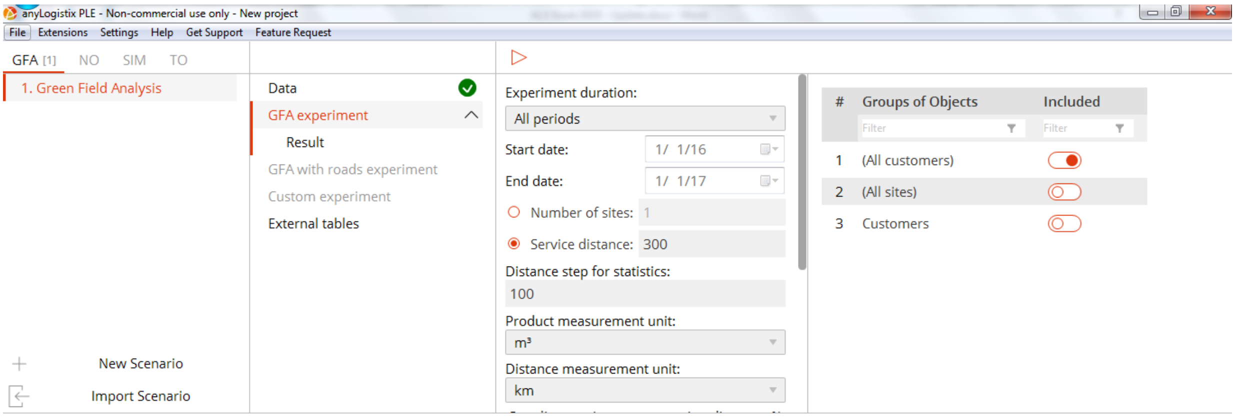


Figure 15: Settings to determine minimal number of warehouses and their locations based on the value we enter for the maximum service distance.

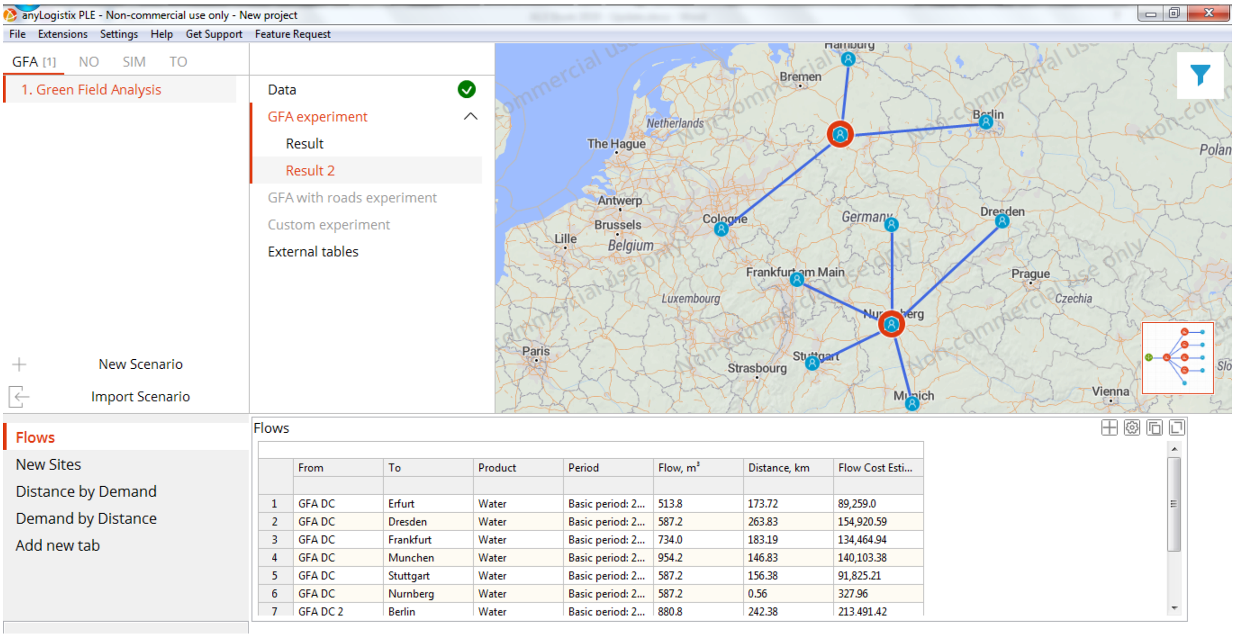


Figure 16: Computation result for the minimal number of warehouses and their locations that meets our need for a maximum service distance of 300 km.

The information in Figure 16 shows us the company needs to install two distribution centers if they want their maximum service distance to be 300 km. This would result in transportation costs reduction from $1,580,871 in the case with 1 DC to $1,141,590 in case with 2 DCs.

Note: You can export the results of your green field analysis to a new scenario as NO or SIM. Doing so will help you perform optimization and simulation experiments.

Note: to compute the sum of costs or flows in GFA Results, just slightly drag the heading of the column “Period” in table “Product flows” in the space over the table.

Discussion Questions

1. If we reduced the maximum service distance, would the number of distribution centers change? Try to compute the case with a maximum service distance of 150 km!
2. What other costs and factors should be part of your facility location planning?

New Simulation Experiment

What is a simulation experiment?

Our simulation experiment is to analyze the performance of the supply chain designed in GFA and observe supply chain behavior in dynamics. The *static* view on supply chain structure in GFA will become a *dynamic* form in simulation. In this example, we’ll simulate the effect of those two new distribution centers. How well will they help us meet our goal of a maximum service distance of 300 km?

First, we need to convert the results of our green field analysis to a SIM scenario by right-clicking **Result 2** in **GFA 1** and **Convert to SIM** (Figure 17). Afterward, AnyLogistix displays **GFA 1: Results 2** in our list of scenarios in **SIM**.

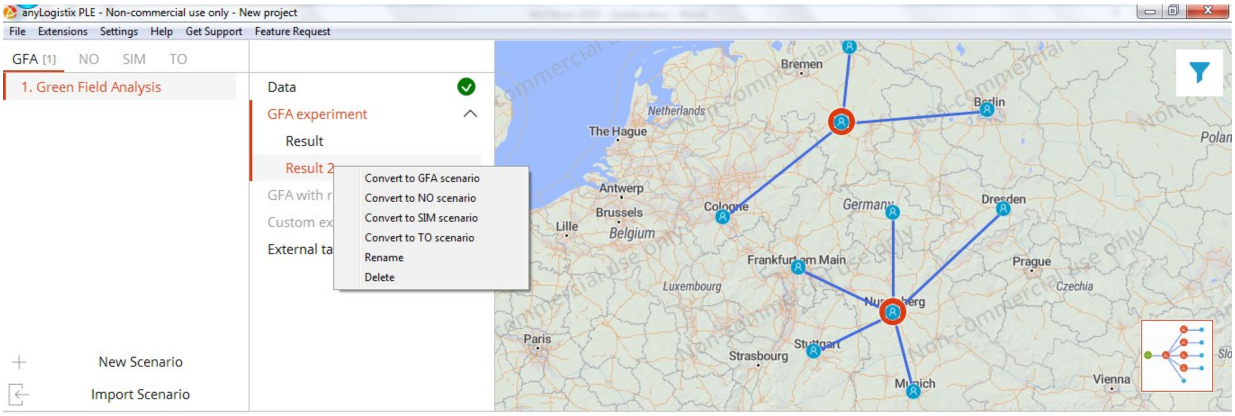


Figure 17: Our transformation of the green field analysis to a SIM scenario.

KPI Dashboard

We select **GFA1: Results 2** as the scenario for simulation experiment and right click on the blank area to add a new KPI via **Add item** (Figure 18).

> **Note:** anyLogistix uses a general term ("statistics") instead of KPI. However, this book uses KPI because it is more familiar to managers.
>
> Full list of KPIs can be accessed via **Configure statistics**

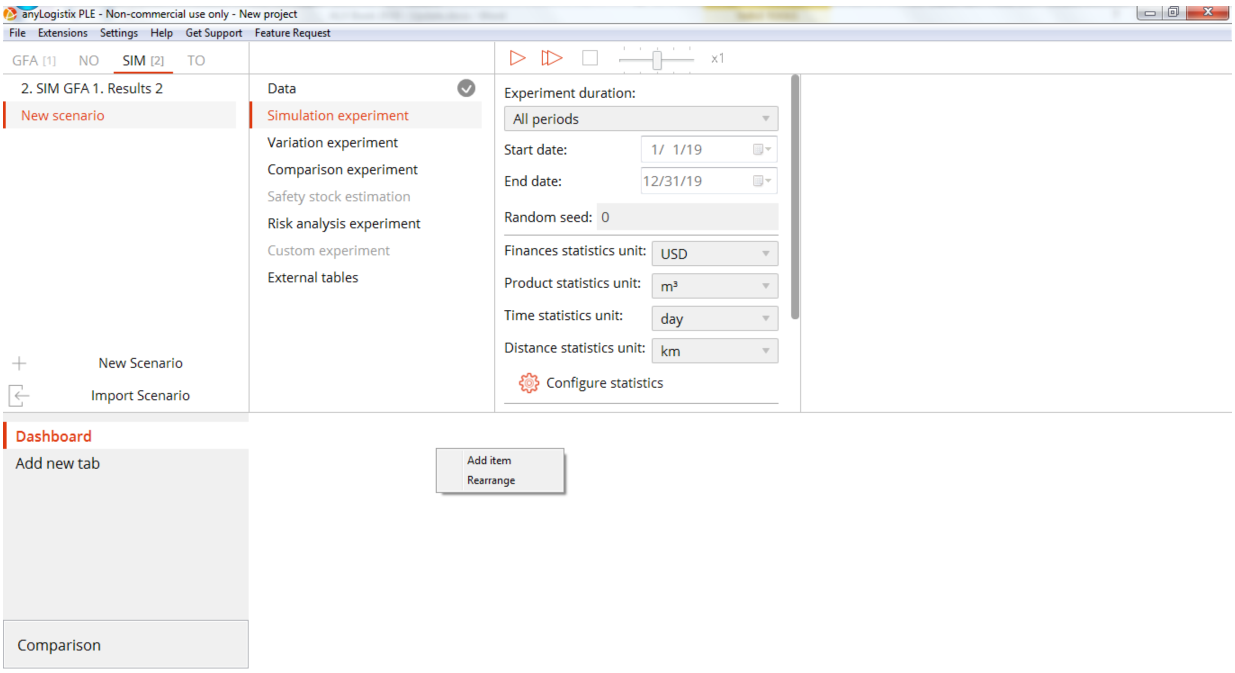


Figure 18: Adding a new KPI to a dashboard.

Note: If anyLogistix's configuration interface changes in upcoming releases, you may have to use another method to structure your KPIs. However, the underlying principles will not change.

To add KPI to the dashboard, right-click on the dashboard, select **Add item**, and then use the following screen to select the KPIs and the form (Figure 19) the KPIs will take.

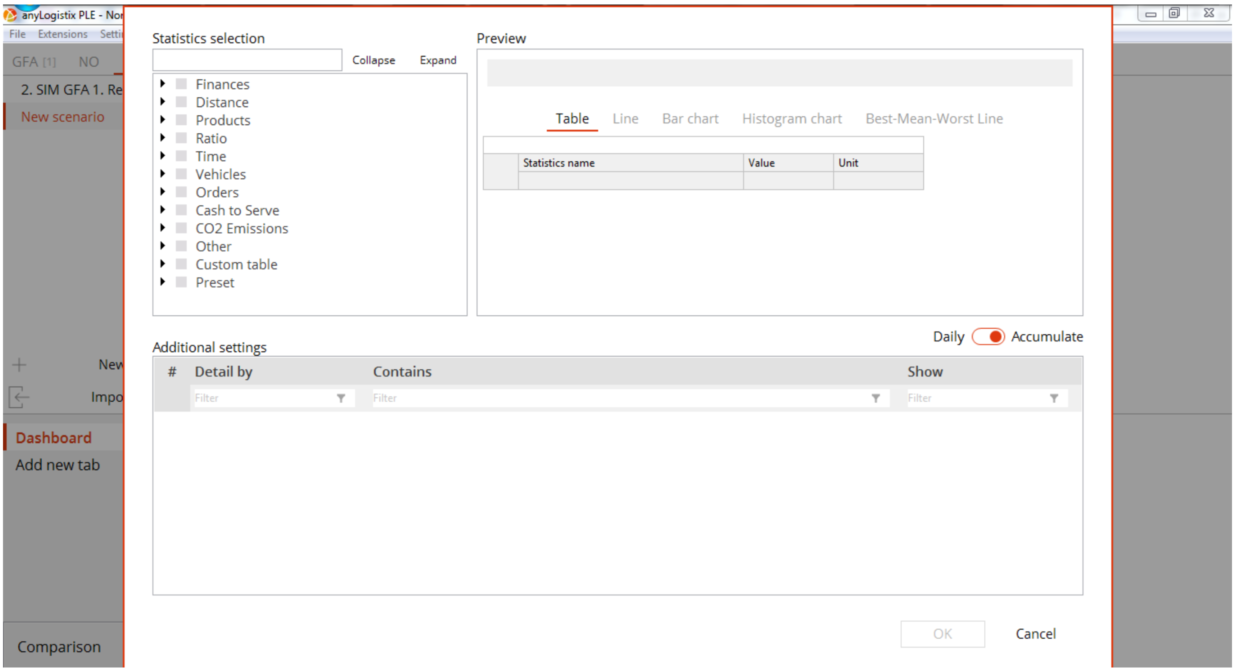


Figure 19: Starting to create a KPI dashboard.

KPI System

By default, anyLogistix classifies the 200 KPIs into six groups:

- KPIs for distribution centers
- KPIs for factories
- KPIs for distribution centers with storage
- KPIs for distribution centers with staff
- KPIs for customers
- KPIs for suppliers

Predefined KPIs can help us analyze financial, operational and customer performance. The KPIs in **Statistics collection** are organized in the following groups:

Table 1: KPI classifications.

Group	Provides
Finances	Detailed information on generated revenue and incurred expenses
Distance	Detailed information on the distance covered by the vehicles
Products	Detailed information on the volume of products in stock

Orders	Detailed information on the quantity of processed (as well as dropped/lost) orders and products.
Ratio	Detailed information on the quality of provided delivery services based on an analysis of the received or initially dropped orders and ordered products
Time	Detailed information on time spent processing tasks or idle time
Vehicles	Statistics related to this group provide detailed information on vehicles used during the Simulation experiment for the specified Scenario
Cash to Serve	Statistics related to this group provide detailed information on cash flows within the supply chain
CO_2 Emissions	Statistics related to this group show data on CO2 emissions within the designed supply chain
Other	Shows statistics on the amount of available staff, rating of DC, amount of delayed batches and etc.
Custom table	A table created by the user within the Anylogic environment
Preset	Grouped sets of regular statistics that allow users to better view and analyze data

In each group, we need to select the KPI and chart type (a table, line, bar chart or histogram chart). For a large model, we can filter or detail KPI by products, types and objects:

- Types: Distribution Center, Factory, Supplier and Customer,
- Objects: individual distribution centers, factories, suppliers and customers
- Products: individual products

Revenue, Costs, Service Level, Lead Time and On-time Delivery

We will create a KPI dashboard for our example. Since we're using a two-stage supply chain, we will take a closer look at the following KPIs for distribution centers and customers:

Financial performance:

- Transportation costs, fixed warehousing costs, total costs, total profit, total revenue

Customer performance:

- ELT service level*, customer revenue, OTD (on-time-delivered) orders, delayed orders, lead-time (that is, the time within which the product is expected to be received by the customer)

anyLogistix uses two types of service levels:

- The **Service level** measures the probability all customer orders that arrive within a given time interval will be completely delivered from stock on hand. Said another way, a lack of stock will not delay the deliveries.

- The **ELT service level** is the ratio of orders delivered within the "Expected lead time" (table demand) to total orders.

❼ The **Service level** does not allow a backlog. If a supply chain can't fulfil the order, the order is rejected. By comparison, the **ELT service level** includes account backlog and transportation time to the customer.

- Ratio
  - Bullwhip Effect by Product
  - ELT Service Level by Orders
  - ELT Service Level by Products
  - ELT Service Level by Revenue
  - Gates Utilization
  - Production Utilization
  - Service Level by Orders
  - Service Level by Products
  - Service Level by Revenue

Since we created distribution centers during our green field analysis, we haven't defined distribution center-based parameters. We need to define variable processing and fixed warehousing costs (**Other costs** in the Facility expenses table and **Outbound processing costs** in the **Processing costs** table) (Figure 20).

Customers [10]
DCs and Factories [2]
Demand [10]
Facility Expenses [2]
Groups [3]

#	Facility	Expense Type	Value	Currency	Time Unit	Product Unit
	Filter	Filter	Filter	Filter	Filter	Filter
1	Green Field Analysis GFA DC 0	Other costs	66	USD	day	
2	Green Field Analysis GFA DC 1	Other costs	66	USD	day	

Inventory [2]
Locations [12]
Paths [1]
Periods [1]
Processing Cost [2]

#	Source	Product	Type	Units	Cost	Currency
	Filter	Filter	Filter	Filter	Filter	Filter
1	Green Field Analysis GFA DC 0	Water	Outbound ship...	m³	10	USD
2	Green Field Analysis GFA DC 1	Water	Outbound ship...	m³	10	USD

Figure 20: Distribution center cost parameters

For both distribution centers, we define fixed warehousing costs per day at $66. Outbound processing costs are set at $10 per m^3. Fixed warehousing costs is defined as **Other Cost**. Inventory holding costs can be defined by **interest ratio** or by setting **carrying costs** for each unit per year. In addition, if we have inventory, we need to define **facility costs** per month per m^3.

Note: We'll discuss inventory management problems in the supply chain and their implementation in anyLogistix in Chapter 2.

We also need to define our product's cost and selling price:

#	Name	Unit	Selling Price	Cost	Currency
	Filter	Filter	Filter	Filter	Filter
1	Water	m³	100	50	USD

Inventory control policy

Inventory control policies are the heart of anyLogistix simulation. We will discuss them in detail in Chapter 2. Inventory control policies determine the decision logic of a distribution center or factory regarding stock replenishment. For the given example, we define a simplified ordering logic "No replenishment" (cf. Inventory Policy descriptions in anyLogistix Help) with some initial stock (it is necessary to start the simulation) (Figure 21).

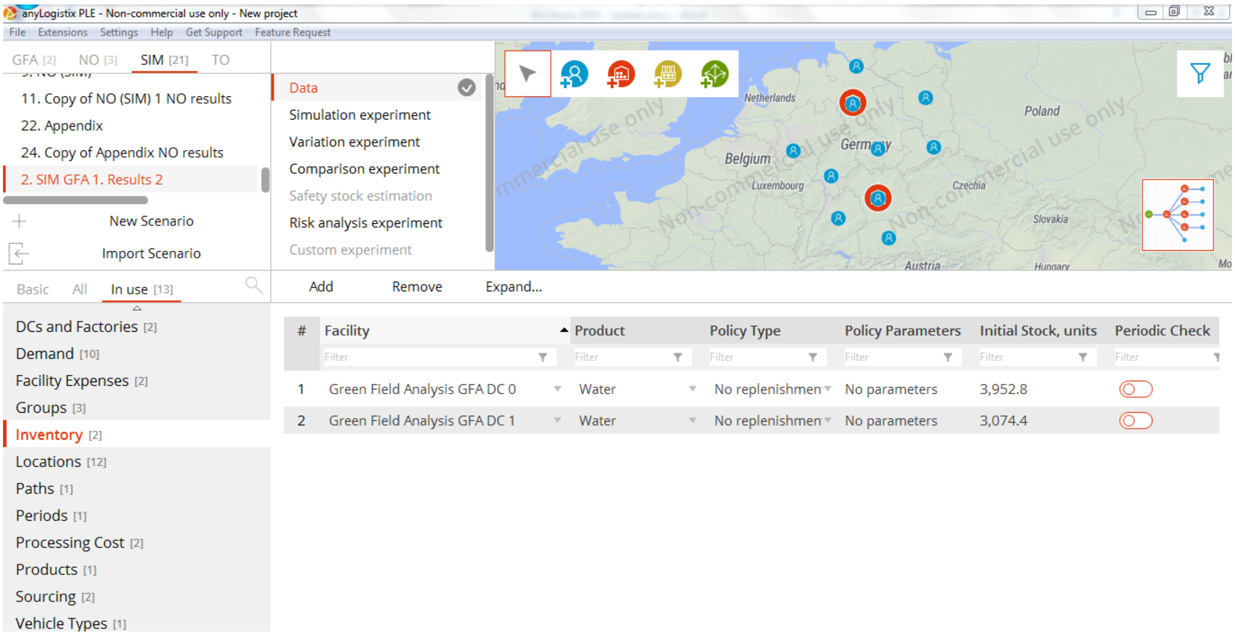


Figure 21: Inventory control policy

Note: "Period" in Table "Inventory" cannot be 0: the minimum value is 1.

Transportation Distance and Costs

The final step in input data setting is defining transportation distances and costs. We'll start by using **Vehicle Types** to define a vehicle type as well as the vehicle's capacity and speed (Figure 22).

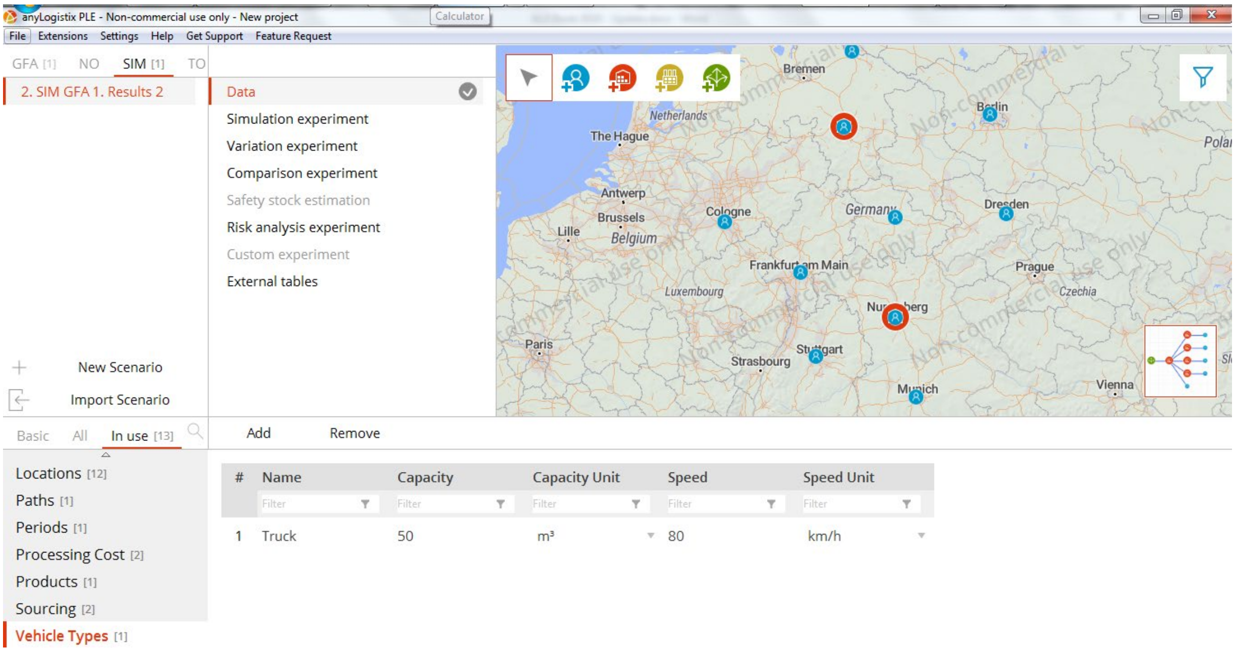


Figure 22: Vehicle type definition.

We now need to use the **Paths** option to define routes and shipment parameters (Figure 23).

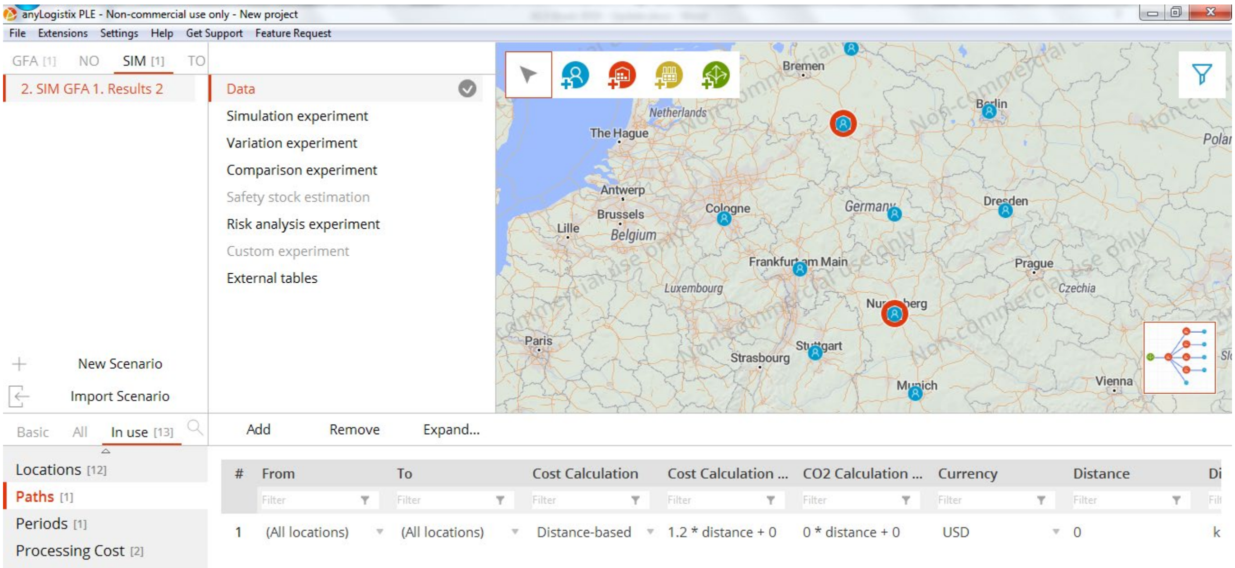
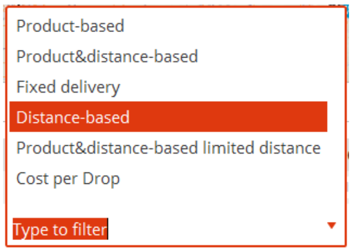


Figure 23: Routes and shipment parameter definition.

In **Paths**, the first step is to define the routes as **From-To**. In our example (Figure 23), we identify only one group of routes "From All locations To All locations". If our model used different supply chain layers such as distribution centers, production factories and suppliers, we could add other paths to differentiate shipment parameters.

Second, we need to define a rule for calculating shipment costs. In our example, we select **Distance-based cost** and then set up a coefficient of 1.2 per kilometer. In simple terms, this means we will pay $1.20 for one kilometer.



Third, we can explicitly define the distance and transportation time or allow AnyLogistix to use truck speed and customer locations to compute them. In this example, we'll allow the program to calculate these values.

Fourth, we can decide which distance metrics to use: straight distances or real routes. For simplicity, **we will use straight lines**.

Fifth, you can select Full Truckload (**FTL**) or Less than Load (**LTL**) transportation options and define minimal load for FTL as well as the rules for order aggregation.

Vehicle Type	Transportation Policy	Min Lo...	Aggregate ...	Aggregation Period
Truck	FTL	0.6	(on)	10

Note: Use the **MinLoad** and **Aggregation Period** columns to define the rules for transportation batching. In this example, we allow shipments with a minimum load of

60% but limit the wait period to 10 days. In ten days, the truck will be dispatched for shipment even if the load is below 60%.

Note: "Aggregation period" in Table "Paths" cannot be 0: the minimum value is 1.

Sourcing Policy Definition

We need to use the **Sourcing** table to define our sourcing rules. The most general rule could be that all sites (that is, all distribution centers) can supply all customers.

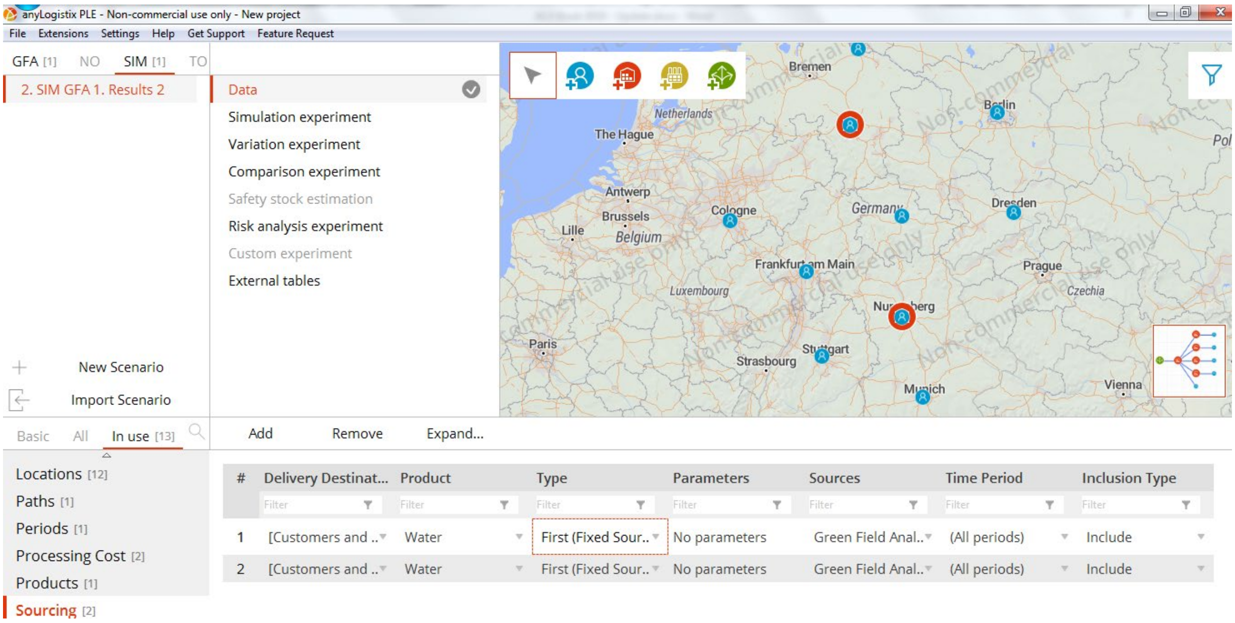


Figure 24: Sourcing rules.

In addition, we can select among different sourcing rules as follows:

Note: In multi-stage supply chains, you can make your simulation modeling flexible and convenient by setting up sourcing policies for each supply chain echelon. Even in a two-stage supply chain, you might need to set up different sourcing policies for different distribution centers, products and customers.

Figure 25 shows our new KPI dashboard.

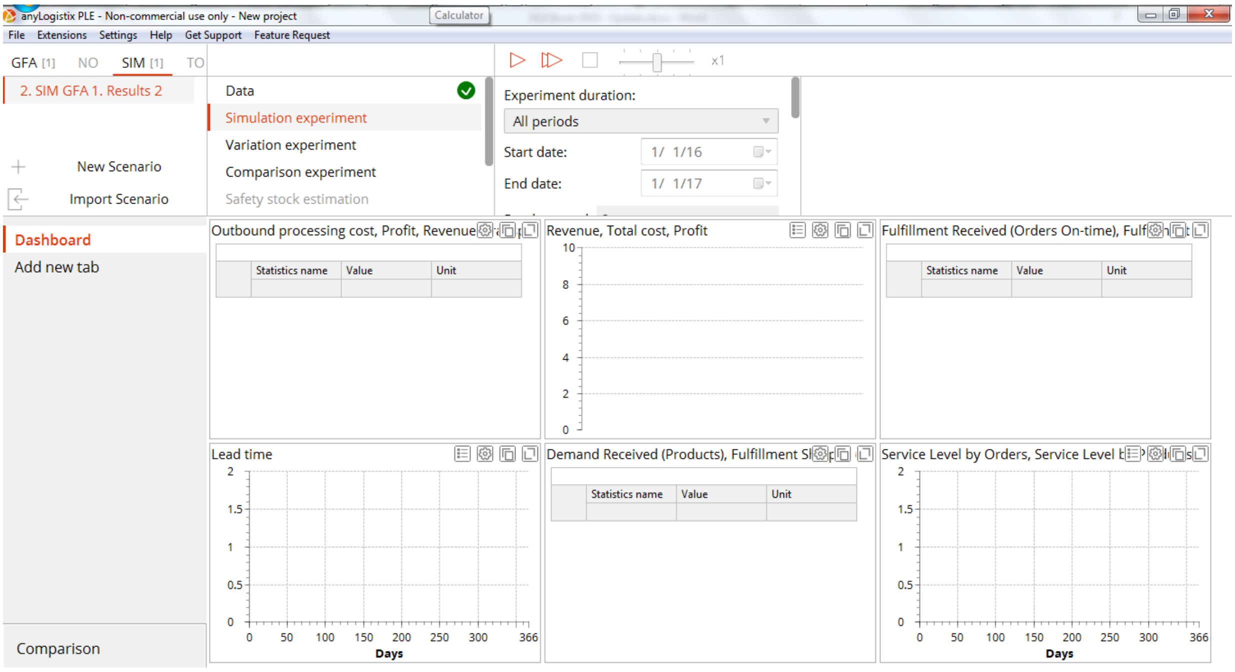


Figure 25: KPI dashboard

You can customize the manner anyLogistix presents each KPI by enlarging the KPI window and using a toolbar (Figure 26).

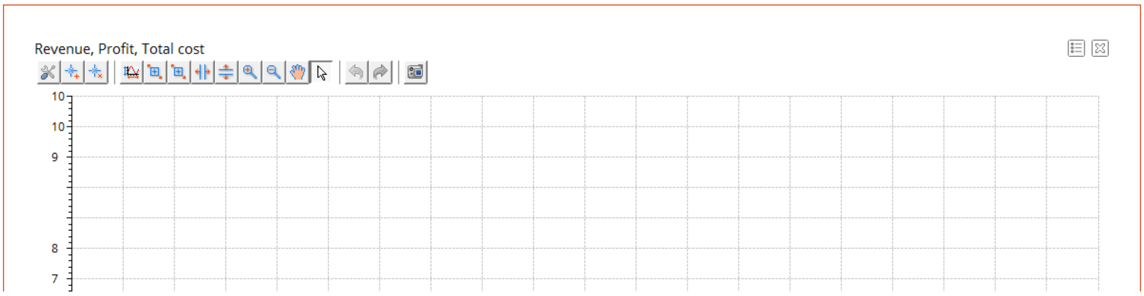


Figure 26: KPI presentation customization in the toolbar

Note: To make a diagram smaller or larger, right-click in the dashboard area, select **rear-range**, and then draw the diagram's lower-right corner. To delete a diagram, close it.

Experiments and Analyses

Simulation Experiments for Multiple Warehouses with Real Routes

We're ready to run a simulation experiment and analyze KPI (Figure 27).

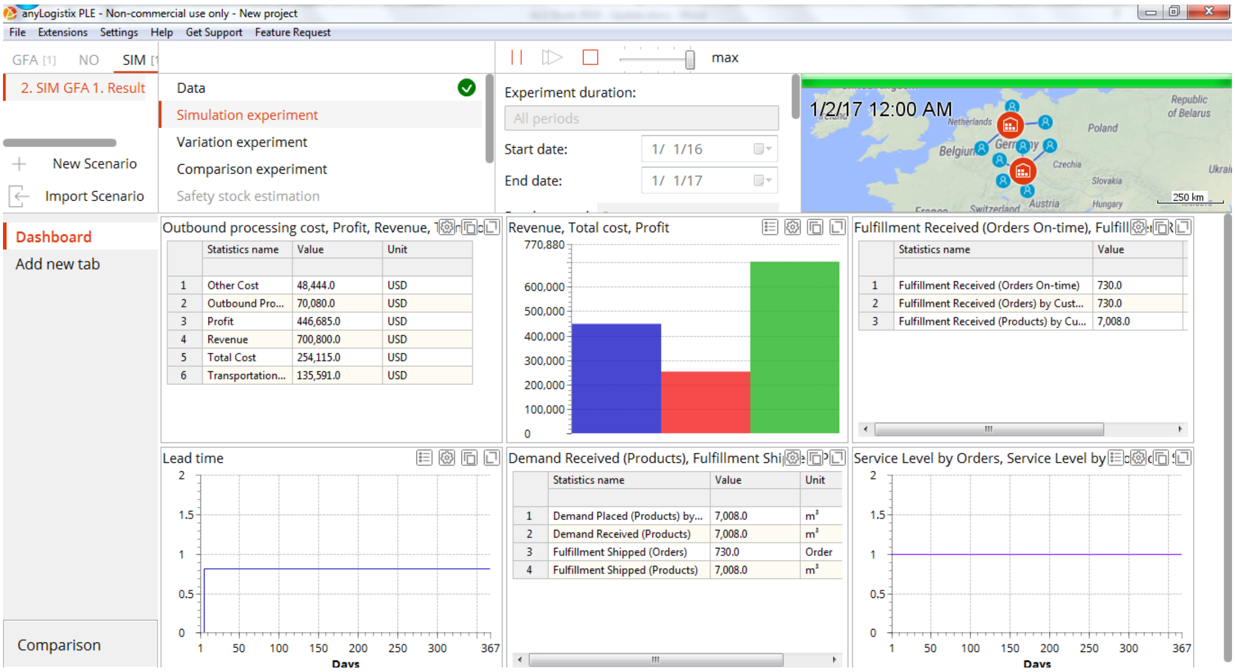


Figure 27: Experimental results.

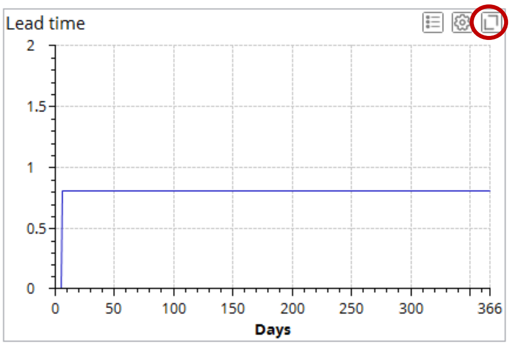
We can see from the experiment's results how our supply chain would perform by analyzing the following KPIs (Table 2).

Table 2: KPIs for GFA analysis with two distribution centers.

KPI	**Value**
Financial DC performance:	
Other cost, $	48 444.0
Outbound processing cost, $	70 080.0
Profit, $	446 685.0
Revenue, $	700 800.0
Total cost, $	254 115.0
Transportation cost, $	135 591.0
Customer performance:	
Lead time, days	0.81*
Service level, %	100*
Customer delayed orders(Fulfillment Late)	0
Customer in-time orders	730.0
Customer items arrived	7 008.0

Customer orders arrived	730.0
Current backlog orders	0
Customer ordered items	7008.0
Incoming replenishment items	7008.0
Items shipped	7008.0
Orders shipped	730.0
Outgoing replenishment orders	0

These KPIs present total lead time and total service level for ten customers. You can change the presentation in the lead time and service level diagrams by detailizing for objects: (Additional setting** → **Detailization by** → **Add** → **Objects**). The presentation would show individual service levels (the ration would be 1) and lead times.*



> **Note:** You can export KPIs to a Microsoft Excel worksheet by pointing to the **File** menu and then clicking **Export**.

To check the quality of the computed solution, copy the current scenario and move the distribution centers to other points (place your cursor on the map, click a site icon and then drag it to another point on the map) and simulate the supply chain with these new locations. Figures 28 and 29 and Table 3 display the results:

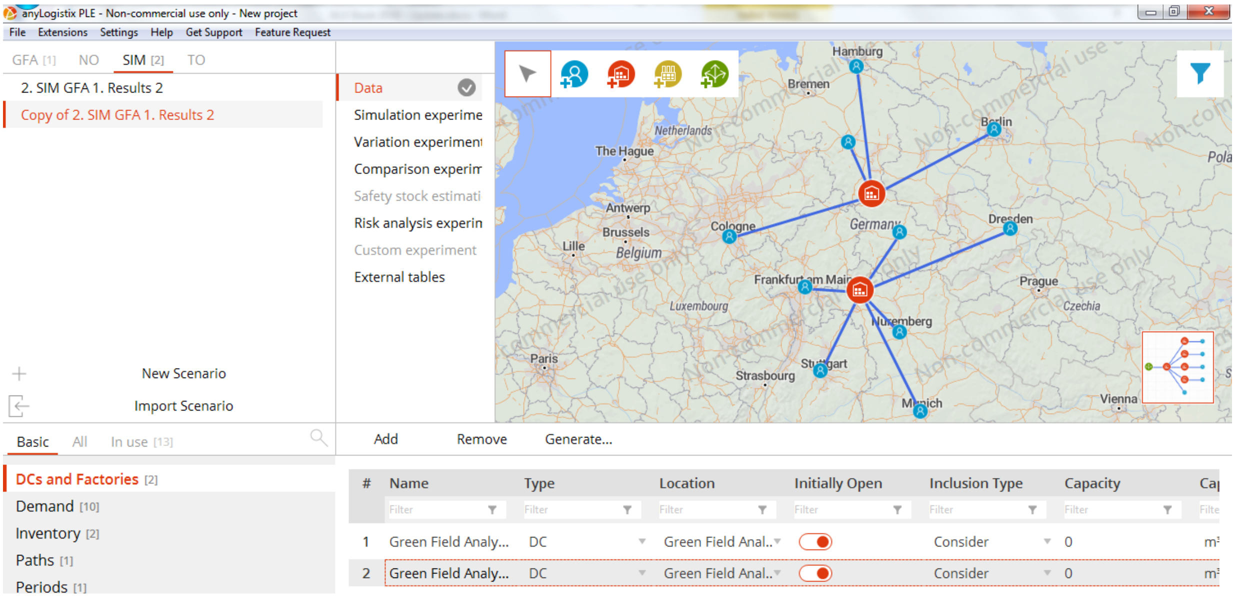


Figure 28: Updated distribution center locations.

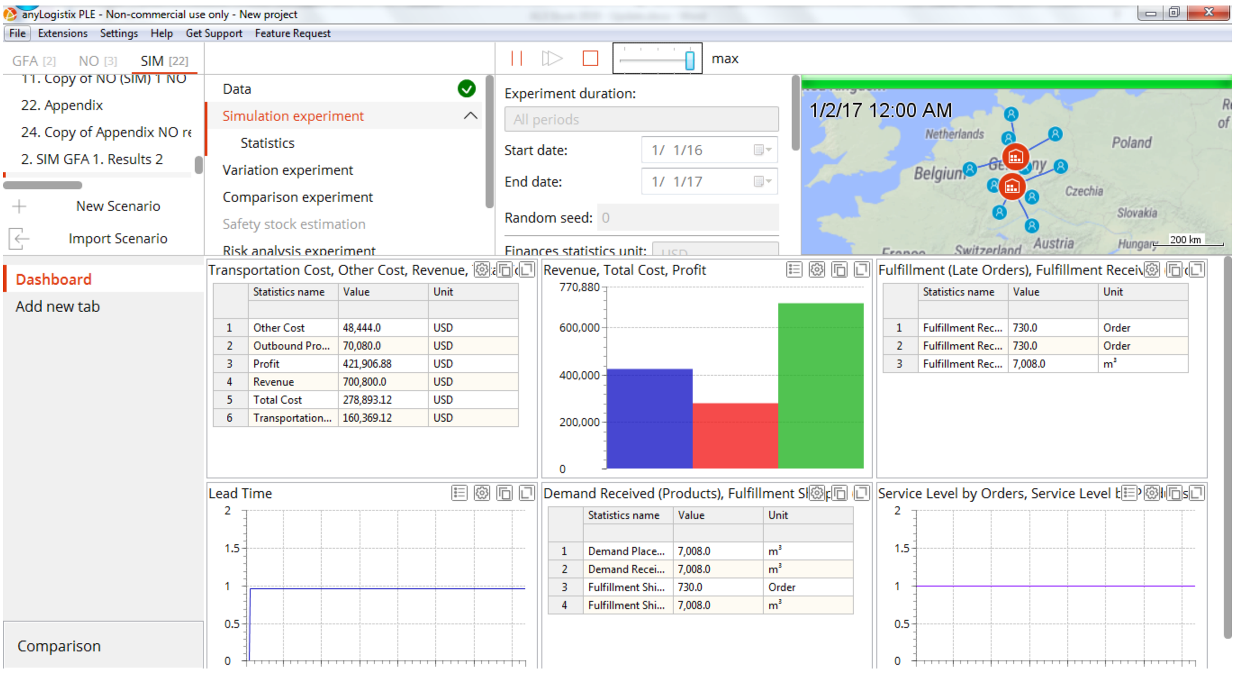


Figure 29: Experimental results with updated distribution center locations.

Table 3: KPI comparison for GFA and changed distribution center locations.

KPI	GFA locations	Changed locations
Financial DC performance:		
Other cost, $	48 444.0	48 444.0
Outbound processing cost, $	70 080.0	70 080.0
Profit, $	446 685.0	**421 906.88**
Revenue, $	700 800.0	700 800.0
Total cost, $	254 115.0	**278 893.12**
Transportation cost, $	135 591.0	**160 369.12**
Customer performance:		
Lead time, days	0.81	**0.95**
Service level, %	100	100
Customer delayed orders	0	0
Customer in-time orders	730.0	730.0
Customer items arrived	7 008.0	7 008.0
Customer orders arrived	730.0	730.0
Current backlog orders	0	0
Customer ordered items	7008.0	7008.0
Incoming replenishment items	7008.0	7008.0
Items shipped	7008.0	7008.0
Orders shipped	730.0	730.0
Outgoing replenishment orders	0	0

You can see in Table 3 that total costs have increased ($278 893.12 as compared to $254 115.0) due to increase in transportation costs. At the same time, the location changes have reduced profit ($421 906.88 compared to $446,685).

Simulation Experiments for Single Warehouses with Real Routes

We've learned the supply chain with two distribution centers is more flexible, more responsive and more expensive. Now, we'll run the simulation with a single distribution center: the location from our first green field analysis experiment.

We convert experimental result **GFA1: Results 1** into a new scenario. Figure 30 and Table 4 display our results:

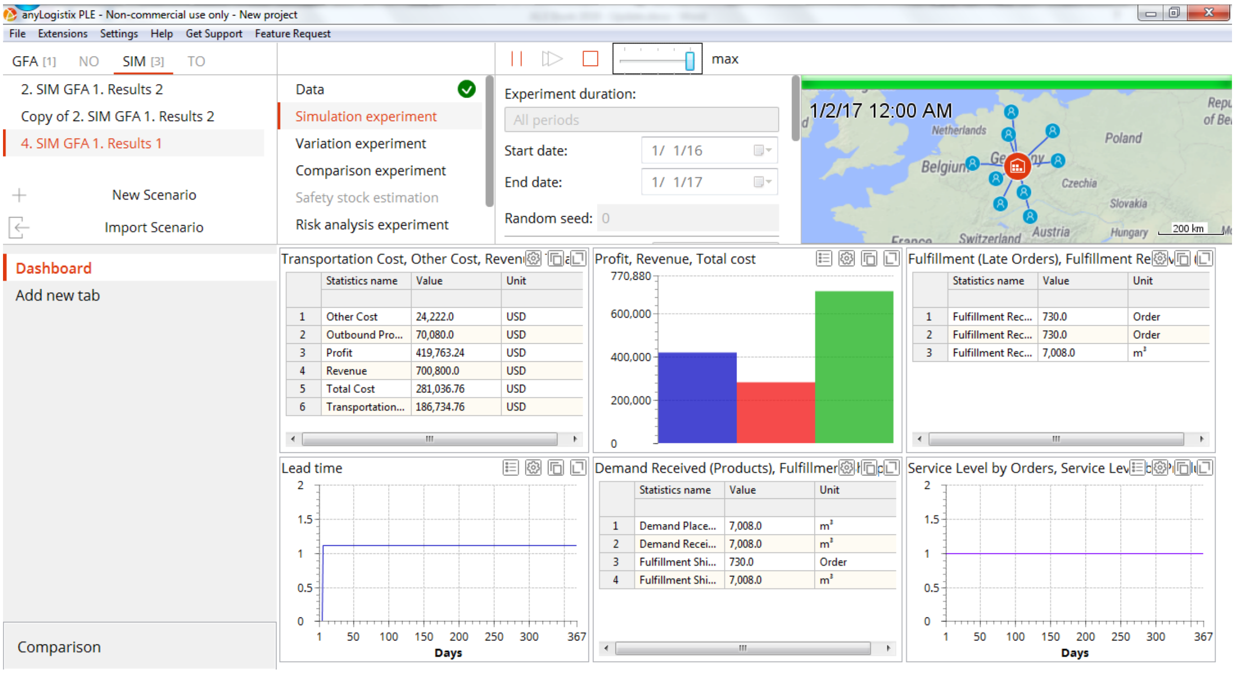


Figure 30: Simulation results for the supply chain with one distribution center.

Table 4: KPI comparison for two distribution centers (GFA and changed distribution center locations) and one distribution center.

KPI	**2 DCs: GFA locations**	**2 DCs: Changed locations**	**Single DC**
Financial DC performance:			
Other cost, $	48 444.0	48 444.0	**24 222.0**
Outbound processing cost, $	70 080.0	70 080.0	70 080.0
Profit, $	446 685.0	**425 392.01**	**419 763.24**
Revenue, $	700 800.0	700 800.0	700 800.0
Total cost, $	254 115.0	**275 407.99**	**281 036.76**
Transportation cost, $	135 591.0	**156 883.99**	**186 734.76**
Customer performance:			

Lead time, days	0.81	**0.95**	1.11
Service level, %	100	100	100
Customer delayed orders	0	0	0
Customer in-time orders	730.0	730.0	730.0
Customer items arrived	7 008.0	7 008.0	7 008.0
Customer orders arrived	730.0	730.0	730.0
Current backlog orders	0	0	0
Customer ordered items	7008.0	7008.0	7008.0
Incoming replenishment items	7008.0	7008.0	7008.0
Items shipped	7008.0	7008.0	7008.0
Orders shipped	730.0	730.0	730.0
Outgoing replenishment orders	0	0	0

Table 4 shows us the one distribution center has lowered distribution center-related costs. However, transportation costs have increased significantly, which has led to higher total costs. In this example, we can easily see the effects of consolidation and centralization in the supply chain design (see Figure 31, adopted from Chopra and Meindl, 2015).

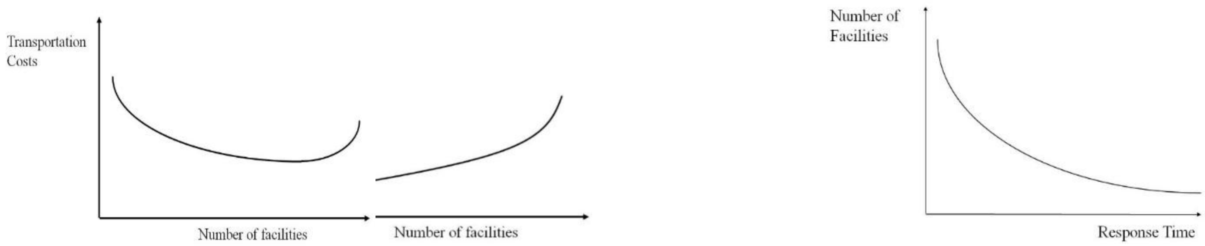


Figure 31: General relations in the supply chain design.

The major concepts we cover in this chapter are:

- Green field analysis helps us determine the optimal facility locations
- Input data: to conduct a green field analysis experiment, you must define:
  - ✓ Locations – the **Locations** table
  - ✓ Customers – the **Customers** table
  - ✓ Products – the **Products** table
  - ✓ Demand – the **Demand** table
- The following green field analysis algorithms are for computation:
  - ✓ K-means algorithm for clustering

    - ✓ Aykin and Babu algorithm for a facility location problem
    - ✓ Criteria: estimation of transportation cost based on volume
- The following tables present green field analysis results:
    - ✓ **Locations**
    - ✓ Distribution Centers/Factories – suggested facilities linked to **Locations** table
    - ✓ Sourcing – defines which product to buy and where to buy it
    - ✓ Locations for the facilities
    - ✓ Inventory – green field analysis creates simple inventory policies for simulation experiment

Because a green field analysis does not count roads, cities or means of transportation, it may suggest placing distribution centers in surprising locations such as on top of a mountain or in the middle of the ocean. A green field analysis considers all customers with coefficients equal to sum on all products of total demand multiplied by product volume.

Chapter 2. Network Optimization and Advanced Simulation with Inventory and Transportation Control: Three-stage Supply Chain

We haven't yet considered network optimization, the effect of inventory control policies such as fixed period or reorder point policies or transportation policies such as full truck load (FTL) and low truck load (LTL). However, both types of policies can play a major role in a company's decisions about its supply chain.

Our Learning Objectives

Our learning objectives for this chapter are to:

1. Understand network and transportation optimization;
2. Provide insight into the impact of inventory control and transportation policies on supply chain and logistics performance;
3. Develop the anyLogistix skills you need to create three-stage supply chain models, perform optimization and simulation experiments and measure their performance.

Theoretical background

Supply chain design and network optimization

Supply chain design consists of a location analysis framework for selecting the locations of source, production, and storage facilities, as well as incorporating the connections between them into the overall supply chain. The supply chain should be designed so that the demand of each individual market is met by the selected facilities.

In management terms, network optimization seeks to find the most efficient (i.e., optimal) combination of factories and distribution centers in the supply chain. Since the number of such possible combinations is very high, this kind of technical optimization model is used to support management decision-making. More details on NO (network optimization) can be found in the Introduction.

In technical terms, network optimization considers the set of alternative locations in which a facility/warehouse can be installed or used (e.g. S = {GER; FRA; UK}) and a set of all markets (e.g. M = {GER; FRA; UK; SEE; SWE; NEU}). The set $T := S \times M$ contains all possible transportation links between a warehouse region and a market. If a facility is opened in region $s \in S$ then the annual costs rise by the amount f_s. The decision to use the transportation link $(s, m) \in T$ between the facility in region $s \in S$ and the market $m \in M$ increases the annual costs by the additional amount c_{sm}. Using the aforementioned sets, we are able to formally present a simplified form of an incapacitated network optimization problem as follows.

First, the *objective function* (2.1) is formulated:

$$Z = \sum_{s \in S} f_s \cdot y_s + \sum_{s \in S} \sum_{m \in M} C_{sm} \cdot x_{sm} \qquad (2.1)$$

The sum of (annual) costs expressed in Eq. (2.1) has to be minimized by varying the values of the *decision variables* y_s as well as x_{sm}. The family y_s of binary decision variables represents the facility opening decisions. All these decision variables are allowed to be set to either 1 (“use this facility”) or 0 (“do not use this facility”). Similarly, x_{sm} code the decisions about whether to use the transportation links in T between warehouses and markets. Although the two decision categories introduced address different managerial decisions, they fall into the same type of decisions: exactly one of two options must be selected (binary decisions). Therefore, the network optimization turns out to be a collection of interdependent binary decisions about the opening of the locations.

If each market has to be served from exactly one facility, it is necessary to ensure that constraint (2.2) is respected.

$$\sum_{s \in S} x_{sm} = 1, \forall m \in M \tag{2.2}$$

In a case where (7.2) remains unfilled, then at least one market in M remains unserved. Since the overall sum of costs for supplying all markets must be minimized: every solution in which a market m ∈ M is connected with two or more facilities implies higher costs and selecting one of these facilities for serving the markets may reduce costs.

Obviously, it is useless to install a transport link between market *m* and facility *s* if *s* is not opened, e.g., if we set $x_{sm} = 1$ if, and at the same time, $y_s = 0$ then we would end up with a useless and unrealizable solution for the network optimization. In order to avoid such a failure, we introduce the constraints (7.3) and (7.4) that couple facility installation with transport link installation decisions and ensure that we install a transport link only if it has been decided that the origin facility should also be installed.

$$x_{sm} \le y_s, \forall s \in S, \forall m \in M \tag{2.3}$$

$$y_s \in \{0;1\} \, \forall s \in S, x_{sm} \in \{0;1\} \, \forall (s,m) \in T \tag{2.4}$$

Using the mathematical model (2.1)-(2.4), we are now ready to state precisely the network optimization problem as follows:

*It is necessary to minimize the total costs for the installation of facilities and transportation links subject to Eq. (*2.1*), so that each market is served by exactly one facility (*2.2*). If we use a facility for supplying a market, then this facility must be open (*2.3*). Each available facility is either opened or closed and each available transportation link is either used or not (*2.4*).*

A pure, formalized problem formulation is as follows: “minimize (2.1) while taking into account (2.2)-(2.4). The collection of mathematical expressions (2.1)-(2.4) is a mathematical model for the network optimization. This model represents the underlying decision problem in a formal way. A solution to this model is comprised of a selection of values for each of the *y*-decision variables as well as each of the *x*-decision variables. Such a solution is called *feasible*, if and only if, all constraints (2.2)-(2.4) are fulfilled, e.g., if the implementation of the selected values for the decision variables leads to logically true statements. Every feasible solution of the proposed model that leads to a non-dominated objective function value is called an optimal solution of the model. Such an optimal solution can be used to derive an optimal solution to the underlying real world network optimization.

Combining optimization and simulation in supply chain design

Consider a combination of simulation and optimization that seeks to find optimal locations for facilities and allocate customers to those locations subject to supply chain profit maximization (i.e., we consider location-allocation problems). Figure 32 depicts major interdependencies between the parameters in supply chain design.

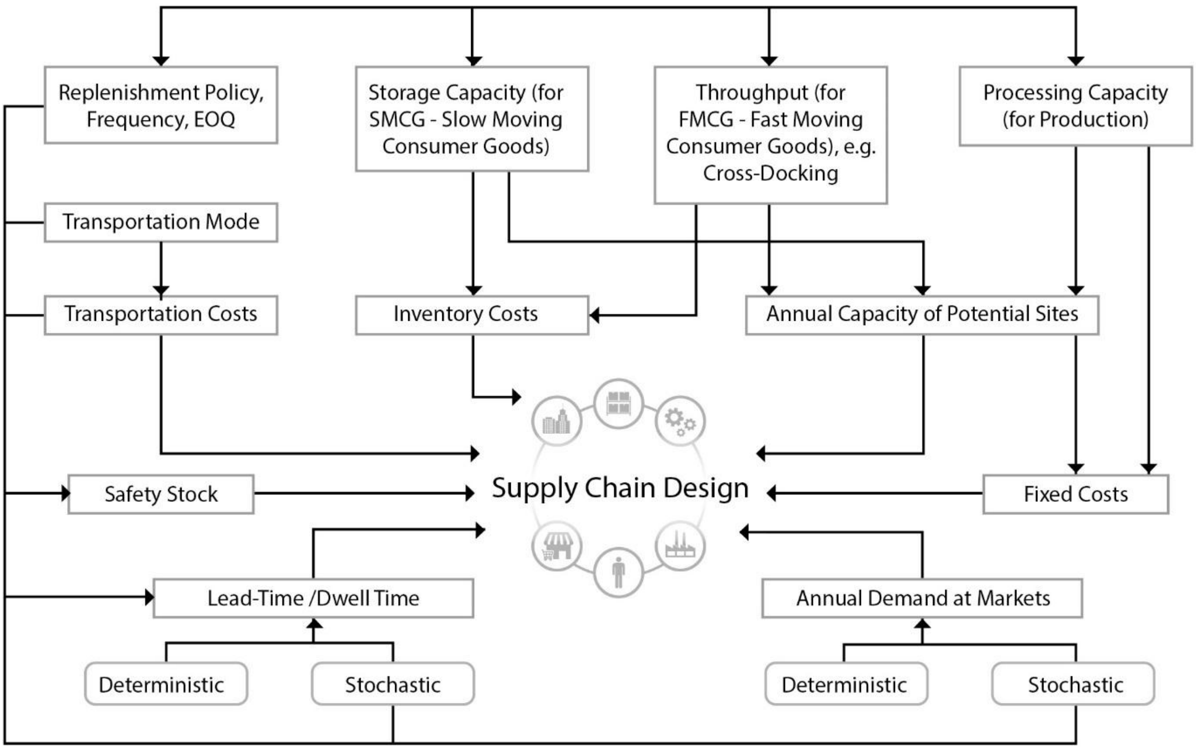


Figure 32: Supply chain design analysis framework

Network optimization can be used for a number of supply chain design problems such as:

- *Incapacitated and capacitated plant location problem;*
- *Distribution network design;*
- *Distribution network design with inventory, lead time, and transportation mode selection;*
- *Production-distribution network design;*
- *Hub location problem;*
- *Supply network design with operational risks;*
- *Supply network design with disruption risks.*

In a generalized form, supply chain design using network optimization considers such parameters as

- Alternative facility locations,
- Customers (markets),

- Production, inventory processing, and transportation costs,
- Fixed facility costs and inventory holding costs,
- Minimum and maximum throughputs and capacities in production, transportation, and storage,
- Demand in the markets,
- Number of periods and products,
- Bill of materials.

The variables to be optimized are

- Facilities to be included in the supply chain design, and
- Quantities (flows) to be delivered from sources to destinations in the supply chain.

The solutions are usually constrained by

- Maximum/minimum demand in the markets and
- Minimum and maximum throughputs and capacities in production, transportation, and storage.

The objective function minimizes total costs.

Even though network optimization can lead to useful insights, some dynamic issues, such as inventory, sourcing, and shipment control policies are not considered within this framework of analysis. As such, simulation can be a useful extension of a network optimization, because it enables consideration of time-dependent uncertainties, such as demand and lead-time fluctuations (i.e., operational risks) and facility breakdowns (i.e., disruption risks). Moreover, simulation can be used to validate optimization results in dynamic and uncertain environments (cf. Figure I-3 in Introduction).

Inventory control

The *role of inventory management* is to strike a balance between inventory investment and customer service. Inventory is one of the most expensive assets of many companies, representing as much as 50% of total invested capital. In making decisions in the scope of inventory management, the following two *basic questions* are put to the forefront for consideration:

- How much should I replenish?
- When should I replenish?

In calculating inventory amounts, the following *costs* are typically considered:

- Holding costs (variable)—the costs of holding inventory over time;
- Ordering costs (fixed)—the costs of placing an order and receiving goods;
- Stockout costs (variable)—the costs of lost customer orders resulting from product shortage, loss-of-goodwill costs.

According to inventory functions and types, inventory can be used to *manage:*

- Economy of scale—this is *cycle inventory*;
- Uncertainty—this is *safety inventory*.

Cycle inventory exists as a result of producing or purchasing in large *lots* or *batches*. A lot or *batch size* is the quantity that a stage in the SC either produces or purchases at a time. The SC can exploit economy of scale and order in large lots to reduce fixed costs. With the increase in lot size, however, also comes an increase in carrying costs. As an example of a cycle stock decisions, consider an online book retailer. This retailer's sales average around 10 truckloads of books per month. The cycle inventory decisions the retailer must make include how much to order for replenishment and how often to place these orders. We will consider cycle inventory optimization in the "Deterministic models" section (for one period) and "Dynamic lot-sizing models" section for many periods.

Safety inventory is carried to satisfy demand subject to unpredictable demand fluctuations and to reduce product shortages. Safety inventory can help the SC manager improve product availability in the presence of uncertainty. In the presence of safety inventory, shortage costs or overage costs can occur. The calculation of safety inventory is based on a predetermined *service level*. Choosing safety inventory involves making a *trade-off* between the costs of having too much inventory and the costs of losing sales due to inventory shortage.

In order to answer the question of how much should we replenish, we introduce the following notations:

q is the number of units per order;

*q** is optimal number of units per order (EOQ – economic order quantity);

b is annual demand in units for the inventory item;

f is set-up or ordering cost for each order;

c is holding or carrying cost per unit per year.

Under the assumption of linear inventory consumption, we get the EOQ formula as follows [Eq. (2.5)]:

$$q^* = \sqrt{\frac{2b \cdot f}{c}} \tag{2.5}$$

The EOQ model answers the "how much" question. The *re-order point* (ROP) tells "when" to order. ROP is introduced to take into account the so called *lead time*, i.e. the time between placement and receipt of an order. With the assumption of constant demand and a set lead time, ROP is calculated as in Eq. (2.6):

$$ROP = d \cdot L, \tag{2.6}$$

where *d* is daily demand and *L* is lead time.

We already know how to determine order quantities and ROPs for situations where demand and lead time are deterministic. However, in many practical cases, both demand and lead time fluctuate. We do not know their values, but can only estimate them on the basis of probability. For such cases, *stochastic* (*probabilistic*) models are needed.

Uncertainty in demand makes it necessary to maintain a certain customer service level or *level of product availability* to avoid stock-outs. The level of product availability is the fraction of demand that is served on time from a product held in inventory. A high level of product availability provides a high level of *responsiveness,* but increases costs because much inventory is held, but rarely used. In contrast, a low level of product availability lowers inventory holding cost, but results in a higher fraction of customers who are not served on time. The basic trade-off when determining the level of product availability is between the cost of inventory to increase product availability in terms of service level and the loss from not serving customers on time.

For example, a 0.05 probability of stock-out corresponds to a 95% service level.

In a situation of demand uncertainty, *safety inventory* is introduced with the objective to ensure product availability even in the case of demand fluctuations. Consider an example in Figs. 33-35.

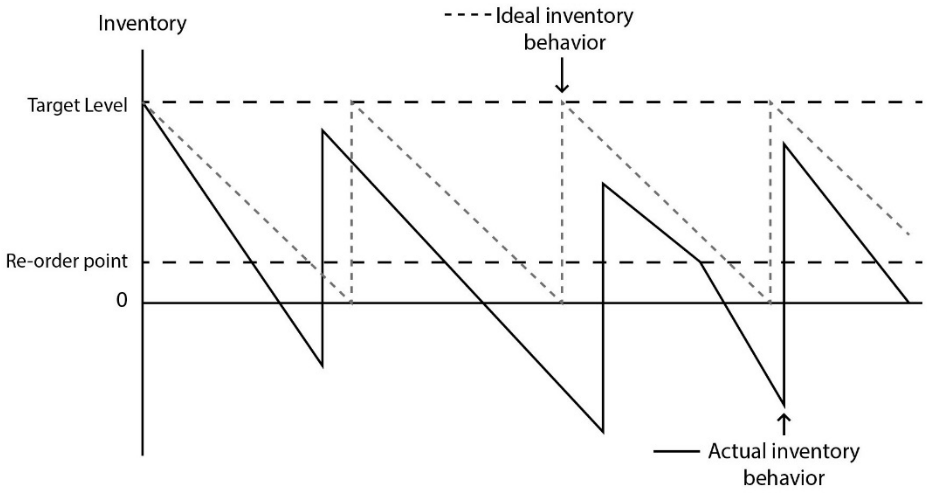


Figure 33 Actual and ideal inventory behavior

Assume that we use Eq. (2.5) and Eq. (2.6) to compute EOQ and ROP, respectively. The dashed line in Fig. 33 reflects the inventory dynamics in the case of using optimal EOQ and ROP and can be named as an ideal inventory behavior. The ideal inventory behavior means in this case that all assumptions of EOQ and ROP models subject to Eq. (2.5) and Eq. (2.6) are met, i.e., demand and lead-time are constant. In reality, this is not the case. Both demand and lead-time fluctuate resulting in actual inventory behavior which is different as the ideal one.

In order to cope with this situation, the ROP should be increased by the safety stock. Consider Figs. 34 and 35.

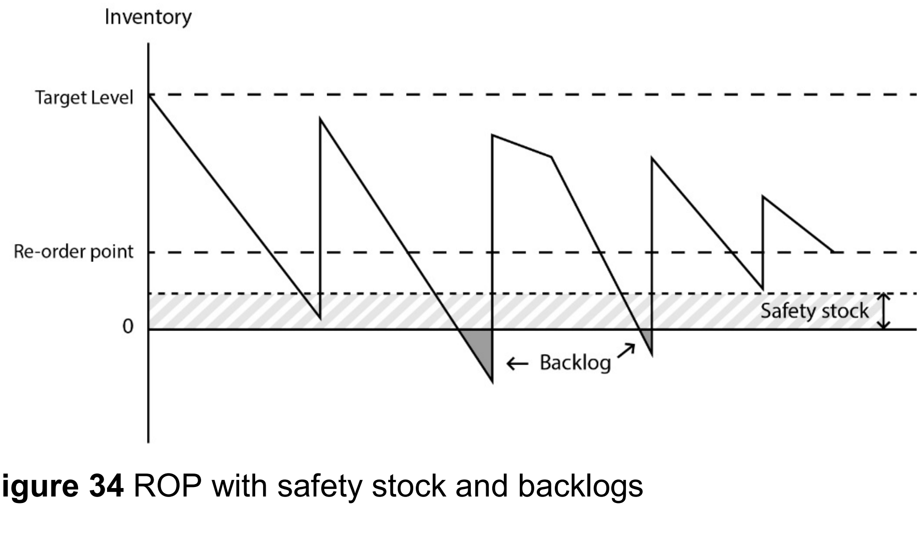


Figure 34 ROP with safety stock and backlogs

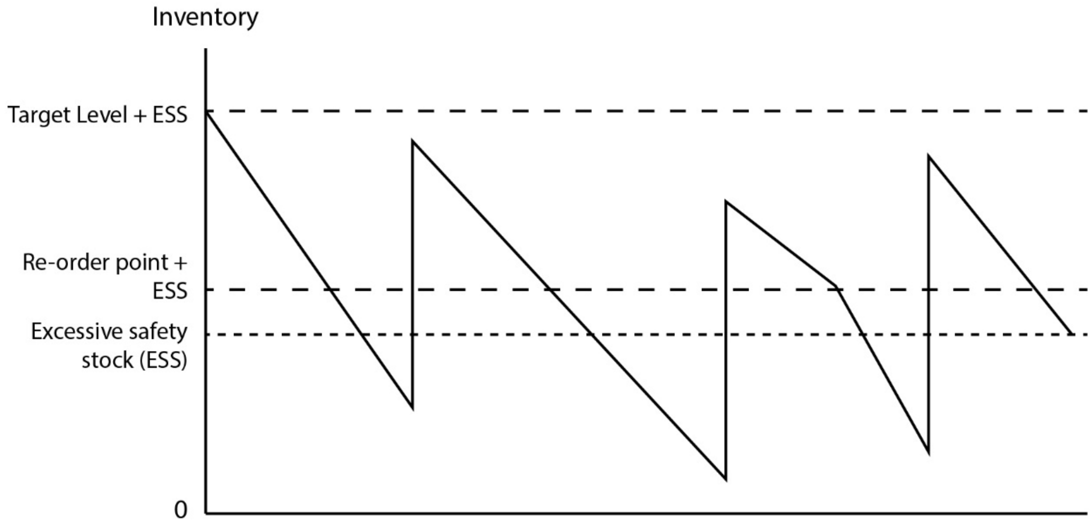


Figure 35 ROP with excessive safety stock and without backlogs

Fig. 34 increases ROP from Fig. 33 by safety stock and considers an example where safety stock allows to cope with demand fluctuations in some cases. However, in other cases there exists a backlog. Fig. 35 shows an example where ROP from Fig. 34 is increased by an excessive safety stock (ESS). The ESS is so high that demand fluctuations would never result in a backlog which means a 100% product availability on stock resulting in a 100% service level. However, the inventory level in Fig. 35 is much higher as compared to Figs. 33 and 34 resulting in higher inventory costs.

The question is *how much safety stock should we plan to find a right balance between the inventory investment and customer satisfaction?* Technically, the safety stock computation is based on the desired service level and demand volatility. In order to calculate safety stock, Eq. (2.7) is used:

$$ss = z \cdot \sigma_{dLT}, \tag{2.7}$$

where *ss* is safety stock, σ_{dLT} is standard deviation of demand during lead-time and *z* is the number of standard deviations.

Demand deviation can be gleaned, e.g., from analysis of demand forecasts and actual sales in the past. For example, $\sigma = 1.25MAD$ is a typical value. The Z-value can easily be determined using table of normal distribution.

The inclusion of safety stock changes the calculation of ROP [see Eq. (2.8)]:

$$ROP = d \cdot L + ss \tag{2.8}$$

In order to calculate ROP, four situations are possible:

- demand is assumed to be normally distributed during the lead time;
- daily distribution of demand is given (i.e., demand is variable) and lead time is constant;
- daily demand is constant and lead time is variable;
- both demand and lead time are variable.

In order to calculate ROP if demand is assumed to be normally distributed during the lead time, formula (2.9) can be used:

$$ROP = d \cdot L + z \cdot \sigma_{dLT} \quad (2.9)$$

If daily distribution of demand is given (i.e., demand is variable) and lead time is constant, formula (2.10) can be used:

$$ROP = d \cdot L + z \cdot \sigma_d \cdot \sqrt{L} \quad (2.10)$$

If daily demand is constant and lead time is variable, formula (2.11) can be used:

$$ROP = d \cdot L + z \cdot d \cdot \sigma_L \quad (2.11)$$

▶ **Practical Insights** Equation (2.11) nicely provides evidence of the importance of reducing lead time variability. We can observe that lead time variability reduction directly influences safety stock levels.

Finally, if both demand and lead time are variable, formula (2.12) can be used:

$$ROP = d \cdot L + z\sqrt{L \cdot \sigma_d^2 + d^2 \cdot \sigma_L^2} \quad (2.12)$$

Inventory control policy is a managerial procedure that helps to define how much and when to order. The review may happen periodically (e.g., at the end of a month) or continuously (i.e., tracking each item and updating inventory levels each time an item is removed from inventory). Four parameters are important in the setting up of inventory control policies:

- *t* is replenishment interval;
- *q* is order quantity;
- *s* is re-order point;
- *S* is target inventory level.

Since order quantity and replenishment intervals may be both fixed and variable, four basic inventory control policies can be classified. If the period between two orders is always the same, we talk about *periodic review systems*. If the point of time of the next replenishment depends on the ROP, we talk about the ROP method of stock control or a *continuous review system*. The above-mentioned four parameters can be fixed or changed (adjusted) in dynamics according to changes in demand and supply. Therefore, *static* and *dynamic* views on inventory control policies can be considered.

Policy 1: t,q
- t: fixed time between two orders
- q: fixed order quantity

In *(t,q)* policy, a fixed amount (q) is ordered for a fixed period of time (t).

(*t,q*) is a simple policy for handling the ordering process. This policy opens possibilities to further automatic control, which improves quality and saves resources, such as labor, energy, or materials. However, the (*t,q*)-policy is inflexible and used very seldom in business. Should uncertainty or fluctuation in demand exist, this policy cannot be adjusted. In addition, shortage or overstocking make the (*t,q*)-policy an unattractive tool for many companies. Thus, it is recommended to implement this policy under constant demand.

Policy 2: t,S

- T: fixed time between two orders
- Q: variable order quantity to stock up to the target level S

In the (*t,S*)-policy, the order quantity (*q*) is variable, and *q* is placed at a fixed time (*t*). We need to order a certain amount of inventory to reach the desired quantity *S* subject to lead time (*lt*). Order quantity is calculated as the target level S— stock on hand.

This policy avoids excessive inventory, which cannot be used for any other purpose and thus involves opportunity costs. The model is easy to use for control of orders. However, the physical control of the inventory could be so expensive that the exact count is only performed once a month, for example. In certain cases the (*t,S*)-policy can lead to relatively high capital commitment because of the high average inventory. This policy also implies high ordering costs because we might not place a large order on the fixed day. At the same time, we might need to wait too long to fulfil our target inventory and thus a shortage can occur. The (*t,S*)-policy is recommended for use in companies with cycled replenishment.

Policy 3: s,q

- t: variable time between two orders
- q: fixed order quantity

This model operates when order quantity (*q*) is fixed and the interval (t) between orders can vary. In this case, the order point (*s*) is defined as ROP. Every order arrives to replenish inventory after a lead time. The lead time is assumed to be known and constant. The only uncertainty is associated with demand. In the following analysis, one should be most concerned with the possibility of shortage during an order cycle, that is, when the inventory level falls below zero. This is also called a stock-out event. Every time we extract inventory, we compare what is left with *s*.

Note: for calculating the ROP, we should take into account the replenishment interval [see Eq. (2.13)]:

$$ROP = d \cdot (T + L) + z \cdot \sigma \cdot \sqrt{(T + L)} \tag{2.13}$$

If the stock level is less than *s*, then we place an order at the rate of *q*. Similar to the (*t,q*)-policy, in the (*s,q*)-policy, *q* also refers to the optimal order quantity. The policy (*s,q*) results in shorter time between orders if there is inventory shortage. Because of its simple operation and full control over results, this policy is widely used in organizations. An advantage of the model is that it considers demand fluctuations. Disadvantages lie in regular inventory control.

Policy 4: s,S

- t: variable time between two orders
- q: variable order quantity between the order level S and ROP *s*

This strategy is used to define the drop of order quantity *s* after every inventory usage.

Should this be the case, a manager should refill inventory to raise the inventory position to the level S, which is desirable property.

Therefore, both order quantity and the time interval between orders is variable. This system can handle any level of demand and at any time, and include demand fluctuations in planning. Target level is calculated as Eq. (2.14):

$$S = ROP + q \tag{2.14}$$

Order policy (*s,S*) avoids an excessive level of inventory and ensures that the business has the right goods on hand to avoid stock-outs. However, this policy requires much effort and high control. It is used in industrial and commercial areas of business, given the fact that flexible order quantity is possible and a target quantity can be predetermined.

Consider the given data and determine parameters and annual holding costs for (s,S)-policy for 95% and 98% service levels respectively:

- demand per day (d) 100 units; standard daily deviation of demand (σ) 20 units;
- annual holding costs (h) \$10 per unit; fixed ordering costs (f) \$100 per order;
- order interval (T) 4 weeks; lead time (L) 2 weeks.

Solution

1. Find *z*-values for 95% and 98% service level; we get 1.65 and 2.05 respectively.
2. $ss = z \cdot \sigma \cdot \sqrt{(T+L)} = 1.65 \cdot 20 \cdot \sqrt{4+2} = 81$ units
3. $ROP = 100 \cdot (4+2) + 81 = 681$ units
4. S = ROP + *q*; $q^* = \sqrt{\frac{2 \cdot 36500 \cdot 100}{10}} = 855$ units; $S = 681 + 855 = 1536$ units.
5. The policy is (681;1536); Average inventory position is (681 + 1536)/2 = 1108.
6. Costs = 1108 · 10 = \$11,082.
7. $ss = 2.05 \cdot 20 \cdot \sqrt{4+2} = 100$; $ROP = 100 \cdot (4+2) + 100 = 700$ units
8. S = ROP + q; $q^* = \sqrt{\frac{2 \cdot 36500 \cdot 100}{10}} = 855$ units. ; S = 700 + 855 = 1555 units.
9. The policy is (700;1555); Average inventory position is (700 + 1555)/2 = 1128.
10. Costs = 1128 · 10 = \$11,282.

In practice, replenishment interval, order quantity, ROP, and target inventory levels are not fixed, but change in dynamics subject to changes in demand, the following changes to the above-mentioned policies must be considered. We have to take into account demand, current and projected inventory, and in-transit quantities as well as planned deliveries.

Transportation policies and routing

LTL (less than truckload) and FTL (full truckload) *transportation policies* differ regarding the capacity utilization of trucks. FTL policy presumes waiting for shipment until the truck is full loaded. LTL policy allows shipment with partial loads. Aggregations of loads in terms of time (e.g., 5 days) or quantity (e.g., minimum 60% load) are possible. LTL policy is more responsive but my result in costs increase. FTL allows for better capacity utilization but the lead time may increase.

Routing optimization addresses the optimization of travel paths in a network structure. In particular, we are looking for the shortest (or quickest) connections between a given start location and a given destination location. These two locations are both part of a network, but there is no direct connection available between them. Instead, it is necessary to determine a sequence of concatenated direct connections between intermediately passed connections/points that connects the start and terminus locations.

We can represent the routing problem as a mathematical graph G = (Ω; Θ; d) with evaluated arcs. The node set Ω consists of the six nodes Ω = {A; B; C; D; E; F}. The arc set Θ comprises exactly those arcs connecting the nodes, so that Θ:={(A; B), (A; C), (A; D), (A; F), (B; F), (C; A), (C; B), (C; D), (C; E), (D; C), (E; C), (E; D), (F; B)}. We incorporate the real-valued mapping d to assign the travel distance d(i; j) to each arc (i; j) ∈ Θ.

In order to prepare the analysis of the derived graph, we introduce several definitions. These definitions help us to discuss the specific properties of a graph-based decision model. Let (i; j) as well as (k; l) be two arcs in a given graph G. We call arc (k; l) a "successor of arc (i; j)" if and only if the two nodes j and k coincide, i.e. if and only if j = k. In such a situation, we also say that arc (k; l) follows arc (i; j) if and only if (k; l) is a successor of (i; j) in the given graph G. In our example arc (F; B) is a successor of arc (A; F), which means that arc (F; B) follows arc (A; F).

We are now prepared to introduce the term "*path*" into a network G. Let s and t be nodes from the node set Ω of G. In our example, s might be node A and t could be node E. Let $(i_0; i_1), (i_1; i_2), \ldots, (i_{k-1}; i_k)$ be a finite sequence of following arcs with the properties $i_0 = s$ and $i_k = t$. We call the arc sequence $(i_0; i_1), (i_1; i_2), \ldots, (i_{k-1}; i_k)$ a path in G from s to t. For short, we call this arc sequence an s-t-path in G.

$$L\left(\left(i_0;i_1\right),\left(i_1;i_2\right),\ldots,\left(i_{k-1};i_k\right)\right) := d\left(s,i_1\right)+d\left(i_1;i_2\right)+\ldots+d\left(i_{k-1};t\right) \tag{2.15}$$

The length of a given s-t-path $(i_0; i_1), (i_1; i_2), \ldots, (i_{k-1}; i_k)$ in G is defined by Eq. (2.15). In a case where all nodes contained in path $(i_0; i_1), (i_1; i_2), \ldots, (i_{k-1}; i_k)$ are pairwise different, we call the s-t-path a "simple path".

The property "pairwise different" refers to a situation in which each two nodes of a given subset of the node set Ω are not the same. A simple path in the graph is, for example, the path (A; D), (D; C), (C; E). In contrast, the path (A; D), (D; A), (A; F) is not a simple path since node A is visited more than once.

Using the aforementioned definitions, we are now prepared to describe the task to determine the shortest path between a pair of nodes in the given network structure formally. We are looking then for a simple s-t-path $(s; i_1), (i_1; i_2), \ldots, (i_{k-1}; t)$ in G with minimal length $L((s; i_1), (i_1; i_2), \ldots, (i_{k-1}; t))$. There are very efficient and quick algorithms available to identify the shortest s-t-path in a given graph G. The only requirement for the applicability of this algorithm is that all arcs (i; j) of G have a non-negative length d(i; j). Applied to determine a shortest s-t-path in G, these algorithms calculate the shortest paths from *s* to every other node in G.

Our Case Study: Distribution Network Design, Inventory Control and Transportation Policies

Davis (CEO), Marina (inventory manager), and Cheng (transportation manager) need to develop an optimal design for their distribution network. To begin, they will use network optimization to compare alternative network facility combinations and paths. Next, Davis, Marina, and Cheng will use simulation to analyze the financial, customer, and operational KPIs of their company's supply chain. Afterward, they'll review their options for changing inventory control and transportation policies to improve their supply chain's performance. Finally, they will perform a transportation optimization.

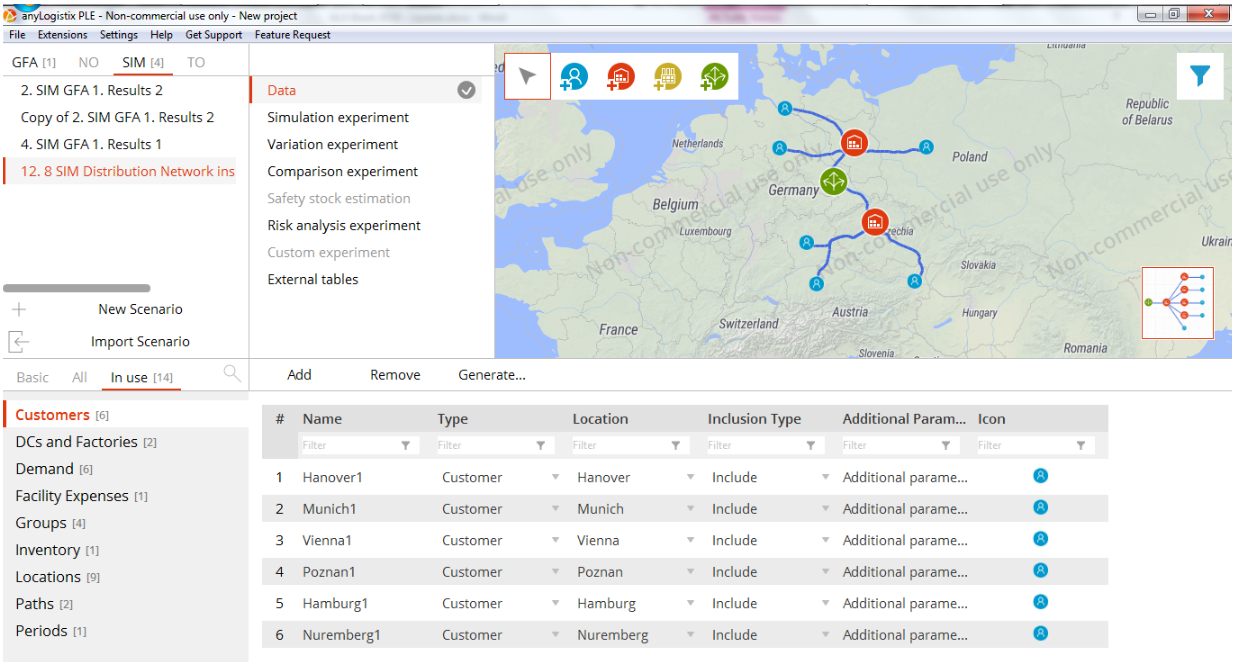
The following background information about this case study is provided:

- Their supply chain offers three products (**PC**, **monitor** and **MFP**) and there are two customers for each product. The customer demand is fixed at 50 units a day.
- The supply chain is made up of customers, two DCs, and one supplier.
- Their supply chain runs at 90% customer service level (CSL) policy.
- The distribution centers for each product use a Min-max (that is, s,S) inventory control policy. The minimum level is 57 units subject to the customer service level of 90%. The maximum level is 113 units subject to the maximum storage area capacity for each product at each distribution center.
- The customer expects to receive their order within two days. The lead time from the supplier to the distribution centers is 0.7 days. The lead time from the distribution centers to customers varies from 1.8 to 1.95 days depending on the loading and unloading processes at the distribution centers.
- Trucks with a 60 m^3 capacity transport products from the supplier to the distribution centers. Lorries with a capacity of 20 m^3 transport products from the distribution centers to the customers.
- LTL shipments are used without minimum load restriction and order aggregation. A direct shipment distribution network is used.

Network Optimization

Starting the Case Study

To start working with this case study, you need to build a simulation model **SIM Distribution Network inside 4 Walls Models** by following the captures below.



#	Name	Unit	Selling Price	Cost	Cost Unit
1	PC	pcs	1,150	350	USD
2	Monitor	pcs	850	250	USD
3	MFP	pcs	700	200	USD

#	Product	Amount from	Unit from		Amount to	Unit to
1	MFP	1	pcs	=	0.1	m^3
2	Monitor	1	pcs	=	0.1	m^3
3	PC	1	pcs	=	0.1	m^3

Figure 36: Customers, products and unit conversions data.

Figure 36 shows the six customer locations we'll use in this case study as well as the distribution centers in Berlin and Prague and the supplier in Leipzig.

Our case study uses three products: **PC**, **Monitor** and **MFP**.

With our products set, we need to convert each product's volume. Doing this will allow anyLogistix to determine the number of products a given vehicle can transport. You can use the **Measurement Unit Conversions** table to convert the user-defined weight and volume units you created in the **Measurement units** table.

Demand and Expected Lead Time

The demand type and expected lead time for each of the case study's six customers are defined as follows:

#	Customer	Product	Demand Ty...	Parameters	Time Period	...	...	Expected Le...	Time Unit	Backorder P
1	Hanover1	MFP	Periodic d..	Order interval=1, Quantity=50	(All periods)	0		2	day	Not allowed
2	Nuremberg1	Monitor	Periodic d..	Order interval=1, Quantity=50	(All periods)	0		2	day	Not allowed
3	Munich1	MFP	Periodic d..	Order interval=1, Quantity=50	(All periods)	0		2	day	Not allowed
4	Poznan1	PC	Periodic d..	Order interval=1, Quantity=50	(All periods)	0		2	day	Not allowed
5	Hamburg1	Monitor	Periodic d..	Order interval=1, Quantity=50	(All periods)	0		2	day	Not allowed
6	Vienna1	PC	Periodic d..	Order interval=1, Quantity=50	(All periods)	0		2	day	Not allowed

Transportation Policy and Costs

We can use two types of vehicles:

#	Name	Capacity	Capacity Unit	Speed	Speed Unit
1	Lorry	20	m³	50.0	km/h
2	Truck	60	m³	50.0	km/h

Transportation costs and time computation are based on the rules you define in the **Paths** table (Figure 37). We can see transportation costs are calculated as $1.0 x volume x distance. We then set the transportation time from our Leipzig-based supplier to both distribution centers to a fixed 0.7 days.

#	From	To	Cost Calculation	Cost Calculation ...	CO2 Calculation ...	Currency	Distance	Distance Unit	Transportation Ti...	Time Unit	Straight	Vehicle Type	Transportation P...	Min Load, ratio	Aggregate
1	Leipzig1	[DCs]	Product&distanc..	1 * product (m³) * ...	0 * product (m³) * ...	USD	0	km	0.7	day		Truck	LTL	0	
2	[DCs]	[All customers]	Product&distanc..	1 * product (m³) * ...	0 * product (m³) * ...	USD	0	km	Uniform(1.8;1.95)	day		Lorry	LTL	0	

Figure 37: Transportation policy.

Stochastic demand and lead time

Note: Numerical values such as demand or lead time can be fixed or stochastic (defined by probability distribution). The corresponding table cells provide the drop-down menu that allows you to set the desired value. You can also enter the value manually.

Uniform(1.8,1.95)
Type: Uniform
Min 1.8
Max 1.95

To enter a numerical value, do one of the following:

Option 1: Entering a value

1. Click the table cell to activate the edit box.
2. Click the arrow next to the cell value to open the drop-down menu.
3. Do one of the following:
    - To enter a fixed value, click the **Type** list and enter the desired value in the **Value** box.

- To enter a stochastic value, click the **Type** list, choose the desired probability distribution, and then set the distribution parameters in the fields below the list.

> **:** anyLogistix supports uniform, triangular, exponential, normal and lognormal probability distributions. The parameters you need to provide vary by the probability distribution type.

4. Save your changes by pressing Enter or clicking outside of the cell.

To discard your changes, press Escape.

Option 2: Manually entering a value:

1. Click the table cell to activate the edit box.
2. Enter the value:
   - To enter a fixed value, enter the desired numerical value.
   - To enter a stochastic value, use the following format to enter the value: *Distribution Type(Parameter 1, Parameter 2, ...)*.

   Example: Uniform(5.0, 6.0).

Reviewing the Path Table's Parameters

You use the **Paths** table to set up the parameters listed in the table below.

Table 9: Parameters available in the **Paths** table.

Parameter	Purpose
From	Defines the path's origin location. This is the reference to the **Locations** table.
To	Defines the path's target location. This is the reference to the **Locations** table.
Cost Calculation	Defines the basis for transportation cost calculations: • **Product(Volume)-based Cost:** *0.0 * volume + 0.0* Formula parameters are volume and Add cost. • **Product(Volume) & Distance-based Cost:** *0.0 * volume * distance* Formula parameters are Cost per m3-km, volume and distance. • **Fixed Delivery Cost:** *0.0 -* Formula parameter is Cost. • **Distance-based Cost:** *0.0 * distance* Formula parameters are Cost per km and distance. • **Product&distance-based limited distance:** Distance range * cost per product measurement unit *volume(unit) * distance • **Cost per drop -** works just like the Fixed delivery, except for the returning segment, which is cost-free

Cost Calculation Parameters	Defines the parameters for cost calculation formulas
Distance	Defines the path length in km/miles. If set to zero, the path length is calculated based on GIS information
Transportation Time	Defines transportation time for the path in days. If set to zero time, the transportation time is calculated based on GIS information
Straight	Defines if anyLogistix should use straight paths between sites or real roads
Vehicle Type	Defines the vehicle type (previously defined vehicles in the **Vehicle Types** table) used for shipping products along the path
Transportation Policy	Regulates the handling of orders for the amount less than the selected vehicle's capacity
Min Load, ratio	In FTL transportation policy, it defines the minimum load ratio
Aggregate Orders	Defines whether the orders are accumulated during the time period defined in **Aggregation Period, days**
Aggregation period	The period during which the orders are aggregated
Inclusion Type	The path's status: ● **Include** - Vehicles can use it to get to their destination ● **Exclude** - The scenario does not use the path

Grouping Supply Chain Elements

In the next step, we'll create four groups (**DCs**, **Customers Prague**, **All customers** and **Customers Berlin**) to make it easier for us to develop our model and analyze our results (Figure 38). Instead of creating individual paths for each customer, we'll create a path from the **DCs** group to the **Customers Prague** group.

#	Group	Description	Customers	Sites	Suppliers	Groups
1	DCs		[]	[DC Prague, DC Berlin]	[]	[]
2	Customers Prague		[Munich, Vienna, Nuremberg]	[]	[]	[]
3	All customers		[Hanover, Munich, Vienna, Poznan, Hamburg, Nuremberg]	[]	[]	[]
4	Customers Berlin		[Hanover, Hamburg, Poznan]	[]	[]	[]

Figure 38: Groups

New Network Optimization Experiment

Preparing Data

Davis, Marina, and Cheng want to analyze the profit of their distribution network with six customer locations, two distribution centers in Berlin and Prague, and a supplier in Leipzig (cf. Figure 32).

First, we open scenario template (**SIM Distribution Network inside 4 Walls Models**) and create an NO copy of this scenario via **Create copy as NO**.

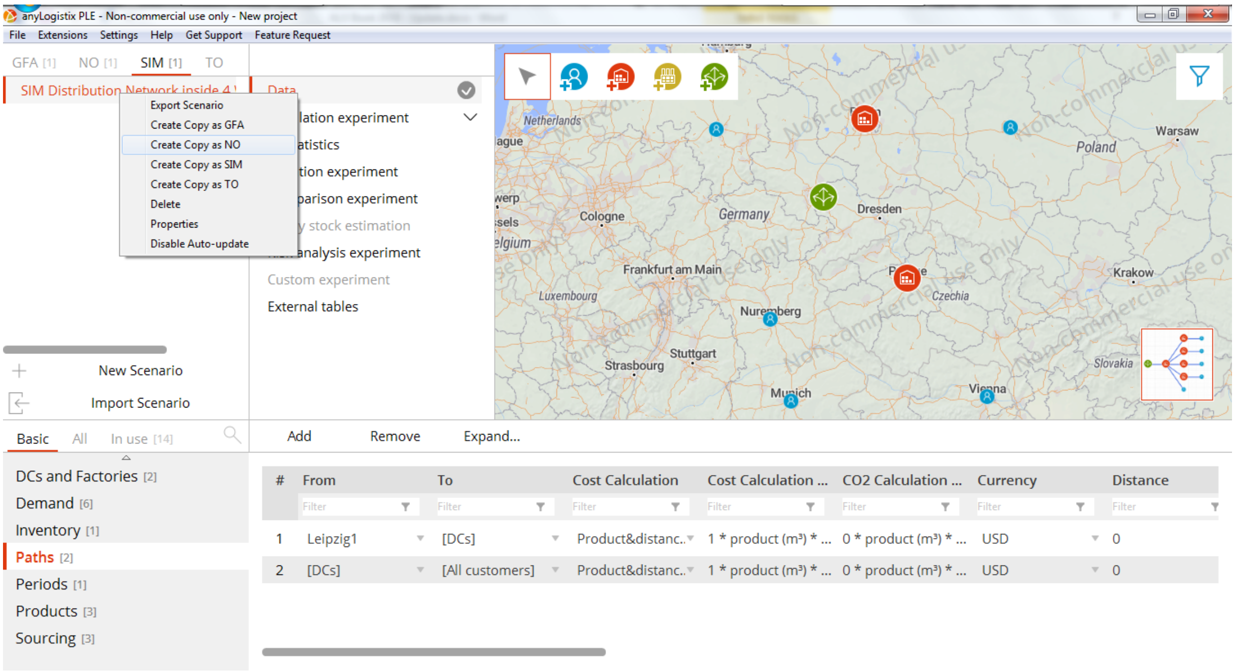


Figure 38: Creating NO scenario from SIM

Note: Similarly, you can create NO or SIM copies from a GFA scenario

Davis, Marina, and Cheng want to analyze whether opening one more DC would make their supply chain more profitable. As such, they place a third alternative DC location in Poland (Figure 39).

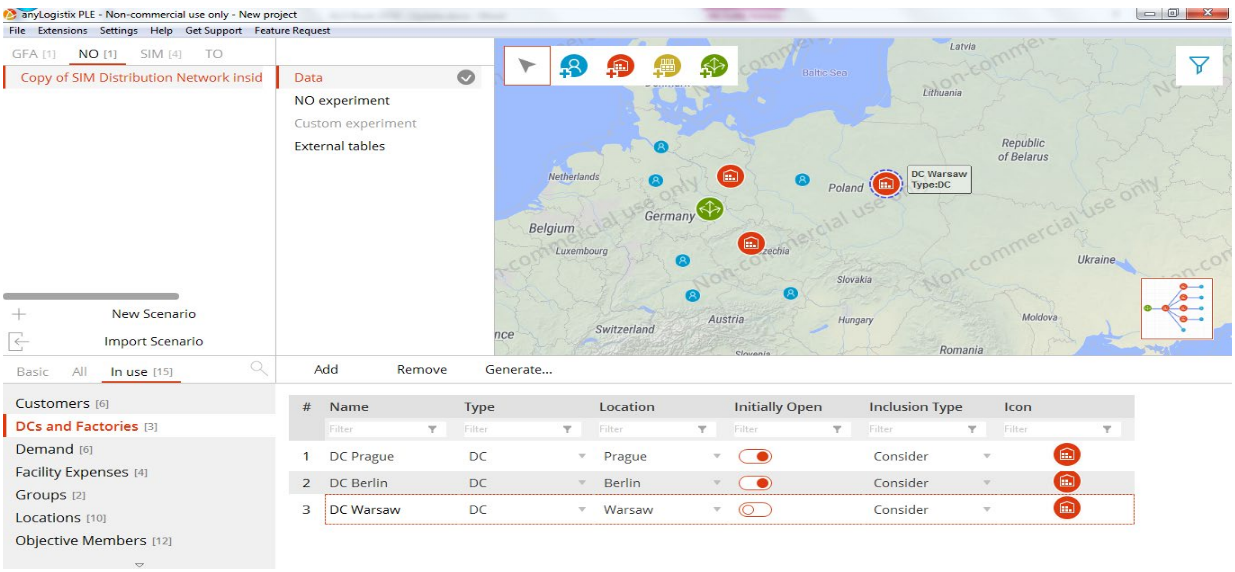


Figure 39: Adding a new alternative DC location in an NO scenario

Note: In order to compare alternative supply chain designs, do not forget to change the **Inclusion Type** from Include to **Consider.** If some of the facilities must be included in the supply chain design, their inclusion type should remain **Include**.

Next, fixed operating costs (**Other costs**) and inventory carrying costs must be added (Figure 40).

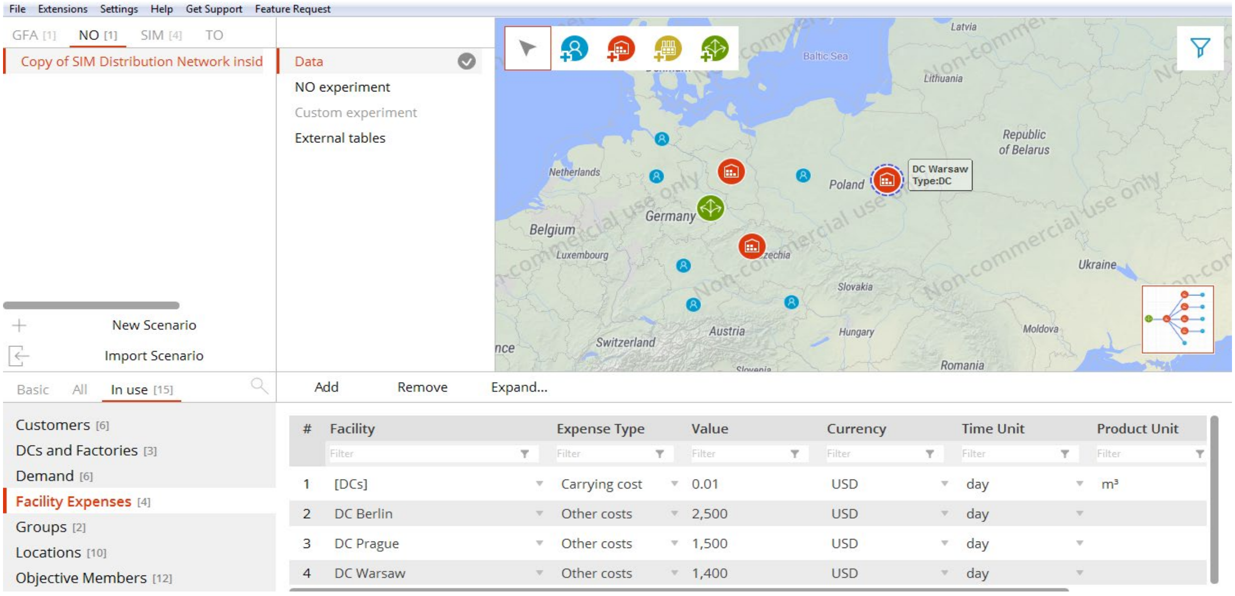


Figure 40: Adding a new alternative DC location in an NO scenario

Note: Fixed costs are computed per day of operating a DC and carrying costs are computed per day and per holding inventory unit.

Make sure that you are using the same **Product Units** throughout the scenario.

The next step should be making the new DC in Poland be connected to the supplier and customers. We need to create these links in **Paths** and **Product Flows**.

Note: Since we already have Paths and Product Flows from the imported SIM scenario, we can simplify the task of connecting the new alternative DC location in Poland to suppliers and customers by adding the new DC in Poland into the **Group** "DCs". Since we already have established paths and flows for the **Group** "DCs", the DC Poland will automatically be connected (Figure 41).

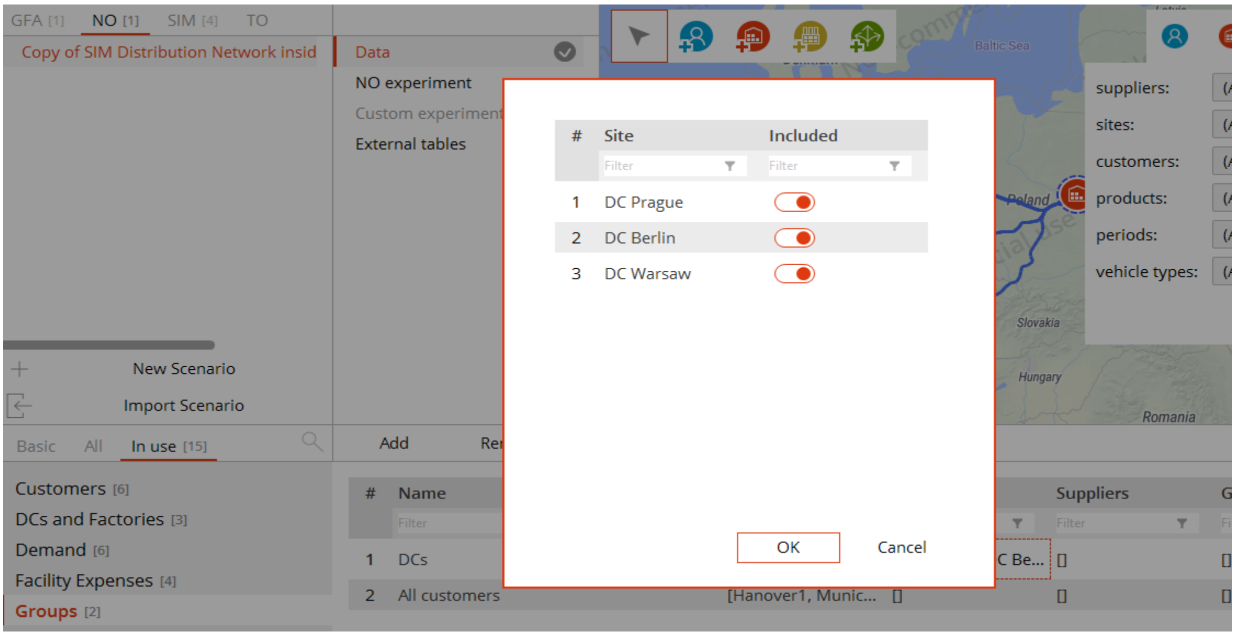


Figure 41: Adding a new alternative DC location to the DC group

Now we have two groups: DCs with all three DCs and All customers with all six customers. Next, we need to establish two product flows and two paths from the supplier Leipzig 1 to all DCs and from DCs to All customers in **Product Flows** and **Paths**, respectively (Figure 42).

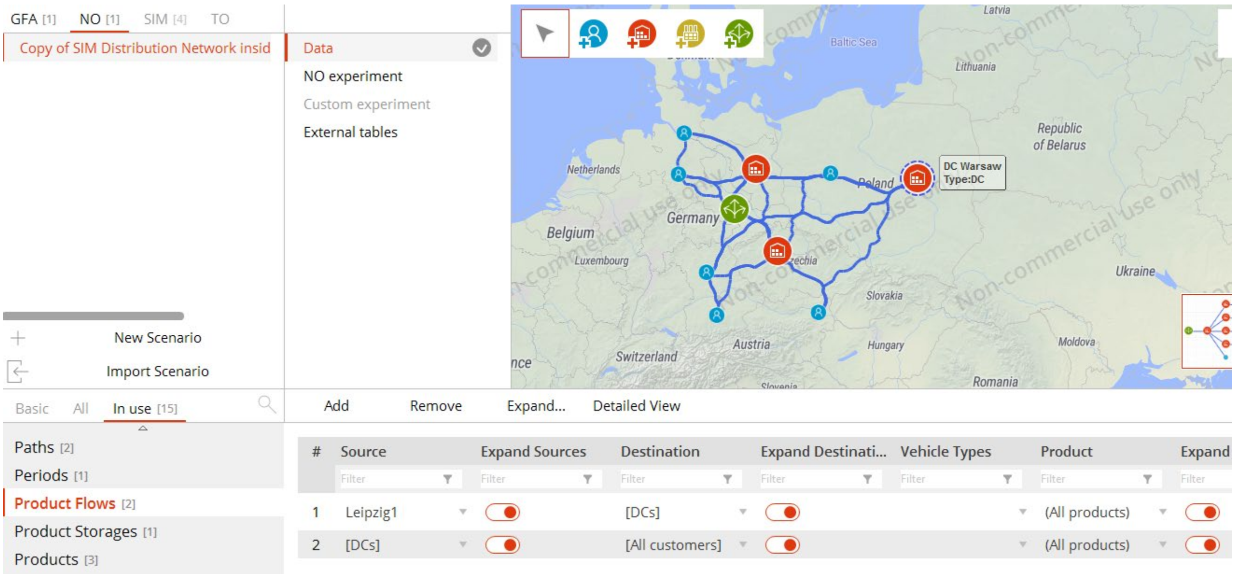


Figure 42: Connecting a new alternative DC location in an NO scenario

Next, we need to go to the table **Product storages** and clean up the parameter **Initial inventory** since if a facility possesses some initial inventory, ALX assumes that this facility should necessarily be included in the supply chain design (Figure 43).

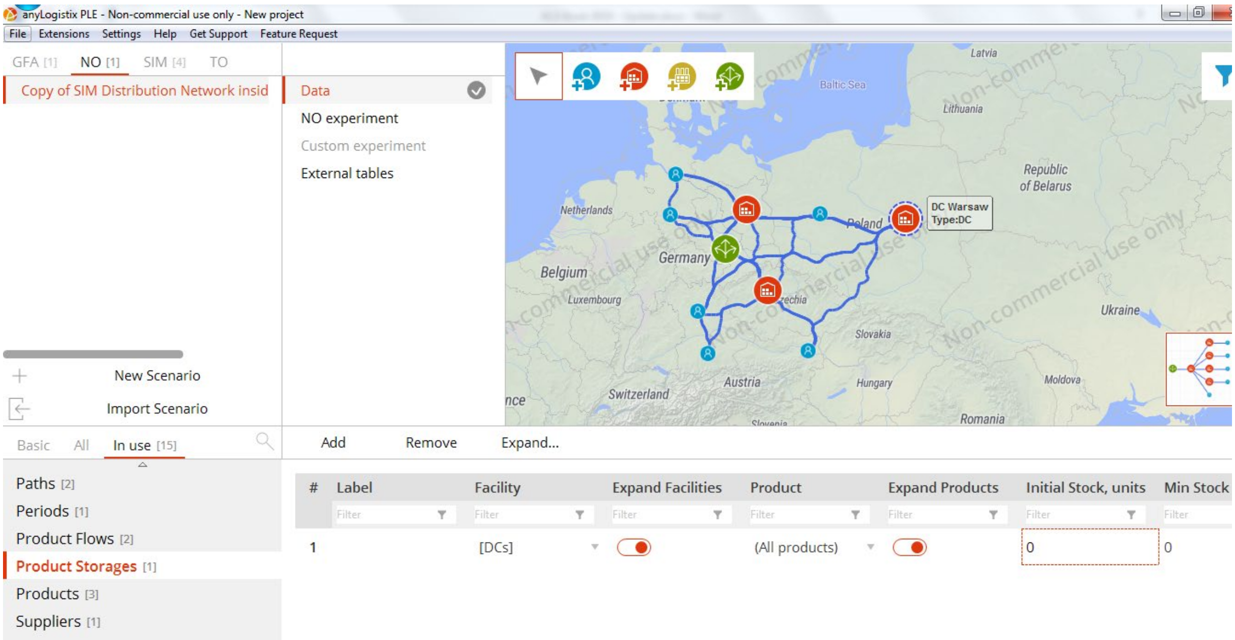


Figure 43: Product storages in NO experiment

Note: by default, the supplier has unlimited inventory. If no further constraints for DCs are considered, the DC is used as a cross-docking center without storage. In this case, we have an incapacitated facility location-allocation problem. In the further course of Chapter 2 and in **Appendix 2** (case-studies 4 and 5), we will develop the capacitated facility location-allocation problem in single and multiple period modes.

Performing the NO experiment

Now we are ready to perform an NO experiment. This experiment enables comparison of alternative distribution network design in terms of expected profits. In our case, seven alternatives exist, i.e.,

- Supplier – all DCs – Customers;
- Supplier – DC Prague/DC Berlin – Customers;
- Supplier – DC Prague/DC Warsaw – Customers;
- Supplier – DC Berlin/DC Warsaw – Customers;
- Supplier – DC Prague – Customers;
- Supplier – DC Warsaw – Customers;
- Supplier – DC Berlin – Customers.

In addition, for cases with two and three DCs, different customer allocations to DCs are possible.

We'll now run the NO experiment that will compute the profits of different supply chain designs and customer allocations and order them according to which is the most profitable. First, we need to define the scheme (i.e., objective function) according to which profit will be computed. This can be done in the table **Objective Members** (Figure 44).

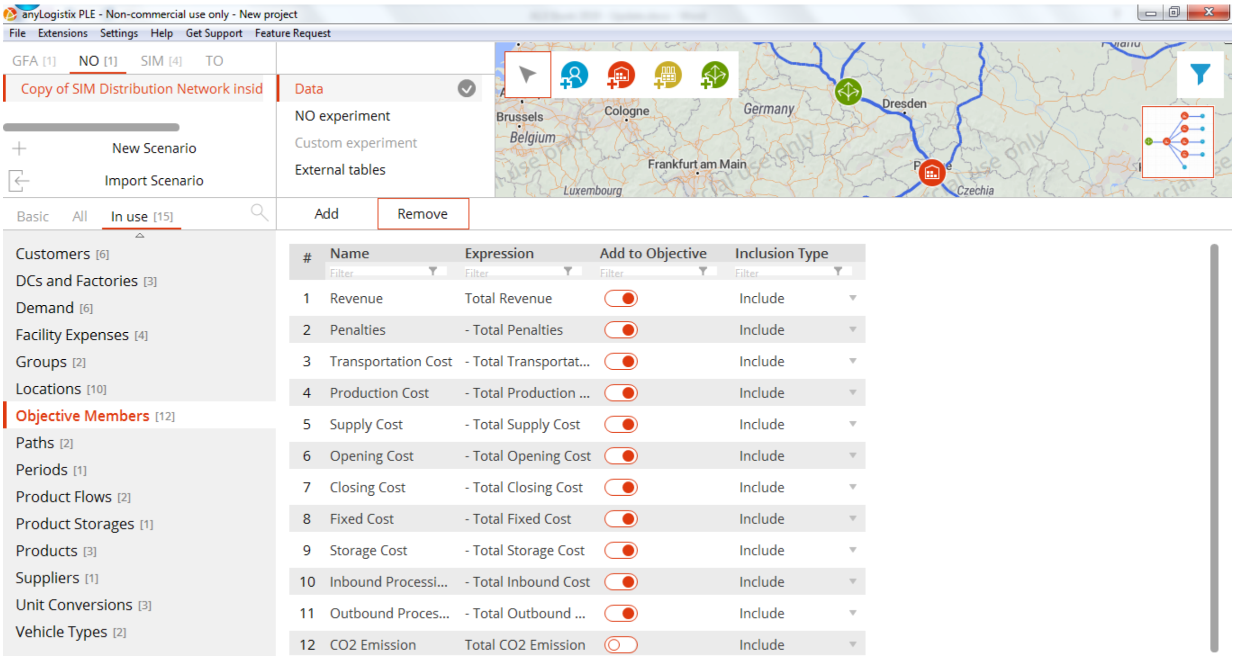


Figure 44: Defining the objective function for profit

In the **Objective Members** table, we can select which costs we want to include in the profit computation. If a particular cost is 0 in the scenario data, it will automatically not be considered regardless of whether it is activated or deactivated in the **Objective Members** table.

Next, we need to define several settings for how the NO algorithm will run and how the optimization results will be presented (Figure 45).

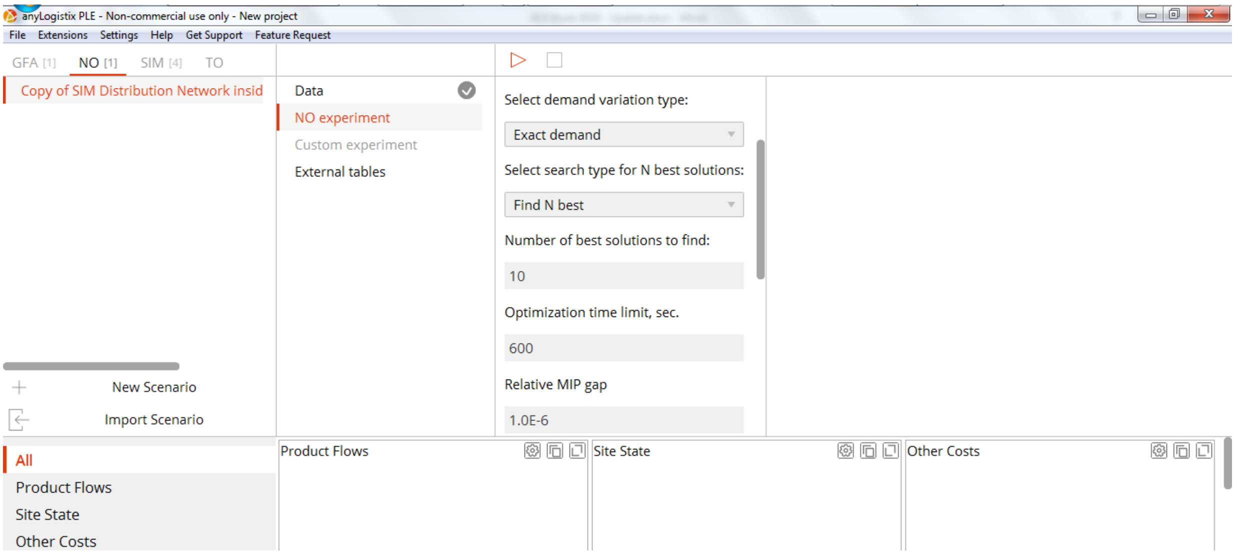


Figure 45: NO experiment settings

First, we can define the number of best solutions to be displayed (in our case in Figure 45, we set up 10). Next, we can decide if the experiment will be performed with exact demand or some demand variation, say between 95-100% or between 100-105% (we can also set up demand variation in the **Demand** data as shown at the beginning of this chapter and in Chapter 1). Now we run the NO experiment by clicking the red triangle on the top of the screen (Figure 46).

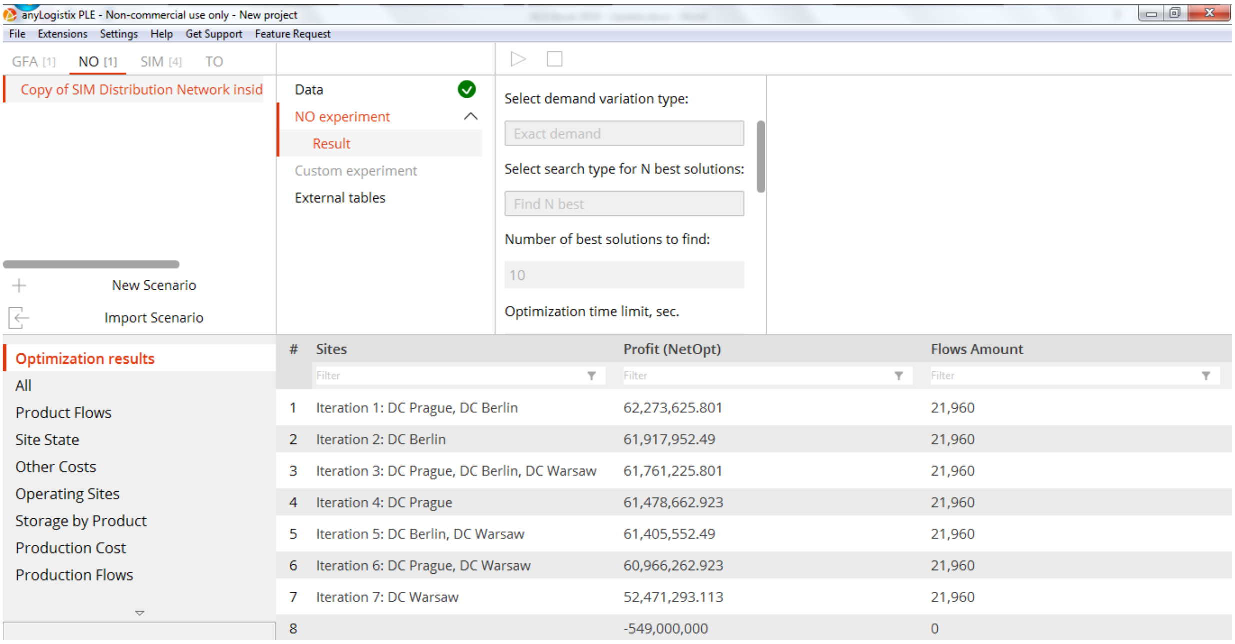


Figure 46: NO experiment results

Figure 46 displays the **Optimization Results** as the profits of all seven distribution network design combinations. It can be observed that the most profitable supply chain design is the one with two DCs in Prague and Berlin.

In tab **Demand Fulfillment** (Figure 47), we can observe 100% of the demand fulfillment for all customers as well as the revenues for different customers in different products.

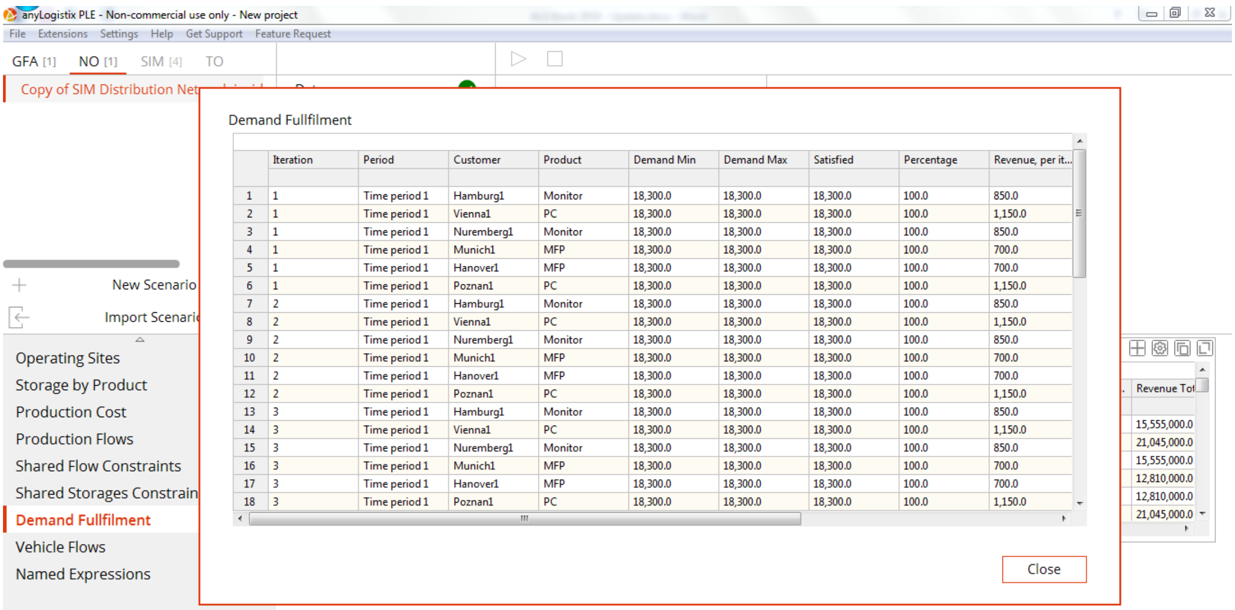


Figure 47: Demand fulfillment

In the tab **Product Flows** (Figure 48), we can view customer allocations to the DCs and the respective product flows.

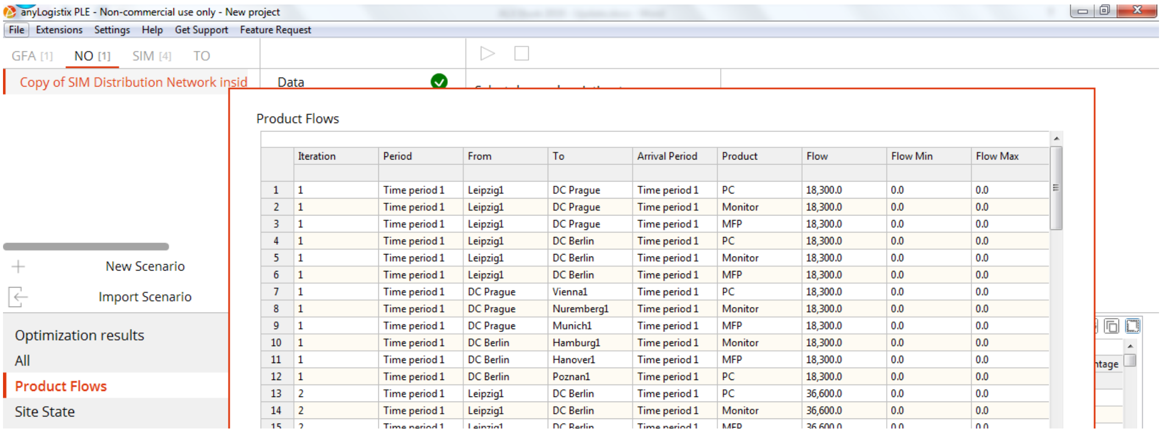


Figure 48: Overall financial performance

We can see in Figure 48 that DC Berlin serves customers in Poznan, Hanover, and Hamburg, and DC Prague serves customers in Vienna, Nuremberg, and Munich.

In the tab **Overall Stats** (Figure 49), we can observe the total revenues, costs, and profits of the different supply chain designs.

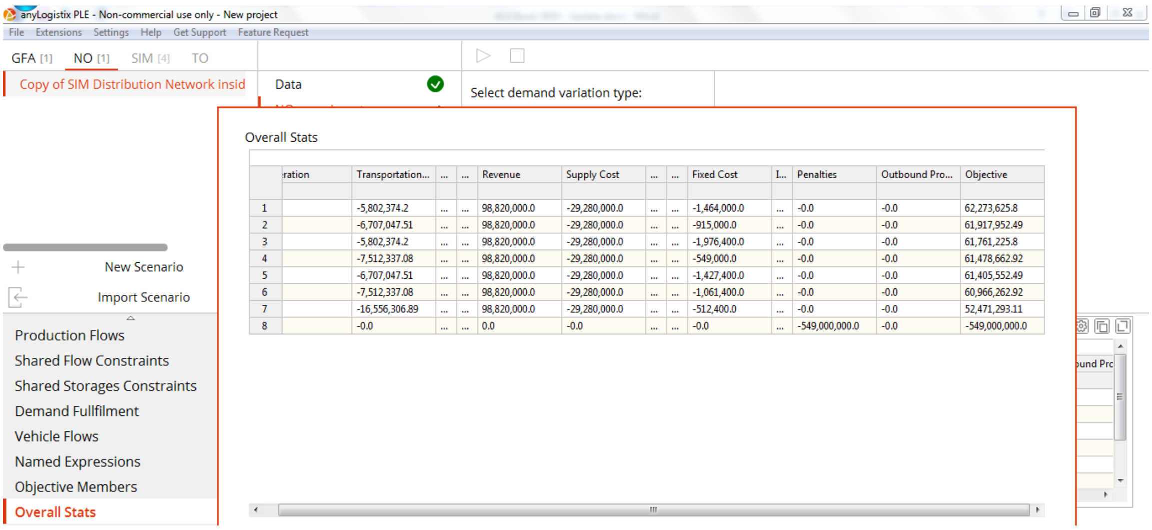


Figure 49: Overall financial performance

Discussion:

Analyze the optimization results. Why does the network design with only one DC in Poland have the lowest profit? Why don't we have any storage costs? When might we incur penalties? Which impact could the capacity restrictions on the supply have on the profits and flows?

What would happen to the profits if, in **Product Storages, Min Stock** was set to 5,000 and **Max Stock** was set to 10,000 with Stock Up Penalties and Stock Down Penalties of $100, respectively? Explain!

Capacitated Network Optimization Experiment

We did not yet consider capacity restrictions of suppliers and DCs. These restrictions can be setup in Product Flows in the column Constraints (Figure 50). Alternatively, you can change in tab Product flows the Compact view to Detailed view and enter the capacity constraints directly in the columns Min Throughput and Max Throughput (Figure 50).

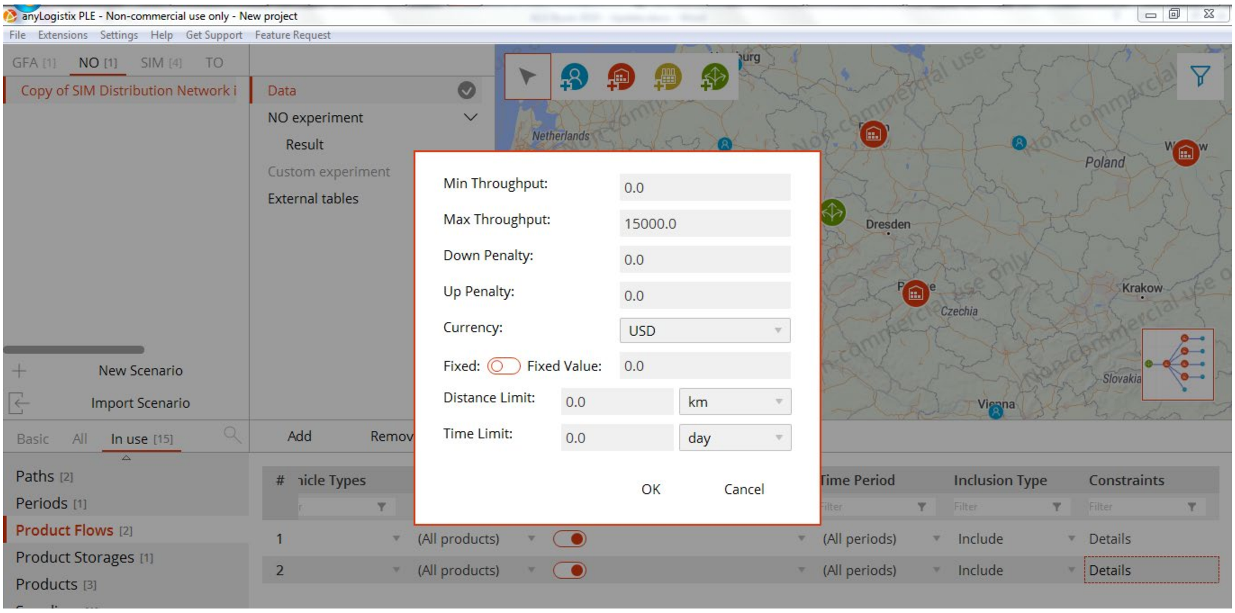


Figure 50: Setting the capacity constraint

In Figure 50, we constrain the maximum quantity which can delivered from any DC to any customer to 15,000 units. It is also possible to setup further constraints, such as minimum throughput, fixed quantity for certain links, distance and time limits, as well as penalties for violating the throughout constraints.

Discussion:

Run the NO experiment for the setting shown in Figure 50. Are there changes in the profits and flows? Explain!

Further analysis of the optimization results might include a comparison of alternative supply chain designs with regards to other criteria such as risks or future demand trends. For example, the difference in profit between the optimum network design (i.e., the best solution in terms of the highest profit) and the third iteration with three DCs in Berlin, Prague, and Warsaw is less than 1%. At the same time, a network design with three DCs is, by tendency, more robust to facility disruptions (cf. Chapter 4) and might provide higher responsiveness in the event that demand increases.

However, Davis, Marina, and Cheng, consider the network design with two DCs robust enough. They do not expect significant demand changes in next few years. They decide to further analyze the optimal design of their supply chain with two DCs in Berlin and Prague and utilizing the optimal allocations of customers to these DCs. First, they perform a transportation optimization of routes to customers from DCs (not possible in PLE version). Second, they will to simulate inventory and shipment control policies.

Transportation Network Optimization (TO)

The TO experiment is possible in professional ALX version only.

Creating a new TO scenario

The task is now to decide on the sequence in which the trucks will deliver goods to customers from DCs. These sequences are called routes. Basically, we have n_i! combinations of routes for each *i*-DC, where *n* is the number of customers at *i*-DC. In our case, each DC serves 3 customers, so there are 6 possible routes for each DC.

First, we create a TO copy of our NO experiment from the previous section. Since we no longer will include DC Warsaw, we need to change its inclusion type to **Exclude** (Figure 51).

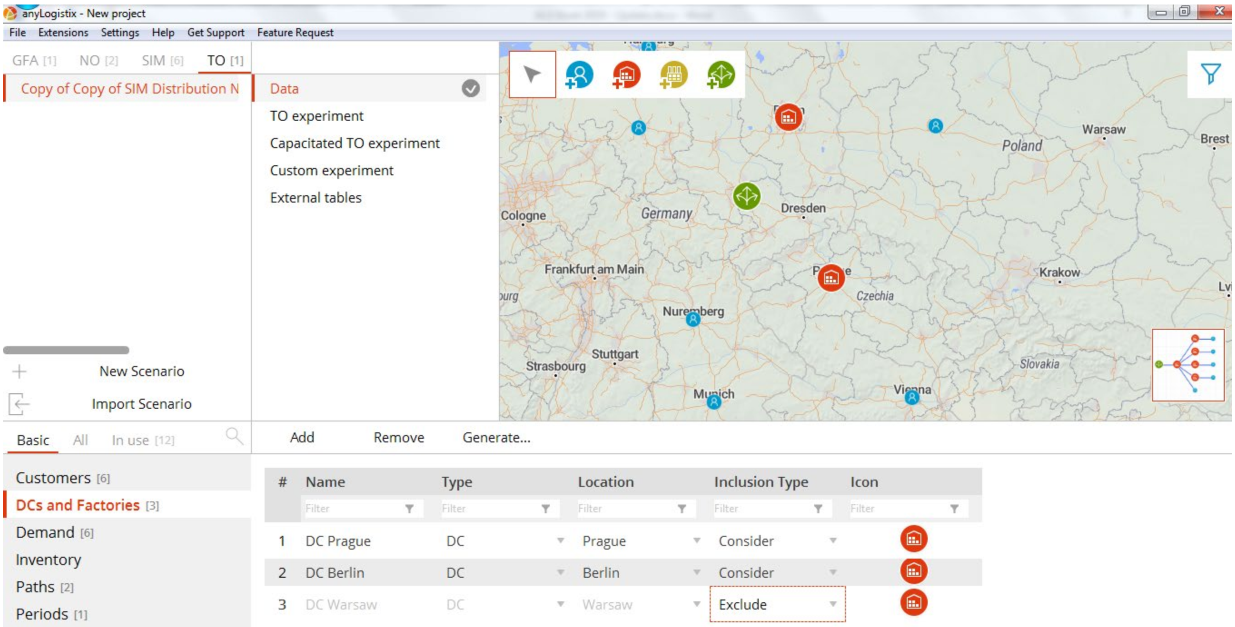


Figure 51: Settings of the distribution network structure

Next, in **Paths** we need to add two new paths to allow for shipment between customers and from customers to DCs when a truck is returning to a depot (Figure 52).

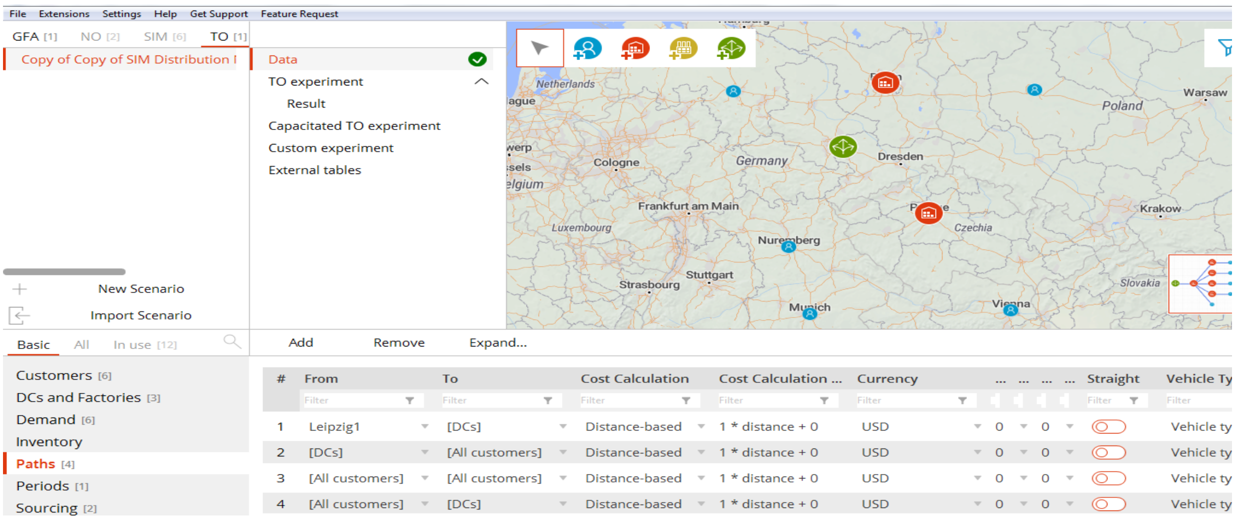
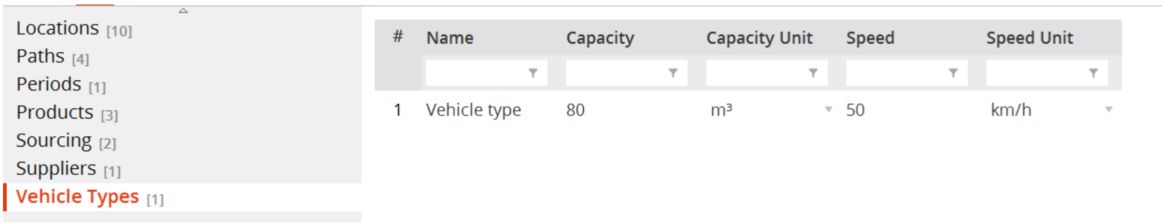


Figure 52: Paths settings

We also need to define the parameters of our trucks in **Vehicle Types**, i.e., the average speed and capacity.



Performing TO experiment

Having defined the TO scenario data, we need to define experiment settings (Figure 53).

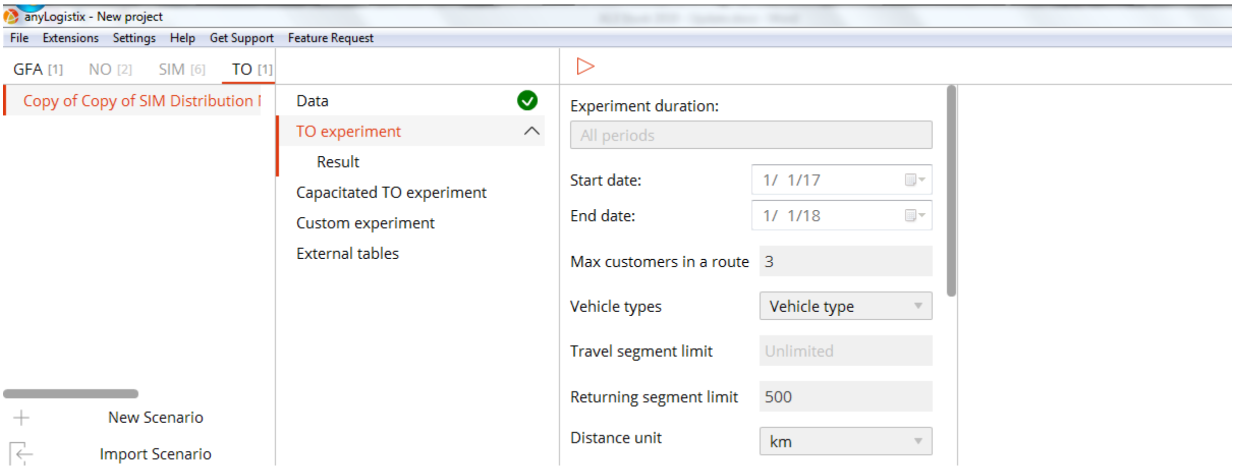
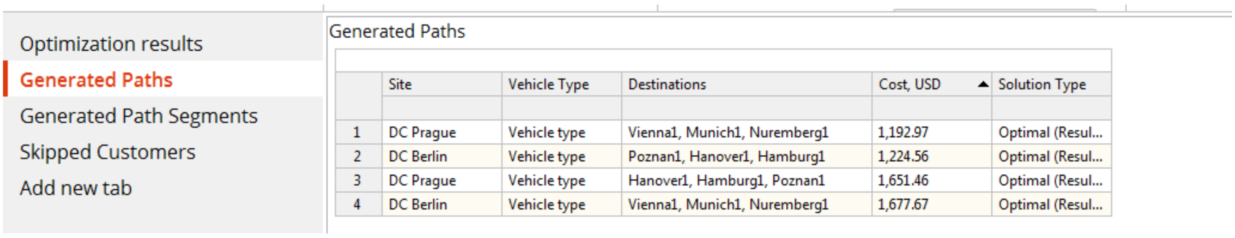


Figure 53: TO experiment settings

First, we can set limits on the maximum distance allowed for a path between two nodes (customers). Next, we can limit the maximum number of customers in a route. In our case, we limit this number to 3 since each DC serves three customers. Now, we run the TO experiment by clicking on the red triangle at the top of the screen (Figure 54).

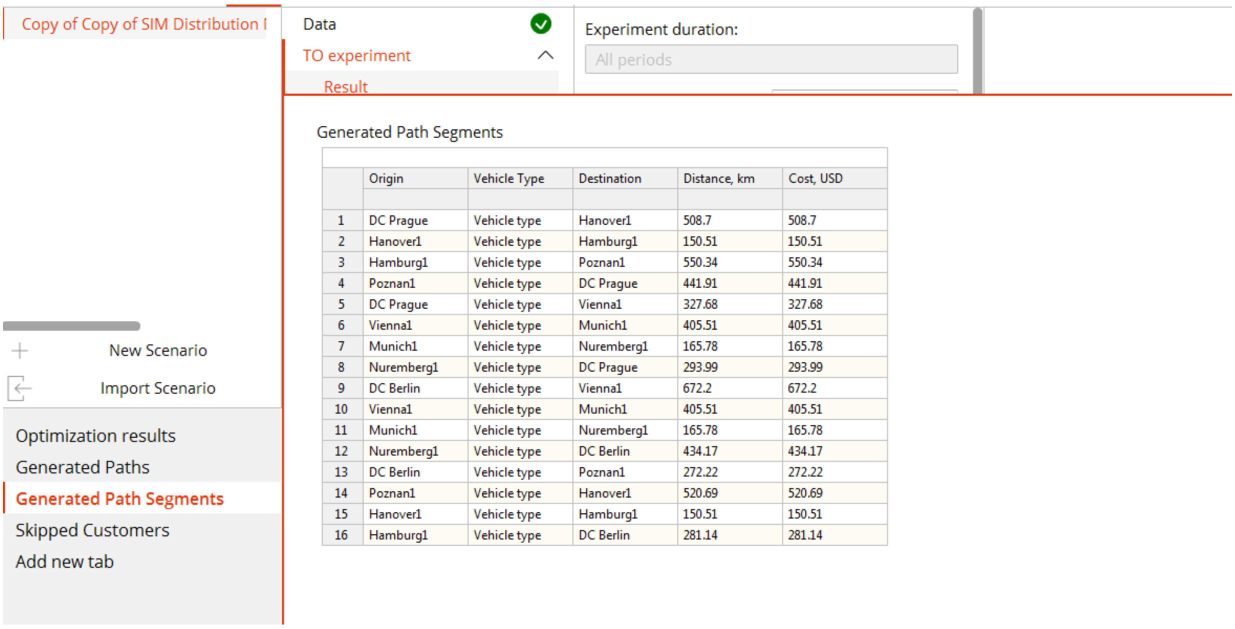


	Site	Vehicle Type	Destinations	Cost, USD	Solution Type
1	DC Prague	Vehicle type	Vienna1, Munich1, Nuremberg1	1,192.97	Optimal (Resul...
2	DC Berlin	Vehicle type	Poznan1, Hanover1, Hamburg1	1,224.56	Optimal (Resul...
3	DC Prague	Vehicle type	Hanover1, Hamburg1, Poznan1	1,651.46	Optimal (Resul...
4	DC Berlin	Vehicle type	Vienna1, Munich1, Nuremberg1	1,677.67	Optimal (Resul...

Figure 54: TO experiment settings

The routing optimization results in Figure 54 depict the optimal route: from DC Prague this route is Prague – Vienna – Munich – Nuremberg – Prague. From DC Berlin, the optimal route is Berlin – Poznan – Hanover– Hamburg. Figure 54 also shows the optimal routes between each DC and all six customers. Such an analysis can be useful if there is unexpected disruption at one of the DCs and the other must fulfill all demand.

Finally, we can observe the path segments generated and the respective distances and costs in the tab **Generated Path Segments** (Figure 55).



	Origin	Vehicle Type	Destination	Distance, km	Cost, USD
1	DC Prague	Vehicle type	Hanover1	508.7	508.7
2	Hanover1	Vehicle type	Hamburg1	150.51	150.51
3	Hamburg1	Vehicle type	Poznan1	550.34	550.34
4	Poznan1	Vehicle type	DC Prague	441.91	441.91
5	DC Prague	Vehicle type	Vienna1	327.68	327.68
6	Vienna1	Vehicle type	Munich1	405.51	405.51
7	Munich1	Vehicle type	Nuremberg1	165.78	165.78
8	Nuremberg1	Vehicle type	DC Prague	293.99	293.99
9	DC Berlin	Vehicle type	Vienna1	672.2	672.2
10	Vienna1	Vehicle type	Munich1	405.51	405.51
11	Munich1	Vehicle type	Nuremberg1	165.78	165.78
12	Nuremberg1	Vehicle type	DC Berlin	434.17	434.17
13	DC Berlin	Vehicle type	Poznan1	272.22	272.22
14	Poznan1	Vehicle type	Hanover1	520.69	520.69
15	Hanover1	Vehicle type	Hamburg1	150.51	150.51
16	Hamburg1	Vehicle type	DC Berlin	281.14	281.14

Figure 55: Path segments generated

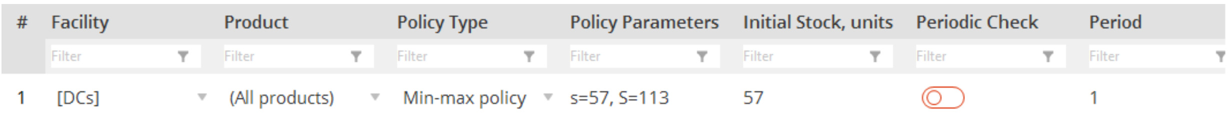
The tab **Generated Path Segments** provides a detailed analysis of the routes computed in terms of distance and costs.

Now, we turn our attention to simulation analysis.

Simulation Experiment

Inventory Control Policy

The information in the **Policy Parameters** column shows us our example uses a (*s*,*S*) inventory control policy (Figure 56).



#	Facility	Product	Policy Type	Policy Parameters	Initial Stock, units	Periodic Check	Period
1	[DCs]	(All products)	Min-max policy	s=57, S=113	57		1

Figure 56: Inventory control policy

Note: anyLogistix uses the **Inventory** table to define an inventory policy's parameters. However, we use "Inventory control policy" throughout this guide to describe the parameters defined in the **Inventory** table.

We use the **Inventory** table to set up the following parameters:

Table 10: Parameters available in the **Inventory** table.

Parameter	Purpose
Facility	The facility or group of facilities for which an inventory policy is specified

Product	The product or group of products which the policy is applied to
Policy Type	The type of inventory control policy
Policy Parameters	The parameters for selected inventory control policy
Initial Stock	The initial quantity of products at the site(s)
Periodic Check	If inventory is checked periodically or after each change
Period	The number of days between inventory level checks
Policy Basis	Whether quantity or days of demand is the policy basis
Stock Calculation Window	The number of days to calculate the mean daily demand
Time Period	The period during which the inventory policy will be considered
Inclusion Type	The status of given inventory policy

Sourcing Policy

Figure 57 shows our sourcing policy.

#	Delivery Destinat...	Product	Type	Parameters	Sources	Time Period	Inclusion Type
1	[DCs]	(All products)	Closest (Fixed So.	No parameters	Leipzig1	(All periods)	Include
2	[Customers Berlir	(All products)	Closest (Fixed So.	No parameters	DC Berlin	(All periods)	Include
3	[Customers Prag..	(All products)	Closest (Fixed So.	No parameters	DC Prague	(All periods)	Include

Figure 57: Sourcing policy.

Defining Operational Costs at Distribution Centres

Finally, we use the **Facility Expenses** table to define the costs of operating the distribution centers. In addition to the cost of operating the distribution centers, our simulation includes interest rate (10%, expressed as 0.1) and inventory carrying costs per day per m^3 ($0.01, expressed as 0.01) (Figure 58).

#	Name	Type	Location	Initially Open	Inclusion...	Capacity	Capacity ...	Interest, ratio pe...	Aggregate
1	DC Prague	ExtendedDC	Prague	on	Include	100	m³	0.1	off
2	DC Berlin	ExtendedDC	Berlin	on	Include	100	m³	0.1	off

#	Facility	Expense Type	Value	Cost Unit	Time Unit	Product Unit	Time Period
1	DCs	carryingCost	0.01	USD	day	m³	(All periods)

Figure 58: Inventory holding costs at distribution centers.

Creating a KPI Dashboard

We will define an extended KPI dashboard by creating the following three tabs:

- Financial and customer performance KPI
- Operational performance KPI
- Inventory and capacity dynamics

Tab 1: Financial and Customer Performance KPI

Our dashboard's **Financial and customer performance** tab will have six blocks to help us assess our supply chain's financial and customer performance (Figure 59).

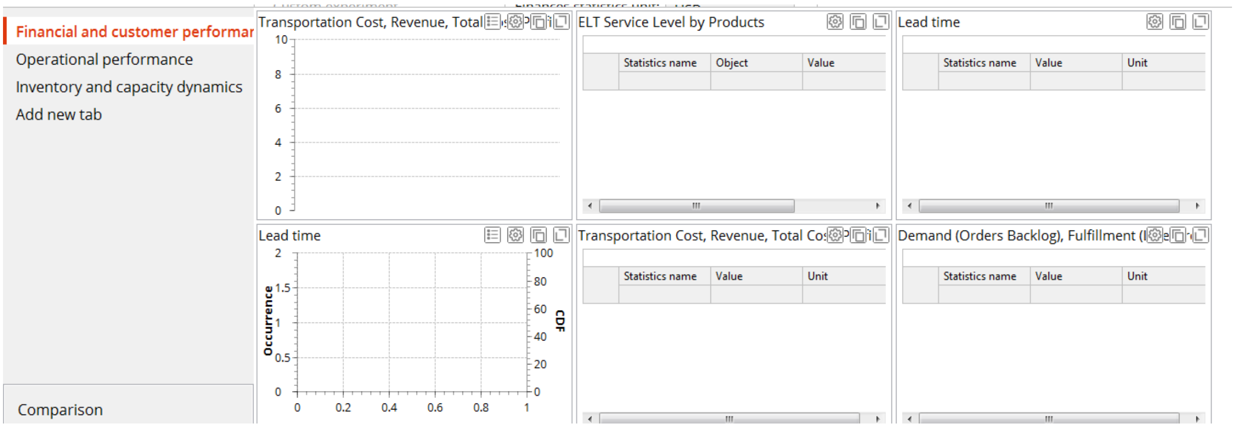


Figure 59: The six blocks that make up our **Financial and customer performance** tab.

> **Note:** For more information about the technical issues of KPI dashboard design, please review Chapter 1 in this guide.

Our dashboard's first block will display information about revenue, total costs, profit, carrying costs, opportunity costs and transportation costs (Figure 60).

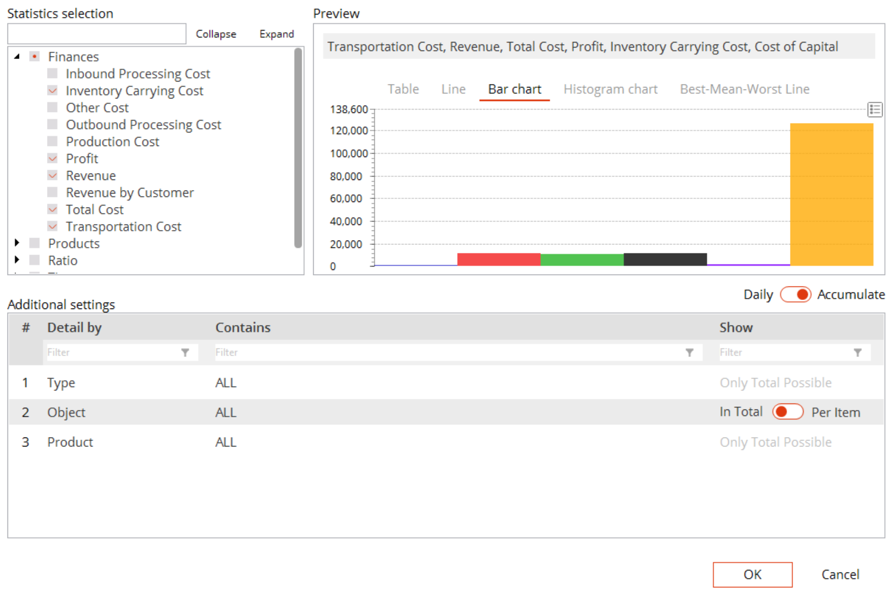


Figure 60: Financial performance statistics.

The second block displays information about our service levels (Figure 61).

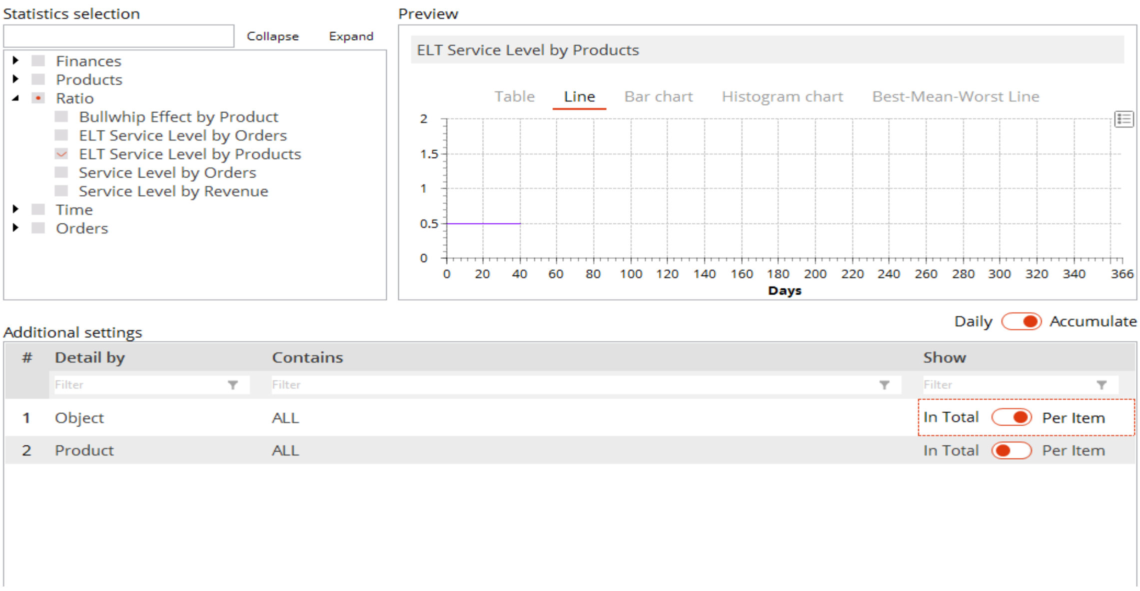


Figure 61: Service level metrics.

For a detailed analysis, we can review the service levels for each distribution center and each product (shown by item).

Our **Financial and customer performance** tab's third and fourth blocks will display a lead time analysis for each distribution center and for each customer. One of the blocks will be a line chart, the other will be a histogram chart (Figures 62 and 63).

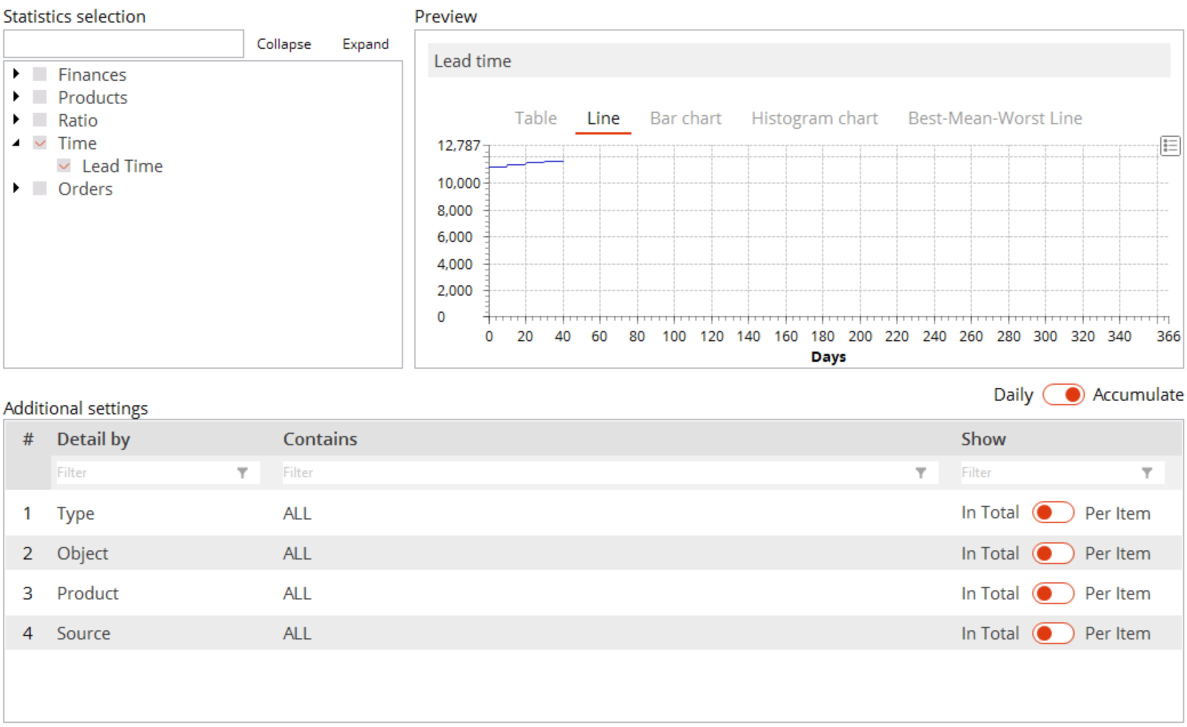


Figure 62: Lead time statistics displayed in a line chart.

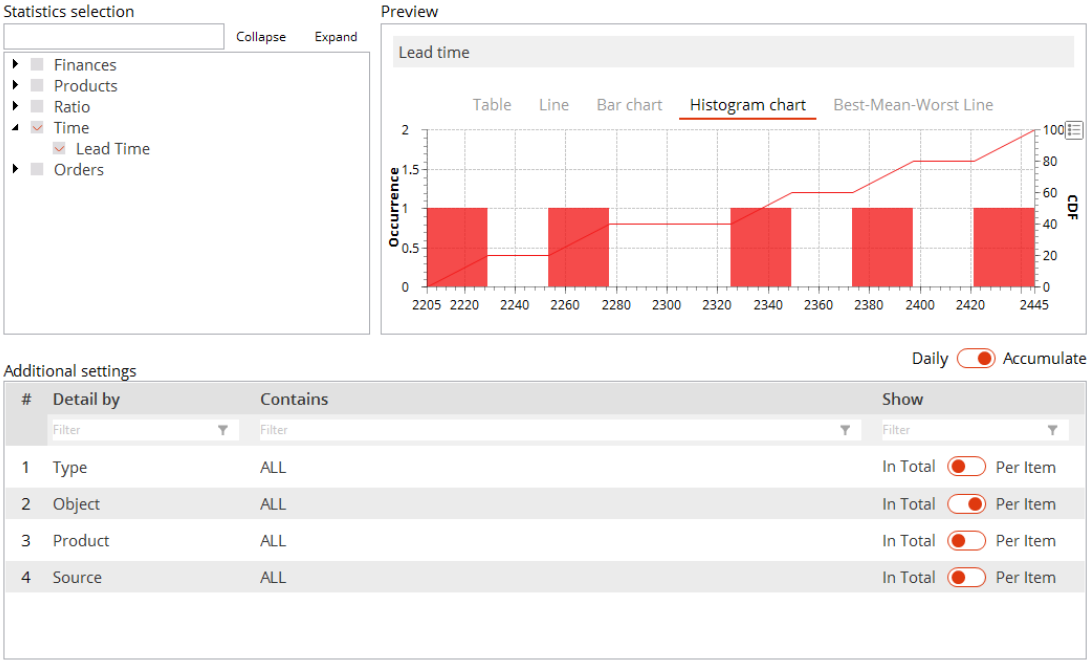


Figure 63: Lead time statistics displayed in a histogram chart.

Our **Financial and customer performance** tab's final two blocks display our financial performance (Figure 64) and our order fulfilment performance (Figure 65).

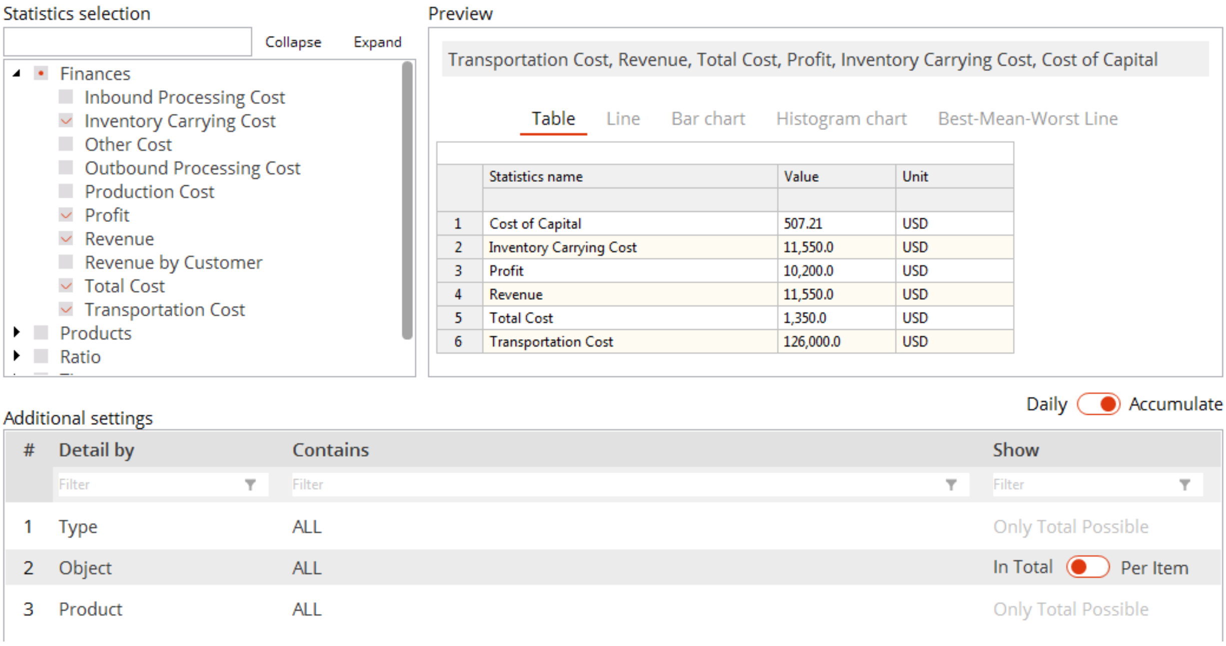


Figure 64: Our dashboard's fifth block displays our financial performance.

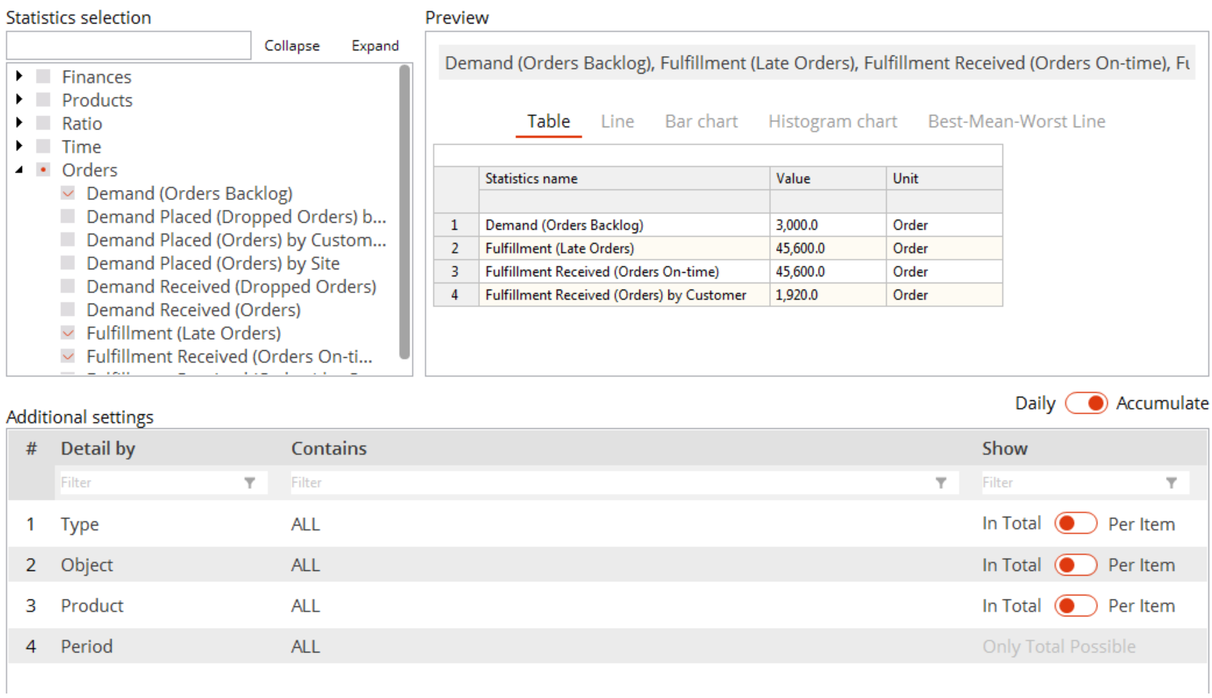


Figure 65: Our dashboard's final block displays our order fulfilment performance.

Tab 2: Operational Performance KPI

Our Operational Performance KPI dashboard will display a capacity and an inventory analysis for the supply chain (Figure 66).

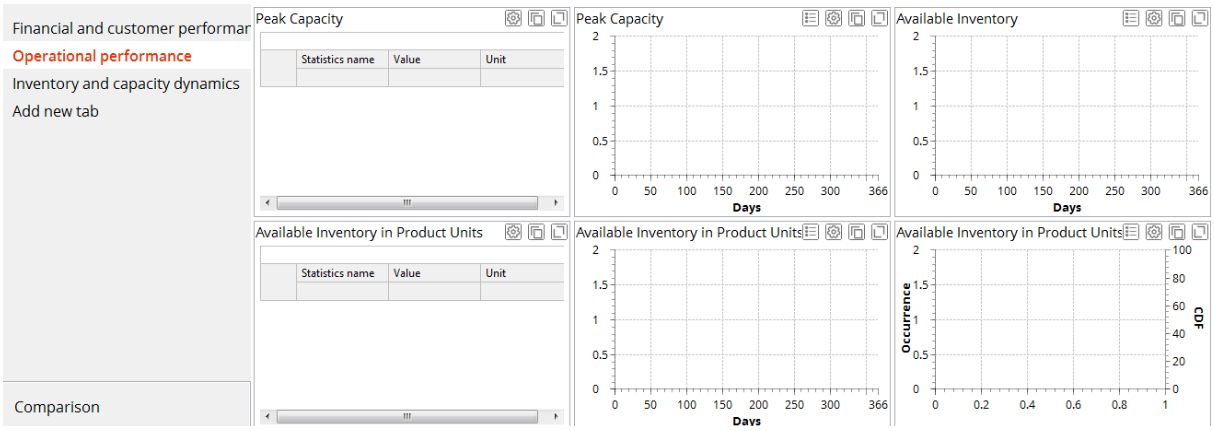


Figure 66: A capacity and inventory analysis for the overall supply chain.

First, the program will display data for maximum distribution center capacity consumption as a histogram chart and as a line (Figures 67 and 68). This data will help us make informed decisions on distribution center capacities.

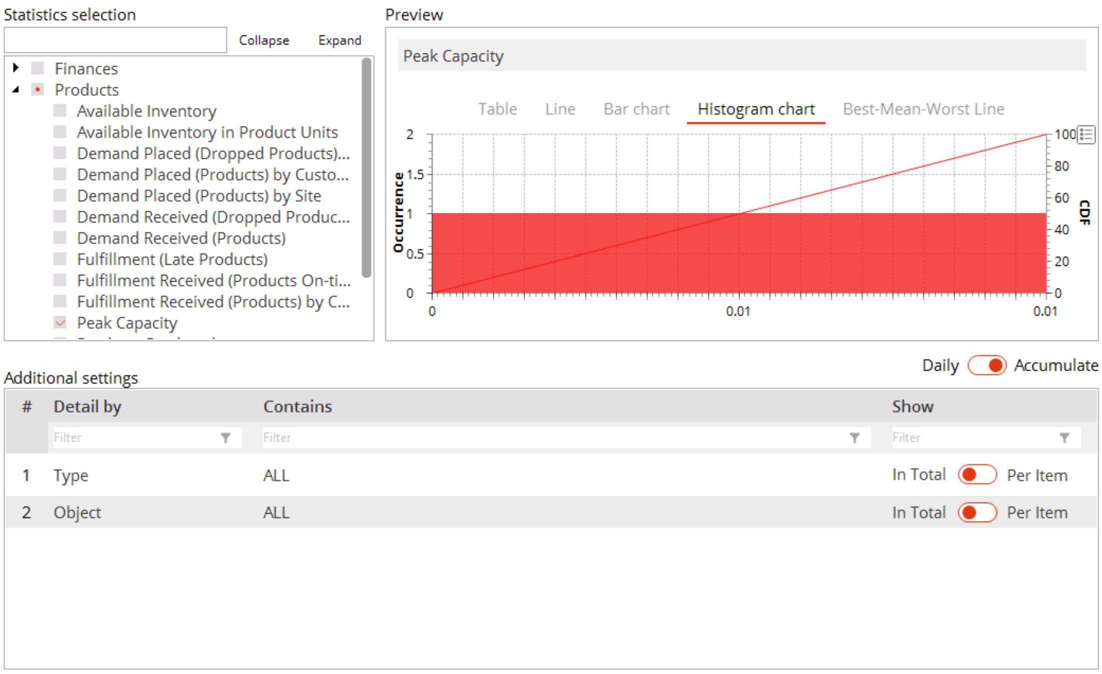


Figure 67: An analysis of maximum distribution center capacity consumption displayed as a histogram chart.

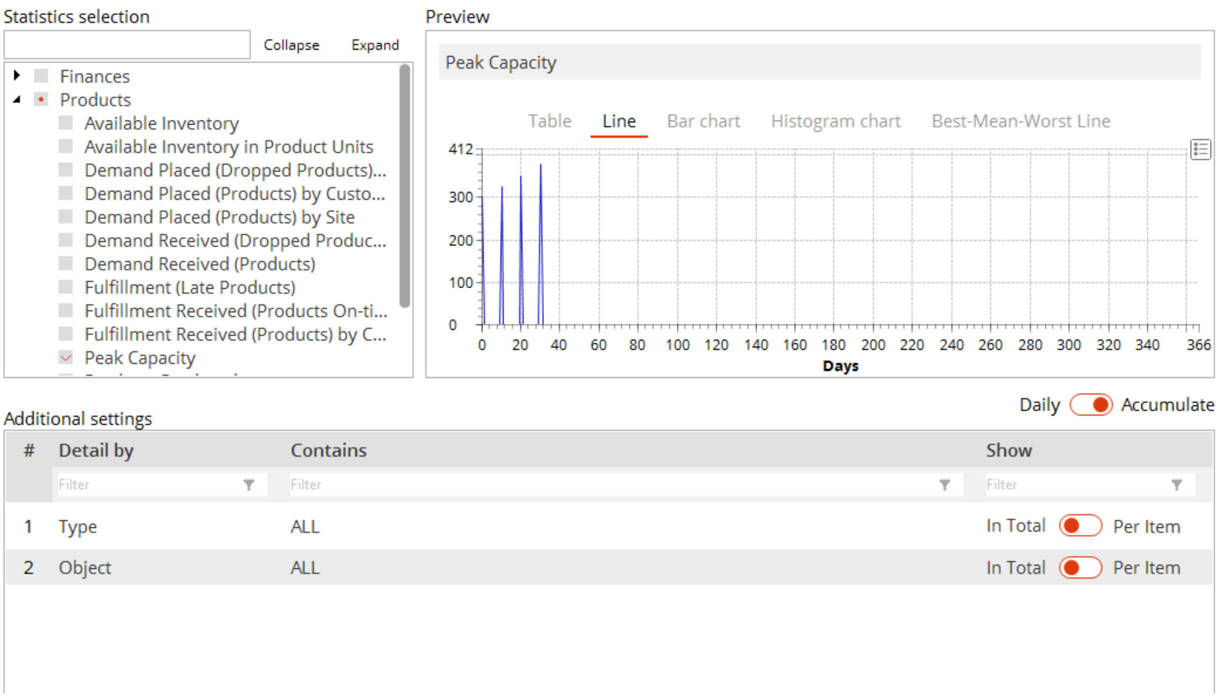


Figure 68: An analysis of maximum distribution center capacity consumption displayed as a line.

The program will present the dynamics of available inventory volume as a line (Figure 69).

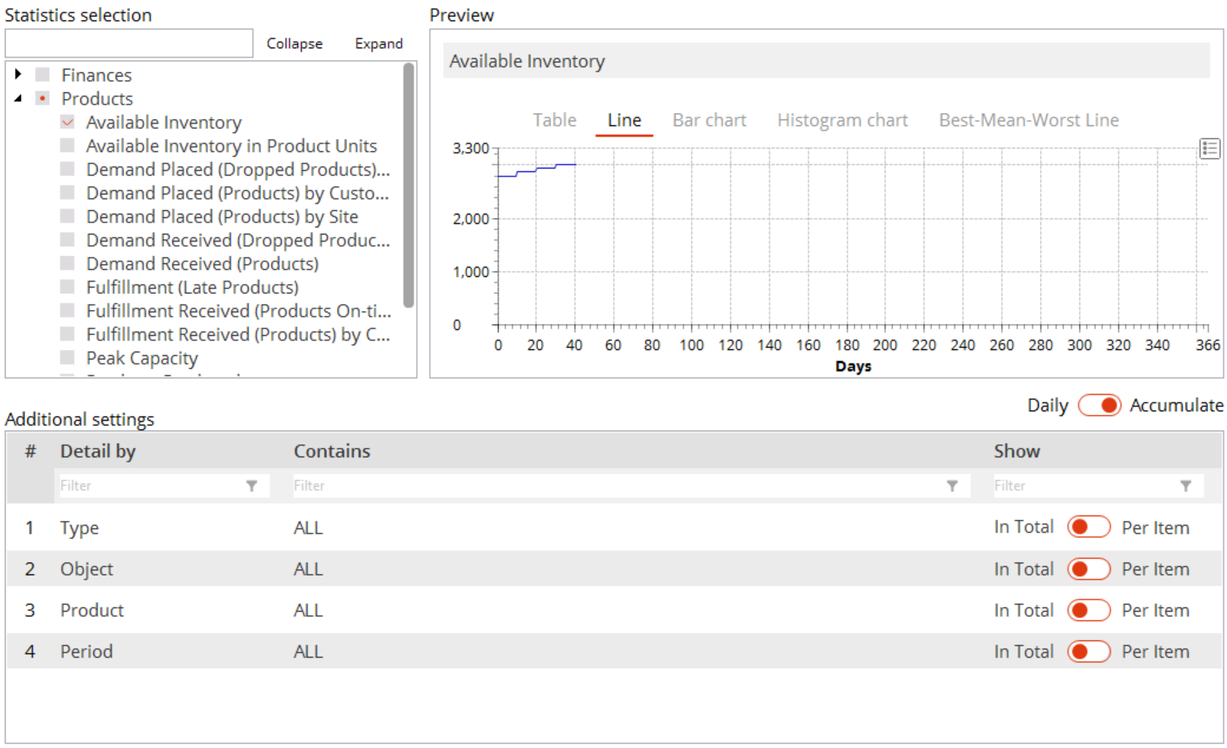


Figure 69: Dynamics of available inventory volume in the supply chain displayed as a line.

Third, the program will display the dynamics of available inventory quantity for the overall supply chain as a line and as a histogram chart. It will display the objects and products as a line (Figures 70-71).

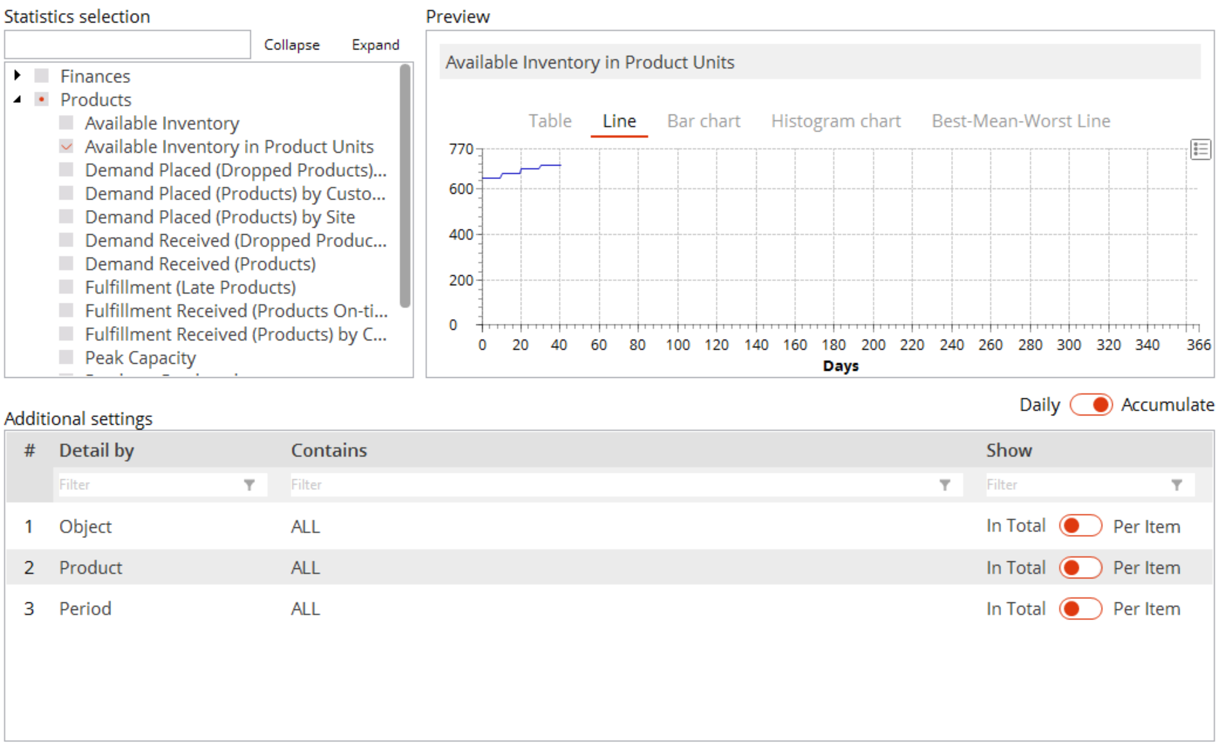


Figure 70: Dynamics of available inventory quantity in the supply chain as a line.

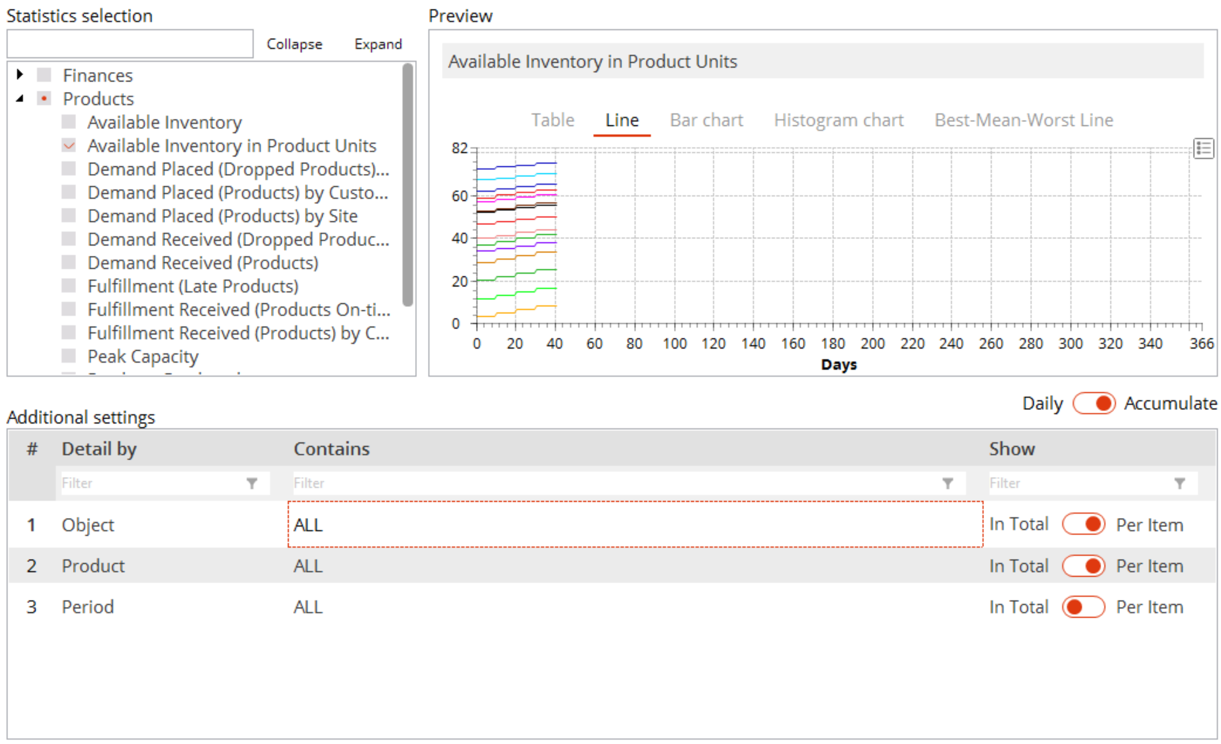


Figure 71: Dynamics of available inventory quantity at objects and for different products displayed as a line.

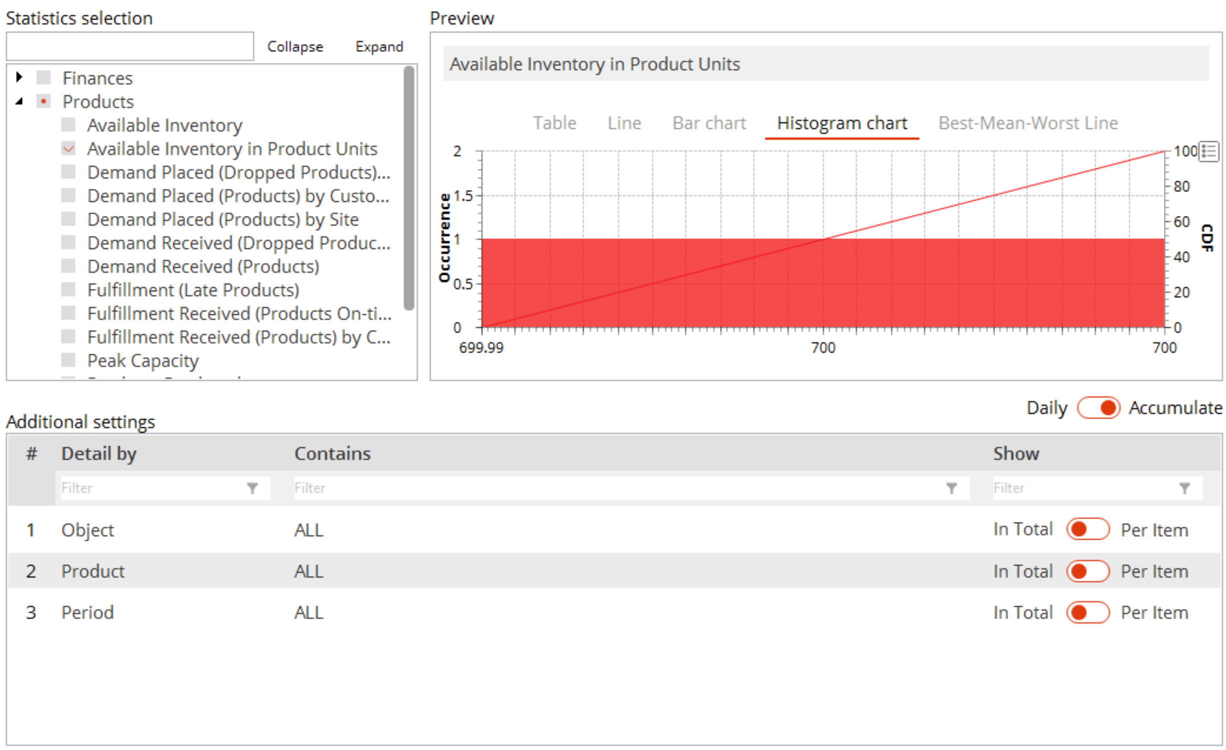


Figure 72: This histogram chart displays the dynamics of the supply chain's available inventory quantity.

Tab 3: Inventory and Capacity Dynamics

This dashboard displays inventory and capacity dynamics at the object and product levels (Figure 73).

Figure 73: Dashboard for dynamics of inventory and capacity at the object and product levels.

The upper three blocks display the inventory dynamics at each distribution center for each of our three products: monitors, PC and MFP. The following image (Figure 74) displays the dynamics for our **monitor** product.

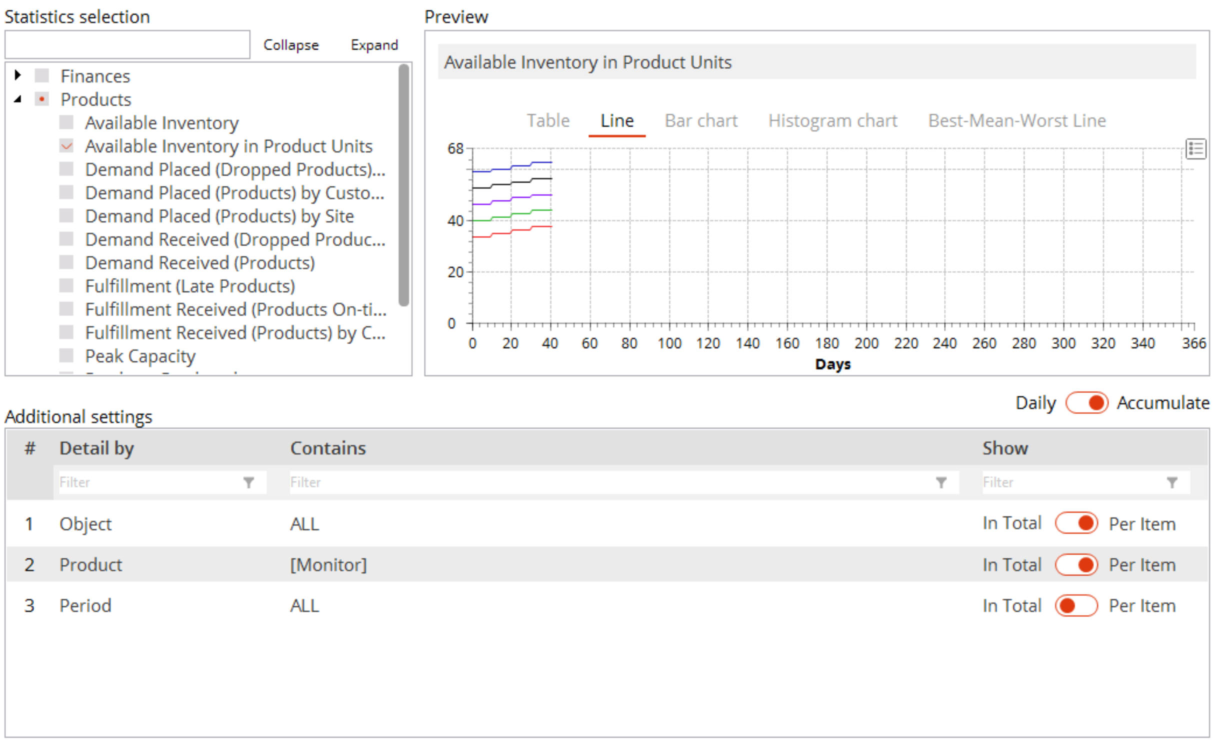


Figure 74: Inventory dynamics for the **monitor** product at each distribution center

The other dashboard blocks (on the bottom) display capacity dynamics for each distribution center as a line and as a histogram chart (Figures 75-76).

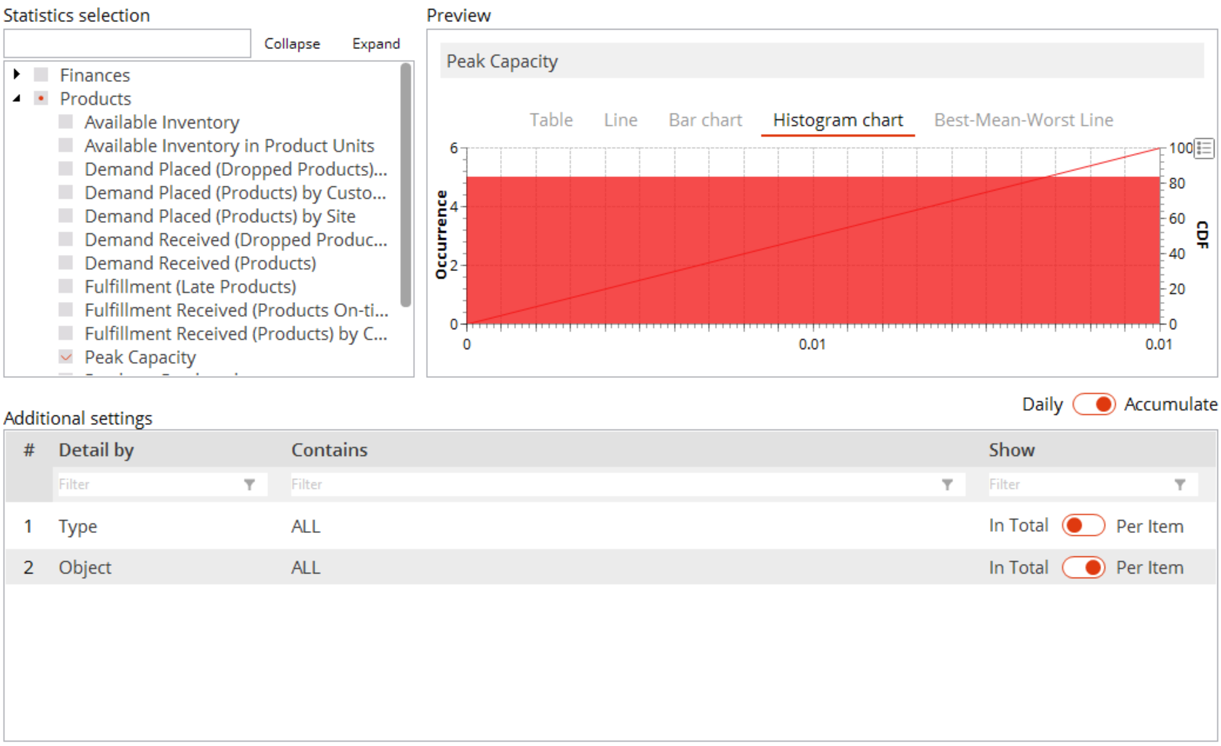


Figure 75: Capacity dynamics for each distribution center as a histogram chart.

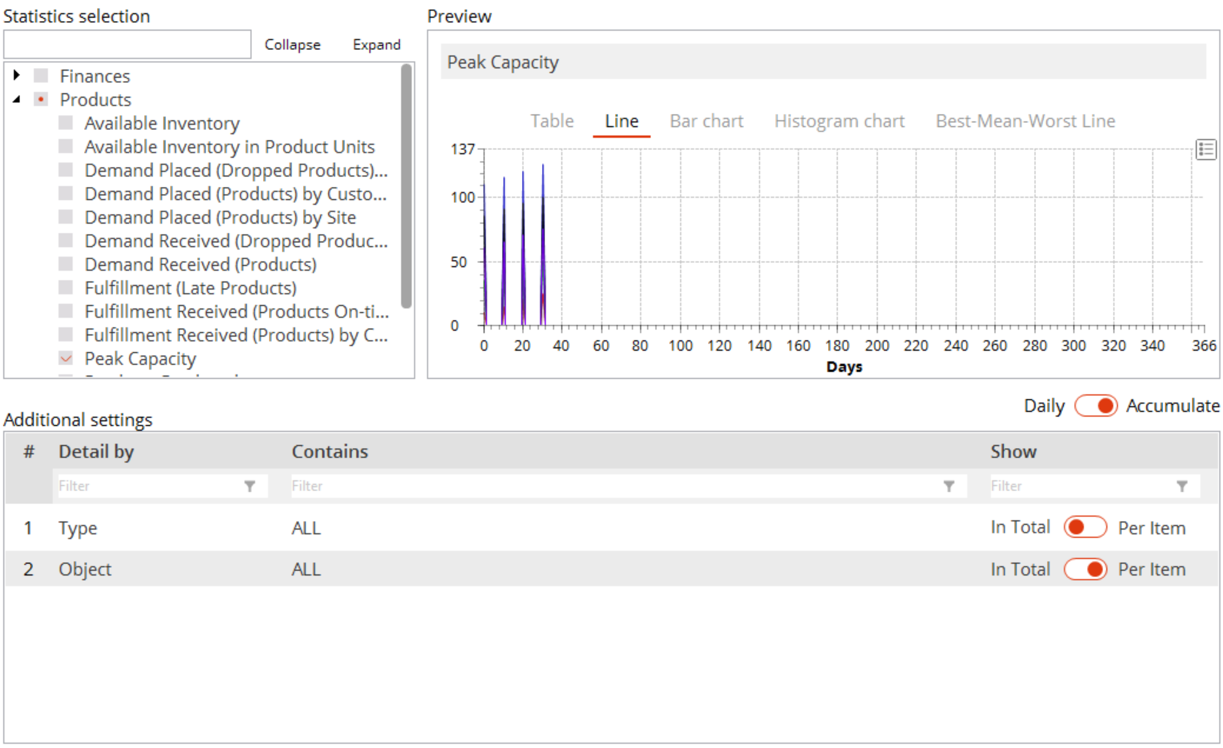


Figure 76: Capacity dynamics for each distribution center as a line.

Experiment and Result Analysis

Experimental Results

In their first executive meeting, Davis (CEO), Marina (inventory manager), and Cheng (transportation manager) use financial, customer and operational KPIs to analyze their supply chain’s performance. Afterward, they use the **SIM Distribution Network inside 4 Walls Models** scenario to run a new simulation experiment. Figures 77-81 display their results.

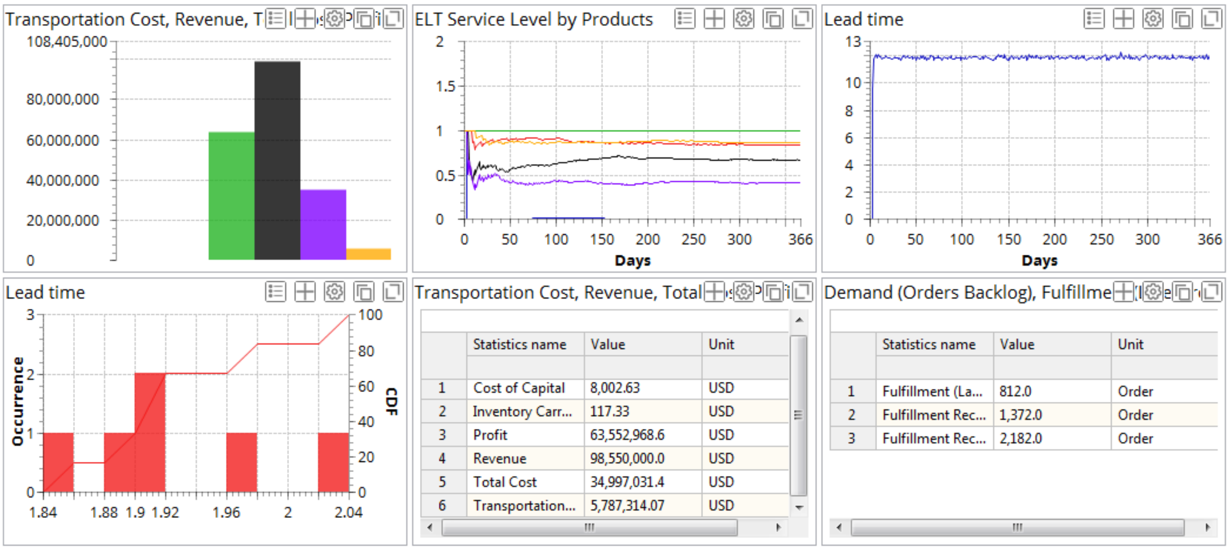
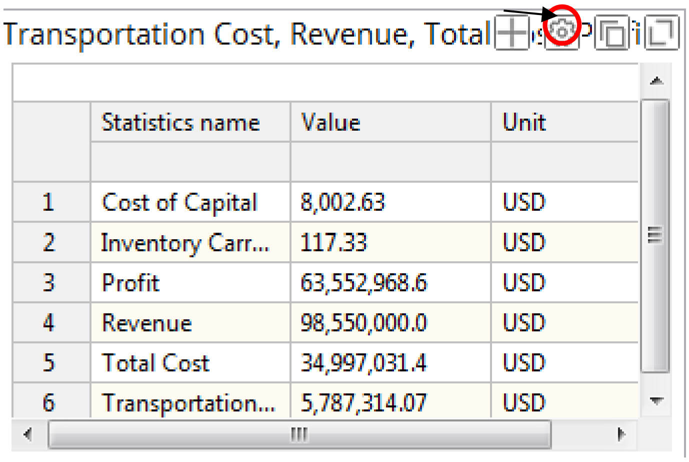


Figure 77: Financial and customer KPIs.

By looking at Figure 77, we can see the supply chain generates a revenue of $98,550,000.0 and profit of $63,552,968.6. Total lead time from the distribution centers to customers is 11.58 days, and there are no backlogged orders. Customers have placed 2,182 orders: 1,372 were fulfilled on time and 812 were delayed.

Note: You can view detailed costs and profit analyses by locating the **Additional Settings** area and then selecting **by item**. Figure 77 shows an example of the detailed view.


Transportation Cost, Revenue, Total

	Statistics name	Value	Unit
1	Cost of Capital	8,002.63	USD
2	Inventory Carr...	117.33	USD
3	Profit	63,552,968.6	USD
4	Revenue	98,550,000.0	USD
5	Total Cost	34,997,031.4	USD
6	Transportation...	5,787,314.07	USD

	Statistics name	Object	Value	Unit
1	Cost of Capital	DC Berlin	4,001.32	USD
2	Cost of Capital	DC Prague	4,001.32	USD
3	Inventory Carr...	DC Berlin	60.58	USD
4	Inventory Carr...	DC Prague	56.74	USD
5	Profit	DC Berlin	33,127,847.76	USD
6	Profit	DC Prague	32,839,029.79	USD
7	Profit	Leipzig1	-2,413,908.94	USD
8	Revenue	DC Berlin	49,275,000.0	USD
9	Revenue	DC Prague	49,275,000.0	USD
10	Total Cost	DC Berlin	16,147,152.24	USD
11	Total Cost	DC Prague	16,435,970.21	USD
12	Total Cost	Leipzig1	2,413,908.94	USD
13	Transportation...	DC Berlin	1,542,291.66	USD
14	Transportation...	DC Prague	1,831,113.47	USD
15	Transportation...	Leipzig1	2,413,908.94	USD

Figure 78: Costs and profit detailization.

Figure 78 shows revenue at DC Prague is $49,275,000 and revenue at DC Berlin is $49,275,000.00. Total costs at DC Prague is $16,435,970.21 and total costs at DC Berlin is $16,147,152.24.

We can also see data on transportation costs. Costs from the supplier in Leipzig to both distribution centers is $2,413,908.94. The transportation from the distribution centers to the customers are $1,831,113.47 (DC Prague) and $1,542,291.66 (DC Berlin).

Note: Be careful with *total* costs, profit and revenue evaluation! In this case, anyLogix calculates total transportation costs for the complete supply chain (that is, the transportation costs across all stages, from suppliers to customers). However, the program calculates total costs, profit and revenue for the distribution centers.

You can use the same diagrams to compare distribution centers and customers. (Figure 79).

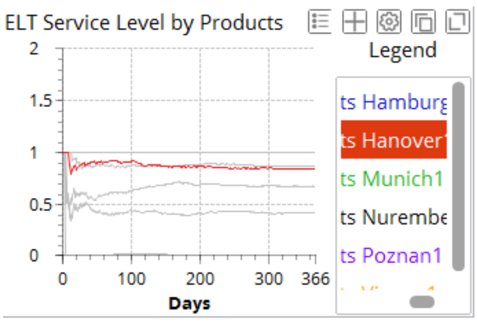


Figure 79: Detailed service level and lead time analysis for the Hamburg-based customer.

Next, we'll consider the overall supply chain's operational performance (Figure 80).

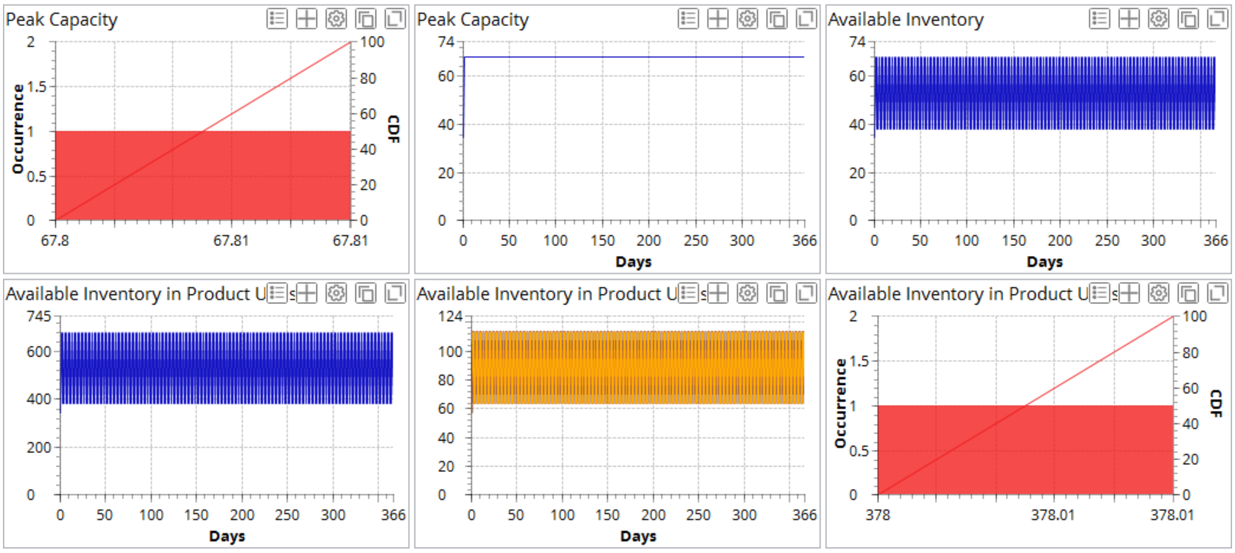


Figure 80: Operational performance for the overall supply chain.

The diagrams in Figure 80 show maximum capacity use at the distribution centers in Prague and Berlin has been 67.8 m^3 in total or 33.9m^3 for each distribution center. The available inventory of each product at each distribution center changed between 39 and 59 units (as set up in Min-Max policy) while the supply chain's total inventory was between 390 and 660 units.

> **Note:** In the diagrams, inventory level does not drop to exactly 57 units (for all products in total) since we always replenish in advance.

The third and fourth dashboards—Inventory and Capacity Dynamics—display these results (Figure 81).

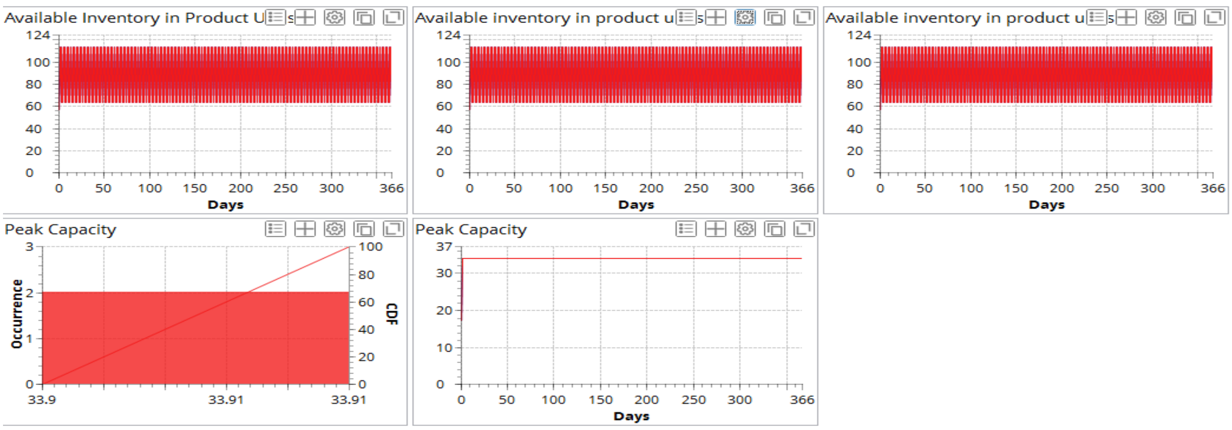


Figure 81: Inventory and Capacity Dynamics Analysis

Result Analysis

Davis, Marina and Cheng (the transportation manager) analyze the gained results. For example, they see the distribution center's total revenue was $98,550,000. Their supply chain includes demand for three products of 50 units respectively, each of which is handled by two distribution centers.

Assuming 365 working days, the annual demand for each product is 3,630 units (36,300 m^3). In other words, their supply chain allows them to meet their demand and receive the maximum possible revenue.

In the min-max inventory control policy, they set **min** = 57 and **max** = 113. With these parameters, total inventory costs (that is, opportunity costs) are $8,002.63. Both distribution centers need to run at capacity of 34 m^3. 2,180 customer orders have been generated for three products supplied from two distribution centers. In other words, every day a new customer order has been generated for each product.

Finally, we can see the LTL transportation policy, trucks with capacity of 60 m^3 used for deliveries from the Leipzig-based supplier to distribution centers are used at 87.5% considering total volume of each delivery as 0.1 + 0.1 + 0.15 (total volume of three products) x 150 units = 52.5 m^3. Two trucks are needed since two distribution centers need to be served. For lorries, we have six direct shipments each of which of 50 units. This results into average capacity utilization of 25% only since just 5% of 20 m^3 is used.

These results support decision-making in many areas of supply chain management, including:

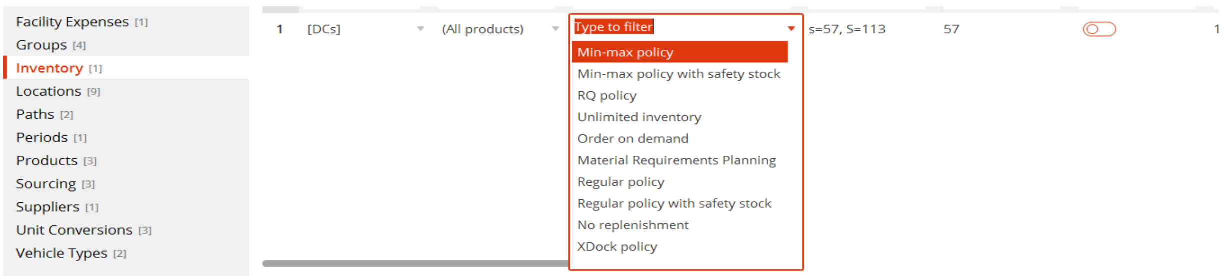
- Capacity design
- Lead time agreements
- Inventory control policy and its parameters
- Transportation policy (FTL/LTL)
- Replenishment planning
- Sales planning
- Budget planning

For example, we can use capacity usage dynamics diagrams to analyze the real distribution center productivity. This extends classical methods based on throughput capacity analysis or setting maximum capacity for some material flows.

By understanding real lead times, order fulfilment dynamics and service levels, we have a solid decision-support basis for our negotiations and contracts with suppliers and customers. Inventory dynamics analysis allows us to estimate and compare the effect of different inventory control policies and their parameters.

Impact of Inventory Control Policy

The professional version of anyLogistix settings offer ten inventory control policies while free version offers nine(Figure 82).



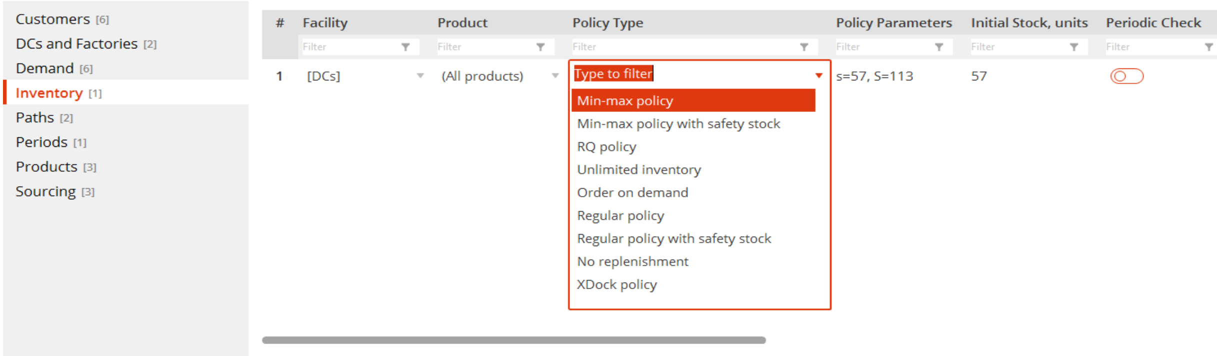


Figure 82: Inventory control policy selection.

Table 11: Inventory control policies.

ALX policy	Described in theory as	Details
Min-max policy	(s, S) inventory policy	Products are ordered 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 S.
Min-max policy with safety stock	(s, S) inventory policy with safety stock	The (s, S) inventory policy with safety stock. Products are ordered when the inventory level falls below a fixed replenishment point (s + safety stock). The ordered quantity is set to such a value that the resulting inventory quantity equals S + safety stock.
RQ policy	(s, q) inventory policy	(R,Q) inventory policy. Fixed replenishment point / fixed replenishment quantity policy. When the inventory level falls below a fixed replenishment point (R), the fixed replenishment quantity (Q) of products is ordered.
Unlimited inventory		Selected by default. By selecting the **Unlimited inventory** policy, we assume products are always in stock at any required quantity.
Order on demand	Similar to Just-in-Tiime	The distribution center does not keep products in stock. The required number of products is ordered only after receiving an order from a customer/factory or another distribution center.
Material Requirements Planning	MRP planning	Schedules inventory replenishment based on safety stock level.
Regular policy [Periodic check option must be enabled]	(t, q) inventory policy	Products are ordered every specified Period
Regular policy with safety stock	(t, q) inventory policy	Products are ordered every specified Period considering the Safety Stock.

No replenishment		The distribution center will not replenish its inventory. If certain initial stock is available, the distribution center will ship products until it runs out of stock.
XDock policy		Distribution center operated like a cross-docking facility. It does not have inventory, it only transfers products from one type of transport to another.

You can set up other inventory control policy parameters:

- Policy type: RQ Policy
- Policy type: R=57, Q=56

You can also define the policies based on the days of supply.

Experiment

In their next executive meeting, Davis, Marina and Cheng analyze the inventory control and transportation policies they can use to improve their supply chain's performance. Marina noticed the Min-level for inventory was calculated based on steady demand for all products—fixed at 50 units a day—and a lead time variation of between 1.7 and 1.95 days (that is, the lead time's standard deviation is 0.125 days).

Since the supply chain is running 90% CSL policy, safety stock was computed as

$ss = z \times \sigma_{LT} \times d_{daily} = 1.28 \times 0.125 \times 50 = 8$ units *

* see the theory on safety stock and reorder point computation in:

Ivanov D., Tsipoulanidis A., Schönberger J. (2017). Global Suppy Chain and Operations Management, Springer, 1st Edition.

Therefore, Min inventory level (that is, the reorder point) was set at 57 units. Marina reduced the safety stock from statistically computed 8 units to 7 units by her expert decision.

Marina now suggests they reduce safety stock. She has noticed demand is always close to the average and 90% CSL is high. She decides to reduce the reorder point to 53 units.

Later, they learn if they change their contract with the Leipzig-based supplier from a Min-Max contract to a fixed-order quantity contract, the supplier can reduce the product per-unit costs by 10%. Based on the required customer lead time of two days and fixed demand of 50 units a day, Marina and Alice set the target level (MAX) at 105 units.

They run the simulation experiment they created during their meeting. Figures 83-86 and Table 12 display the results:

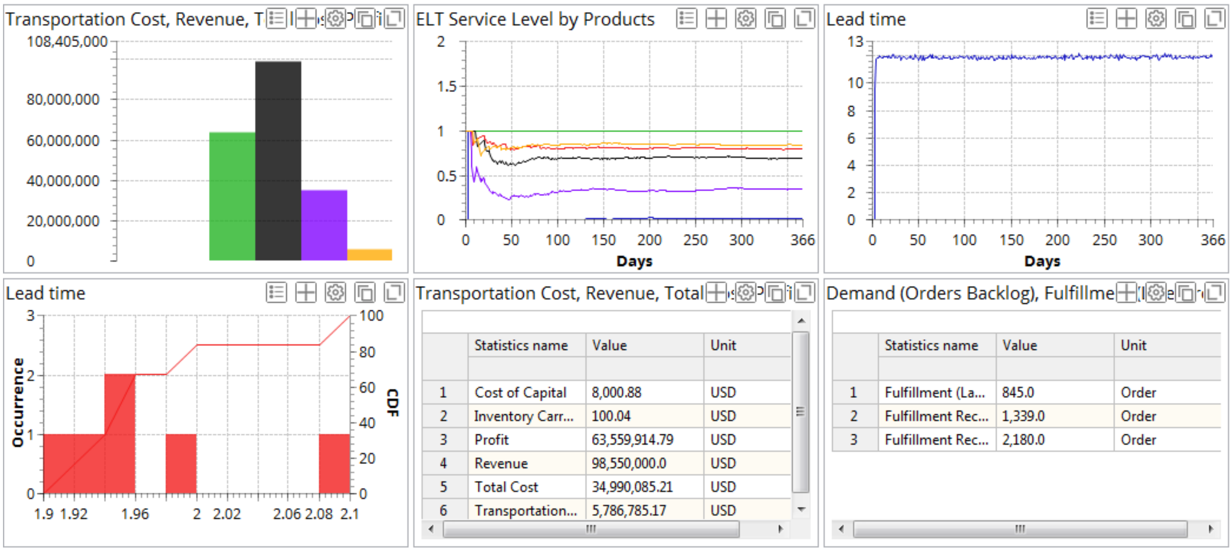


Figure 83: Financial and customer performance dashboard.

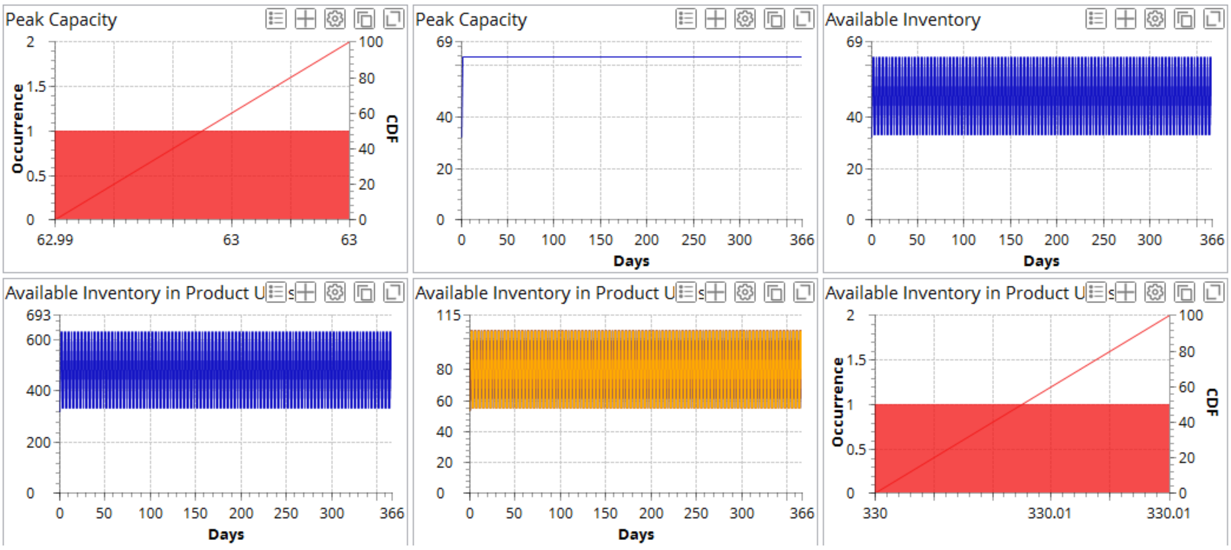


Figure 84: Operational performance dashboard.

Figure 85: Inventory and capacity dashboard.

Table 12: KPI comparison.

KPI	Initial Supply Chain	New Inventory Control Policy
Financial distribution center performance:		
Carrying cost	117.33	100.04
Opportunity cost(Capital)	8 002.63	8 000.88
Profit	63,552,968.6	63,559,914.79
Revenue	98,550,000.0	98,550,000.0
Total cost	34,997,031.4	34,990,085.21
Transportation cost	5,787,314.07	5,786,785.17
Customer performance:		
Maximum lead time, days	2.03	2.1
Min-Max Service level, %	10-100	1-100
Current backlog orders	0	0
Customer delayed orders	812.0	845.0
Customer in-time orders	1372.0	1339.0
Customer orders arrived	2182.0	2180.0
Operational performance:		
Maximum capacity usage in the supply chain, m^3	67.8	63.0
Maximum inventory in the supply chain, units	378.0	330.0

Results Analysis

The results above show us the new inventory policy increases the supply chain profit and improves both inventory management performance and the service level.

What else can they improve? Cheng suggests they think about order quantities and customer lead time requirements. An increase in order quantity and a transition from daily deliveries to twice-a-week deliveries would improve transportation capacity utilization. However, Marina points out limited warehouse capacity rules out an increase in order quantity.

Marina and Cheng will now use anyLogistix with embedded AnyLogic functionality to understand the effect warehouse processes will have over time.

Using AnyLogic to Extend anyLogistix

One of anyLogistix's advantages is the opportunity to use AnyLogic to extend an object. For example, you can use AnyLogic to extend the distribution center operations in a way that simulates internal processes such as forklift capacity utilization and loading times. (Figure 87).

> **Note:** anyLogistix's Personal Learning Edition (PLE) does not allow you to create extensions.

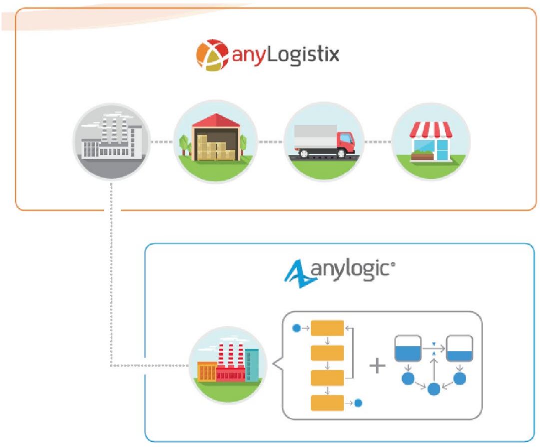


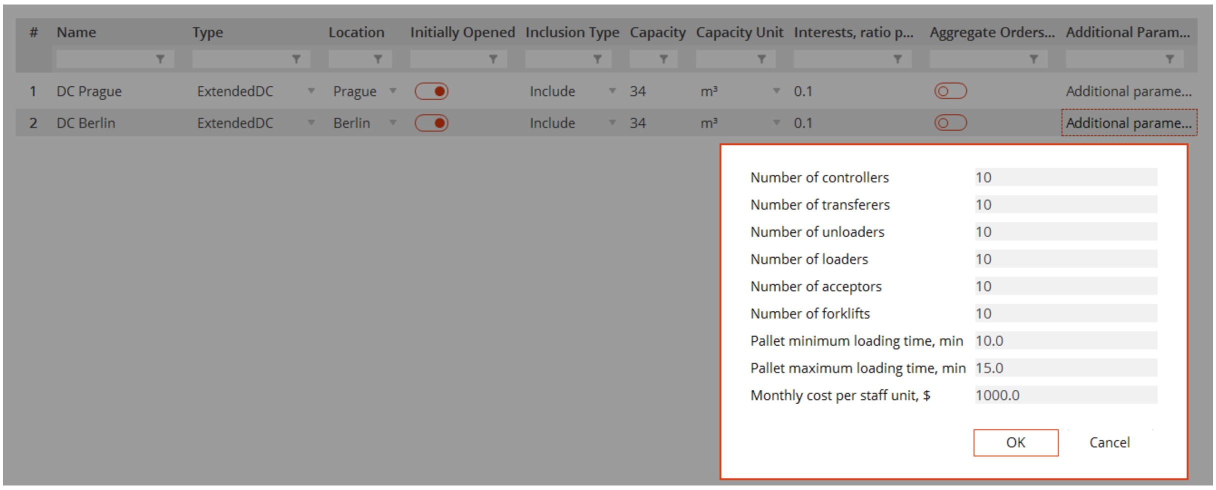
Figure 87: Extensions to anyLogistix in AnyLogic

In anyLogistix's main menu, point to **Extensions** and then click **Run AnyLogic**. For more information about creating inventory control policies or distribution center operational models in AnyLogic, refer to:

- The book AnyLogic in Three Days
- The book Operations and Supply Chain Simulation with AnyLogic
- Sample models in AnyLogic such as **Distribution Center**, **Adaptive Supply chain**, **Supply chain** and **Wholesale Warehouse**.

In AnyLogic, we need to extend a template that describes a network object's behavior. After we implement the export as a library (C:\Users\User\.anyLogistix\Extensions\extension.jar), we need to restart anyLogistix.

For example, the sample Microsoft Excel workbook--**8 SIM Distribution Network inside 4 Walls Models**—embeds additional parameters into the distribution centers' activities:



You can watch the distribution center operation in the simulation run by clicking the **distribution center** icon (Figures 88-89).

Figure 88: Embedded AnyLogic model in the anyLogistix: 2D view.

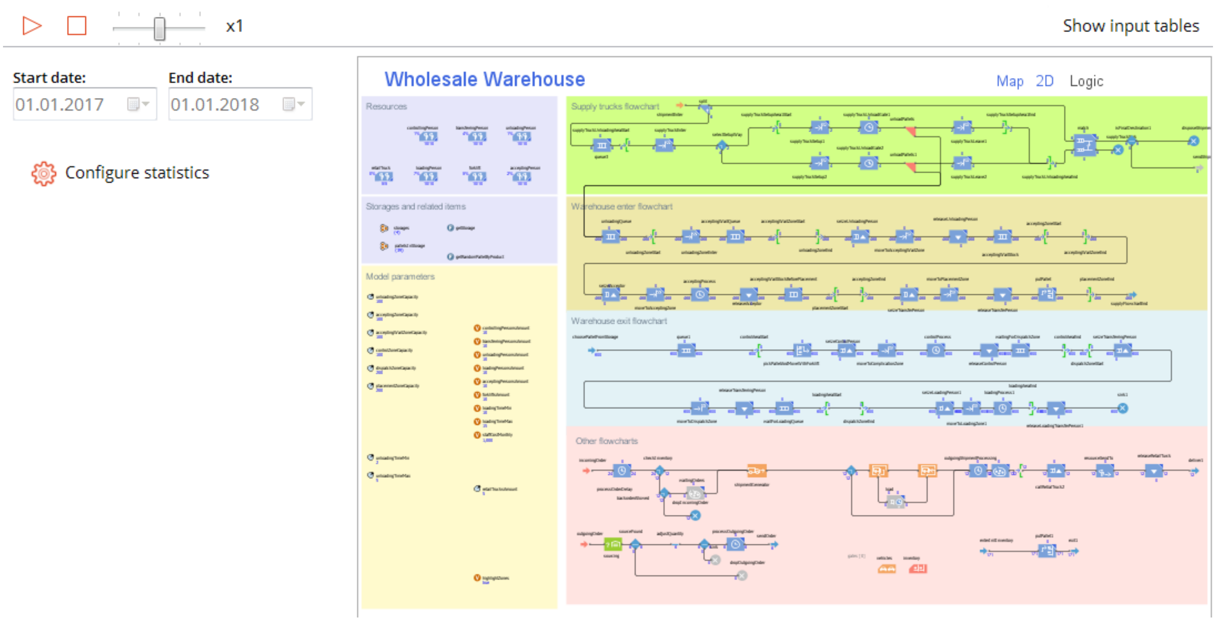


Figure 89: Embedded AnyLogic model in the anyLogistix: process logic view.

The mutual, multi-facted extensions of AnyLogic and anyLogistix include the following issues:

- Customized supply chain model based on anyLogistix scenario data
- Additional data sources such as an external database, other files or Internet sources
- Data pre/post processing
- External solvers
- Your own optimization algorithms
- Heuristics
- Custom statistics
- Results: New anyLogistix scenarios (like GFA and NetOpt)

You can use these extensions with several anyLogistix elements, including **DC**, **Factory** or **Customer**. You can customize sourcing, inventory and transportation policies as well as the decision-making logic that takes factors such as shipment times, shipment grouping, source selection logic or route selection logic in account. You can also create custom experiments.

Impact of Transportation Policy

You use the **Vehicle Types** and **Paths** tables to manage transportation policy. In the **Vehicle Types** table, you can set the transportation mode, capacity and speed. The **Paths** table allows you to set up FTL or LTL policy, transportation costs and time computation schemes, minimum load and order aggregation parameters.

You can based your transportation cost computations on four rules:

- Weight x volume x distance
- Distance-based
- Fixed delivery costs
- Weight-based costs

The transportation time can be fixed or determined automatically based on real routes and transportation speed.

Experiment

In their next executive meeting, Davis, Marina, and Cheng review their options. Their goal is to change the transportation policy in a way that helps improve their supply chain’s performance.

While Cheng has noticed the capacity utilization of lorries is very low (25%), there are ways to improve it. For example, the company might decide to change their schedule from daily deliveries to a delivery every four days based on the FTL policy. However, this would imply an order quantity of at least 200 units, an amount that exceeds the maximum storage capacity of 113 units. Davis tells the others a short-term capacity extension like this is impossible.

Cheng wants to try another option: replace the lorries that have a capacity of 20 m^3 with lorries that have a capacity of 7 m^3. This would reduce transportation costs from

$1 for km and m^3 to $0.5 for km and m^3. Afterward, they change the lead time from distribution centers to the customers to [0.7; 0.9]. Figure 90 and Table 13 display their results:

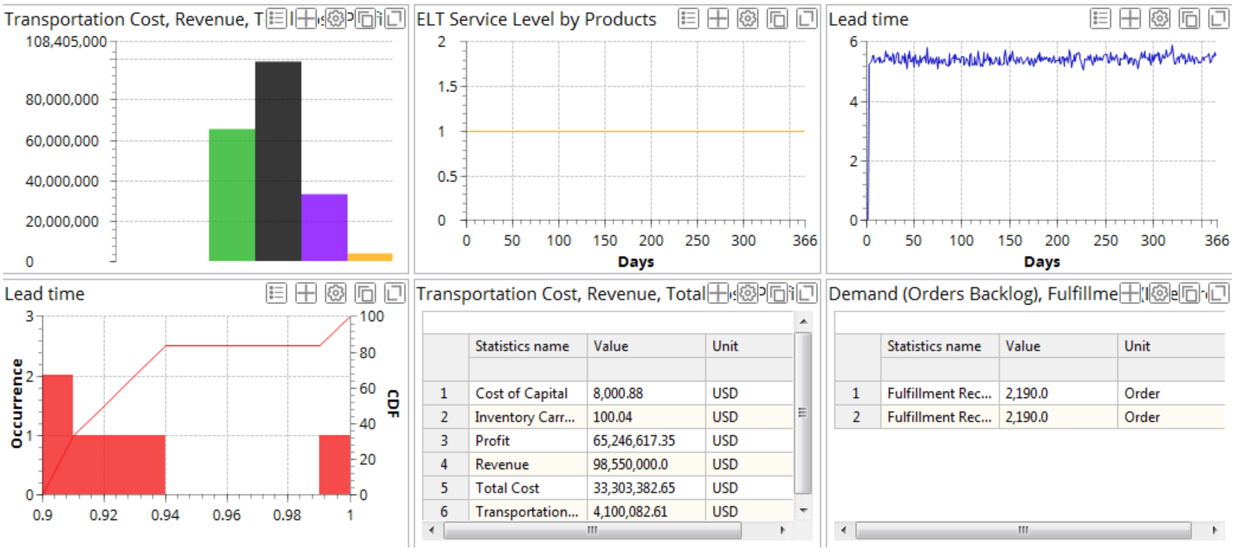


Figure 90: Financial and customer performance for changed transportation capacity.

Table 13: KPI comparison

KPIs	Initial Supply Chain	New Inventory Control Policy	New Inventory Control Policy + New Transportation Policy
Financial distribution center performance:			
Carrying cost	117.33	100.04	100.04
Opportunity cost	8 002.63	8 000.88	8 000.88
Profit	63,552,968.6	63,559,914.79	65,246,617.35
Revenue	98,550,000.0	98,550,000.0	98,550,000.0
Total cost	34,997,031.4	34,990,085.21	33,303,382.65
Transportation cost	5,787,314.07	5,786,785.17	4,100,082.61
Customer performance:			
Maximum lead time, days	2.03	2.1	1
Min-Max Service level, %	10-100	1-100	100
Current backlog orders	0	0	0
Customer delayed orders	812.0	845.0	0

Customer in-time orders	1372.0	1339.0	2190.0
Customer orders arrived	2182.0	2180.0	2190.0
Operational performance:			
Maximum capacity usage in the supply chain, m^3	67.8	63.0	63.0
Maximum inventory in the supply chain, units	378.0	330.0	330.0

Results Analysis

Table 9 shows us total profit has increased. This is evidence of the transportation capacity utilization impact on the supply chain costs.

Finally, Davis wants to estimate the effect of reducing lead time from two days to one day since this would increase supply chain competitiveness and might result in a sales increase. Reducing the lead time from two days to one day would likely result in lower inventories (good for Marina!) but higher transportation costs (a problem for Cheng!).

They change **Expected lead time** in the **Demand** table to **1** day, lead time from distribution centers to the customers to [0.6; 0.8], and transportation costs from the distribution centers to the customers to $0.02.

Figure 91 and Table 14 display the simulation's results:

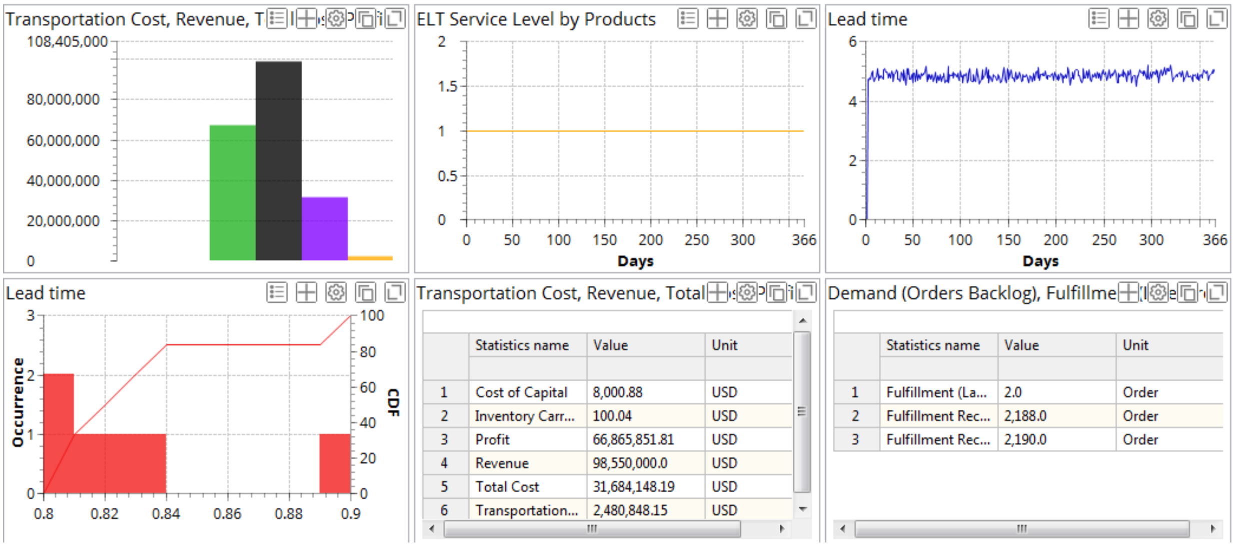


Figure 91: Financial and customer performance.

Table 14: KPI Comparison

KPI	Initial Supply Chain	New Inventory Control Policy	Lead Time = 1 Day
Financial distribution center performance:			

Carrying cost	117.33	100.04	100.04
Opportunity cost	8 002.63	8 000.88	8,000.88
Profit	63,552,968.6	63,559,914.79	66,865,851.81
Revenue	98,550,000.0	98,550,000.0	98,550,000.0
Total cost	34,997,031.4	34,990,085.21	31,684,148.19
Transportation cost	5,787,314.07	5,786,785.17	2,480,848.15
Customer performance:			
Maximum lead time, days	2.03	2.1	0.90
Min-Max Service level, %	10-100	1-100	100
Current backlog orders	0	0	0
Customer delayed orders	812.0	845.0	2
Customer in-time orders	1372.0	1339.0	2188.0
Customer orders arrived	2182.0	2180.0	2190.0
Operational performance:			
Maximum capacity usage in the supply chain, m^3	67.8	63.0	63.0
Maximum inventory in the supply chain, units	378.0	330.0	630.0

By comparing the results, we can see the reduced lead time has increased supply chain profit. It also improves inventory efficiency, order fulfilment rates and service levels, measures which can all strengthen the company's competitive position.

Chapter 3. Simulation with Production Factories and Sourcing Policies: Four-Stage Supply Chain

Our Learning Objectives

Our learning objectives for this chapter are to:

1. Gain insight into the impact of production and sourcing policies on supply chain and logistics performance;
2. Develop the anyLogistix skills needed to create four-stage supply chain models, perform experiments and measure performance;
3. Understand trade-offs in single vs dual sourcing strategies.

Theoretical background

Before you decide on a supply chain design, you should analyze additional factors, including (Ivanov et al. 2019): production cost, use of available resources, focus on core competencies, cost restructuring, time-to-market, risk sharing, know-how sharing, quality issues, flexibility, and taxes.

By reducing your supplier base, you can order larger volumes from one supplier (single sourcing strategy) with the goal of generating volume bundling (supply chain) effects.

However, your dependence on a single supplier may be too high a risk. Recent disruptions have forced supply chain managers to rethink this lean sourcing strategy. In 2011, tsunamis and floods in Japan and Thailand affected many suppliers based in these countries. Many factories did not operate for months.

With this in mind, you may want to work with a second or third supplier who can provide a part or module. This supplier strategy—typically called dual sourcing—might even grow to be a multiple sourcing strategy which better balances the global flows of material and reduces risk.

The discussion above raises some critical issues that we need to consider before we commit to a single, dual, or multiple sourcing strategy. These include v*olume, product variety, demand uncertainty, lead time importance, disruption and other risks, transportation costs, manufacturing complexity, coordination complexity, and post-sale issues.*

Single Sourcing Advantages

Some common advantages of single sourcing are:

- Long-term agreements,
- Price stability,
- The opportunity to include Suppliers in the product development process at a very early stage,
- Low transactional costs,
- Supply chain effects.

Single Sourcing Disadvantages

Single sourcing also has several shortcomings:

- Inefficient price policy,
- Lead time, quality, and service issues,
- Lack of collaboration with many suppliers.

For *global sourcing*, items of high volume, steady demand, and low transportation costs are preferable. However, the different *chances and risks* associated with costs, service, quality, and sustainability should be part of the analysis.

- Costs: labor, taxes, transportation, insurance, transshipment, duties, and transactions.
- Quality: bill-of-materials, quality control, after-sales service, and certifications.
- Service: on-time delivery, responsiveness, flexibility, technical equipment, image and reliability.
- Sustainability: political, economic, and social issues.

Global sourcing offers many advantages, including access to the broadest available range of suppliers. At the same time, the work required to establish relationships with global vendors or partners is higher, and might even include certain language skills.

Global sourcing also requires time for traveling to suppliers and transporting goods. Topics such as currency risks, political stability, and different cultures, norms and standards are important considerations as well.

Production Factories

Case Study: Smartphone Supply Chain

WHC is a supply chain for smartphone production and distribution (Figure 93).

The smartphone assembly process that takes place at the Chinese factory requires one display and two chips. The Chinese supplier delivers their displays by truck and the Taiwanese supplier delivers their chips by ferry.

The factory delivers the smartphones by air to the distribution center in the U.S. From there, the distribution center ships them by air to the customers. The factory and distribution center are running Min-Max inventory control policy at a 1% interest rate.

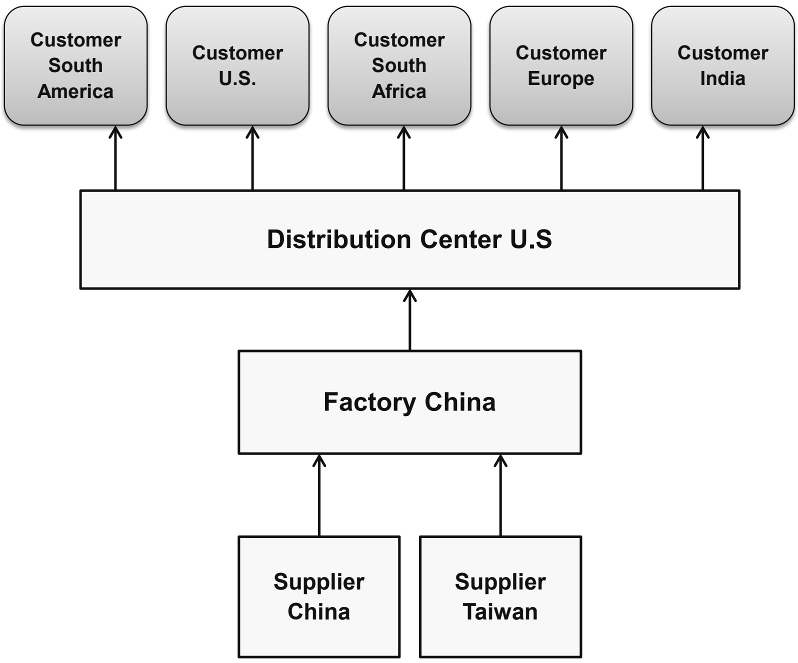


Figure 93: WHC supply chain

We need to analyze two demand scenarios: a positive and a negative market for smartphones.

Assessment Questions:

- What strategies—production, distribution, sourcing and transportation—does this case study use?
- What other inventory control policies do you know?

Supply Chain Design

Multi-stage Supply Chain Design

In Figure 94, we start a new scenario and set up the supply chain design to match Figure 93.

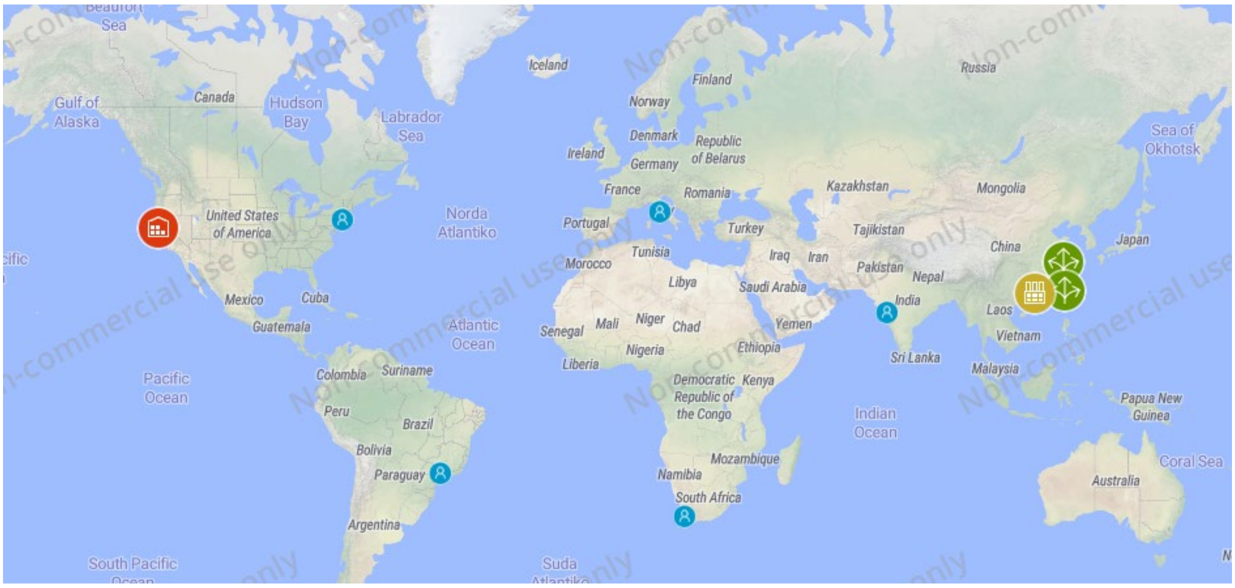


Figure 94: Supply chain design.

We'll first rename the default Suppliers and Customers by their locations (**Supplier China**, **Supplier Taiwan**, **US**, **Brazil**, **South Africa**, **Italy** and **India**) and then rename Site 1 to **DC** and Site 2 to **Factory**.

Transportation, Sourcing and Inventory Policy

Afterward our renaming is complete, we then define the following model elements (Figures 95-100):

- products
- demand and lead time
- vehicle types
- sourcing policy
- the paths
- inventory control policy

#	Name	Unit	Selling Price	Cost	Cost Unit
1	Smartphone	pcs	600	200	USD
2	Display	pcs	30	10	USD
3	Chip	pcs	20	5	USD

Figure 95: Products.

#	Product	Amount from	Unit from		Amount to	Unit to
1	Smartphone	1	pcs	=	0.001	m³
2	Display	1	pcs	=	0.0005	m³
3	Chip	1	pcs	=	0.000001	m³

Figure 96: Measurement unit conversions.

#	Name	Capacity	Capacity Unit	Speed	Speed Unit
1	Airplane	40	m³	800.0	km/h
2	Truck	20	m³	50.0	km/h
3	Ship	2,000	m³	50.0	km/h
4	Ferry	2,000	m³	50.0	km/h

Figure 97: Vehicle types.

#	Delivery Destinat...	Product	Type	Parameters	Sources	Time Period	Inclusion Type
1	Factory	Display	Closest (Fixed So.	No parameters	Supplier China	(All periods)	Include
2	Factory	Chip	Closest (Fixed So.	No parameters	Supplier Taiwan	(All periods)	Include
3	DC	Smartphone	Closest (Fixed So.	No parameters	Factory	(All periods)	Include
4	(All customers)	Smartphone	Closest (Fixed So.	No parameters	DC	(All periods)	Include

Figure 98: Sourcing policy.

#	From	To	Cost Calculation	Cost Calculation ...	...	Curre...	...	Distance ...	Transp...	Time ...	Straight	Vehicle ...	Transport
1	Supplier China	Factory	Distance-based	0.5 * distance + 0	...	USD	0	km	0	day		Truck	LTL
2	Supplier Taiwan	Factory	Distance-based	0.8 * distance + 0	...	USD	0	km	0	day		Ferry	LTL
3	Factory	DC	Product&distanc..	0.01 * product (m...	...	USD	0	km	2	day		Airplan	LTL
4	DC	(All loca.	Product&distanc..	0.01 * product (m...	...	USD	0	km	2	day		Airplan	LTL

Figure 99: Paths.

#	Facility	Product	Policy Type	Policy Parameters	Initial Stock, units	Periodic Chec
1	DC	Smartphone	Min-max policy	s=20, S=50	40	
2	Factory	Smartphone	Min-max policy	s=30, S=60	40	
3	Factory	Chip	Unlimited inventory	Unlimited	N/A	
4	Factory	Display	Unlimited inventory	Unlimited	N/A	

Figure 100: Inventory control policy.

Since our objective is to compare two scenarios with different customer demands, we rename our scenario to **Four-Stage supply chain (Optimistic scenario)**, copy it and name the copy **Four-Stage supply chain (Pessimistic scenario)**. We'll define the demand for both scenarios in the following way (Figure 101-102):

#	Customer	Product	Demand Ty...	Parameters	Time Period	...	...	Exp...	Tim...	Backo
1	US	Smartphone	Periodic d..	Order interval=10, Quantity=35	(All periods)	0		30	day	Not a
2	Brazil	Smartphone	Periodic d..	Order interval=10, Quantity=15	(All periods)	0		30	day	Not a
3	South Africa	Smartphone	Periodic d..	Order interval=10, Quantity=10	(All periods)	0		30	day	Not a
4	Italy	Smartphone	Periodic d..	Order interval=10, Quantity=10	(All periods)	0		30	day	Not a
5	India	Smartphone	Periodic d..	Order interval=10, Quantity=30	(All periods)	0		30	day	Not a

Figure 101: The optimistic scenario for positive market development.

#	Customer	Product	Demand Ty...	Parameters	Time Period	...	...	Exp...	Tim...	Backo
1	US	Smartphone	Periodic d..	Order interval=10, Quantity=7	(All periods)	0		30	day	Not a
2	Brazil	Smartphone	Periodic d..	Order interval=10, Quantity=3	(All periods)	0		30	day	Not a
3	South Africa	Smartphone	Periodic d..	Order interval=10, Quantity=2	(All periods)	0		30	day	Not a
4	Italy	Smartphone	Periodic d..	Order interval=10, Quantity=2	(All periods)	0		30	day	Not a
5	India	Smartphone	Periodic d..	Order interval=10, Quantity=6	(All periods)	0		30	day	Not a

Figure 102: The pessimistic scenario for negative market development.

Production Policy and Bill of Materials (BOM)

Because our example has a factory and two suppliers, we need to define the parameters for BOM (bill-of-material) and the Production policy (Figures 103-104):

#	Name	End Product	Quantity	Co-products	Components
1	BOM 1	Smartphone	1	[]	[Display:1.0, Chip:2.0]

Figure 103: BOM (bill-of-materials).

#	Site	Product	Type	Parameters	BOM	Production Cost	Currency	CO2 per product	Time F
1	Factory	Smartphone	Simple make pol.	Time = 0.01 (day)	BOM 1	50	USD	0	(All pe

Figure 104: Production policy.

Production and Sales Batches

You can use the main menus—**Production Batch** and **Sales Batch**—to set up production and sales batches as additional parameters. For simplicity, we will not consider these options in this example. For more information about these options, see Chapter 4, Sect. 6 "Bullwhip Effect".

AS-IS Simulation

Experiment Preparation and KPI Dashboard

Note: A good modeler tends to modify the existing models for similar problem statements instead of creating models from scratch each time.

Because we chose **pcs** as our product unit, we need to change the value in the **Product statistics unit** field. We do this by changing **"Product statistics unit"** to **pcs** which is **m³** by default as shown in Figure 105.

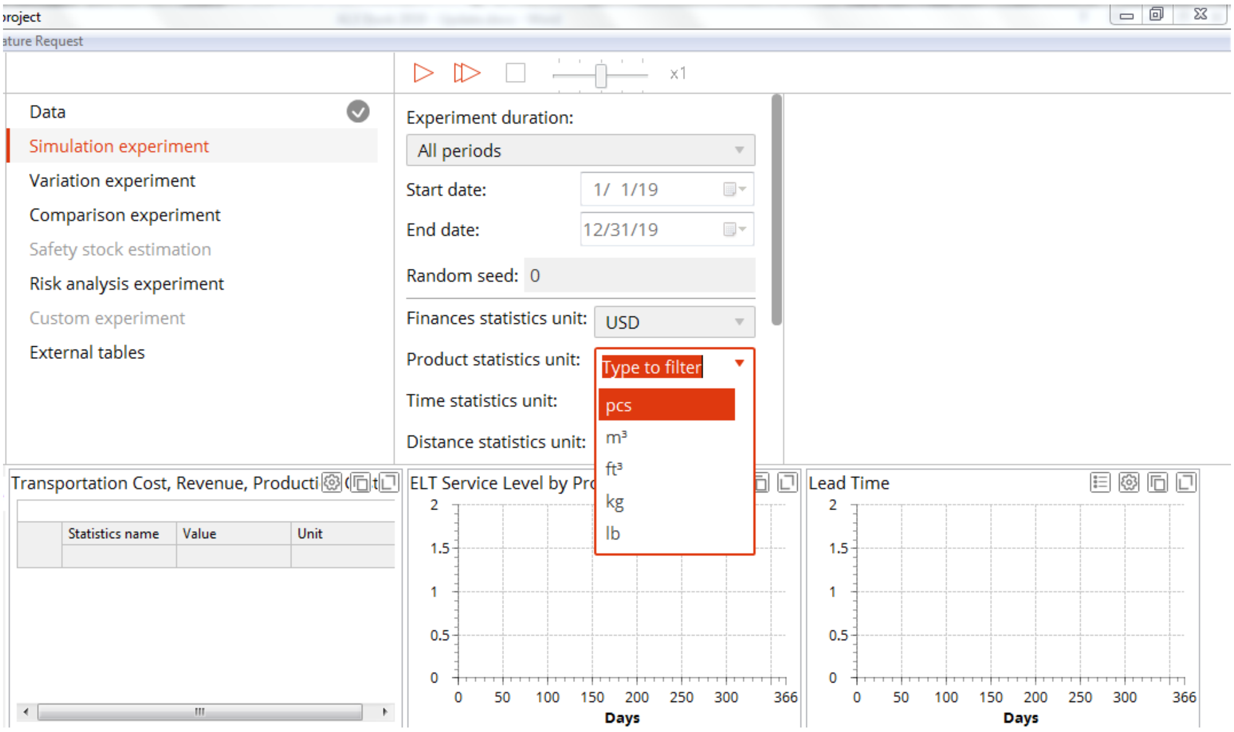


Figure 105: Product statistic unit.

We'll create a KPI dashboard for our example:

Financial and customer performance:

- Cost of Capital, Production cost, Profit, Revenue, Total cost, Transportation cost (table)
- ELT service level by orders (line)
- Lead-time (line)

Operational performance:

- Peak capacity (line)
- Available inventory (line)

Production and Sourcing:

- Production cost, Transportation cost (table, "Object" show ❼ by item)
- Demand (Orders Backlog), Demand Placed (Dropped Orders) by Customer, Demand Placed (Orders) by Customer, Fulfillment (Late Orders), Fulfillment Received (Orders On-time), Fulfillment Received (Orders) by Customer, Products Produced

Experimental Result for Pessimistic Scenario

The simulation provides the following results for the pessimistic scenario with low demand (Figures 106-108).

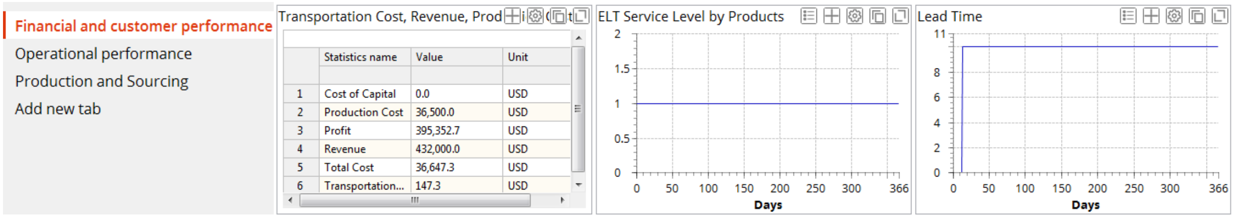


Figure 106: Financial and customer performance.

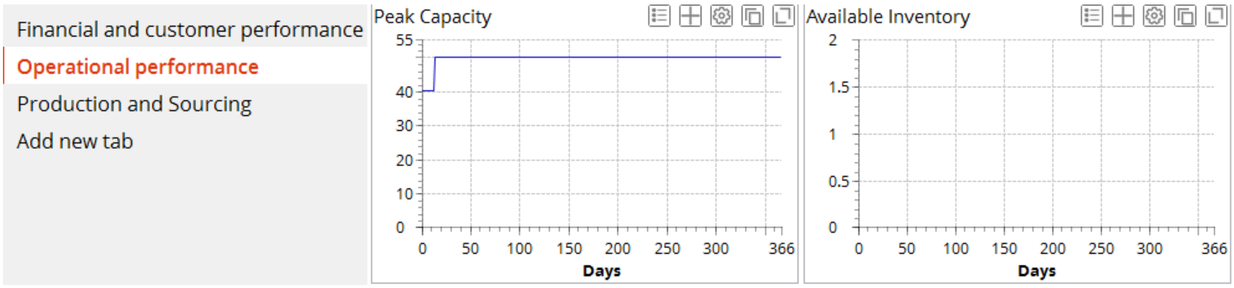


Figure 107: Operational performance.

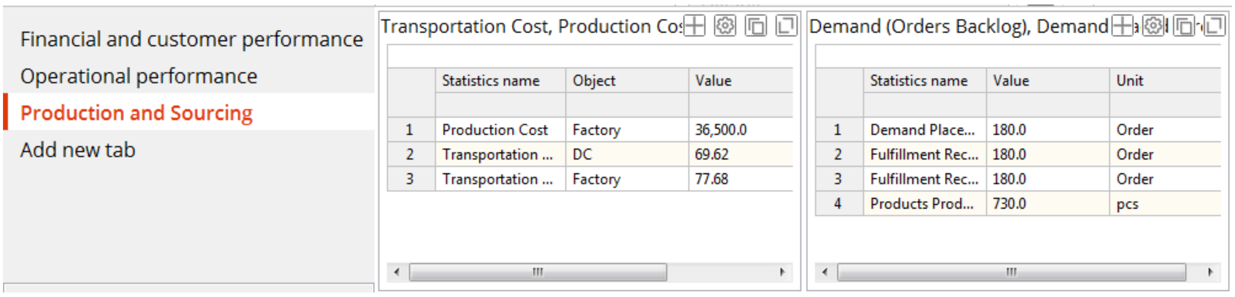


Figure 108: Production and sourcing performance.

Why is the **Available inventory** histogram blank? To address this issue, we need to open the **Inventory** table and update our settings.

Experimental Result for Optimistic Scenario

The simulation provides the following results for the optimistic scenario with high demand (Figure 109 to Figure 111).

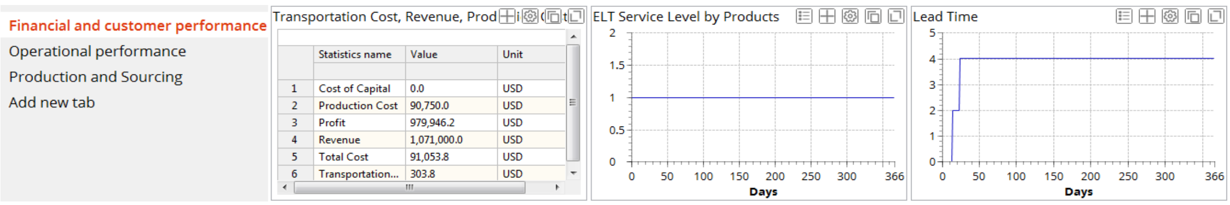


Figure 109: Financial and customer performance.

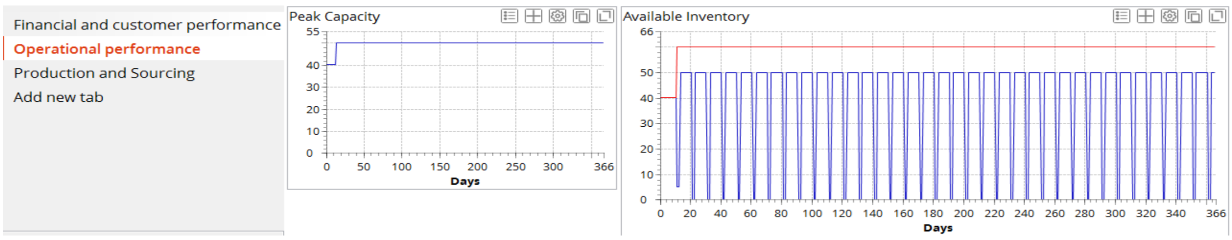


Figure 110: Operational performance.

Compare the data in the **Available inventory** histogram with our previous results.

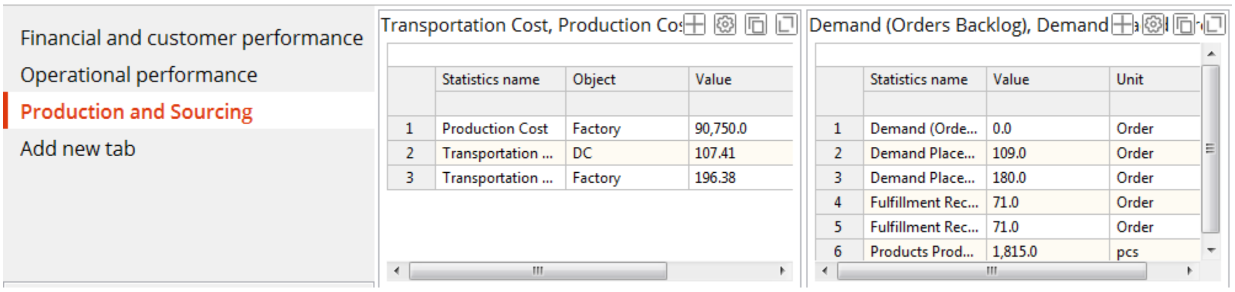


Figure 111: Production and sourcing performance.

Result Analysis

Table 15 shows the KPI from the pessimistic and optimistic scenarios.

Table 15: KPI comparison.

KPI	Pessimistic Scenario	Optimistic Scenario
Financial and customer performance:		
Opportunity cost, $	0.0	0.0
Production cost, $	36 500.0	90 750.0
Profit, $	395 352.7	979 946.2
Revenue, $	432 000.0	1 071 000.0
Total cost, $	36 647.3	91 053.8
Transportation cost (distribution center), $	69.62	107.41
Transportation cost (Factory), $	77.8	196.38
Service level, %	100%	100%
Lead time, days	10	4
Operational performance:		
Maximum capacity usage in the supply chain, pcs	50	50
Maximum inventory in the supply chain (distribution center), pcs	50	50
Maximum inventory in the supply chain (Factory), pcs	60	60
Production and sourcing performance:		

Current backlog orders	0	0
Customer delayed orders	0	0
Customer dropped orders	0	109.0
Customer in-time orders	180.0	71.0
Customer orders	720.0	180.0
Customer orders arrived	180.0	71.0
Produced, pcs	730.0	1815.0

In Table 15, we can see higher demand has led to increased supply chain profit. At the same time, order fulfilment rates have fallen. This analysis shows the supply chain design's limits and provides evidence the company will need to redesign their supply chain if they believe the optimistic scenario is realistic.

Sourcing Policies

Our Case Study: Extended Supply Chain for Smartphones

WHC's supply chain manager suggests we analyze two options for improving the supply chain performance for a positive market development:

Option	Fixed Costs
Increase distribution center capacity and imply new Min-Max values 100-200 at distribution center and 120-240 at factory in the inventory control policy	**$10,000**
Build a second distribution center in China and imply Dual Sourcing	**$50,000**

Improvement Action: Single Distribution Center - Increased Capacity

Experimental Result

The simulation provides the following results for the optimistic scenario with high demand and supply chain redesign in the **single distribution center-increased capacity** option (Figures 112-114).

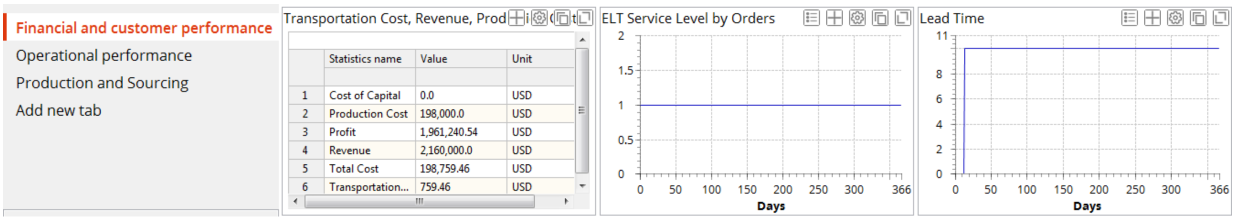


Figure 112: Financial and customer performance.

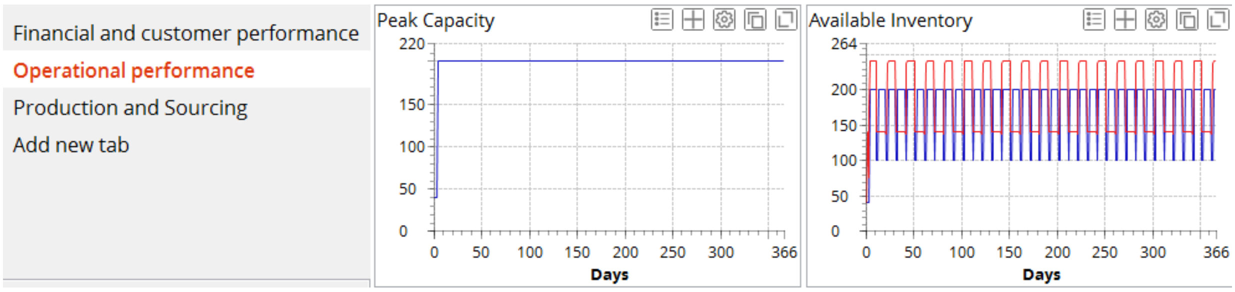


Figure 113: Operational performance.

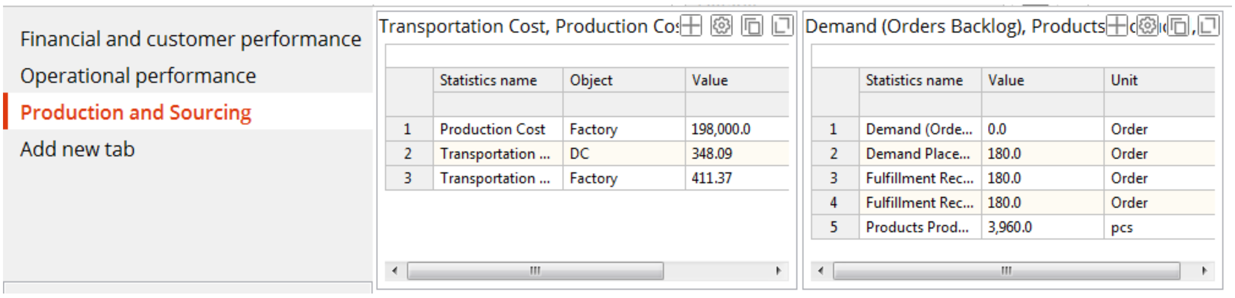


Figure 114: Production and sourcing performance.

Result Analysis

Table 16 shows us the redesigned supply chain’s impact on the KPI.

Table 16: KPI comparison

KPI	**Optimistic Scenario** **AS-IS Supply Chain Design**	**Optimistic Scenario Redesign** **“single distribution center - increased capacity”**
Financial and customer performance:		
Opportunity cost, $	0.0	0.0
Production cost, $	90 750.0	198 000.0
Profit, $	979 946.2	1 961 240.54
Revenue, $	1 071 000.0	2 160 000.0
Total cost, $	91 053.8	198 759.46
Transportation cost (distribution center), $	107.41	348.09
Transportation cost (Factory), $	196.38	411.37
Service level, %	100%	100%
Lead time, days	4	10
Operational performance:		

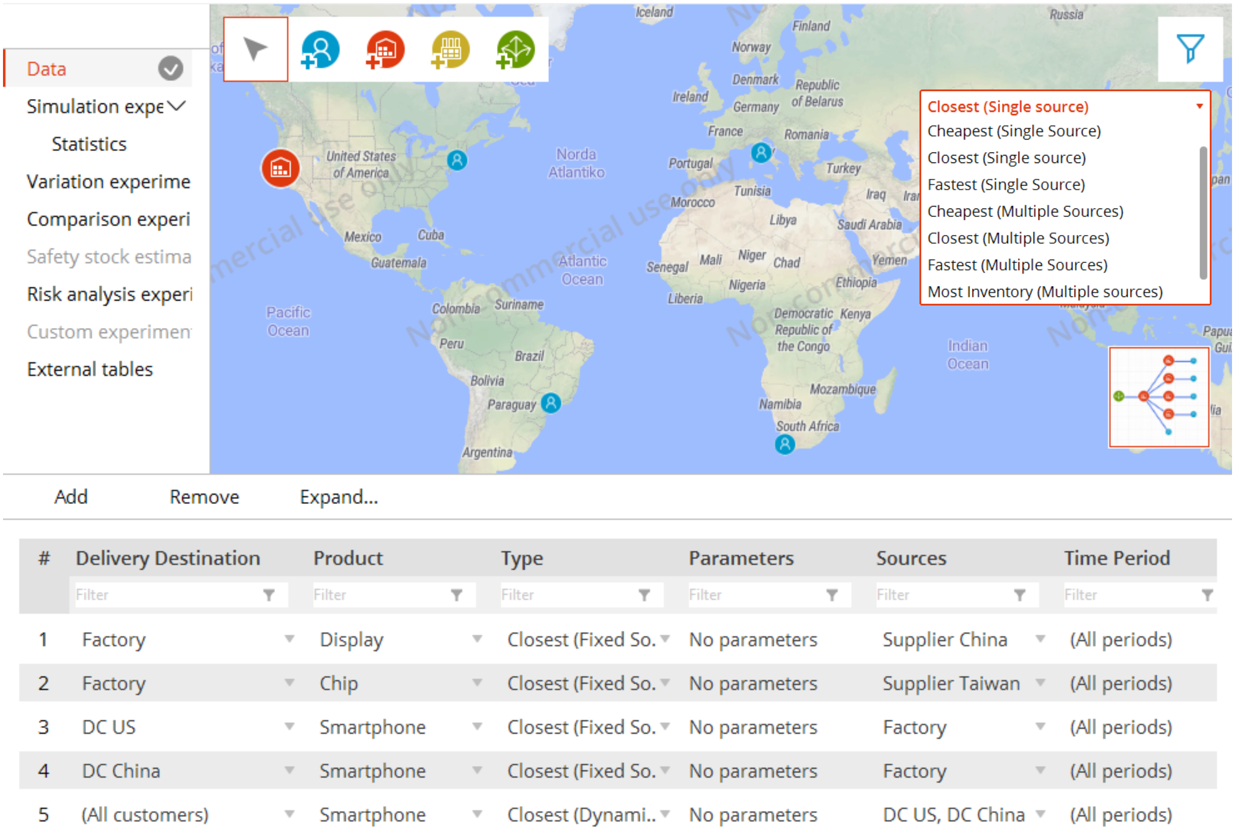
Maximum capacity usage in the supply chain, pcs	50	200
Maximum inventory in the supply chain (distribution center), pcs	50	200
Maximum inventory in the supply chain (Factory), pcs	60	240
Production and sourcing performance:		
Current backlog orders	0	0
Customer delayed orders	0	0
Customer dropped orders	109.0	0
Customer in-time orders	71.0	180.0
Customer orders	180.0	180.0
Customer orders arrived	71.0	180.0
Produced, pcs	1815.0	3 960.0

Table 16 shows us the redesigned supply chain performs far better than the AS-IS supply chain design. Financial, customer, and operational performance have all improved and the WHC can almost double its total profit. The results also point to the maximum capacity the extended distribution center will need (200 pcs) as well as the required production capacity (3,960 units).

Improvement Action: New Distribution Center - Dual Sourcing

Changing the Scenario's Sourcing Policy

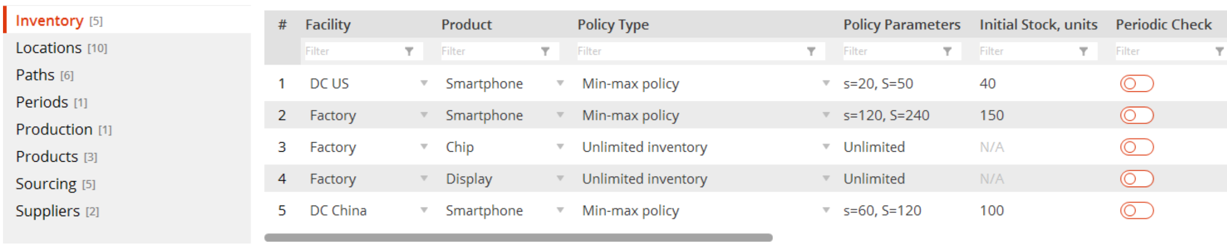
To perform an experiment that uses dual sourcing, we need to update our scenario. First, we need to go to **Sourcing** to change the single sourcing policy to multiple source policy for deliveries from the distribution centers to the customers by changing sourcing policy from **"Closest Fixed Source"** to **"Closest Dynamic Sources"**. Do not forget to create the new distribution center in China! (Figure 115).



#	Delivery Destination	Product	Type	Parameters	Sources	Time Period
1	Factory	Display	Closest (Fixed So.	No parameters	Supplier China	(All periods)
2	Factory	Chip	Closest (Fixed So.	No parameters	Supplier Taiwan	(All periods)
3	DC US	Smartphone	Closest (Fixed So.	No parameters	Factory	(All periods)
4	DC China	Smartphone	Closest (Fixed So.	No parameters	Factory	(All periods)
5	(All customers)	Smartphone	Closest (Dynami..	No parameters	DC US, DC China	(All periods)

Figure 115: Sourcing policy selection.

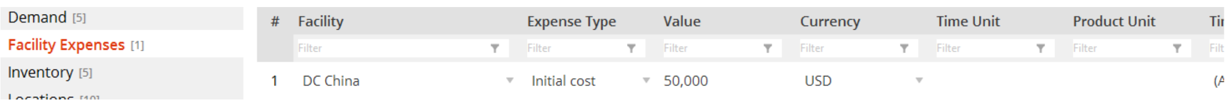
Second, we set up inventory control parameters (Figure 116).



#	Facility	Product	Policy Type	Policy Parameters	Initial Stock, units	Periodic Check
1	DC US	Smartphone	Min-max policy	s=20, S=50	40	
2	Factory	Smartphone	Min-max policy	s=120, S=240	150	
3	Factory	Chip	Unlimited inventory	Unlimited	N/A	
4	Factory	Display	Unlimited inventory	Unlimited	N/A	
5	DC China	Smartphone	Min-max policy	s=60, S=120	100	

Figure 116: Inventory control policy.

Third, we consider **$50,000** as fixed costs for opening the new distribution center in China (Figure 117).



#	Facility	Expense Type	Value	Currency	Time Unit	Product Unit	Ti
1	DC China	Initial cost	50,000	USD			(A

Figure 117: Distribution center/factory settings.

Finally, we add paths to and from the new distribution center in China (Figure 118).

#	From	To	Cost Calculation	Cost Calculation ...	...	Curre...	...	Distance ...	Transp...	Time ...	Straight	Vehicle ...	Trans
1	Supplier China	Factory	Distance-based	0.5 * distance + 0	...	USD	0	km	0	day		Truck	LTL
2	Supplier Taiwan	Factory	Distance-based	0.8 * distance + 0	...	USD	0	km	0	day		Ferry	LTL
3	Factory	DC US	Product&distanc..	0.01 * product (m...	...	USD	0	km	2	day		Airplan	LTL
4	DC US	(All loca.	Product&distanc..	0.01 * product (m...	...	USD	0	km	0	day		Airplan	LTL
5	Factory	DC Chin	Product&distanc..	0.005 * product (...	...	USD	0	km	0	day		Truck	LTL
6	DC China	(All loca.	Product&distanc..	0.005 * product (...	...	USD	0	km	0	day		Airplan	LTL

Figure 118: Transportation policy.

Note: Inventory control policies immediately interact with production policy. Production is controlled by parameters of inventory policies.

Experimental Result

The simulation provides the results for the following optimistic scenario with high demand and supply chain redesign in the **new distribution center – dual sourcing** option (Figures 119-122).

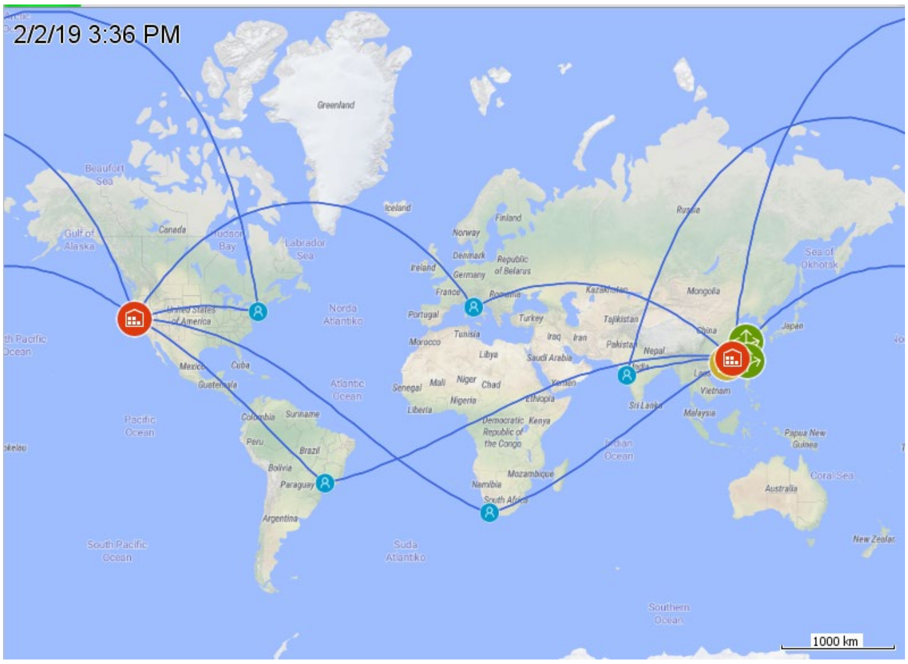
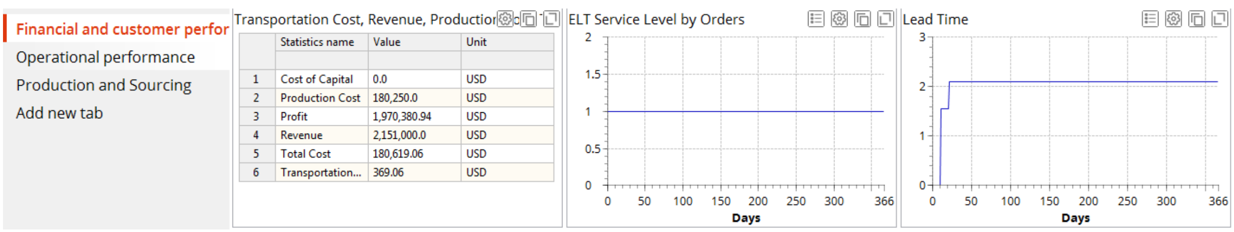


Figure 119: Dual sourcing experiment.



	Statistics name	Value	Unit
1	Cost of Capital	0.0	USD
2	Production Cost	180,250.0	USD
3	Profit	1,970,380.94	USD
4	Revenue	2,151,000.0	USD
5	Total Cost	180,619.06	USD
6	Transportation...	369.06	USD

Figure 120: Financial and customer performance.

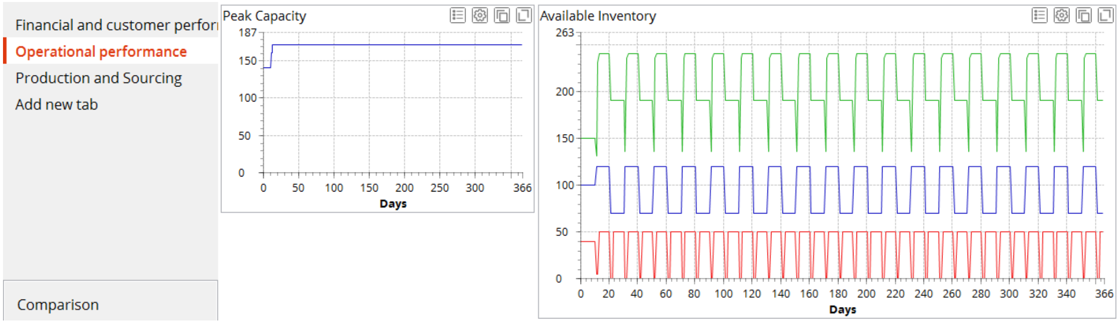


Figure 121: Operational performance

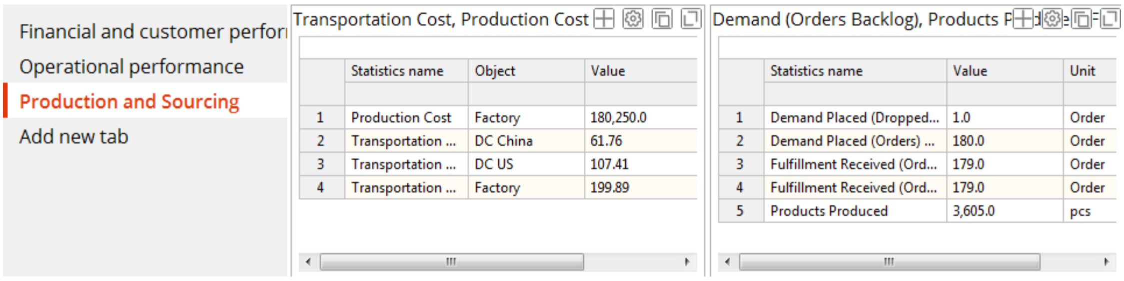


Figure 122: Production and sourcing performance

Result Analysis

Table 17 shows the redesigned supply chain's impact on the KPI.

Table 17: KPI comparison.

KPI	**Optimistic Scenario** **AS-IS Supply Chain Design**	**Optimistic Scenario** **Supply Chain Redesign** **"single distribution center - increased capacity"**	**Optimistic Scenario** **Supply Chain Redesign** **"new distribution center – dual sourcing"**
Financial and customer performance:			
Opportunity cost, $	0.0	0.0	0.0
Production cost, $	90 750.0	198 000.0	180 250.0
Profit, $	979 946.2	1 961 240.54	1 970 380.94
Revenue, $	1 071 000.0	2 160 000.0	2 151 000.0
Total cost, $	91 053.8	198 759.46	180 619.06
Transportation cost (distribution center US), $	107.41	348.09	107.41
Transportation cost (distribution center China), $	-	-	61.76

Transportation cost (Factory), $	196.38	411.37	199.89
Service level, %	100%	100%	100%
Lead time, days	4	10	2.09
Operational performance:			
Maximum capacity usage in the supply chain, pcs	50	200	170
Maximum inventory in the supply chain (distribution center US), pcs	50	200	50
Maximum inventory in the supply chain (distribution center China), pcs	-	-	120
Maximum inventory in the supply chain (Factory), pcs	60	240	240
Production and sourcing performance:			
Current backlog orders	0	0	0
Customer delayed orders	0	0	0
Customer dropped orders	109.0	0	1.0
Customer in-time orders	71.0	180.0	179.0
Customer orders	180.0	180.0	180.0
Customer orders arrived	71.0	180.0	179.0
Produced, pcs	1815.0	3 960.0	3 605.0

Table 17 shows us the redesigned supply chain performs much better than the AS-IS supply chain design and the first supply chain redesign option. Financial, customer and operational performance have all improved, and the WHC can double its total profit compared to the first supply chain redesign option.

The results are also evidence of the maximum distribution center capacity that the new distribution center in China (170 m^3) needs as well as the production capacity (3,605 units). For a more detailed analysis, you need to include warehousing costs for the second distribution center in China.

Comparison to New Distribution Center – Single Sourcing

To estimate whether a dual sourcing policy will perform better than a single sourcing policy, we simulate the same example but with single sourcing policy. The U.S.-based distribution center ships to customers in the U.S. and Brazil, and the China-based distribution center ships to all other customers (Figure 123).

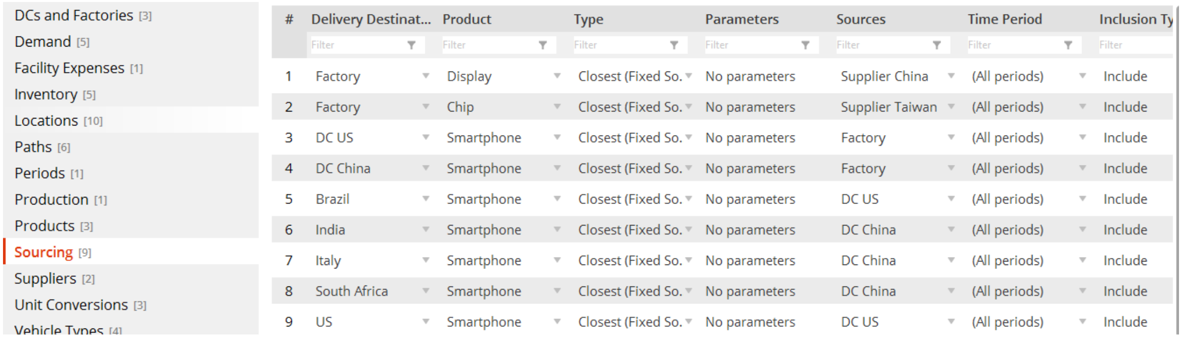


Figure 123: A supply chain design that uses a single sourcing policy with a second distribution center.

The simulation provides the following results for the optimistic scenario with high demand and supply chain redesign in the **new distribution center – single sourcing** option (Figure 124).

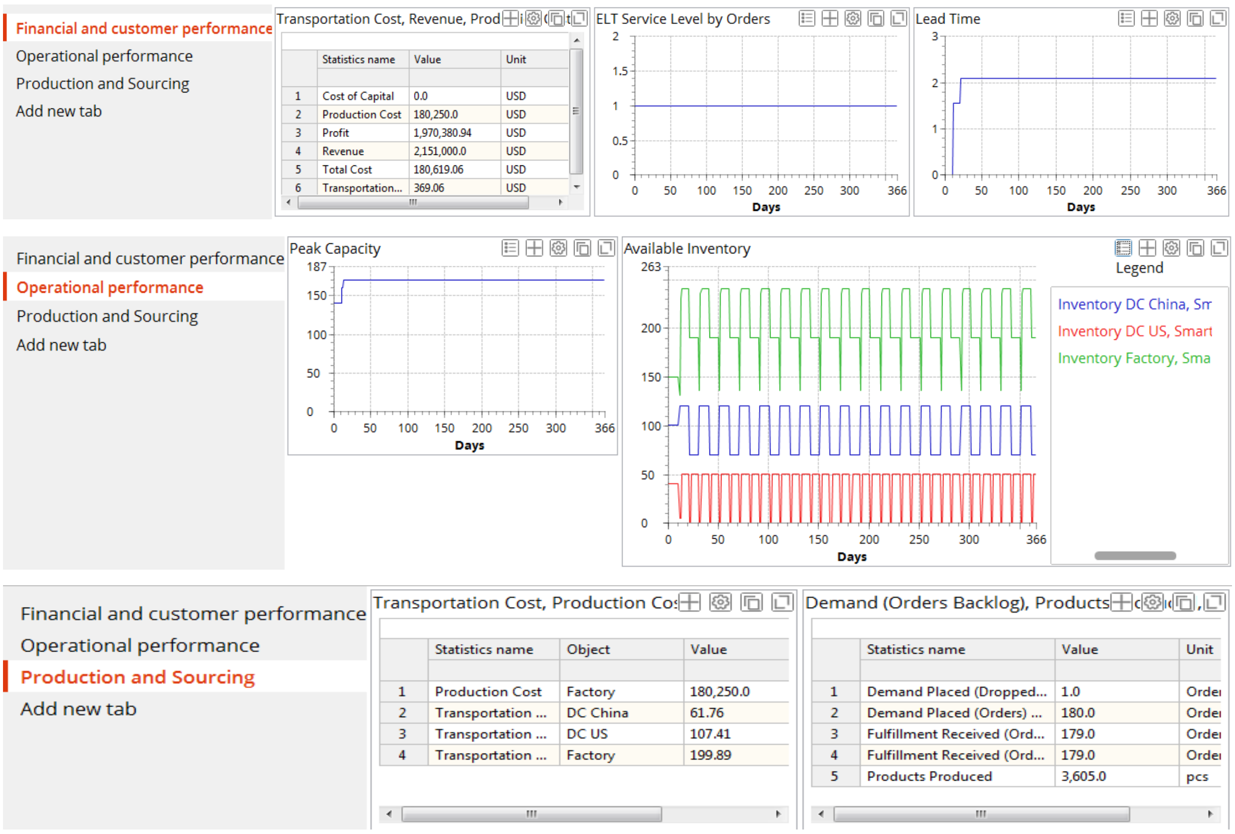


Figure 124: Supply chain performance.

Table 18 displays the results.

Table 18: KPI comparison.

KPI	Optimistic Scenario Supply Chain Redesign	Optimistic Scenario Supply Chain Redesign	Optimistic Scenario Supply Chain Redesign

	"single distribution center - increased capacity"	**"new distribution center – dual sourcing"**	**"new distribution center – single sourcing"**
Financial and customer performance:			
Opportunity cost, $	0.0	0.0	0.0
Production cost, $	198 000.0	180 250.0	180 250.0
Profit, $	1 961 240.54	1 970 380.94	1 970 380.94
Revenue, $	2 160 000.0	2 151 000.0	2 151 000.0
Total cost, $	198 759.46	180 619.06	180 619.06
Transportation cost (distribution center US), $	348.09	107.41	107.41
Transportation cost (distribution center China), $	-	61.76	61.76
Transportation cost (Factory), $	411.37	199.89	199.89
Service level, %	100%	100%	100%
Lead time, days	10	2.09	2.09
Operational performance:			
Maximum capacity usage in the supply chain, pcs	200	170	170
Maximum inventory in the supply chain (distribution center US), pcs	200	50	50
Maximum inventory in the supply chain (distribution center China), pcs	-	120	120
Maximum inventory in the supply chain (Factory), pcs	240	240	240
Production and sourcing performance:			
Current backlog orders	0	0	0
Customer delayed orders	0	0	0
Customer dropped orders	0	1.0	1.0

Customer in-time orders	180.0	179.0	179.0
Customer orders	180.0	180.0	180.0
Customer orders arrived	180.0	179.0	179.0
Produced, pcs	3 960.0	3 605.0	3 605.0

Table 18 shows us the major impact of building a new distribution center is lower lead time. The SXC design with a new distribution center allows us to achieve the highest total profit with single and dual sourcing policy.

Chapter 4. Risk Management in Supply Chains

Our Learning Objectives

Our learning objectives for this chapter are to:

1. Develop analytical and management skills to analyze bullwhip and ripple effects in the supply chain;
2. Develop technical skills on batching, ordering rules and events;
3. Performing variation, comparison, and risk analysis experiments in AnyLogistix;
4. Understand major trade-offs in supply chain risk management.

Theoretical Background

Operational and disruption risks: Bullwhip effect and Ripple effect

Risk is a measure of the set of possible (negative) outcomes from a single rational decision and their probabilistic values. Supply chain risk management has become one of the most important topics in practice over the last two decades. This paper is devoted to risk management in the supply chain and the power of simulation to help supply chain managers make decisions regarding operational and disruption risks. In supply chain design and planning, we need to take uncertainty and risk into account as we develop problem statements and decision-oriented solutions. Recent literature suggests we need to consider recurrent or *operational* risks and *disruptive* risks (Dolgui et al. 2018, Ivanov 2018).

Risks in supply chains appear at different times and have different impacts on performance. High-frequency-low-impact disruptions are considered by the bullwhip-effect and refer to demand and lead-time fluctuations. The bullwhip effect considers weekly/daily demand and lead-time fluctuations as primary drivers of the supply chain changes which take place at the parametric level and can be eliminated in a short-term perspective. In light of low-frequency-high-impact disruptions, the ripple effect has also been identified as an important consideration (Ivanov et al. 2014).

In the last two decades, considerable advancements have been achieved in research regarding the mitigation of inventory and production shortages and the response to demand fluctuations. In particular, the *bullwhip-effect* in a supply chain subject to *randomness uncertainty* has been extensively studied with the help of stochastic and simulation models.

In recent years, the research community has also begun to investigate severe supply chain disruptions with long-term impacts that can be caused, for example, by natural disasters, political conflicts, terrorism, maritime piracy, economic crises, destruction of information systems, or transport infrastructure failures. When changes in the supply chain occur at the structural level as a result of natural and man-made disasters and recovery may take mid- and long-term periods of time with a significant impact on output performance, such as annual revenues, we refer to this as the ripple effect. In this context, supply chain disruption management is a critical capability which helps to create cost-efficient supply chain protection and facilitates the implementation of appropriate actions to recover from supply chain disruptions and performance.

The ripple effect, which deals with low-frequency-high-impact *disruption* or *exceptional risk*, is the inverse of the bullwhip effect, which considers for low-frequency-high-impact risks, which are *operational* and *recurrent*. Ivanov et al. (2014) were the first to explore the term in depth and define it as resulting “from disruption propagation of an initial disruption towards other SC stages in the supply, production, and distribution networks”. The ripple effect often quickly follows a singular disruption and consequences worsen with each new propagation (Dolgui et al. 2018, Ivanov 2018).

Let us consider in detail the different levels according to which the ripple effect in the supply chain can be investigated with the help of simulation research methodology.

Structural dynamics level

Randomness in disruptions. The first stage is to decide how to model the disruptions. Realistic estimations are important here in regard to the frequency and duration of disruptions. One possible option is to work with homogenous or heterogeneous probabilities of disruptions at different supply chain elements. The second option is to perform a preliminary analysis and to derive the most critical elements in the supply chain in regard to the ripple effect’s impact on supply chain performance. For these critical elements, random or scheduled disruption events can be modelled and the duration of the events actuated according to a probability distribution.

Randomness in recovery. The ripple effect’s impact on supply chain performance depends both on the severity of disruptions and the speed and scale of recovery actions. Recovery can be modelled in two basic ways. The simplest is to schedule different periods for capacity restoration and assign recovery costs such that the quickest recovery implies the highest recovery cost. The second is to program individual recovery policies and define the rules of recovery policy activation depending on the occurrence time, expected duration, and the severity of the disruption in regard to both local disturbances and ripple effect propagation and impact on supply chain performance.

Operational parameter dynamics level

Inventory, supply, production and transportation dynamics are major supply chain processes which are influenced by disruptions and recoveries and which, in turn, influence supply chain behavior and ripple effect severity. At this stage, inventory control policies, back-ordering rules, production batching and scheduling algorithms as well as shipment rules and policies need to be defined and balanced with each other for both normal and disrupted modes. Some preliminary analysis may be helpful in this area in regard to safety stocks, reorder points, etc.

Performance impact dynamics level

The direct impact of the ripple effect is reflected in the changes of key performance indicators (KPI). Revenue, sales, service level, fill rate, and costs are typically considered in this setting. A number of issues need to be addressed in this area. The first decision whether planned performance should be fully recovered or changes to KPI targets accepted. The second decision is whether the planned KPI targets should be recovered as soon as possible or at the end of the planning horizon. The final decision concerns how to aggregate the individual performance impacts of the ripple effect at different nodes and arcs in the network.

Simulation and optimization applications to supply chain risk management

Simulation and optimization are two dominant techniques in supply chain risk management. With the help of optimization and simulation, current research generates new knowledge about the influence of disruption propagation on supply chain output performance while considering disruption location, duration, and propagation and recovery policies.

Optimization models produce notable insights for managers and can be applied where the probability of disruption can be roughly estimated. Optimization studies on ripple effect analysis apply linear or non-linear mathematical programming approaches using mixed-integer programs. Using parametric variations, these models allow analysis of the impact of disruptions on supply chain performance. The optimization problem statements with multiple products and many periods consider inventory, backordering, and available capacity levels in settings with *redundancies,* such as backup suppliers, reserved capacity, and risk mitigation inventory, that satisfy demand at higher prices without the disrupted facility. Non-linear optimization models have been applied to develop a resilient supply chain topology that is able to recover from and react quickly to disruptions.

Naturally, simulation is used to study disruption propagation and the ripple effect in the supply chain, and existing studies account for the time and length of disruption in recovery policies. For complex problem settings with situational system behavior changes in time, simulation can be even more powerful than analytical closed form analysis.

Optimization and simulation studies on supply chain dynamics and disruptions differ from each other regarding problem statements, complexities, and analysis objectives. Optimization studies empower decision makers to determine performance impact and resilient supply chain redesign policies within rigorous analytical solutions. These studies consider a large variety of parameters, variables, and objectives. However, in many cases simulation can enlarge the scope of a ripple effect investigation.

In optimization studies, performance impact analysis has typically been performed for disrupted elements while assuming that other elements are not affected by that disruption and continue operation in the planned mode. Optimization studies typically reduce real complexity to obtain feasible solutions in a reasonable time. By nature, randomness and time-related factors of disruptions and recovery actions are difficult to represent in closed forms of mathematical equations.

Since ripple effect analysis includes both dynamic and static parametrical sets, the next objective of this study is to identify recommendations on the preferable applications of simulation and optimization methods. A rich diversity of knowledge has been developed for the integration of optimization and simulation methods for managing supply chain disruptions and the ripple effect. However, analysis of the research reviewed shows that knowledge and findings are diversified, but still fragmented and contextually-limited across the literature. Thus, this section aims to explore how combinations of optimization and simulation can enhance decision-making in the age of risk analytics.

Ivanov et al. (2018) identified several problem classes and datasets for which optimization, simulation, and hybrid optimization-simulation methods can be recommended. The following classification have been obtained (Figure 125).

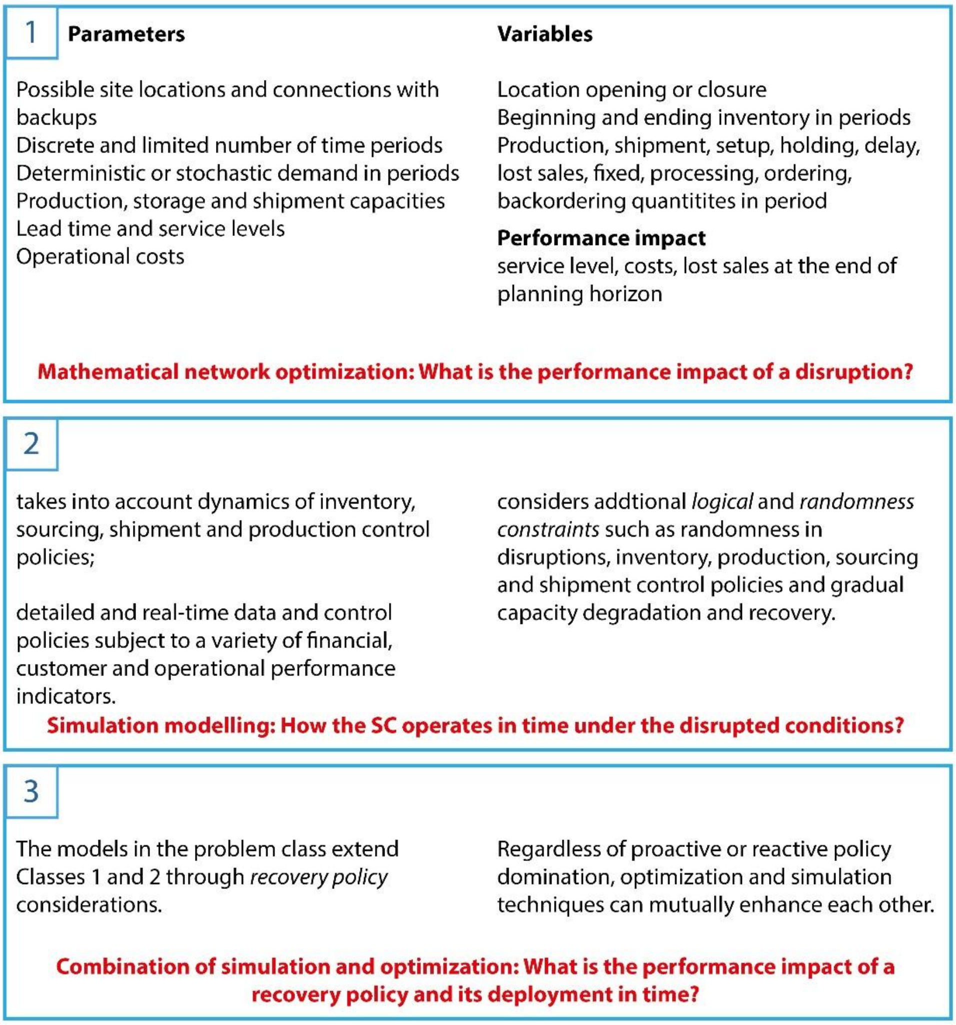


Figure 125: Three problem classes in the ripple effect analysis

Let us consider these three classes of ripple effect analysis in detail.

Problem class 1. Static ripple effect analysis

The models in the problem class allow computation of the performance impact of disruption and recommendation of a resilient supply chain design based on aggregate location and flow data subject to cost minimization or profit maximization. This problem class considers the following dataset:

Parameters

- Possible site locations and connections (nodes and paths) with back-ups
- Discrete and limited number of time periods
- Deterministic or stochastic demand in periods
- Production, storage, and shipment capacities in periods
- Lead time and service levels
- Operational costs

Variables

- Location opening or closure
- Beginning and ending inventory in periods
- Production, shipment, setup, holding, delay, lost sales, fixed, processing, ordering, backordering quantities in periods

Performance impact: service level, costs, lost sales at the end of planning horizon

Network optimization has typically been used for this class. These models are done on the supply chain design level and assist analysis of the impact of disruptions on supply chain performance by deactivating some structural elements, changing some operational parameters (e.g., capacity), and observing the resulting changes on costs or sales. This analysis is helpful at the strategic decision-making level. At the same time, these models do not take into account the dynamics of inventory, sourcing, shipment, and production control policies.

Problem class 2. Dynamic ripple effect analysis

The models in the problem class allow supply chain behavior to be analyzed over time, computation of the performance impact of the disruption, and recommendation of a resilient supply chain design based on detailed and real time data and control policies subject to a variety of financial, customer, and operational performance indicators. In addition to the more detailed data from the Class 1 dataset, this problem class considers additional *logical* and *randomness constraints,* such as randomness in disruptions, inventory, production, sourcing, and shipment control policies, and gradual capacity degradation and recovery. For problems in this class, simulation has been dominantly applied. Since simulation studies on the ripple effect deal with time-dependent parameters, duration of recovery measures, and capacity degradation and recovery, they have earned an important place in academic research. Simulation has the advantage that it can extend the handling of the complex problem settings in Class 1 with situational behavior changes in the system over time.

Problem class 3. Dynamic ripple effect analysis with recovery considerations

The models in this problem class extend Classes 1 and 2 through recovery policy considerations. Independent of proactive or reactive policy domination, optimization and simulation techniques can mutually enhance each other. For problems in this class, a combination of network optimization and simulation (e.g., simulation runs over optimization results) is recommended. An integrated optimization-simulation framework with consideration of disruption risks and ripple effect is shown in Figure 126. More specifically, two problems are integrated within the framework. The first problem is network optimization to minimize total supply chain cost. The second problem is dynamic analysis of ordering, production, inventory, and sourcing control policies using simulation.

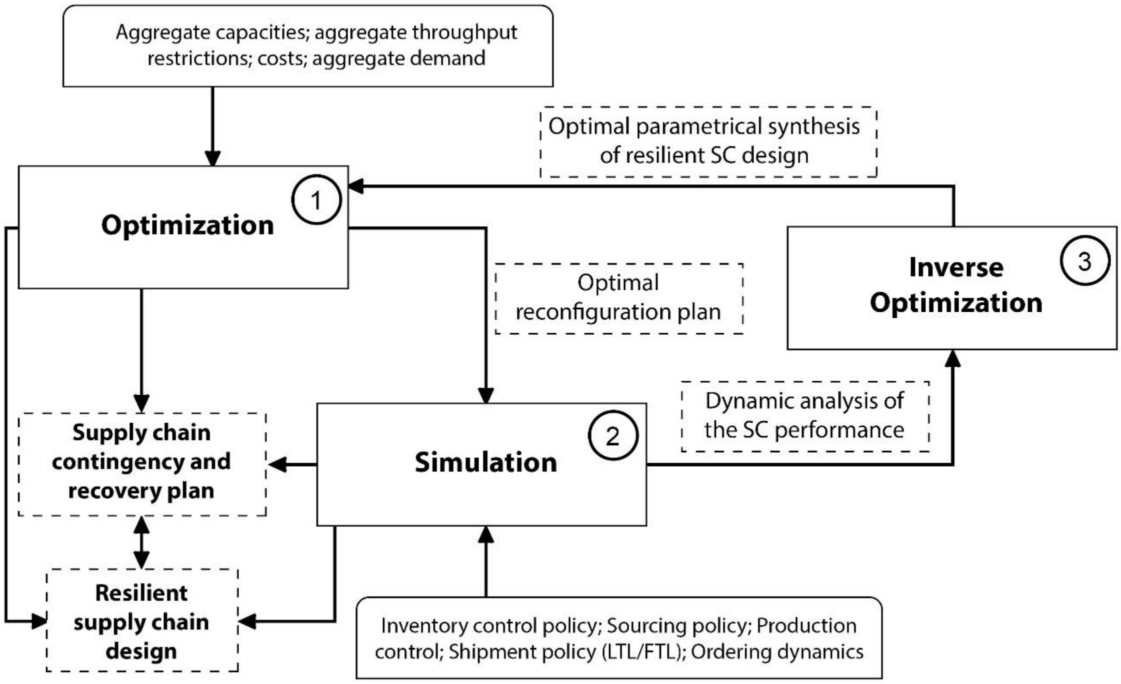


Figure 126: Integrated simulation-optimization modeling of resilient supply chain

According to Figure 126, the first step is to set and solve a multi-period, multi-stage network optimization problem. The second step is to set and experimentally run simulations to investigate the dynamics of the aggregate flows found in step 1.

Severe disruptions may ripple quickly through global supply chains and cause significant losses in revenue, sales, service level and total profits. These risks are a challenge for industries that face the *ripple effect* that arises from vulnerability, instability and disruptions in supply chains (Ivanov et al. 2014).

We can talk about ripple effect in a supply chain if a disruption at a supplier or a transportation link spreads to other parts of the supply chain. Unlike the well-known bullwhip effect that considers high-frequency-low-impact *operational risks*, the ripple effect studies low-frequency-high-impact *disruptive risks* (Table 20).

Table 20: Bullwhip effect and ripple effect.

Feature	Ripple Effect	Bullwhip Effect
Risks	Disruptions (for example, an explosion)	Operational (for example, a demand fluctuation)
Affected areas	Structures and critical parameters (such as supplier unavailability or lost sales)	Operational parameters such as lead-time and inventory
Recovery	Middle- and long-term; significant coordination efforts and investments	Short-term coordination to balance demand and supply
Decreased performance	Output performance such as annual sales or profits	Current performance such as stock-out/overage costs

Ripple effect describes the impact of a disruption on supply chain performance, disruption propagation, and disruption-based scope of changes in the supply chain structures and parameters (Ivanov 2017). The ripple effect's scope and its impact on economic performance depends on the amount in reserve (for example, redundancies like inventory or capacity buffers), flexibility in products and processes, disruption duration, and speed and scale of recovery measures.

The ripple effect is a phenomenon of disruption propagations in the supply chain and their impact on output supply chain performance (for example, sales, on-time delivery and total profit). If a disruption occurs in the supply chain, three questions are important:

- What is the disruption's impact on operational and financial performance?
- What parts of the supply chain are affected by the disruption (that is, what is the scope of disruption propagation)?
- Is stabilization or recovery needed? If yes, what changes are necessary? When are those changes necessary?

Two basic approaches to hedging supply chain against the negative impacts of disruptions – *proactive* and *reactive*. A proactive approach creates certain protections and takes into account possible perturbations during the supply chain design. A reactive approach aims to adjust supply chain processes and structures in the presence of unexpected events.

It is natural to use *simulation* to study the disruption propagations and ripple effect in the supply chain considering time and length of disruptions and recovery policies.

Bullwhip Effect in the Supply Chain: Our Case-Study

We consider a supply chain for beer production and distribution made up of a supplier, a brewery, a distribution center and a customer (Figure 127).

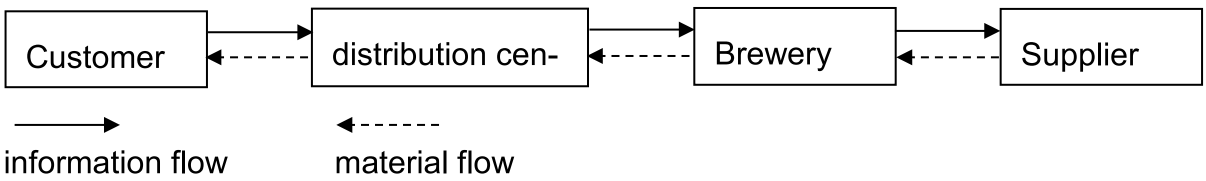


Figure 127: Supply chain structure.

The customer demand (in units) fluctuates and is distributed over 36 days (Table 19).

Table 19: Demand distribution by periods

1-5	6-10	11-15	16-20	21-25	26-30	31-35	36
4	4	9	7	11	14	8	9
4	4	7	8	9	8	11	
4	10	8	6	4	9	7	
2	11	6	10	11	6	9	
5	7	10	7	9	9	10	

Experiment and Bullwhip Effect Analysis

Supply Chain Design and Policies

First, we create a new scenario (**BWE**) and set up the locations (Figure 128).

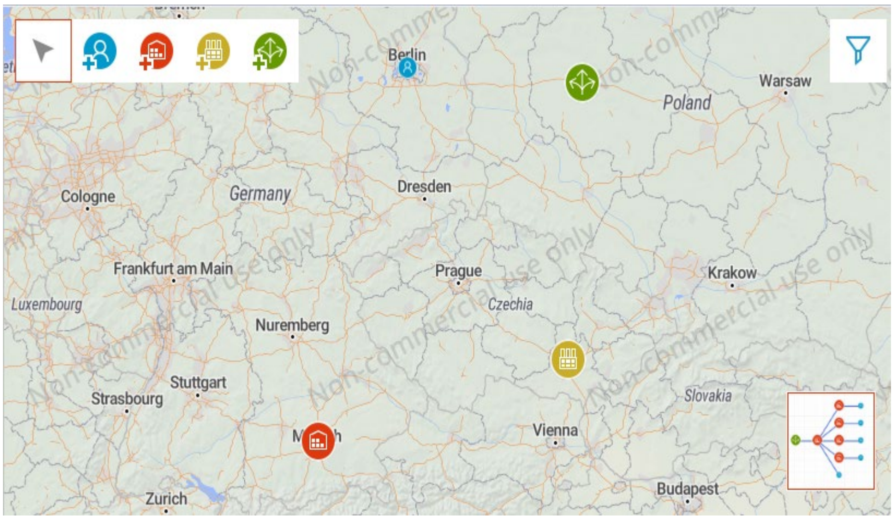


Figure 128: Our scenario's supply chain locations.

Our next step is to create a new product (**Beer**) and a new vehicle (**Truck**), and set up demand (**historic demand**), inventory control policy (**Min**=5; M**ax**=20), and sourcing policy and production time (Figures 129-136).

#	Name	Unit	Selling Price	Cost	Cost Unit
1	Beer	pcs	2	1	USD

Figure 129: Product.

#	Product	Amount from	Unit from		Amount to	Unit to
1	Beer	1	pcs	=	0.001	m³

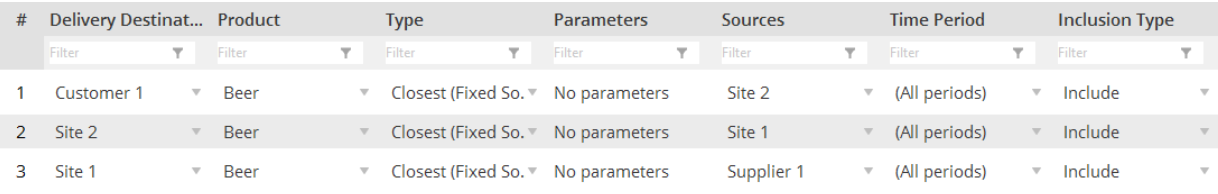
Figure 130: Unit Conversions.

#	Name	Capacity	Capacity Unit	Speed	Speed Unit
1	Truck	6	m³	50.0	km/h

Figure 131: Vehicle Type.

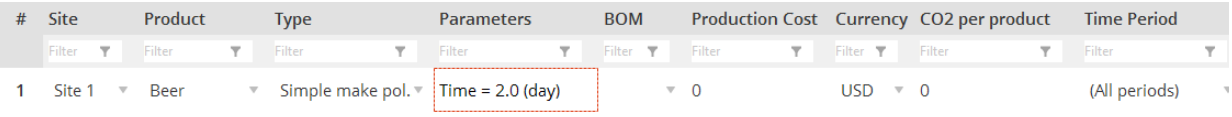
#	From	To	Cost Calculation	Cost C...	CO2 ...	Curre...	...	Dista...	Transp...	Time ...	Straight	Vehicle ...	Transportation P...	Min
1	Supplier 1	Site 1	Fixed delivery	0	0	USD	0	km	3	day		Truck	LTL	0
2	Site 1	Site 2	Fixed delivery	0	0	USD	0	km	2	day		Truck	LTL	0
3	Site 2	Custom.	Fixed delivery	0	0	USD	0	km	1	day		Truck	LTL	0

Figure 132: Transportation policy(Paths).



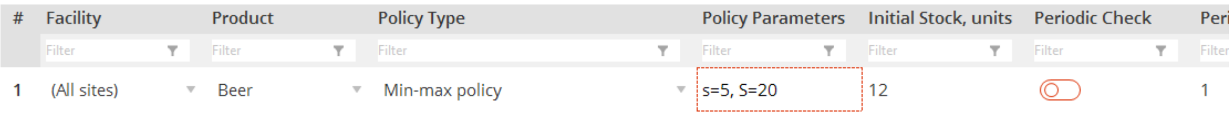
#	Delivery Destinat...	Product	Type	Parameters	Sources	Time Period	Inclusion Type
1	Customer 1	Beer	Closest (Fixed So.	No parameters	Site 2	(All periods)	Include
2	Site 2	Beer	Closest (Fixed So.	No parameters	Site 1	(All periods)	Include
3	Site 1	Beer	Closest (Fixed So.	No parameters	Supplier 1	(All periods)	Include

Figure 133: Sourcing policy.



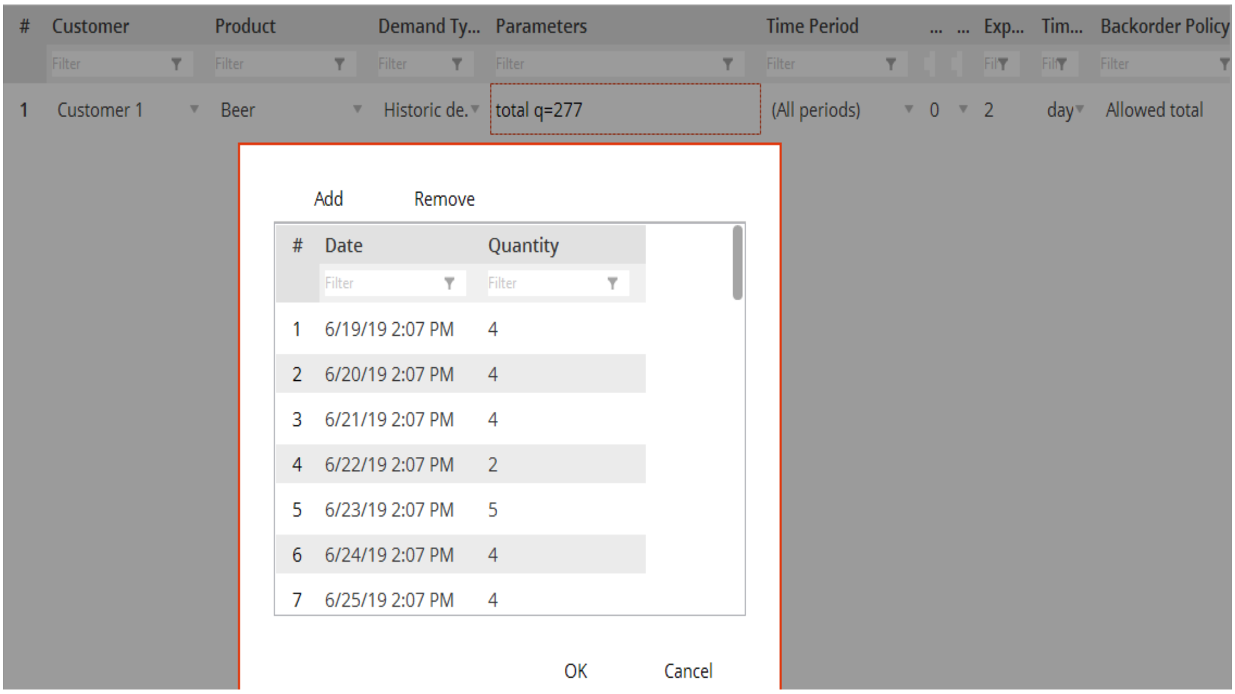
#	Site	Product	Type	Parameters	BOM	Production Cost	Currency	CO2 per product	Time Period
1	Site 1	Beer	Simple make pol.	Time = 2.0 (day)		0	USD	0	(All periods)

Figure 134: Production policy.



#	Facility	Product	Policy Type	Policy Parameters	Initial Stock, units	Periodic Check	Peri
1	(All sites)	Beer	Min-max policy	s=5, S=20	12		1

Figure 135: Inventory control policy.



#	Customer	Product	Demand Ty...	Parameters	Time Period	...	...	Exp...	Tim...	Backorder Policy
1	Customer 1	Beer	Historic de.	total q=277	(All periods)	0		2	day	Allowed total

#	Date	Quantity
1	6/19/19 2:07 PM	4
2	6/20/19 2:07 PM	4
3	6/21/19 2:07 PM	4
4	6/22/19 2:07 PM	2
5	6/23/19 2:07 PM	5
6	6/24/19 2:07 PM	4
7	6/25/19 2:07 PM	4

Figure 136: Demand data.

Note *backordering* is allowed in this case.

KPI Dashboard

For bullwhip effect analysis, we design the following two-part KPI dashboard (Figures 137 and 139).

Figure 137: KPI dashboard for bullwhip-effect analysis.

The **Demand Received(Products) / Demand Placed (Products) by Site** diagrams will display the quantities of incoming and outgoing deliveries. The program's computation of the variation of incoming and outgoing deliveries allows us to compute the BWE (bullwhip-effect) index as shown in Figure 138 (based on Heizer and Render 2014).

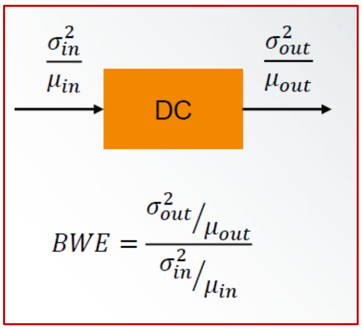


Figure 138: BWE computation

The **Products bullwhip effect** diagram will use the BWE index. If the BWE measure is:

> 1 – Variance amplification is present

= 1 – No amplification is present

< 1 – Smoothing or dampening is occurring

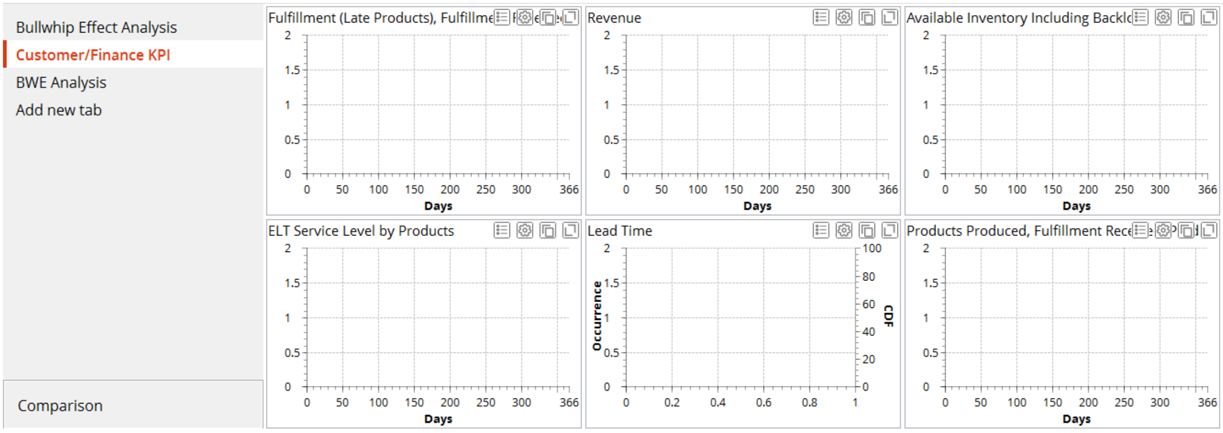


Figure 139: Dashboard with customer and financial KPI.

Experiments and Result Analysis

We start a new simulation experiment for the data described in the case study. You'll find our results in Figures 140-142.

Figure 140: Customer and financial KPI.

Figure 141: KPI dashboard for bullwhip-effect analysis.

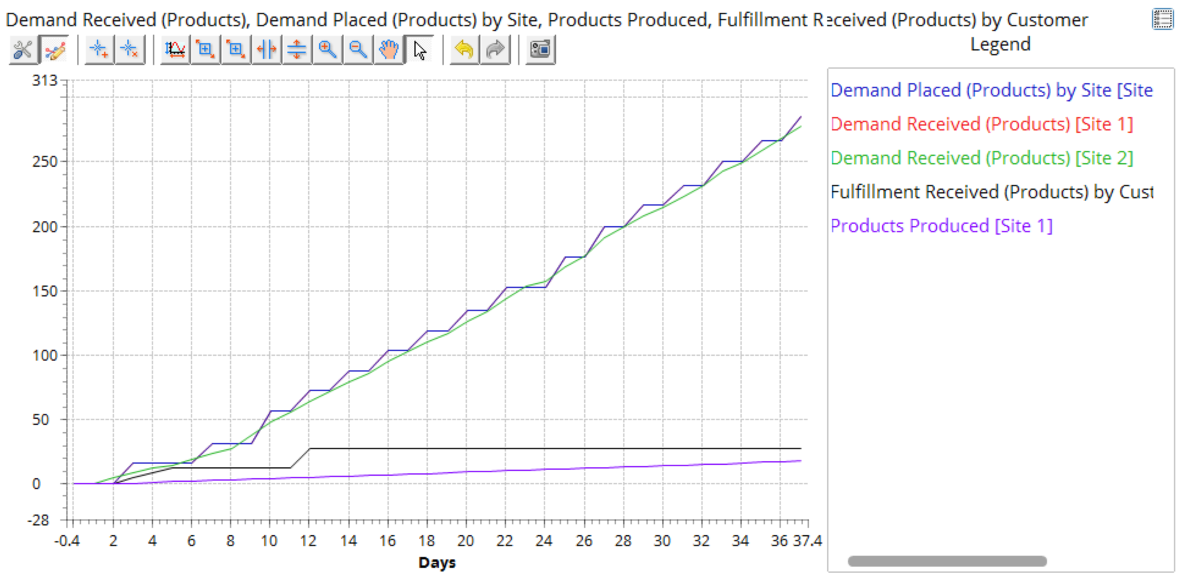


Figure 142: A detailed view of bullwhip-effect analysis.

We can see two things in Figure 140: our revenue was $54 and our already-low service level is decreasing. The one to seven-day lead time for some orders is increasing both the number of delayed products and the backlog. We can see the production speed is very low compared to the incoming customer orders. Moreover, Figures 141 and 142 show us the supply chain does not display a bullwhip effect. The variability of delivered quantities is decreasing.

Note: The **Products bullwhip effect** diagram is cumulative.

The simulation shows our supply chain has two major problems: our inventory is too low and our production time is too long. We'll use the following parameters to conduct the next experiment:

- Production time is changed from 2 days to 0.1 day;
- Min-Max levels are changed from 5-20 to 20-40.

Figures 143-144 display our results:

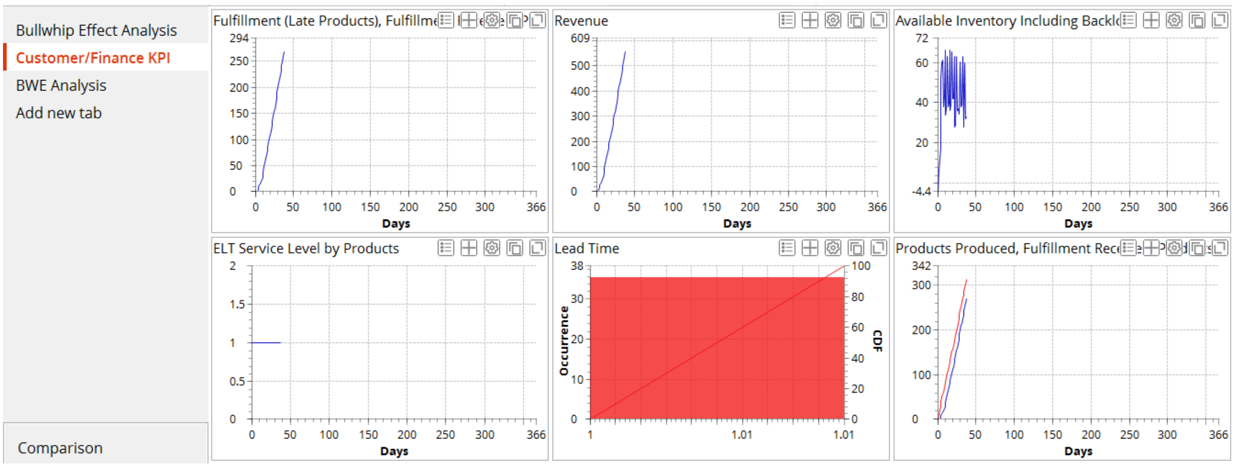


Figure 143: Customer and financial KPI.

Figure 144: KPI dashboard for bullwhip-effect analysis.

Figure 143 shows us we received a revenue of more than $500 (compared to $54 in the initial supply chain), our service level is 100% and our lead time is 1 day. This results in 100% on-time delivered products and no backlog: we can see production speed is aligned with the incoming customer orders.

Moreover, Figure 144 shows the supply chain does not display a bullwhip effect. The variability of delivered quantities is decreasing. By comparing the results from the two experiments, you can see the second setting has reduced the BWE.

Batching and Ordering Rules

Knowing production, sales and transportation quantities can be batched, we'll review how to set up batching and ordering rules and analyze their effect on the bullwhip effect.

Transportation Batches

To aggregate transportation orders to a batch, we use the **Paths** table to set up the amount of time or a minimum load (Figure 145).

#	From	To	Cost Calc...	Cost ...	CO2 ...	Currency	D...	Distan...	Tran...	Time ...	Straight	Vehicle...	Trans...	Min L...	Aggre...	Aggregation Peri
	Filter	Filter	Filter	Filt	Filter	Filter		Filter	Filt	Filter	Filter	Filter	Filter	Filter	Filter	Filter
1	Supplier 1	Site 1	Fixed de.	0	0	USD	0	km	3	day		Truck	LTL	0		1
2	Site 1	Site 2	Fixed de.	0	0	USD	0	km	2	day		Truck	LTL	0		5
3	Site 2	Customer 1	Fixed de.	0	0	USD	0	km	1	day		Truck	LTL	0		1

Figure 145: Transportation order aggregation

In Figure 145, we used the **Aggregation Period** column to set a five-day aggregation period for shipments from the factory to the distribution center. This means our simulation will batch five days of shipments. As an alternative, we could have used a batching rule that set the minimum load of trucks. As an example, we could enter 0.6 to set the minimum truck capacity to 60%. (cf. Sect. 1.6.3).

Sales and Production Batches

We need to set up the batch sizes in **Sales Batch** and **Production Batch**, respectively (Figures 146-147) to batch sales and production orders.

#	Source	Product	Type	Batch Size	Step Size	Price (per unit)	Price (per batc...	Currency	Time Period
	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter
1	Site 2	Beer	Exact	5	5	2	10	USD	(All periods)

Figure 146: Setting sales batch sizes.

#	Source	Product	Type	Batch Size	Step Size	Round ...	Production Cost ...	Production Cost (...	Currency	Production Time (...	Production Time (...	Time Unit
	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter
1	Site 1	Beer	Exact	10	0		1	10	USD	0.05	0.5	day

Figure 147: Setting production batch sizes.

In Figure 146, we set up a sales batch with a size of 5 units and a size step (that is, the amount the batch can be increased) of 5 units. In Figure 147, we set up a production batch with a size of 10 units and a size step of 0.

Our production batch function uses the following rule:

- Inventory policy for finished goods warehouse tells how much to order (Q)
- If **Production batch** > Q, then nothing is produced
- If **Production batch** < Q, then the factory produces the closest number of products using the policies we defined for the batch but not more than Q.

Example 1: Batch: 100; Q=90 → Nothing produced

Example 2: Batch: 100, Size step: 100, Q: 290 → factory will produce 200 and the rest 90 will be added to the next order

Ordering Rules

We use the **Ordering rules** table to set the batch size requirements (Figure 148).

#	Destination	Product	Rule	Limit, units
1	Customer 1	Beer	Can Increase	5
2	Customer 1	Beer	Can Decrease	5
3	(All sites)	Beer	Can Increase	5
4	(All sites)	Beer	Can Decrease	5

Figure 148: Ordering rules.

- **Destination** – defines the product destination
- **Product** – defines the product
- **Rule** – allows to choose an ordering rule

Can Increase – allows an increase in order size up to the number in the **Limit** column
Can Decrease – allows a decrease in order size up to the number in the **Limit** column

- **Limit, units** – the number of units within the order size can be adjusted

In our example, we allow five-unit increases and decreases in batch size.

Impact of Batching and Ordering Rules on Bullwhip Effect

In this section, we'll perform a simulation experiment that uses the batching and ordering rules we described above. First, we aggregate transportation orders for five days.

Note: We increased the transportation quantity, but we also need to increase the inventory control policy's MAX-Level. If we do not, an insufficient warehouse capacity will stop our simulation experiment. We should also increase the MIN-level to account for the increased replenishment interval.

We change the inventory control policy parameters from 20-40 to 50-100. Figures 149 and 150 display our results:

Figure 149: KPI dashboard for bullwhip effect analysis.

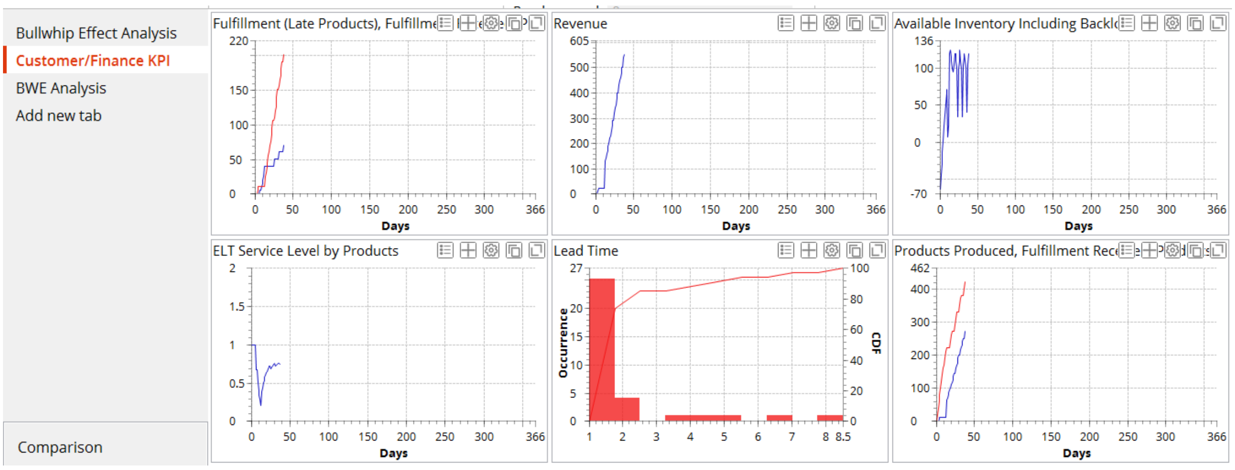


Figure 150: Customer and financial KPI.

Figure 150 shows us we received more than $500 of revenue and our service level is very low. With our lead time unequally distributed between 1 and 9 days, we can see the transportation batch rule is not aligned with the incoming customer orders, an issue which leads to a backlog and a reduced service level.

Moreover, Figure 149 shows the bullwhip effect in the supply chain started on day 10. The variability of delivered quantities increases from day 10 because the quantities of incoming products that arrive at the distribution center exceed the outgoing deliveries.

This experiment shows us batching can lead to bullwhip effect. But what will happen if we increase our maximum stock level from 100 to 200? Figures 151-152 display our simulation's results.

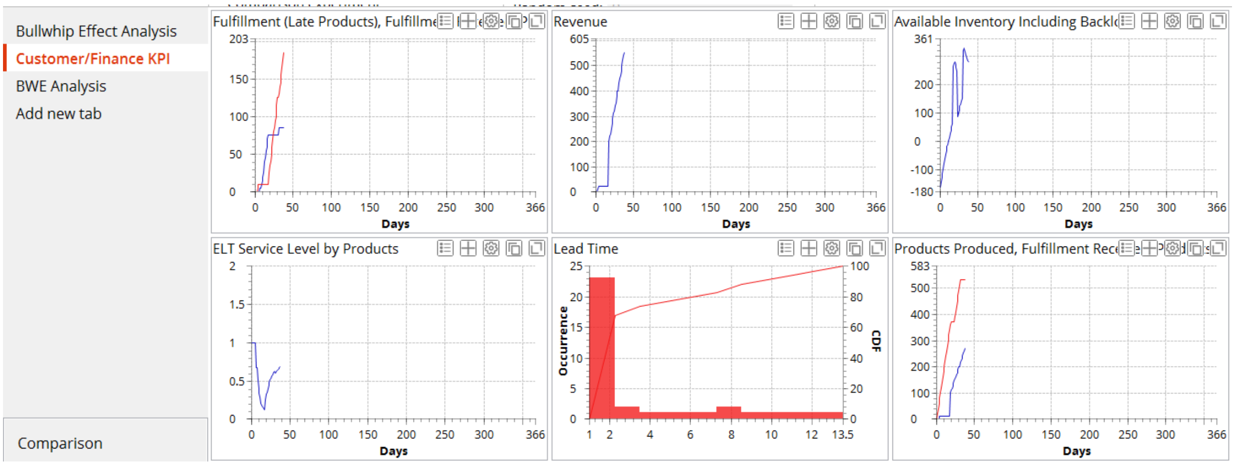


Figure 151: Customer and financial KPI.

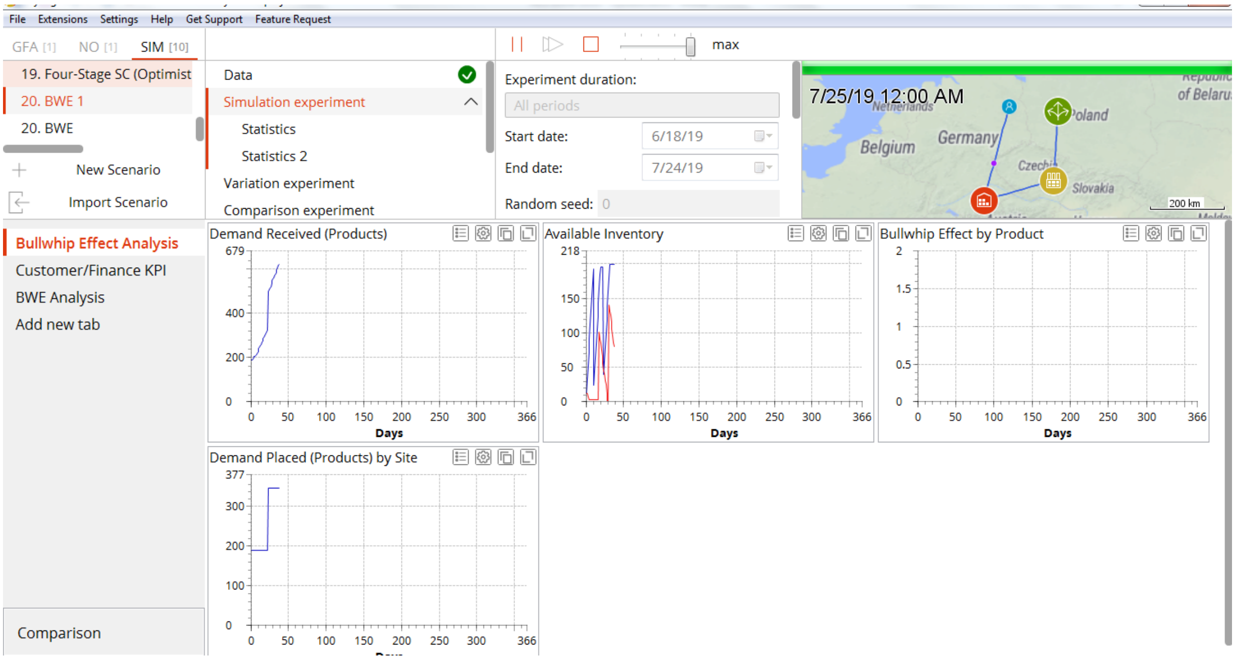


Figure 152: KPI dashboard for bullwhip-effect analysis.

Figure 151 shows us our revenue hasn't changed and our service level is low. The lead time is unequally distributed between 1 and 13 days, which results in an increasing number of delayed products and a backlog. Our transportation batch and inventory control rules--that are not aligned with the incoming customer orders--has led to a backlog and a lower service level.

However, Figure 151 also shows us the bullwhip effect has reduced. The variability of incoming products to the distribution center is balanced with outgoing deliveries. This experiment show us an inventory increase leads to a reduced bullwhip effect.

Finally, we perform simulation experiment using sales and production batching and ordering (cf. Figures 146-148). There are no transportation batches and inventory MIN-MAX levels are 20-40, respectively. We copy the **BWE** scenario and use the new **Copy of BWE** scenario for this simulation. Figures 153-154 show the results.

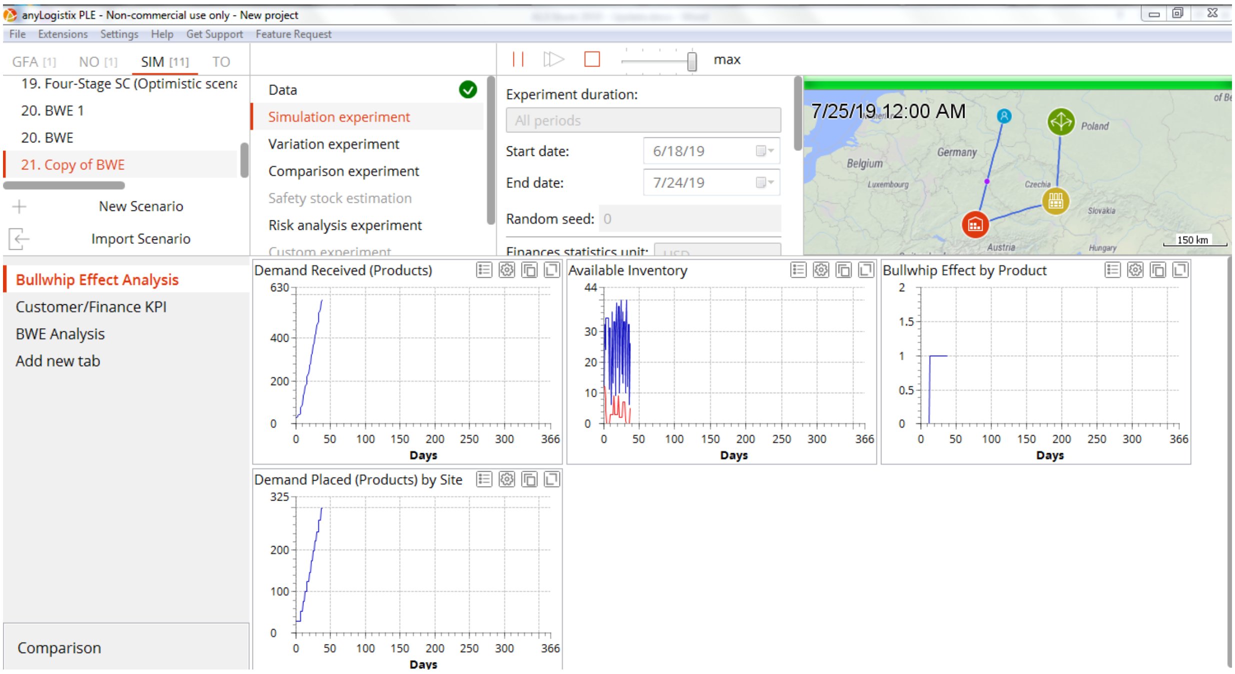


Figure 153: KPI dashboard for bullwhip-effect analysis.

Figure 154: Customer and financial KPI.

Figure 154 shows us we received less than $500 of revenue and our service level is low. With lead time between 1 and 6 days, we can see our production speed aligns with the incoming six orders and our supply chain does not have a bullwhip effect. The variability of delivered quantities is decreasing.

Comparison Experiment

A convenient way to compare the KPI and statistics of experiments is the **Comparison** experiment that allows us to compare supply chain structures.

To perform a comparison, we need to select scenarios for our comparison and use the **Configure statistics** table to activate the respective KPI. Our comparison of the experiments (cf. Figures 143-144 and 152-154) gives us the following results (Figures 155-156).

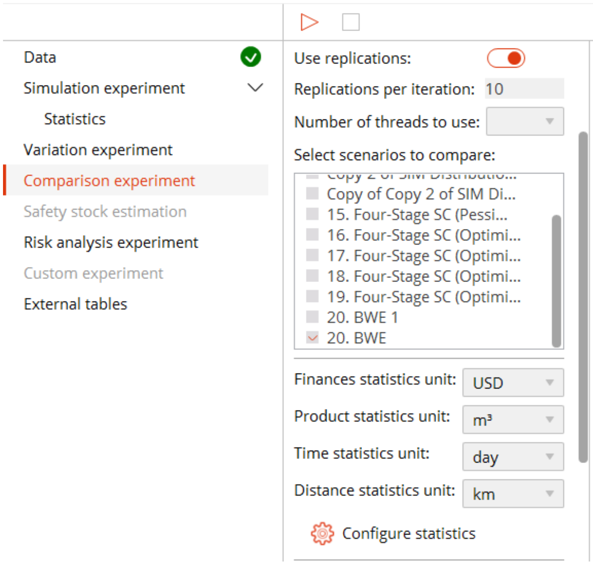
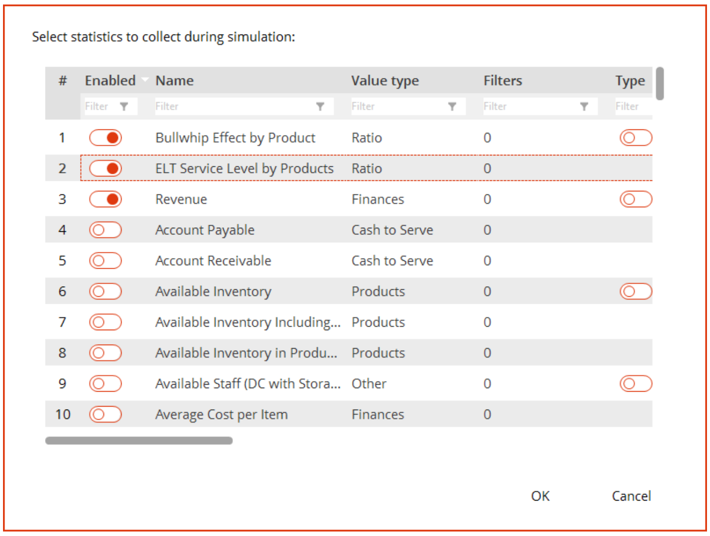


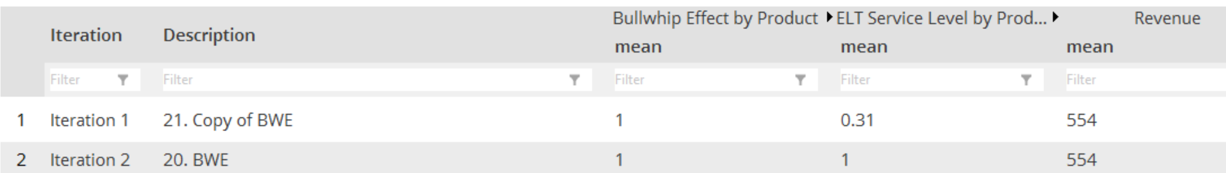
Figure 155: Selecting supply chain scenarios for our comparison experiment.


Select statistics to collect during simulation:

#	Enabled	Name	Value type	Filters	Type
1	on	Bullwhip Effect by Product	Ratio	0	
2	on	ELT Service Level by Products	Ratio	0	
3	on	Revenue	Finances	0	
4	off	Account Payable	Cash to Serve	0	
5	off	Account Receivable	Cash to Serve	0	
6	off	Available Inventory	Products	0	
7	off	Available Inventory Including...	Products	0	
8	off	Available Inventory in Produ...	Products	0	
9	off	Available Staff (DC with Stora...	Other	0	
10	off	Average Cost per Item	Finances	0	

OK Cancel

Figure 156: Selecting statistics for our comparison experiment.



	Iteration	Description	Bullwhip Effect by Product mean	ELT Service Level by Prod... mean	Revenue mean
1	Iteration 1	21. Copy of BWE	1	0.31	554
2	Iteration 2	20. BWE	1	1	554

Figure 157: A comparison for three KPI.

Figure 157 shows us the Comparison experiment is a useful tool for comparing the KPIs from different scenarios without running full simulations. In this case, we see batching (the **Copy of BWE** scenario) leads to a service level reduction from 100% to 31%.

Ripple Effect in the Supply Chain

Case Study: A Distribution Center Stops Working for a Month

The goal of this case study is to show you how you can use anyLogistix to perform a disruption risk analysis.

Consider the smartphone supply chain described in Sect. 5.1-5.2 and Figure 93. A fire disrupts a U.S.-based distribution center and prevents it from making or accepting deliveries during the one-month recovery time. The supply chain manager needs to estimate the disruption's impact on the supply chain performance for the following KPI:

- Products received (incoming orders)
- Products delivered (outgoing orders)
- Expected magnitude (that is, lost sales)
- Customer service level

Afterward, the supply chain manager needs to select the most efficient proactive and reactive strategies. He or she can use two proactive strategies: an inventory increase in the supply chain and a backup distribution center or two reactive strategies: fast and expensive distribution center recovery and slow and efficient distribution center recovery.

Events

We change the inventory policy at distribution center to s=100, S=200 and then use the **Event** option (Figure 158) to create a disruption in the supply chain simulation model.

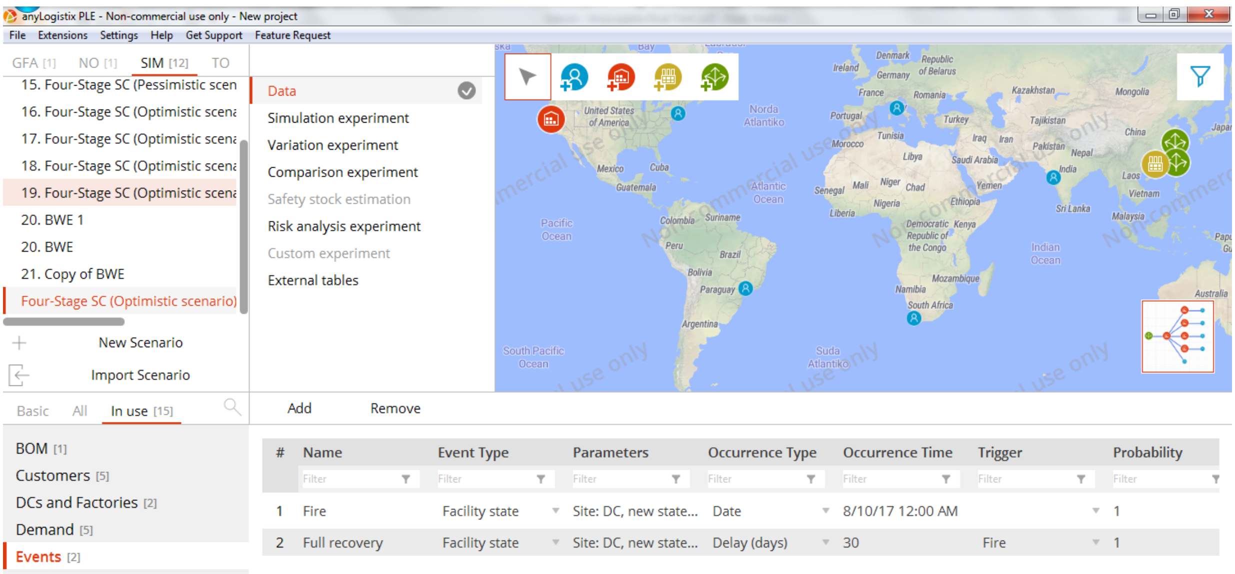


Figure 158: Events as disruptions in the supply chain.

You use the **Events** table to dynamically open and close supply chain sites or change demand:

- **Name** – Name of the event
- **Event type** – The type of the event, which defines an object's parameter that will change when the event occurs.
- **Parameters -** The value that is assigned to the parameter when the event occurs
- **Occurrence type** – The event occurrence type, which defines when the event will occur.
  - ➢ *Date* – the event will occur on the specified date
  - ➢ *Random* – the period of time, within which the event will occur at random.
  - ➢ *Delay* – the event occurrence will be delayed for the number of days specified in the **Occurrence Time** column.
- **Occurrence time** – The event occurrence time, which you set according to the event's **Occurrence Type.**
- **Trigger** – A trigger is a condition that schedules an event. If an event is not triggered, it will not occur.
- **Probability** - The probability value (between 0 and 1) of the current event to occur.

Events is a powerful function that allows us to model conditions such as:

- Seasonality
- Closing/opening sites
- Closing/opening paths
- Some paths may be available only during winter time
- Change the demand for a particular customer
- One Event may be triggered by another Event that allows you to model very complex behavior
- We may add their own Event through extension of anyLogistix with AnyLogic

In our case, we created two events. The first event – **Fire** – takes place at a specific time: August 10, 2017. In the **Parameters** column, we switch off the distribution center on this date. The second event – **Full recovery** – switches on the distribution center after a 30-day delay triggered by the first event **Fire**.

Simulation Experiment for Ripple Effect

Let's analyze how the disruption at the distribution center will affect the following KPI:

- Products received (incoming orders)
- Products delivered (outgoing orders)
- Expected magnitude (that is, lost sales)
- Customer service level

First, we run the simulation experiment for the non-disruption case (that is, we set the probabilities in the **Events** tab to **0**), see Figure 159.

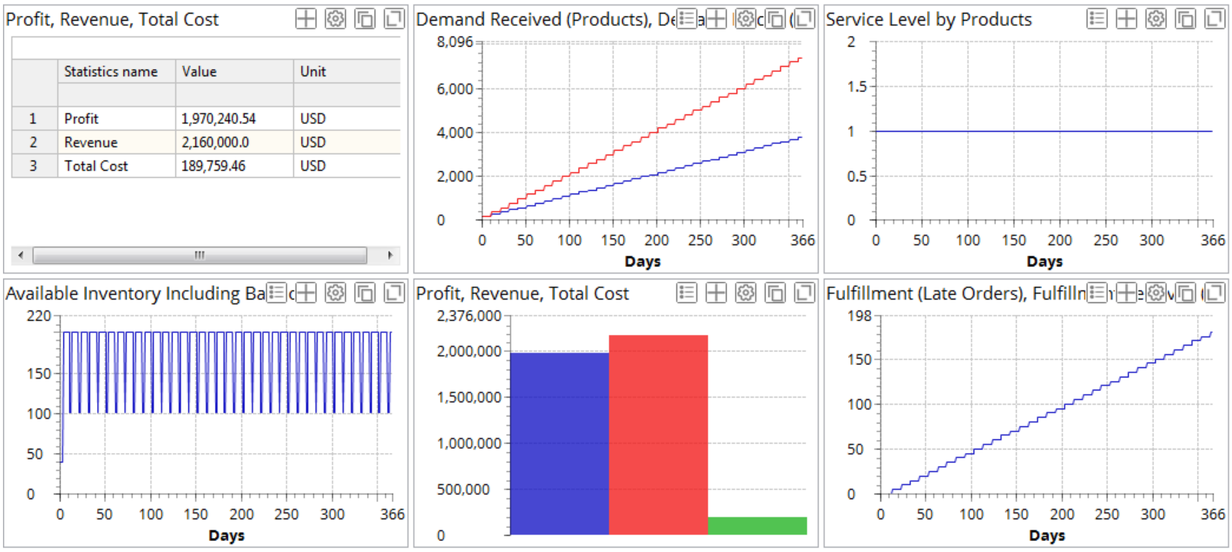


Figure 159: Simulation results for the non-disruption case.

We can see the opportunity to receive a profit of $1,970,240.54 and total revenue of $2,160,000.0. The service level is 100% and there is no interruption in replenishment and customer-in-time orders.

Second, we perform the simulation experiment for the disruption case (that is, we set the probabilities in the **Events** tab to **1**). see Figure 160.

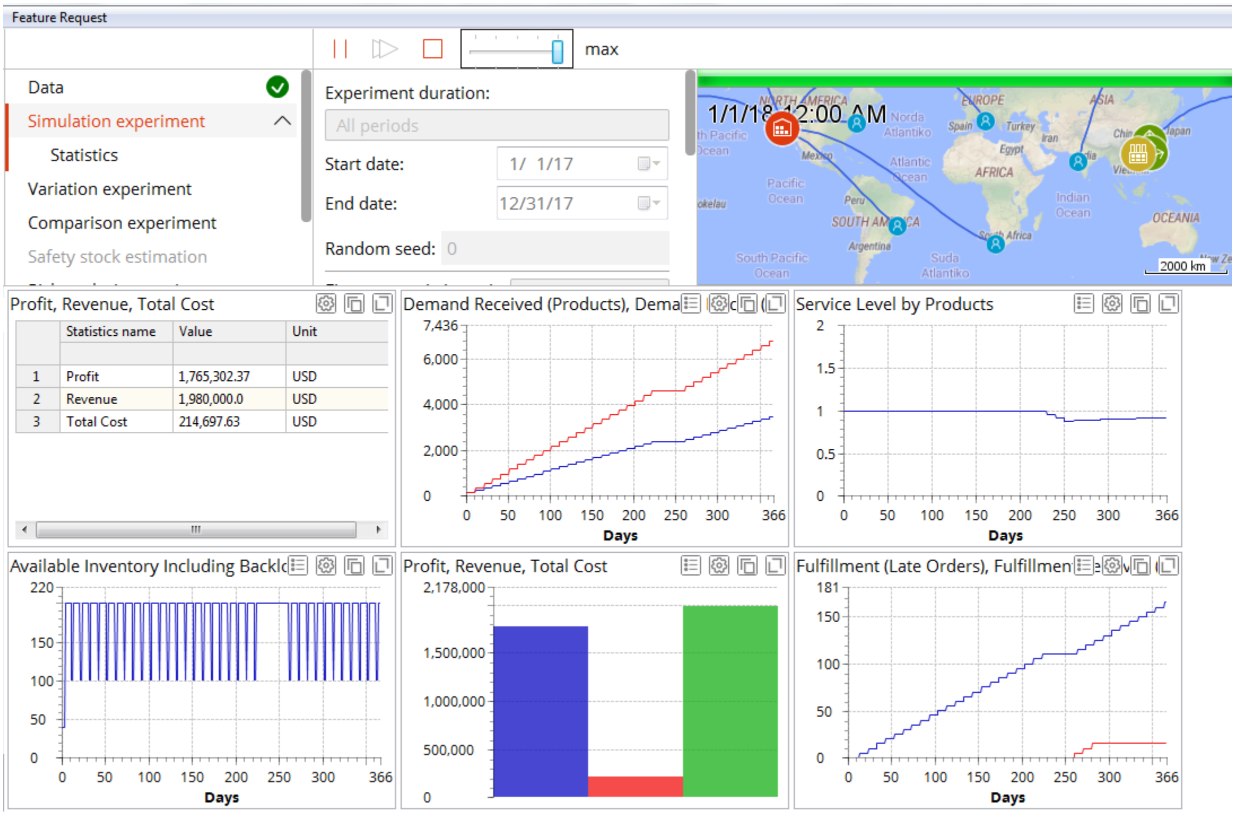


Figure 160: Simulation results for the disruption case.

Figure 160 displays a profit of $1,765,302.37 (instead of $1,968,173.76) and total revenue of $1,980,000.0 (instead of $2,160,000.0) due to an interruption in replenishment and customer-in-time orders.

Analysis of Proactive and Reactive Policies

The supply chain manager needs to select the most efficient proactive and reactive strategies. They can opt for proactive strategies such as an inventory increase in the supply chain and a backup distribution center. They can also apply reactive strategies, including a fast and expensive distribution center recovery and a slow and efficient distribution center recovery.

Impact of Inventory Increase

We change the distribution center's inventory policy from s=100, S=200 to s=100, S=400. Figure 161 shows our simulation's results:

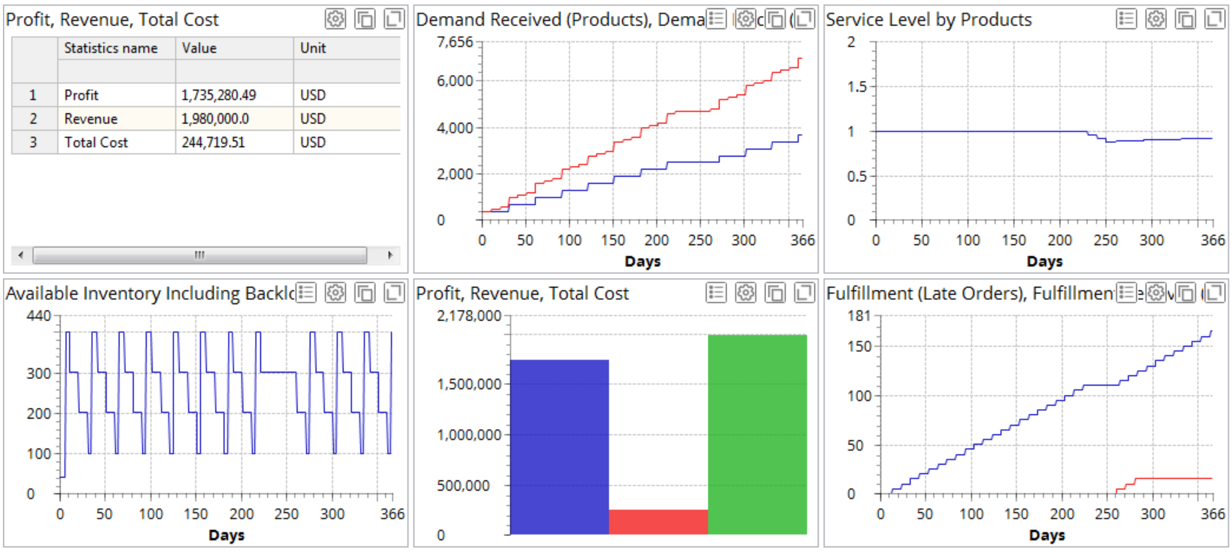


Figure 161: Impact of the change to the distribution center's inventory policy from s=100, S=200 to s=100, S=400.

Figure 161 shows the supply chain's performance could not be improved. In fact, higher opportunity costs have reduced our supply chain's performance. We can see inventory increase is sensible downstream but not at this point.

What would happen to the supply chain if the area within the distribution center that accepts incoming deliveries was destroyed? What effect would the inventory increase have if the distribution center's storage and outgoing areas operated normally? How would you simulate this in anyLogistix?

Impact of a Backup Distribution Center

We now add a backup distribution center near the main distribution center. This distribution center isn't part of our normal supply chain, but it's available should the need arise. We define this policy by new events 3 and 4 (Figure 162).

#	Name	Event Type	Parameters	Occurrence Type	Occurrence Time	Trigger	Probability
1	Fire	Facility state	Site: DC, new state: Temporarily closed	Date	8/10/17 12:00 AM		1
2	Full recovery	Facility state	Site: DC, new state: Open	Delay (days)	30	Fire	1
3	In back-up DC	Facility state	Site: Back-up DC, new state: Open	Date	8/10/17 12:00 AM	Fire	1
4	Out back-up DC	Facility state	Site: Back-up DC, new state: Temporarily clos...	Date	9/10/17 12:00 AM	In back-up DC	1

Figure 162: New events for backup distribution center.

The capacity *flexibility* is costly: the backup distribution center creates initialization costs of $40,000 (Figure 163).

#	Facility	Expense Type	Value	Currency	Time Unit	Product Unit	Time Period
1	Back-up DC	Initial cost	40,000	USD			(All periods)

Figure 163: Data for backup distribution center.

We also need to extend the sourcing, inventory and transportation policies for the backup distribution centre (Figures 164-166).

#	Delivery Destinat...	Product	Type	Parameters	Sources	Time Period	Inclusion Type
1	Factory	Display	Closest (Dynami..	No parameters	Supplier China	(All periods)	Include
2	Factory	Chip	Closest (Dynami..	No parameters	Supplier Taiwan	(All periods)	Include
3	DC	Smartphone	Closest (Dynami..	No parameters	Factory	(All periods)	Include
4	(All customers)	Smartphone	Closest (Dynami..	No parameters	DC, Back-up DC	(All periods)	Include
5	Back-up DC	Smartphone	Closest (Fixed So.	No parameters	Factory	(All periods)	Include

Figure 164: Extended sourcing policy.

#	Facility	Product	Policy Type	Policy Parameters	Initial Stock, units	Periodic Check	Period
1	DC	Smartphone	Min-max policy	s=100, S=200	150		1
2	Factory	Smartphone	Min-max policy	s=30, S=60	40		1
3	Factory	Chip	Unlimited invent.	Unlimited	N/A		1
4	Factory	Display	Unlimited invent.	Unlimited	N/A		1
5	Back-up DC	Smartphone	Min-max policy	s=100, S=200	50		1

Figure 165: Extended inventory policy.

#	From	To	Cost Calc...	Cost ...	CO2 ...	Currency	D...	Distan...	Tran...	Time ...	Straight	Vehicle...	Trans...
1	Supplier China	Factory	Distance.	0.5 *...	0 * di...	USD	0	km	0	day		Truck	LTL
2	Supplier Taiwan	Factory	Distance.	0.8 *...	0 * di...	USD	0	km	0	day		Ferry	LTL
3	Factory	DC	Product..	0.01 ...	0 * pr...	USD	0	km	2	day		Airpla..	LTL
4	DC	(All locations	Product..	0.01 ...	0 * pr...	USD	0	km	2	day		Airpla..	LTL
5	Back-up DC	(All locations	Product..	0.01 ...	0 * pr...	USD	0	km	2	day		Airpla..	LTL
6	Factory	Back-up DC	Product..	0.01 ...	0 * pr...	USD	0	km	2	day		Airpla..	LTL

Figure 166: Extended transportation policy.

Figure 167 shows the simulation results.

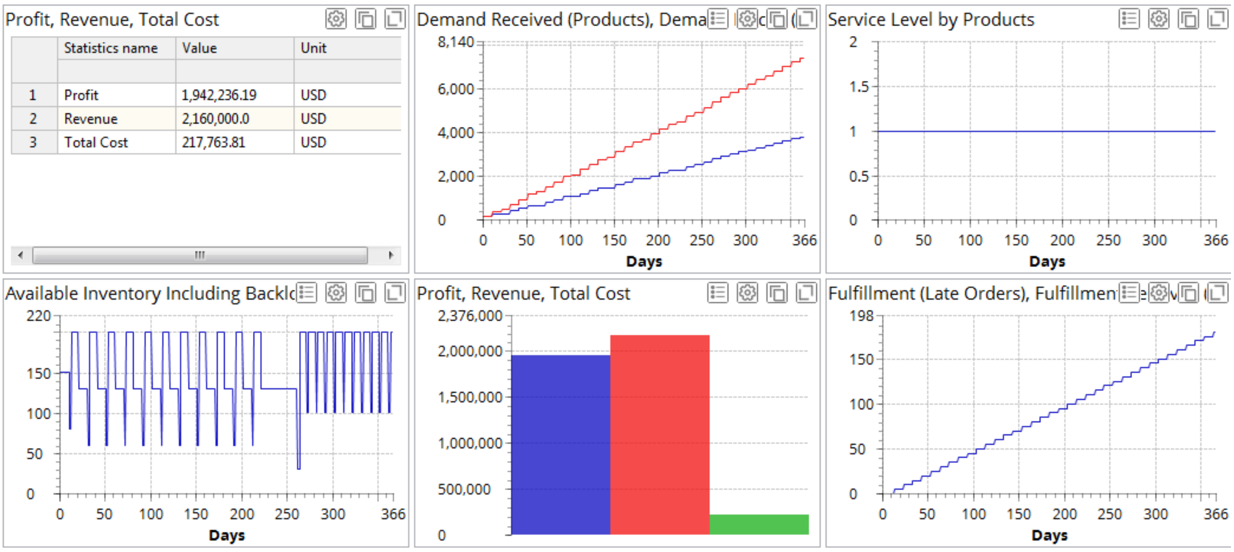


Figure 167: The backup distribution center's impact on supply chain performance.

We compare this result with Figure 160. We can see Profit of $1,942,236.19 (instead of $1,765,302.37) and total revenue of $2,160,000.0 (instead of $1,980,000.0) can be achieved. The service level is 100% and both replenishment and customer-in-time orders are uninterrupted.

The supply chain manager needs to decide if they want to invest in the supply chain. Should they avoid investing to receive the highest possible profit in the case of the disruption-free scenario? Or should they make an investment (that is, invest in the backup distribution center)? If a disruption occurs, this investment would increase profits. But if nothing happens, it would reduce profits.

Impact of Recovery Strategies

Instead of or jointly with proactive actions, we can consider different recovery strategies and analyze their impact on performance. In our example, you can compare two reactive strategies: a fast and expensive distribution center recovery and a slow and efficient distribution center recovery.

Let's assume using the backup distribution center is referred to as the fast and expensive distribution center recovery (Sect. 8.4.2). We'll also assume a recovery in 30 days without any proactive strategy (Sect. 8.3) is referred to as the slow and efficient distribution center recovery. In this case, we follow the discussion about Figure 167 and find we can recommend the fast and expensive distribution center recovery strategy that uses the backup distribution center.

Safety Stock Estimation Experiment

You use the **Safety Stock Estimation experiment** to simulate how much safety stock you need (cf. Figs. 33-35 in "Inventory control" section of theoretical introduction to this Chapter). We select Safety Stock Estimation, the desired service level (98%), and run this experiment for the ripple effect scenario (Fig. 168).

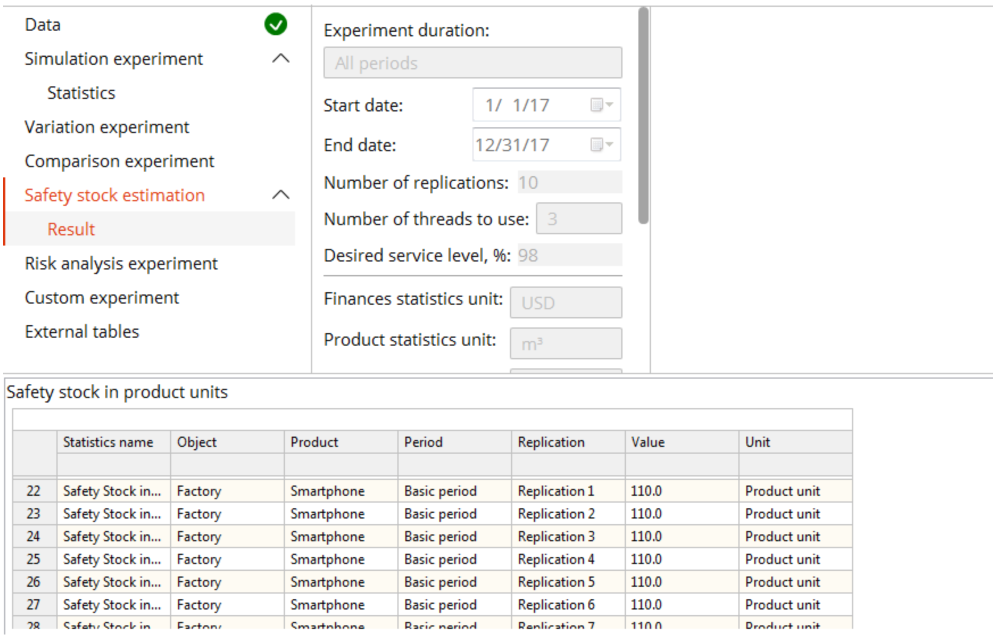


Figure 168: Safety stock estimation experiment.

We can observe that for service level of 98%, it is recommended to carry 110 smartphones as safety stock at factory. This number is equal in all the replications. In case of stochastic demand or lead time, different replications would suggest different safety stocks.

The management implications of **Safety Stock Estimation** experiment are multiple. On one hand, different service levels can be analyzed in terms of their influence on the safety stock and inventory costs. On the other hand, the suggested safety stock estimations can be used in multiple simulation runs to analyze the system behavior and adjust the safety stocks if needed. Such an analysis can also be supported by **Variation Experiment.**

Variation Experiment

A simulation experiment runs the model once, but which experiment should you use if you want to do 20 iterations and look at minimums, maximums, means and standard deviations?

Our goal for this section is to show you how to use the **Variation** experiment and how you can use it to address problems. We will create a variation experiment, vary the backup distribution center's initialization costs, and measure the performance impact.

Create New Variation Experiment

We need to complete the following steps to create a variation experiment (Figures 169-170):

1. Create the experiment.
2. Replications number (anyLogistix's Personal Learning Edition limits you to 10 replications).
3. Configure statistics.
4. Select parameters to vary and the variation range and step.
5. Run the variation experiment.

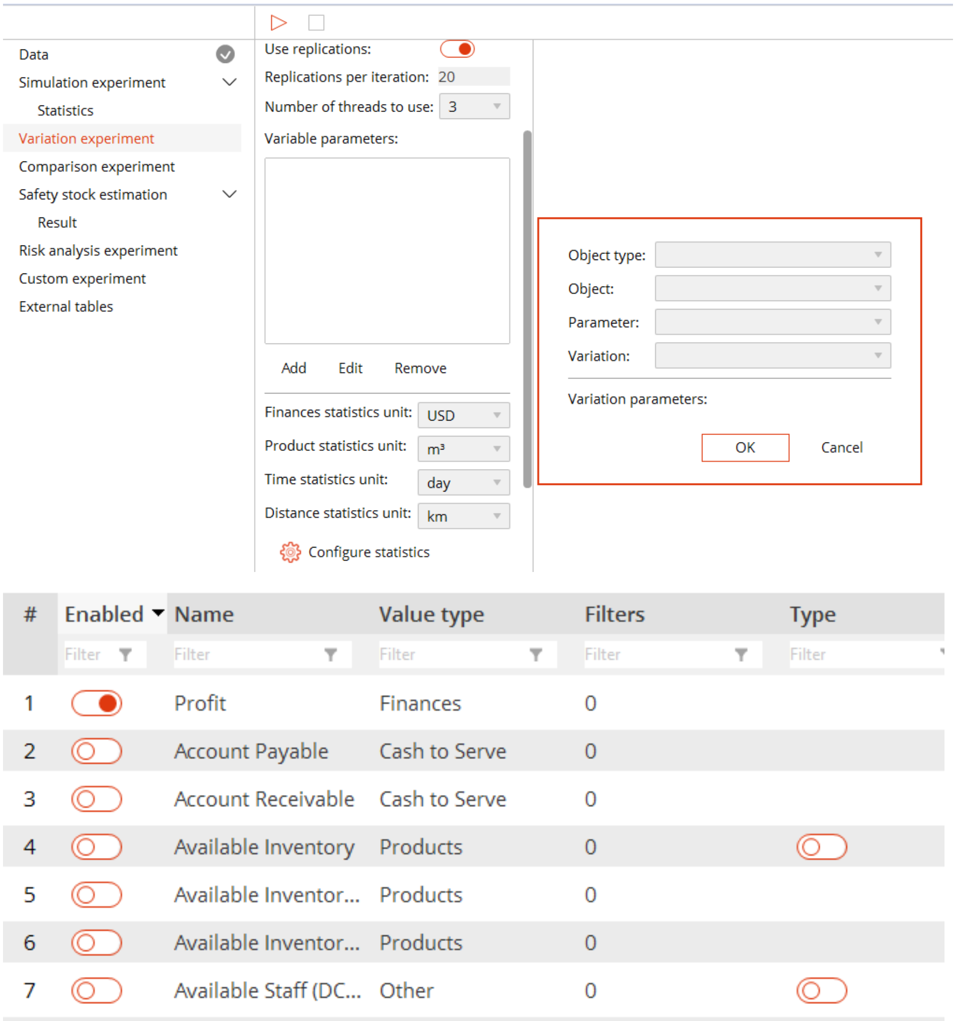


Figure 169: KPI selection.

> **Note:** You can filter the **Enabled** column's contents according to the activated statistics by typing **True** in the field below the column name. This helps you find enabled statistics and avoid including unwanted statistics in the experiment results.

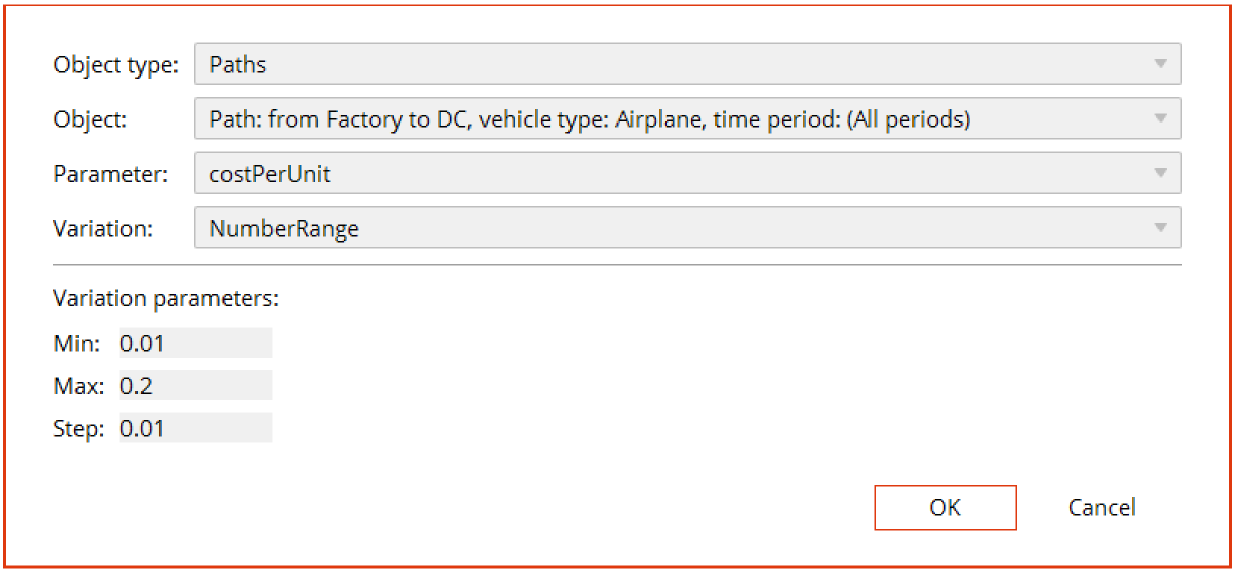


Figure 170: Variation parameter and range selection.

Performing a Variation Experiment

We run the variation experiment to see the impact of the transportation costs. Figure 171 displays the results.

	Iteration	Description	Profit mean
1	Iteration 1	costPerUnit: 0.01	1,942,236.191
2	Iteration 2	costPerUnit: 0.02	1,941,941.889
3	Iteration 3	costPerUnit: 0.03	1,941,647.587
4	Iteration 4	costPerUnit: 0.04	1,941,353.286
5	Iteration 5	costPerUnit: 0.05	1,941,058.984
6	Iteration 6	costPerUnit: 0.06	1,940,764.682
7	Iteration 7	costPerUnit: 0.07	1,940,470.38
8	Iteration 8	costPerUnit: 0.08	1,940,176.078
9	Iteration 9	costPerUnit: 0.09	1,939,881.776
10	Iteration 10	costPerUnit: 0.1	1,939,587.474
11	Iteration 11	costPerUnit: 0.11	1,939,293.172
12	Iteration 12	costPerUnit: 0.12	1,938,998.87
13	Iteration 13	costPerUnit: 0.13	1,938,704.568
14	Iteration 14	costPerUnit: 0.14	1,938,410.266
15	Iteration 15	costPerUnit: 0.15	1,938,115.964
16	Iteration 16	costPerUnit: 0.16	1,937,821.662
17	Iteration 17	costPerUnit: 0.17	1,937,527.36

Figure 171: Variation results

Figure 171 shows a linear relation between the transportation costs and profit.

Risk Analysis Experiment

The **risk analysis** experiment allows the performance impact of supply chain disruptions to be measured. We consider **Four-Stage supply chain (Optimistic scenario)** (see Figure 172). This scenario was used at the beginning of this section (cf. Figure 158 and sub-section **Events**).

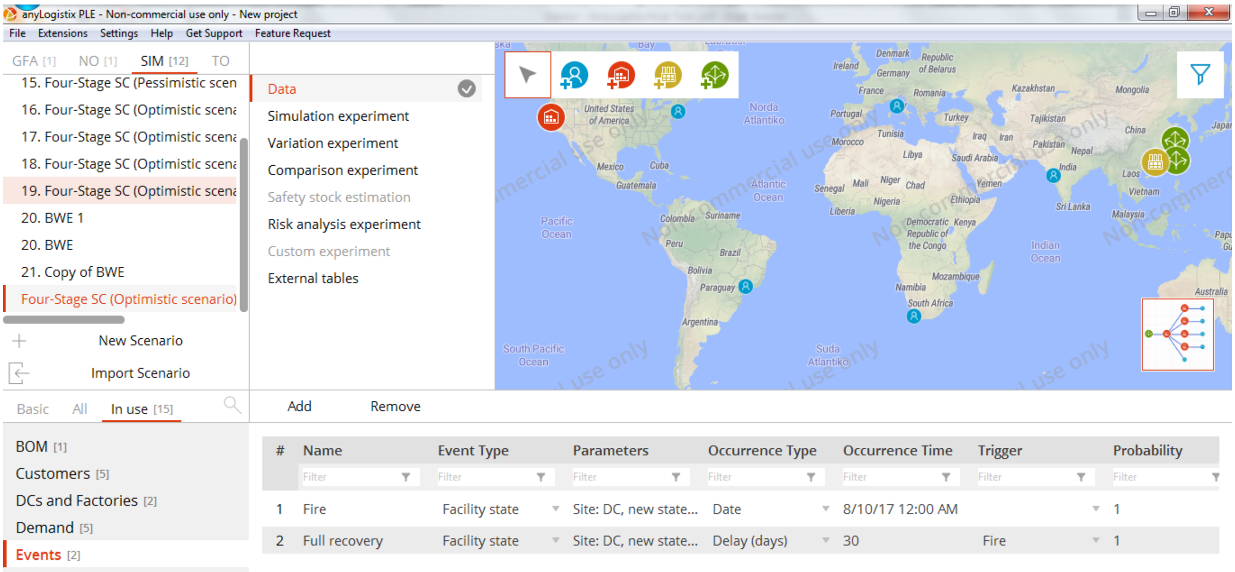


Figure 172: Disruption scenario for risk analysis experiment

Create New Risk Analysis Experiment

When creating a new **Risk Analysis** experiment in the **SIM** tab, we can define several settings (Figure 173).

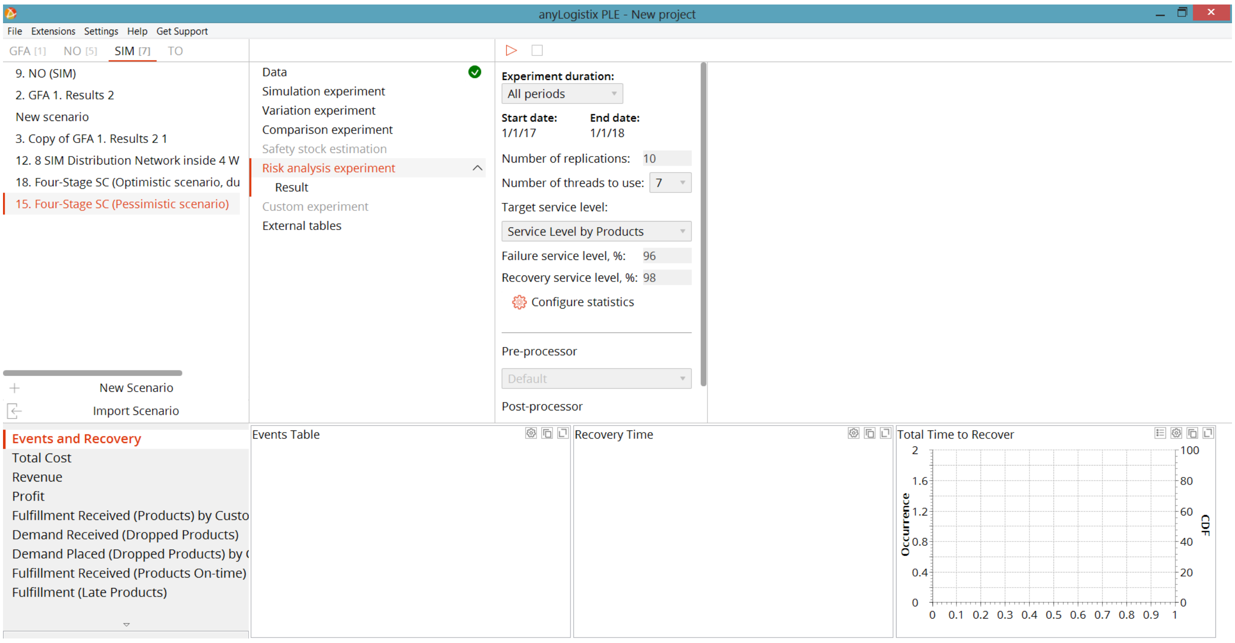


Figure 173: Preparing a risk analysis experiment

First, we can define the number of replications to be used. Second, failure and recovery service levels can be set.

Performing New Risk Analysis Experiment

Next, we click the red triangle on the top of the screen and run the **Risk Analysis** experiment (Figures 174-177).

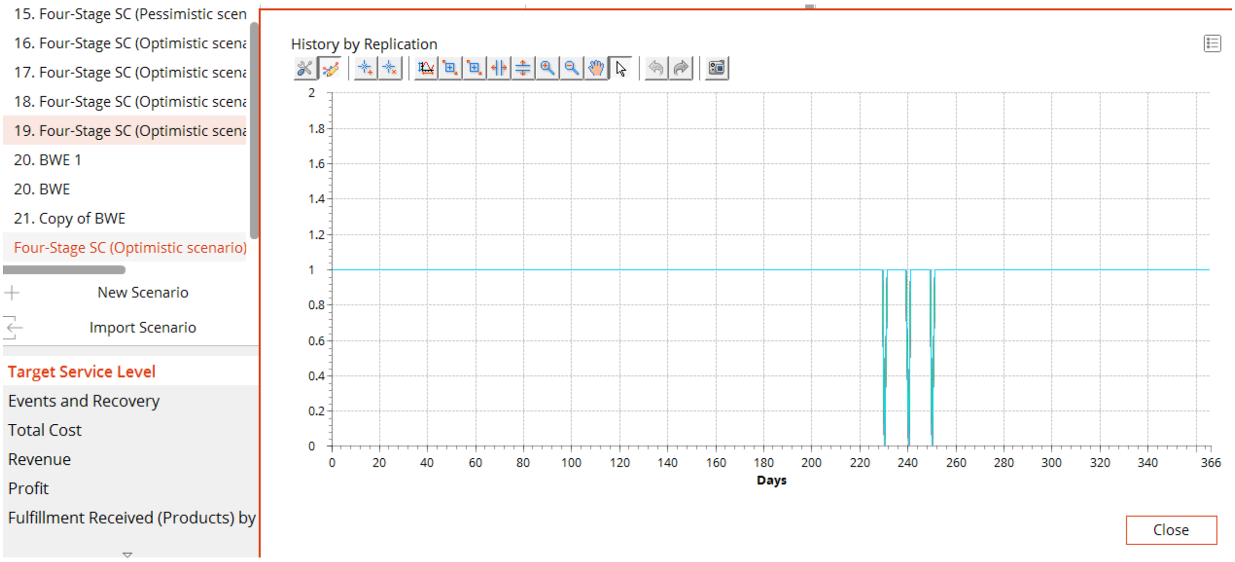


Figure 174: Service level impact

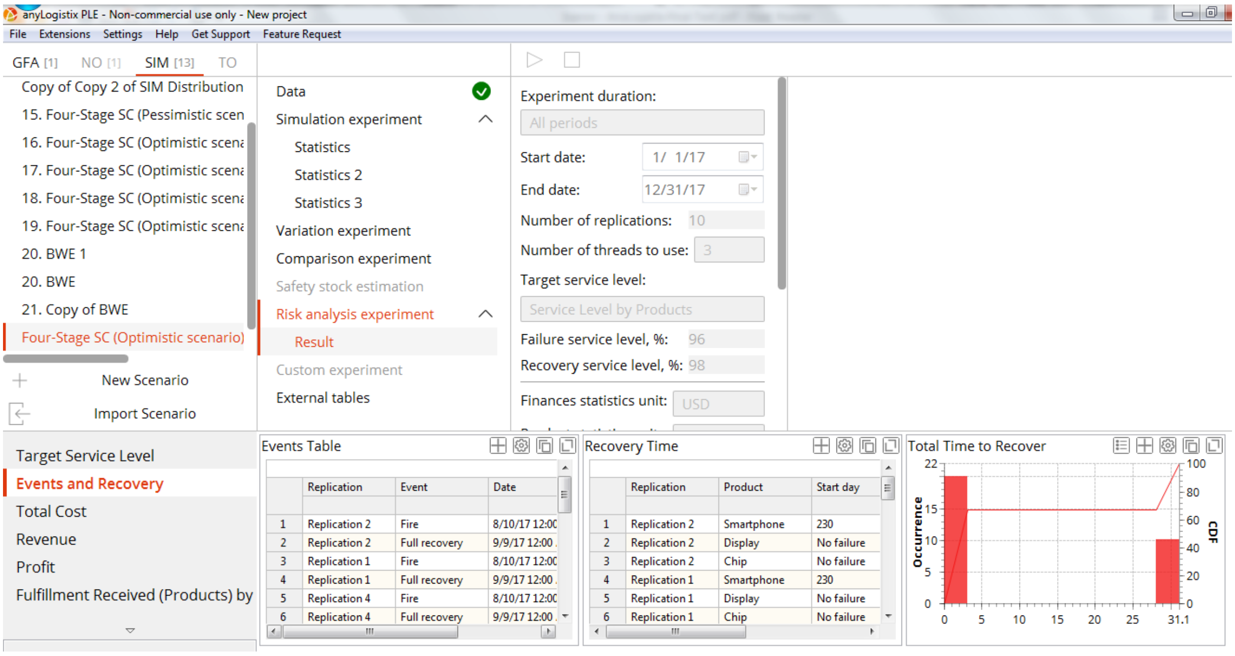


Figure 175: Disruption and recovery time for different replications

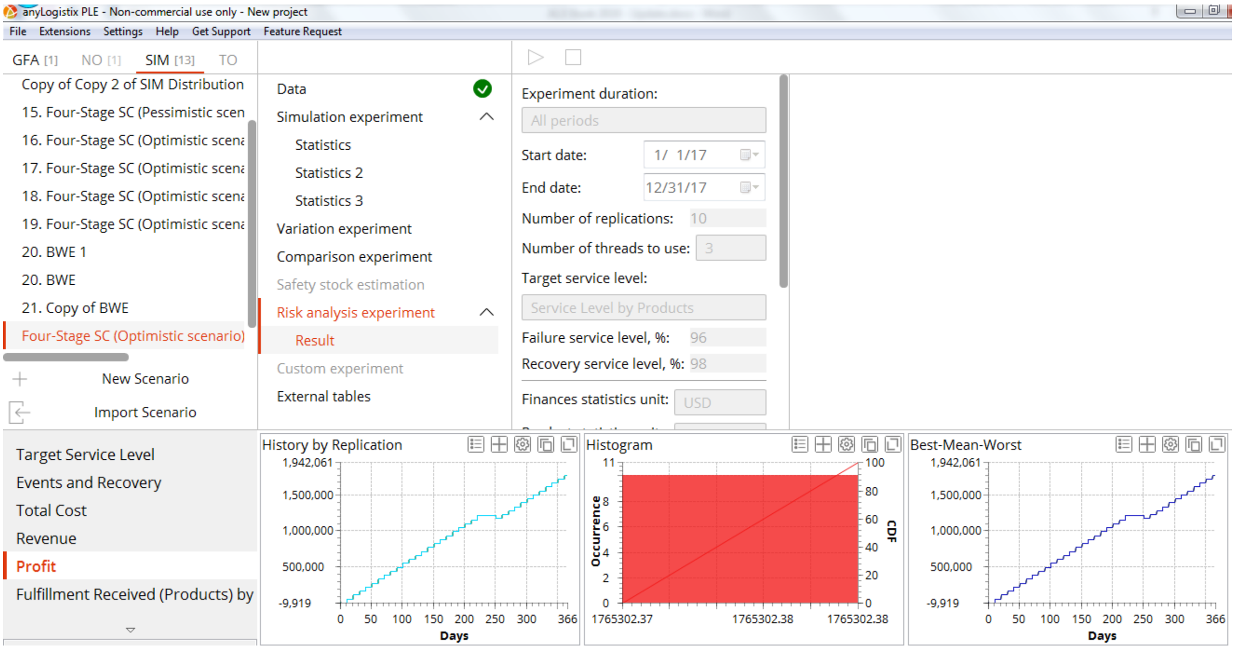


Figure 176: Profit impact

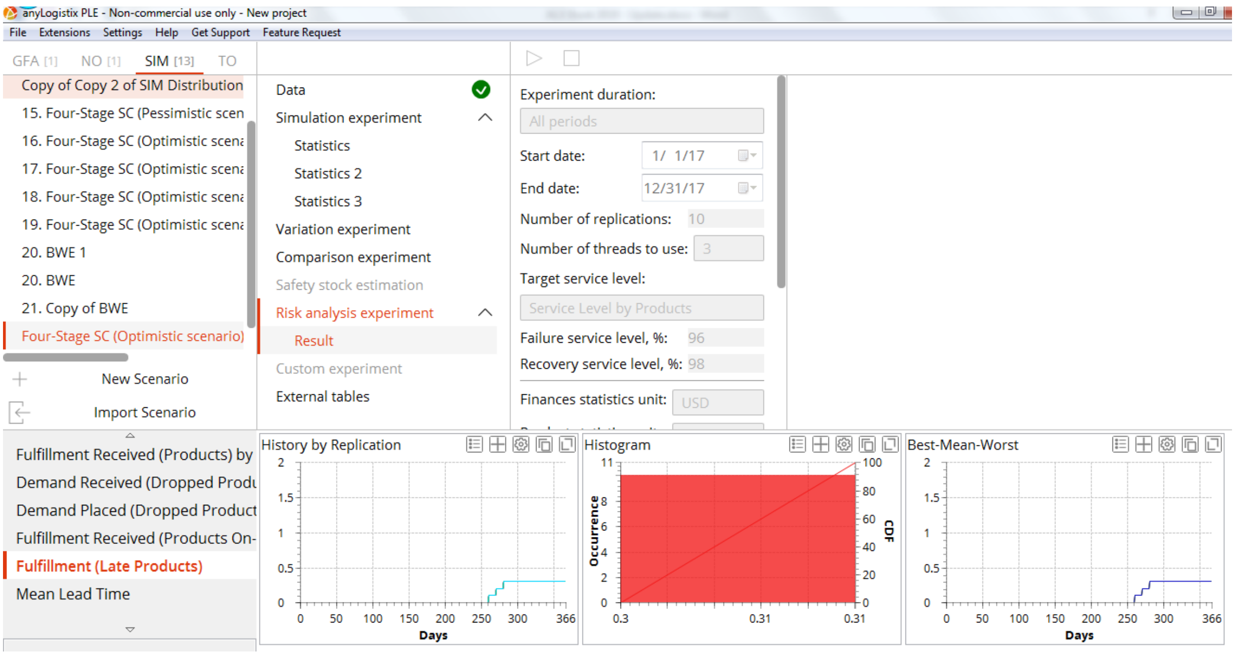


Figure 177: Delayed products due to disruption (impact on supplier reliability)

Figures 174-177 depict the impact of DC disruption on August 10, 2017 for the period of 30 days on supply chain service level, profit, and supplier reliability. We can observe a decrease in service level and profits (Figures 174 and 176) and an increase in non-fulfilled orders resulting from delayed products (Figure 177).

If we change the probability of disruption (cf. Figure 172) from 1 to say 0.5, different replications in Figure 175 would show different event and recovery times (Figure 178).

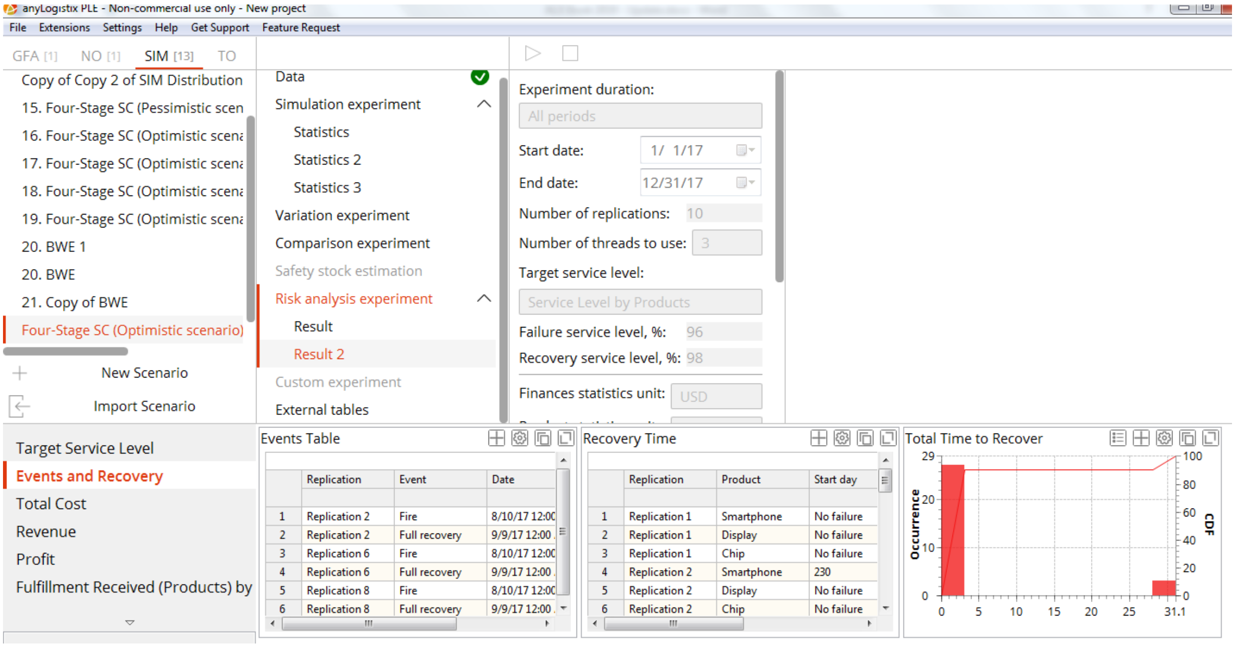


Figure 178: Disruption and recovery time for different replications with disruption and recovery probability 0.5

As we can see in Figure 178, different replications return different recovery times. This is because the disrupted DC was not restored in 30 days since the probability of this restoration was 0.5. Further analysis may include adding other events at possible times of DC disruption and recovery and assigning different probabilities to these events.

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Summary and Discussion Questions

Chapter 1

In Chapter 1, we learned how to create a new supply chain model, design the KPI dashboard, and perform simulation, network optimization and simulation-based optimization experiments.

We learned how to create a scenario and define its customers, products, supply chain facility locations, sourcing and transportation policies. We used the created supply chain model for facility location planning and network optimization tasks. We learned how to apply anyLogistix to green field analysis for single and multiple warehouse locations and different objectives, that is, costs and service distance.

We extended our analysis to network optimization using mathematical programming models. We learned the similarities, differences and application areas of simulation and optimization methods in supply chain design. Using anyLogistix, we reviewed the advantages and disadvantages of different facilities, facility costs, transportation costs and response time.

Finally, we learned how to create new KPI dashboard, collect statistics, prepare and run simulation and network optimization experiments of supply chain design analysis improvement.

Discussion questions:

- Imagine you are selling lithium batteries for electric vehicles. How would you create a scenario for GFA analysis? What parameters do you need? What optimization criteria can you use?
- Now imagine you are responsible for reverse logistics and you need to design the closed-loop supply chain. You need to define optimal number and locations of the collection centers and then analyze the dynamics of the collection processes. How can you use anyLogistix for these decisions?
- If you want to build two distribution centers in the US and use a green field analysis experiment to find the suggested areas, will you get the same results for the following experiment settings?
    - ✓ Number of distribution centers –2
    - ✓ Service distance – 2100 km (data about US: West to East –4200 km, North to South-2500 km)
- What is the difference between Network Optimization and Simulation-based Network Optimization experiments?
- What is the difference between alpha, beta and ELT service levels?
- When does it make sense to use simulation-based network optimization instead of analytical network optimization?
- How can you include capacity limitations in the analysis?

Chapter 2

In Chapter 2, we took several inventory control policies (for example, fixed period or reorder point policies) and transportation policies (for example, FTL – full truck load and LTL – low truck load) into consideration. In practice, inventory control and transportation policies often impact decisions on supply chain design and operations. In this chapter, we gained skills on impact of inventory control and transportation policies on supply chain and logistics performance.

We created a three-stage supply chain structure, performed experiments and measured performance. Using this model, we learned about the trade-offs among the various inventory control policies, transportation frequencies, and lead times. We also learned how to use AnyLogic to extend anyLogistix.

Discussion Questions:

- You need to increase the frequency of transportation from your suppliers to your distribution center to respond to customer demand changes. How would you model this situation in anyLogistix? What tradeoffs should you consider for inventory control and warehouse capacity?
- How can you use anyLogistix to analyze capacity utilization at your warehouse?
- Imagine we want to ship a product to the US from China. Which experiment should we use to decide which port is the best option?
- Imagine your chief asks you to analyze the impact of current inventory control policy on total supply chain costs. How would you model this in anyLogistix?
- Is there a difference in NO results if you use LTL or FTL transportation policy?
- Is there a difference in NO results if you use incapacitated or capacitated throughputs?
- Let’s assume you supply luxury goods and you want to analyze the service level you will be able to provide to your customers with the given supply chain structure. How could you estimate it with anyLogistix?

Chapter 3

In Chapter 3, we considered the effect of different production and sourcing policies. We used anyLogistix to create a four-stage supply chain structure, perform experiments and measure performance. Using this model, we learned about the trade-offs among single and multiple sourcing, production times, transportation frequencies, inventory control policies and lead time. We also learned how to create BOM (bill-of-materials) and how to include soft facts to move from a model-based result to a management decision.

Discussion Questions:

- Imagine increased demand requires you to increase the amount you ship from your factory to your distribution center. How would you model this situation in anyLogistix? What trade-offs should you consider for transportation policy, inventory control and warehouse capacity?
- How can you use anyLogistix to analyze lead time at your customers in dynamics?
- Imagine you want to ship a product to the US from China and from India. How would you decide if single or dual sourcing is more efficient?
- Imagine your manager asks you to analyze the impact of currently used sourcing policy on the lead time. How would you model this situation in anyLogistix?

Chapter 4

In Chapter 4, we considered anyLogistix applications to risk management and control in supply chains. Risks in supply chains are characterized by different frequency and performance impact.

High-frequency-low-impact disruptions are typically considered in light of bullwhip-effect and refer to demand and lead-time fluctuations. Bullwhip effect considers weekly/daily demand and lead-time fluctuations as primary drivers of the changes in the supply chain which occur at the parametric level and can be eliminated in a short-term perspective. In light of low-frequency-high-impact disruptions, we also considered ripple effect.

We learned how to use anyLogistix to model and quantify bullwhip effect and ripple effect. We developed technical skills on batching, ordering rules and events. Later, we learned how to prepare and run variation and comparison experiments.

Finally, we focused on understanding the major trade-offs in supply chain risk management and their effect on efficiency and resilience. We included proactive and reactive recovery strategies in analysis.

Discussion questions:

- What is the difference between bullwhip effect and ripple effect?
- How can you explain the meaning of the **Products Bullwhip Effect** statistics in anyLogistix?
- Imagine you need to increase the sales batch size because of transportation policy optimization. How might this decision affect other decisions or policies in the supply chain? How can you use anyLogistix to analyze them?
- What does BWE mean? Why does it allow to identify a bullwhip effect?
- What does it mean if BWE = 1?
- Does it make sense to measure BWE for a number of products?
- How does the BWE depend on the inventory control policy?
- Create three scenarios with different demand distributions and use the **Comparison** experiment to compare them
- What kinds of events can you add to your model?
- Imagine you need to analyze performance impacts of a strike at a transportation company, a fire at a distribution center, and an explosion at a factory. How would you model this in anyLogistix? Which experiments would you use?
- How can you analyze different ways an event may happen?
- If you want to vary the location of a factory how would you do this?
- How do you vary suppliers in sourcing policy?
- How do **Variation** and **Comparison** experiments differ?
- Which supply chain parameters can be varied and in what decisions?
- How can you use the Risk Analysis experiment to compare supply chain performance for different probabilities of disruption and recovery events?

Avoiding Typical Conceptual Mistakes

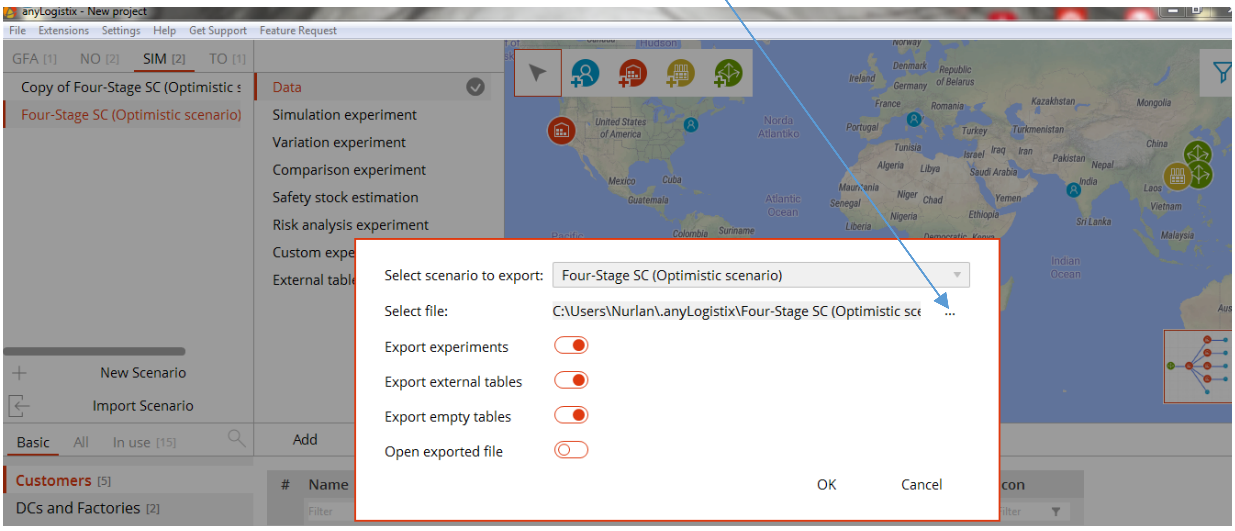
Number	Description	Possible Remedies
1	Your simulation experiment does not start; the supply chain objects are not connected on the map.	You need to define sourcing rules.
2	Your simulation experiment does not start or it starts, but ends quickly.	• Check maximum warehouse or factory capacity • Too long production time or processing time • Check the assignments of objects and products to groups • You need to define Inventory policies need for all sites • You need to define Paths for all stages in the supply chain
3	In the network optimization experiment, you cannot select some sites for optimization.	In **Factory/distribution centers**, the **Inclusion type** should be **Consider**.
4	After an order aggregation in transportation policy, your simulation experiment does not run.	Our decision to increase the transportation quantity means we also need to increase the inventory control policy's MAX-Level. If we don't increase the MAX-Level, the insufficient warehouse capacity will stop our simulation experiment. It's also a good idea to increase the MIN-level since the replenishment interval will be increased. --or— Ensure the aggregation policy is aligned with the inventory control policy's Max value.
5	Your experiment with BOM does not show any activities between the suppliers and the assembly factory.	In Inventory, you need to define the inventory policy for all products of BOM, not only for the final product.
6	You cannot see the experiment's complete results.	Click any other experiment or scenario and then return to your experiment. You should see the complete results.
7	In the experiment's results, you only see transportation costs for the connection between the customers and distribution center. You don't see costs for the connection between the distribution center and factory.	Activate transportation costs for the factory in your experiment's **Configure statistics** area.

8	In your simulation experiment, time is running but nothing is shipped.	Check demand parameters, backorder policy and initial inventory.
9	Orders are not shipped to custom-ers.	Check LTL and FTL policies and the corre-sponding minimum ratio, aggregation periods as well as product characteristics and trans-portation capacities.
10	Orders are not shipped to custom-ers.	The inventory policies, vehicle types and transportation policies are not compatible. For example, some large vehicles with a LTL policy of min. load 0.8 and an aggregation period of 10 days waste time waiting to load the vehicles. You can fulfill more customer orders by re-ducing the vehicle size and increasing your inventory policy's parameters.
11	In NO experiment, only one itera-tion is shown in the results.	You entered some initial stock for all sites; ALX presumes in this case that these sites need to be included in supply chain design.
12	In NO experiment, transportation costs equals zero even but the goods are delivered.	In Paths, Distance-based policy is selected. This means that transportation costs is com-puted for orders. NO operates in terms of flows. As such, select Product&distance-based policy.

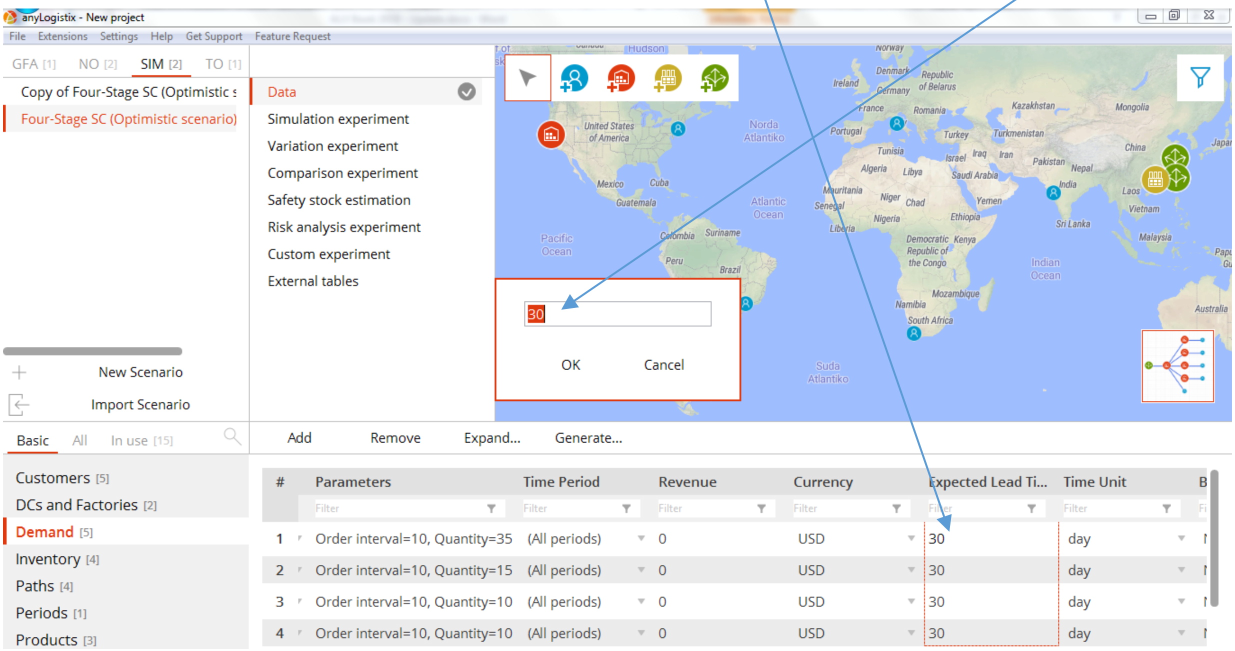
Convenience Hints

In this section, we elaborate useful hints for making data processing in ALX more convenient.

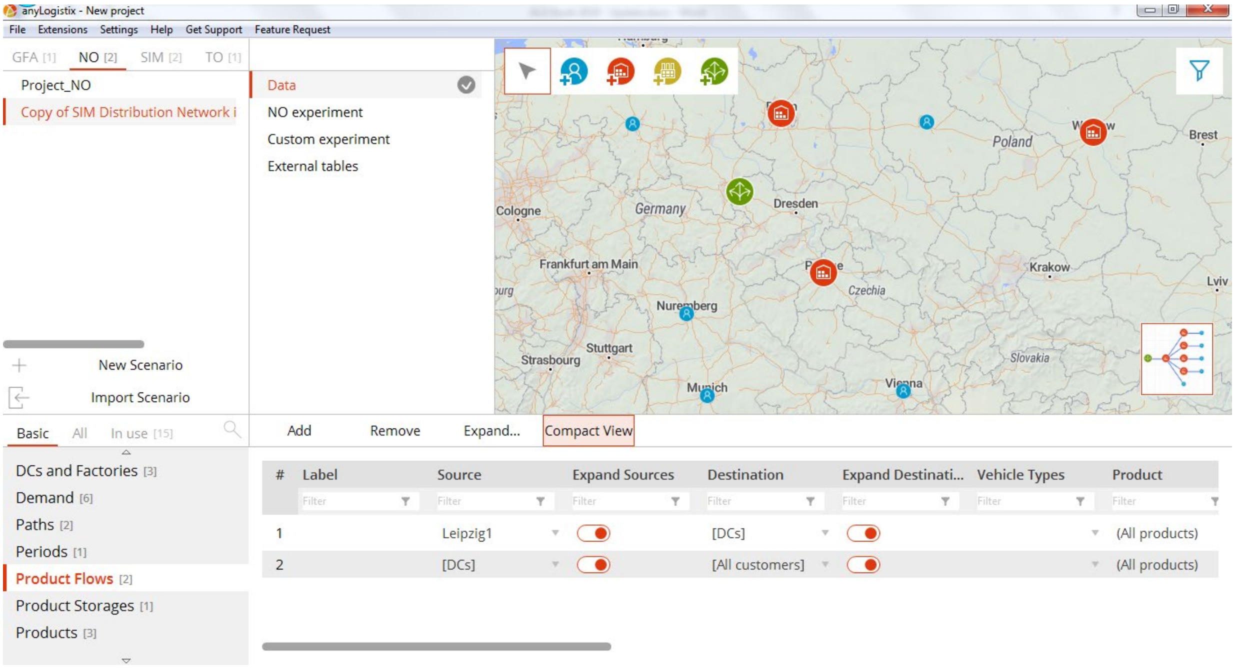
1. If you export a scenario, you need to double click on the right-hand side of the scenario name to select the folder and save the scenario. Then press "OK".



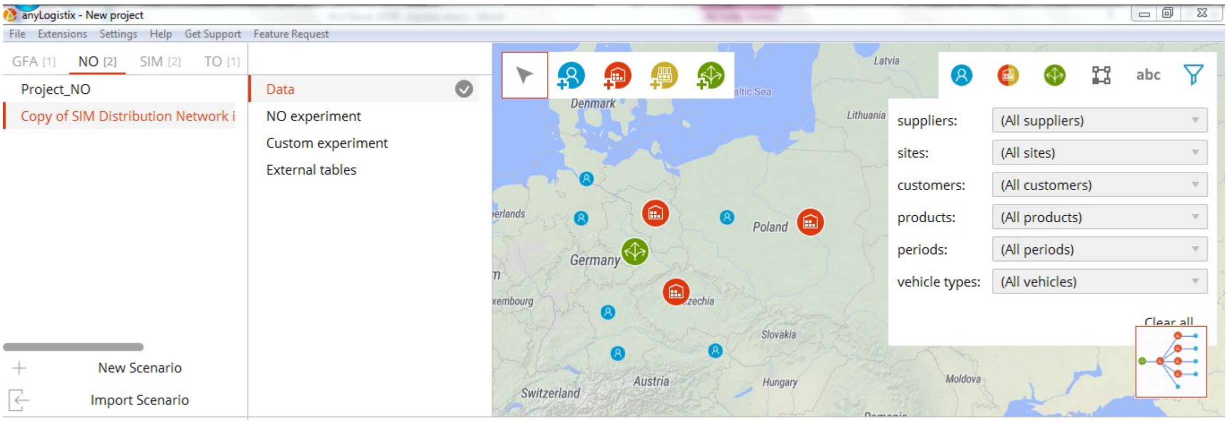
2. To enter the same number in many cells, just select the area of cells and enter the number you want, then click OK.

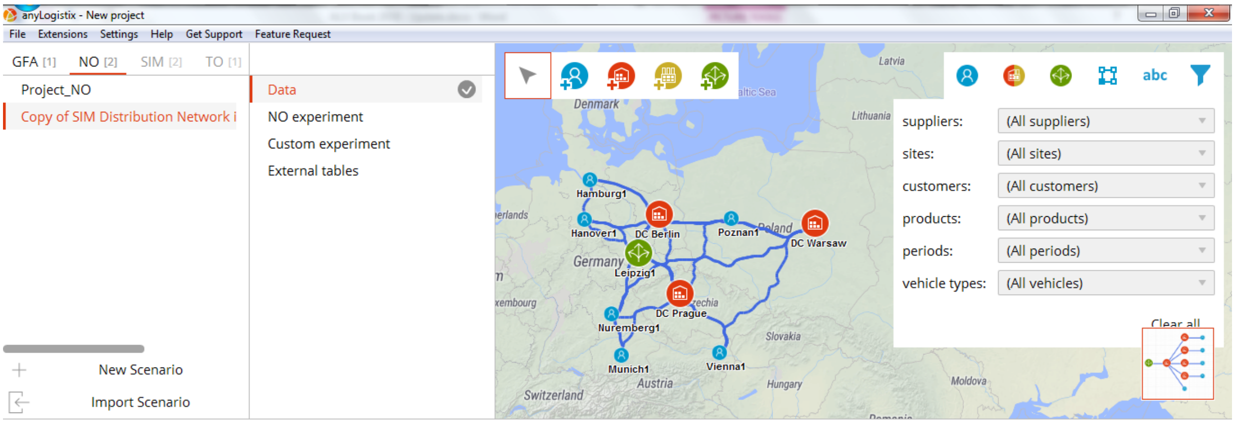


3. In Network Optimization (NO), you can select either **Compact View** or **Detailed View** to show or hide some columns, e.g., **Min und Max Throughputs**



4. On the map, you can select different views, such as with or without flows and with or without the names of supply chain objects





Appendix 1: Examples of Case Study Problem Statements

Example 1

Our learning objective: students become familiar with model-based decision-making principles in supply chain management on the example of optimization and simulation application to analysis of a real-life location-allocation problem in a global retail supply chain.

Management Problem Statement

Object of Investigation

A global retail company comprises producers of fruits and vegetables and regional distributions centers (distribution center).

Investigation Process

We investigate the process of fruit and vegetable delivery from suppliers to regional distribution centers.

The Problem and its Relationship to the Literature

The products are shipped from suppliers to regional distribution centers directly using LTL policy with an average of 15 pallets per delivery. This causes high coordination complexity, low fleet capacity utilization, higher transportation costs and higher inventory holding costs.

The retail company wants to build central distribution centers between the suppliers and the regional distribution centers (Figure 1).

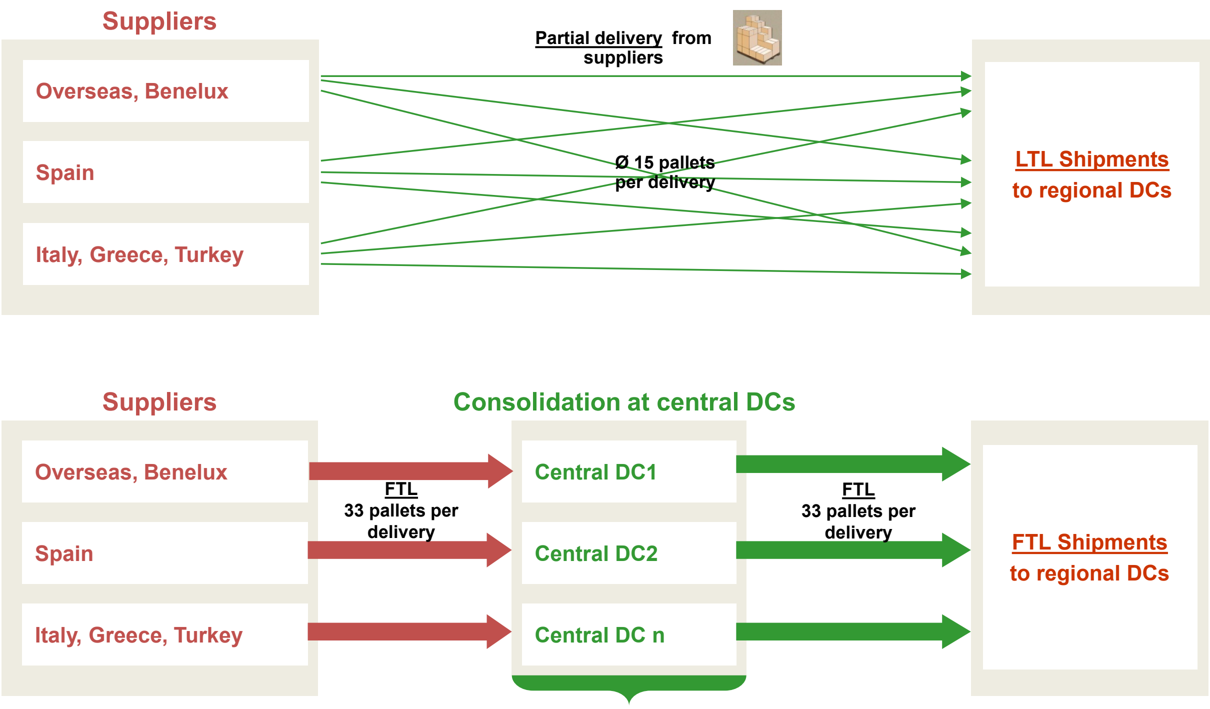


Figure 1: Initial and planned supply chain design.

The problem is how to determine the number of central distribution centers, their locations, and the allocation of regional distribution center demands to central distribution centers. It is to balance the distribution center capacities, transportation policy, sourcing policy and inventory control policy in the most efficient way subject to a predetermined customer service level.

This problem statement corresponds to the standard location-allocation problem in the literature.

Two scenarios need to be analyzed and compared subject to Figure 1:

- Direct shipments
- Shipments via central distribution centers

In addition, we need to account for future shifts in demand up to 30% to 50% at some regional distribution centers in regard to population growth forecasts and local farmer market development forecasts.

The Goal of Investigation

The goal of our investigation is to increase supply chain efficiency without decreasing the customer service level.

Our Main Decision

The main decision is to determine the number of central distribution centers, their locations, and the allocation of regional distribution centers to central distribution centers. In addition, we need to decide:

- what capacity we should use at the distribution centers
- our fleet size and transportation policy
- our inventory control policy and its parameters
- our sourcing policy
- our resilience policy

Research Question

The main research question is to analyze the impact of supply chain redesign on (i) location-allocation options, (ii) impact of transportation, sourcing, and inventory control policies as well as (iii) future capacity and demand changes on supply chain financial, customer, and operational performance.

Questions to be Answered to Make the Decision

- compare supply chain without central distribution centers and with central distribution centers on supply chain financial, customer and operational performance
- compare different location-allocation variants on supply chain financial, customer and operational performance
- compare the impact of LTL and FTL shipment policies on supply chain financial, customer, and operational performance
- compare inventory control policies on supply chain financial, customer and operational performance
- compare the impact of sourcing policies on supply chain financial, customer and operational performance
- analyze the impact of future demand changes on supply chain financial, customer and operational performance
- analyze the impact of capacity disruption risks on supply chain financial, customer and operational performance

- analyze the impact of distribution center capacity changes on supply chain financial, customer and operational performance

Table 1: KPI to measure the results of investigation.

Financial Distribution Center Performance	**Customer Performance**
total profit (EBIDTA), $	Maximum lead time, days
total revenue, $	Min-Max Service level, %
opportunity costs, $	OTD (on-time delivery), orders
production costs, $	Total incoming orders from customers
inventory holding costs, $	Total outgoing orders to customers
transportation costs at suppliers, $	Total orders shipped to customers
transportation costs at distribution center, $	Operational performance:
profit and lost statement, $	Maximum capacity usage at distribution centers, m^3
total costs at distribution center, $	Maximum inventory in the supply chain, units

Data Needed to Solve Management Problem

The following data is needed to solve the problem described above:

Table 2: Demand at regional distribution centers.

Regional Distribution Center	**Forecasted Demand (Pallets per Day)**	**Initial Inventory (Pallets)**
1		
…		
n		

Table 3: Supply to regional distribution centers with direct shipment

	RDC 1	**…**	**…**	**…**	**RDC m**
Supplier 1					
…					
Supplier k					

Table 4: Costs and profits.

Costs and profits	**$**
distribution center inbound operating costs	
distribution center outbound operating costs	
Initial costs for building distribution center	
Facility operating costs	
Opportunity costs	
Inventory carrying costs	
Fixed distribution center costs	
Transportation costs	
Sales price	

Table 5: Further estimations.

Parameters	
Lead time	
Transportation mean capacity	
Distribution center capacity	
Expected lead time	
…	

Direct shipment analysis

It is to compute for initial scenario's financial, customer, and operational performance subject to KPI in §1.8 for:

- AS-IS parametric setting
- Changed parametric settings subject future shifts in demand up to 30% to 50% at some regional distribution centers in regard to population growth forecasts and local farmer market development forecasts
- Changed parametric settings subject to severe disruptions in supplier and regional distribution center capacities

Experiment used: Simulation (inventory control policy parameters can be computed analytically prior to simulation)

Central Distribution Center Shipment Analysis

We need to analyze the scenarios with central distribution centers:

- How many central distribution centers should we use?
- Where should we locate the distribution centers?

- How should we allocate regional distribution centers to central distribution centers?

Experiments: Analytical: Green Field Analysis and Network Optimization

- what capacity at the distribution centers should be used
- fleet size and transportation policy
- inventory control policy and its parameters
- sourcing policy
- resilience policy

Experiment: Simulation (inventory control policy parameters can be computed analytically prior to simulation)

Comparing Two Scenarios

You need to compare the financial, customer and operational performance of:

- A supply chain with and without central distribution centers
- Different location-allocation variants
- LTL and FTL shipment policies
- Inventory control policies
- compare the impact of sourcing policies on supply chain financial, customer and operational performance
- analyze the impact of future demand changes on supply chain financial, customer and operational performance
- analyze the impact of capacity disruption risks on supply chain financial, customer and operational performance
- analyze the impact of distribution center capacity changes on supply chain financial, customer and operational performance

Experiments: Comparison and Variation

Project report structure

1. Management problem statement (object of investigation, process of investigation, main goal of investigation, decision to be taken, sub-questions to be answered to take the decision, KPI to measure results of investigation)
2. Data needed to solve management problem
3. Model description (objective function, constraints, parameters, variables; if optimization models: set of equations, if simulation model: process diagrams and themes)
4. Description of software
5. Implementation in software
6. Description of experiments
7. Presentation of computational results
8. Analysis of results
9. Recommendations on the solution of the management problem stated in 1) on main goal of investigation, decision to be taken, sub-questions we need to answer to make the decision, and KPI to measure the investigation’s results.

Example 2

The demand for the ETC company's high-quality wines led them to build distribution centers in Europe, Asia, and North and South America. Now that demand is fluctuating, ETC's management wants to know:

- After taking all the available information into account—customer demand, the locations of their customers and the distances from their warehouses to their customers—where should ETC locate their distribution centers?
- Would closing ETC's South American distribution center make the company's supply chain more cost-effective?
- ETC's CEO wants to compare the important KPIs from scenario 1 (which uses 4 distribution centers) to those from scenario 2 (which uses 3 distribution centers). Which scenario's KPIs are better?

Example 3

ZSE is a Berlin-based e-commerce company that wants to be the European Union's most successful online shopping platform. To reach their goal, the company has developed a four-year strategy focused on fast product delivery, excellent customer service and an efficient supply chain.

To expand the business in Europe and meet the expected increase in demand, ZSE needs to decide whether they should open a new distribution center or expand their German distribution center.

If they decide to open a new distribution center, they'll need to determine the best location to help them minimize their supply chain costs and meet their minimum service level requirements.

Example 4

Pharmapacks ships everything you expect to find in a drug store. The company sells almost 25,000 different products, ships 570,000 orders each month, and has agreements with 16 suppliers.

Their pricing management software—"Master Mind"—has helped the company to dominate their market. It calculates the best price and manages their whole stock and sales/demand forecasts. They have increased their sales six fold in a year. Their revenue in 2016 amounted to $160 million and from 2011 to 2013 they grew by 3,035 percent. When looking at the performance indicators, the delivery time is slow, which is caused by having only one warehouse, in New York City.

Does it make sense to open a second warehouse on the West coast to speed delivery to the Western United States and meet customer expectations?

Example 5

The case-study is based on a FMCG company that produces juices/beverages for four regional markets. The supply chain comprises four production plants and four regional distribution centers (DCs). So in each of four regions, there is a market, a plant, and a regional DC. Former supply chain manager of the company decided to close a production plant in one of the regions (and we have the highest demand in this region among all four regions!) and to supply the DC in this region from three other plants which are located quite distant from this DC. Just a couple of months after the plant closure, the DC in this region crashed due to construction quality problems. A huge amount of juice inventory has been destroyed.

As new supply chain manager of this company, you are now responsible to react to this disruptive event. You first estimate the immediate impact and time-to-recovery. The inventory in this DC was supposed to supply the regional market with the juices for three months. The re-construction of the DC will take about six months. You understand that a short-term and mid-term recovery policy is needed. You consider four options, i.e.;

- Increasing capacities of three other production plants in other, geographically distant regions. You understand that those capacities are limited (but some potential for an increase still exists) and these plants are far away from the regional market
- Using capacity of the milk producing plant of your company in the same region where the DC crashed. The technological process is quite similar, but some adaptations will be needed
- Using capacity of your other plants in neighborhood countries
- Finding a subcontractor

In addition, this disruption forces the CEO of your company to develop a business continuity plan. The supply chain contingency plan should become a part of this company business continuity plan. You need to suggest new supply chain design that contains proactive and reactive policies for making your supply chain resilient.

You will need the following data (but not limited to):
1. SC design: locations of SC elements (factories and DCs) and links in between them
2. Demand in the markets and its uncertainty
3. Parameters of SC elements (e.g., production capacities, throughputs, prices, costs)
4. Operating policies of SC elements (e.g., inventory control policy, production control policy, shipment control policy, sourcing control policy)

You will need to perform the following experiments:
1. Network optimization to determine how many plants and DCs you actually need and where they should be located, without disruption considerations
2. Simulation experiment with the DC disruption with and without the closed factory

3. Simulation experiments with four immediate recovery policies:
- back-up contractors (you might want to use GFA and network optimization experiment to determine their optimal location)
- capacity flexibility (capacities of milk producing plant)
- increasing capacities at other plants in other regions
- using capacity of your other plants in neighborhood countries

4. Network optimization and simulation experiments with two resilience policies for new supply chain design:
- new central DC that would be installed instead of or in addition to many regional DCs and serve as a hub in the normal mode and as a back-up in the disruption

mode (you might want to use GFA and network optimization experiment to determine the optimal location)

- suggest another possible option for new resilient supply chain design

5. Variation experiment to validate your model by analyzing result sensitivity to changing some parameters

6. Comparison experiment to compare results obtained in 3) and 4). You may use as KPIs profits, costs, service level, lead time, etc.

Appendix 2: Case-Studies on Combined Usage of Optimization and Simulation for Supply Chain Design

Case Study 1: Multi-Product Supply Chain Redesign

Alexander, a supply chain manager at a U.S.-based FMCG company, needs to reduce supply chain costs in a distribution network. The supply chain is made up of customers with the following periodic demands and lead time requirements (Table 1):

Table 1: Customer demand

Customer	Product	Parameters	Expected lead time
New York City 1	Lighting	Quantity=8.0;Period, days=5.0	30
Philadelphia 2	Gardening equipment	Quantity=20.0;Period, days=5.0	30
New York City 8	Gardening equipment	Quantity=20.0;Period, days=5.0	30
Fort Worth	Gardening equipment	Quantity=20.0;Period, days=5.0	30
Boston	Gardening equipment	Quantity=20.0;Period, days=5.0	30
New York City 2	Gardening equipment	Quantity=20.0;Period, days=5.0	30
Portland	Furniture	Quantity=16.0;Period, days=5.0	30
Phoenix 3	Lighting	Quantity=8.0;Period, days=5.0	30
San Jose 2	Gardening equipment	Quantity=20.0;Period, days=5.0	30
San Francisco	Small appliances	Quantity=4.0;Period, days=5.0	30
Memphis	Large home appliances	Quantity=12.0;Period, days=5.0	30
New York City 14	Small appliances	Quantity=4.0;Period, days=5.0	30
Charlotte	Large home appliances	Quantity=12.0;Period, days=5.0	30
Oklahoma City	Gardening equipment	Quantity=20.0;Period, days=5.0	30
Nashville	Gardening equipment	Quantity=20.0;Period, days=5.0	30
Columbus	Furniture	Quantity=16.0;Period, days=5.0	30
Chicago 3	Lighting	Quantity=8.0;Period, days=5.0	30
Philadelphia 3	Furniture	Quantity=16.0;Period, days=5.0	30
New York City 12	Large home appliances	Quantity=12.0;Period, days=5.0	30
Los Angeles 3	Furniture	Quantity=16.0;Period, days=5.0	30
New York City 6	Lighting	Quantity=8.0;Period, days=5.0	30
San Jose 1	Small appliances	Quantity=4.0;Period, days=5.0	30
Tucson	Small appliances	Quantity=4.0;Period, days=5.0	30
Columbus	Large home appliances	Quantity=12.0;Period, days=5.0	30
San Antonio 1	Large home appliances	Quantity=12.0;Period, days=5.0	30
Chicago 2	Gardening equipment	Quantity=20.0;Period, days=5.0	30
New York City 15	Lighting	Quantity=8.0;Period, days=5.0	30
Nashville	Large home appliances	Quantity=12.0;Period, days=5.0	30
Washington D.C.	Lighting	Quantity=8.0;Period, days=5.0	30
Houston 4	Furniture	Quantity=16.0;Period, days=5.0	30
Dallas 1	Large home appliances	Quantity=12.0;Period, days=5.0	30
Baltimore	Small appliances	Quantity=4.0;Period, days=5.0	30

Denver	Lighting	Quantity=8.0;Period, days=5.0	30
Austin	Small appliances	Quantity=4.0;Period, days=5.0	30
Houston 3	Small appliances	Quantity=4.0;Period, days=5.0	30
Indianapolis	Small appliances	Quantity=4.0;Period, days=5.0	30
New York City 11	Gardening equipment	Quantity=20.0;Period, days=5.0	30
Louisville	Furniture	Quantity=16.0;Period, days=5.0	30
Memphis	Furniture	Quantity=16.0;Period, days=5.0	30
New York City 7	Gardening equipment	Quantity=20.0;Period, days=5.0	30
Chicago 4	Large home appliances	Quantity=12.0;Period, days=5.0	30
Dallas 2	Small appliances	Quantity=4.0;Period, days=5.0	30
Phoenix 2	Small appliances	Quantity=4.0;Period, days=5.0	30
San Diego 1	Furniture	Quantity=16.0;Period, days=5.0	30
Los Angeles 2	Lighting	Quantity=8.0;Period, days=5.0	30
Boston	Large home appliances	Quantity=12.0;Period, days=5.0	30
Jacksonville	Furniture	Quantity=16.0;Period, days=5.0	30
Chicago 5	Gardening equipment	Quantity=20.0;Period, days=5.0	30
Los Angeles 1	Large home appliances	Quantity=12.0;Period, days=5.0	30
Albuquerque	Furniture	Quantity=16.0;Period, days=5.0	30
Fresno	Furniture	Quantity=16.0;Period, days=5.0	30
Jacksonville	Lighting	Quantity=8.0;Period, days=5.0	30
New York City 16	Small appliances	Quantity=4.0;Period, days=5.0	30
Houston 1	Furniture	Quantity=16.0;Period, days=5.0	30
El Paso	Gardening equipment	Quantity=20.0;Period, days=5.0	30
Chicago 1	Lighting	Quantity=8.0;Period, days=5.0	30
Portland	Lighting	Quantity=8.0;Period, days=5.0	30
Los Angeles 7	Small appliances	Quantity=4.0;Period, days=5.0	30
Baltimore	Gardening equipment	Quantity=20.0;Period, days=5.0	30
Albuquerque	Large home appliances	Quantity=12.0;Period, days=5.0	30
Milwaukee	Small appliances	Quantity=4.0;Period, days=5.0	30
Austin	Gardening equipment	Quantity=20.0;Period, days=5.0	30
New York City 5	Large home appliances	Quantity=12.0;Period, days=5.0	30
San Diego 2	Small appliances	Quantity=4.0;Period, days=5.0	30
Los Angeles 4	Small appliances	Quantity=4.0;Period, days=5.0	30
Houston 2	Furniture	Quantity=16.0;Period, days=5.0	30
Seattle	Furniture	Quantity=16.0;Period, days=5.0	30
El Paso	Large home appliances	Quantity=12.0;Period, days=5.0	30
New York City 10	Large home appliances	Quantity=12.0;Period, days=5.0	30
San Antonio 2	Lighting	Quantity=8.0;Period, days=5.0	30
Detroit	Large home appliances	Quantity=12.0;Period, days=5.0	30
Detroit	Furniture	Quantity=16.0;Period, days=5.0	30
San Francisco	Lighting	Quantity=8.0;Period, days=5.0	30

New York City 9	Small appliances	Quantity=4.0;Period, days=5.0	30
New York City 13	Furniture	Quantity=16.0;Period, days=5.0	30
Phoenix 1	Large home appliances	Quantity=12.0;Period, days=5.0	30
Los Angeles 6	Large home appliances	Quantity=12.0;Period, days=5.0	30
Milwaukee	Gardening equipment	Quantity=20.0;Period, days=5.0	30
Fort Worth	Small appliances	Quantity=4.0;Period, days=5.0	30
Philadelphia 1	Gardening equipment	Quantity=20.0;Period, days=5.0	30
Los Angeles 5	Small appliances	Quantity=4.0;Period, days=5.0	30
New York City 4	Lighting	Quantity=8.0;Period, days=5.0	30
New York City 3	Lighting	Quantity=8.0;Period, days=5.0	30
Las Vegas	Large home appliances	Quantity=12.0;Period, days=5.0	30

Note: This data is included in the sample Microsoft Excel workbook (**US Distribution Network**) you can find by pointing to the **Help** menu and clicking **Import Example**. We avoid a detailed description of different parameters and simulation policies in the example considered and refer to the aforementioned sample scenario.

The supply chain handles five products:

#	Name	Unit
1	Small appliances	pcs
2	Large home appliances	pcs
3	Lighting	pcs
4	Gardening equipment	pcs
5	Furniture	pcs

Figure 1: Product list.

The supply chain is made up of three distribution centers. Figure 2 shows all three distribution centers and their operating parameters.

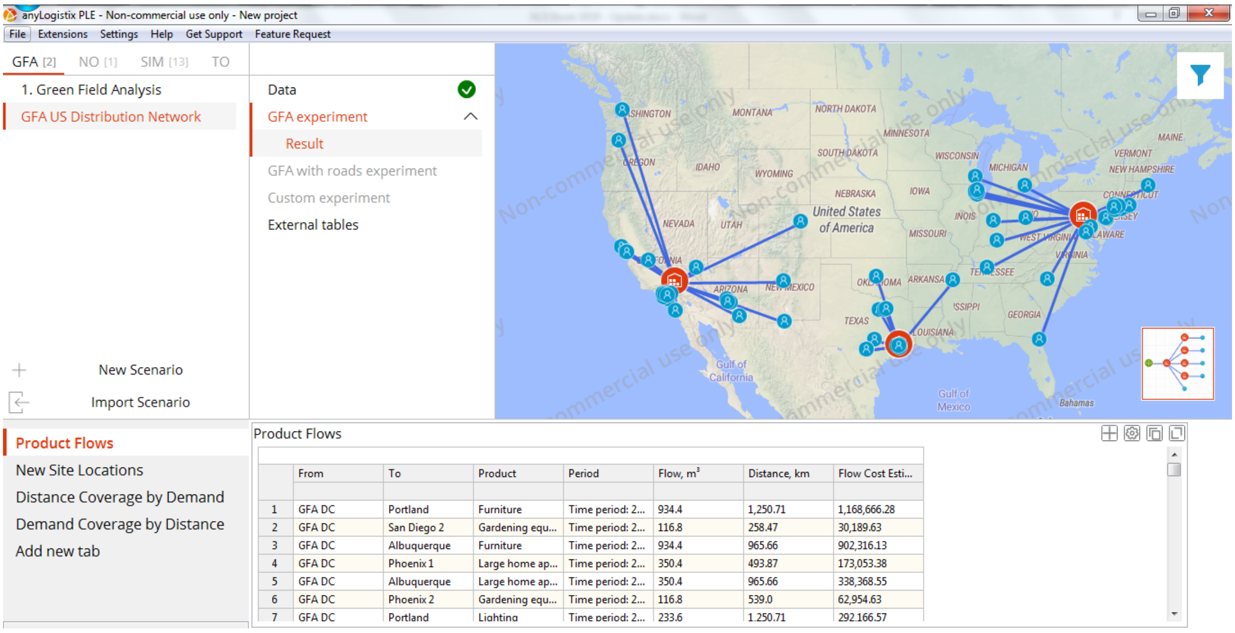


Figure 2: The supply chain's distribution centers.

Scenario Settings

During the executive meeting, Alexander suggests the company improve their supply chain's performance by locating their distribution centers no more than 1,000 km from their customers. A Green Field Analysis gives him the following results (Figure 3):

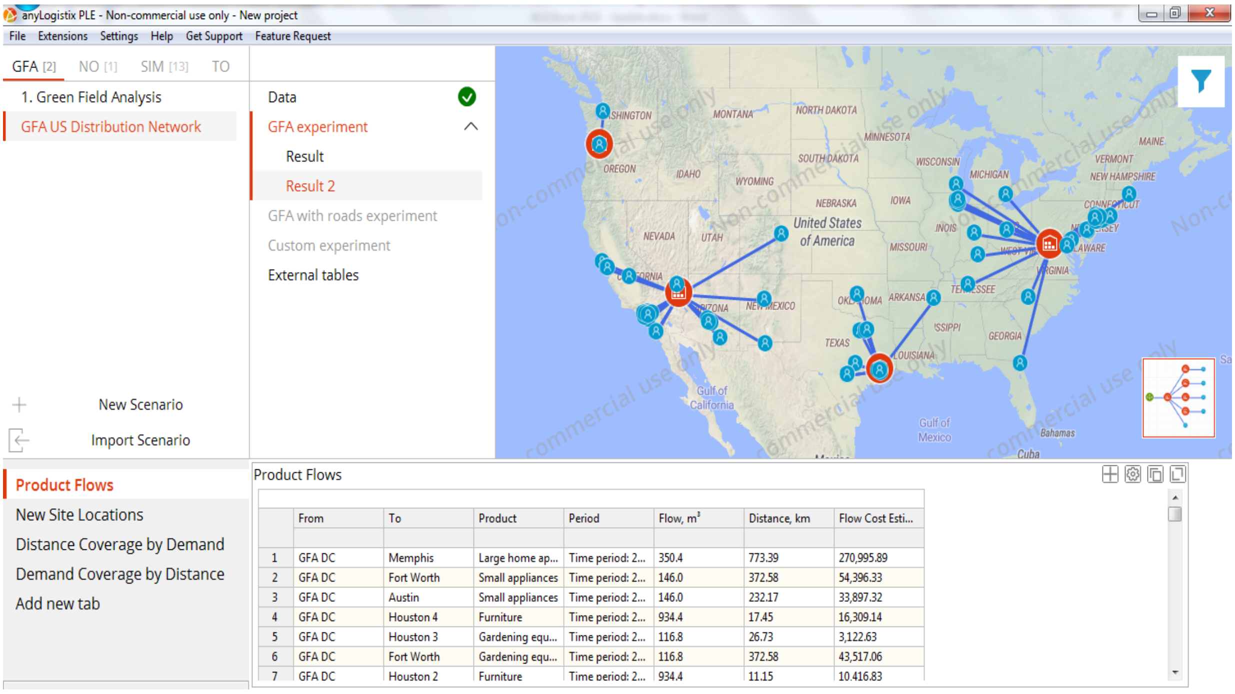


Figure 3: The optimal supply chain design for a maximum service distance of 1,000 km.

The green field analysis suggests the company needs to place three distribution centers in new locations. In the next step, we'll build a KPI dashboard like the example you saw in Section 1.

Simulation Experiments

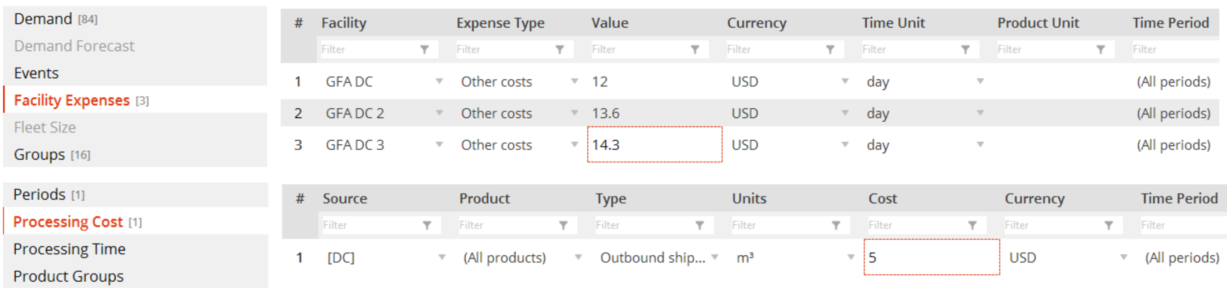
Before we compare simulation experiment results of our AS-IS and redesigned supply chain scenarios, we convert both green field analysis results to SIM scenarios. Then put the following data to related tables in both scenarios:

- New **DC** group (activate all objects in the **Sites** column);
- A **Truck** vehicle type with a capacity of 20 m^3 and an average speed of 50 km/hour (to be defined in **Vehicle Types**);
- Transportation costs computation is based on the rule "product x distance x $15". LTL shipments are allowed;
- Unlimited inventory policy type for all products (this policy assumes the specified products are always in stock at the given facility at any required quantity);
- Product cost parameters:

#	Name	Unit	Selling Price	Cost	Cost Unit
1	Small appliances	pcs	2,000	700	USD
2	Large home appliances	pcs	6,000	2,500	USD
3	Lighting	pcs	5,000	2,000	USD
4	Gardening equipment	pcs	5,500	2,500	USD
5	Furniture	pcs	8,000	300	USD

AS-IS Supply Chain Simulation

To analyze the existing supply chain, Alexander needs to define variable processing and fixed warehousing costs (Figure 4).



#	Facility	Expense Type	Value	Currency	Time Unit	Product Unit	Time Period
1	GFA DC	Other costs	12	USD	day		(All periods)
2	GFA DC 2	Other costs	13.6	USD	day		(All periods)
3	GFA DC 3	Other costs	14.3	USD	day		(All periods)

#	Source	Product	Type	Units	Cost	Currency	Time Period
1	[DC]	(All products)	Outbound ship...	m³	5	USD	(All periods)

Figure 4: Distribution center-related costs for the existing supply chain

Our first experiment simulates the AS-IS supply chain. Figure 5 displays the results.

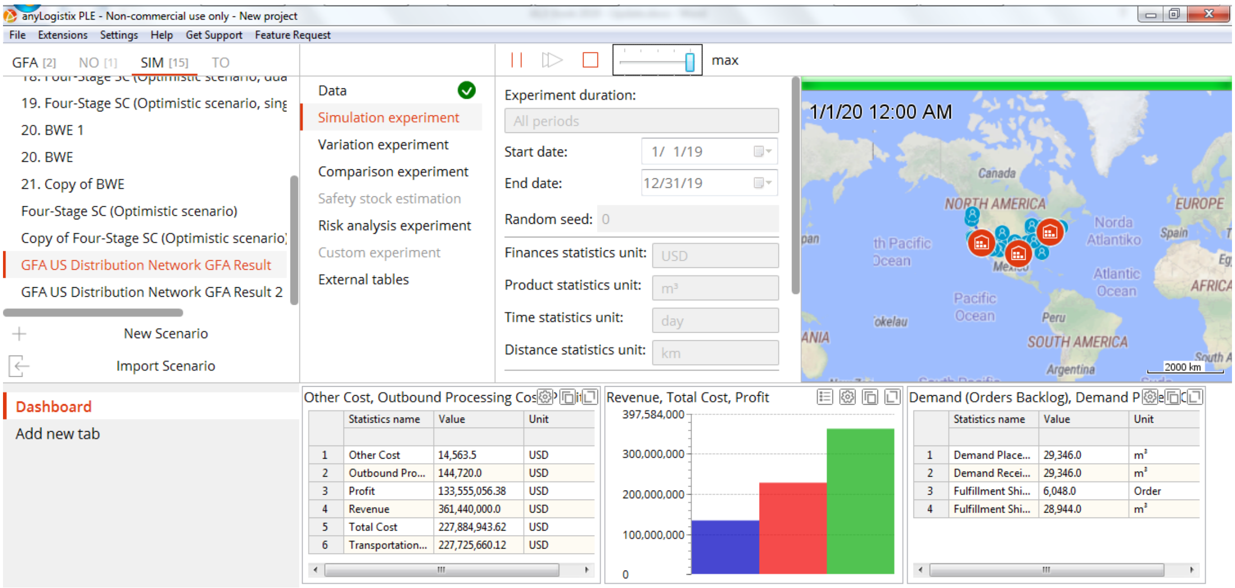


Figure 5: Experimental results for AS-IS supply chain.

Supply Chain Redesign

Alexander will now analyze supply chain efficiency by changing the distribution center locations to match the outcome of the green field analysis. He first estimates distribution center-related operational costs as shown in Figure 6.

Figure 6: Distribution center-related costs for new supply chain design.

Alexander now simulates this new supply chain design. Figure 7 and Table 2 display the results.

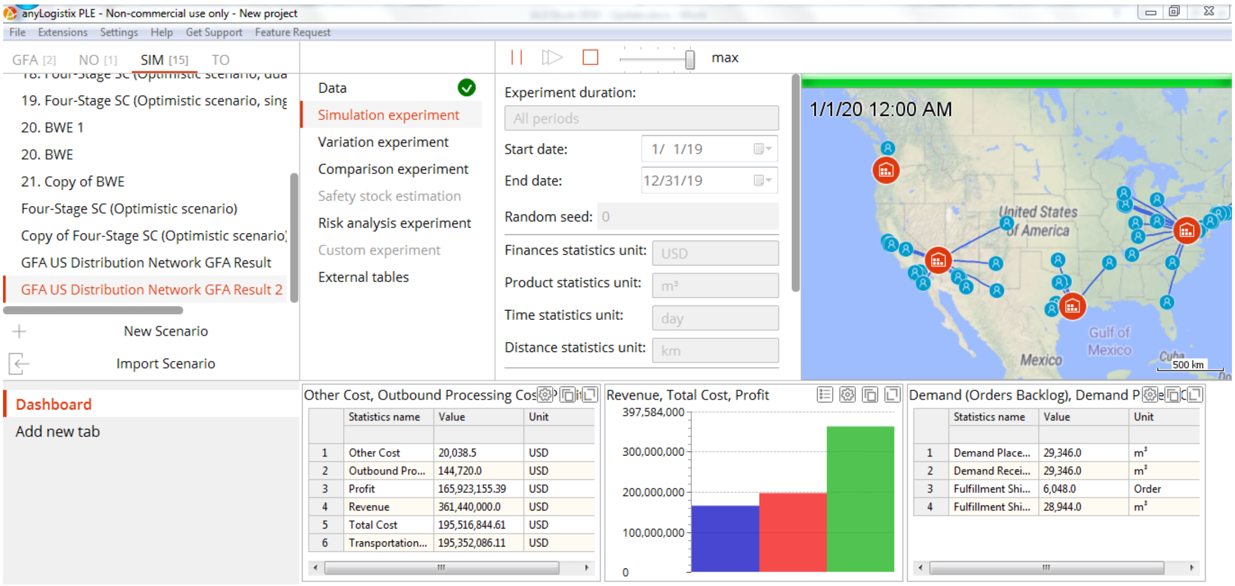


Figure 7: Experiment results for the green field analysis.

Table 2: KPI comparison

KPI	**AS-IS**	**Redesigned Supply Chain**
Financial Distribution Center Performance:		
Other cost, $	**14 563.5**	**20 038.5**
Outbound processing cost, $	144 720.0	144 720.0
Profit, $	**133 555 056.38**	**165 923 155.39**
Revenue, $	361 440 000.0	361 440 000.0
Total cost, $	**227 884 943.62**	**195 516 844.61**
Transportation cost, $	**227 725 660.12**	**195 352 086.11**
Customer performance:		
Current backlog orders	0	0
Customer ordered items	29 346.0	29 346.0
Incoming replenishment items	29 346.0	29 346.0
Items shipped	28 944.0	28 944.0
Orders shipped	6 048.0	6 048.0
Outgoing replenishment orders	0	0

Table 2 shows us a supply chain design that uses four distribution centers is more efficient and profitable. It could reduce total supply chain costs and increase total profit by almost 33 million U.S. dollars without affecting customer performance.

Alexander understands it will be too expensive to build four new warehouses. He notes the suggested locations on the East and West coasts are close to the company's current locations. The south location in Texas is also near the current location in Houston. With that in mind, he decides to analyze the supply chain efficiency for three current locations and a new distribution center in Portland (GFA DC 4).

Let's create a copy of AS-IS supply chain scenario, then add new site and activate it in our group distribution centers.

Adding a site may change inventory policies and sourcing paths. That means we first need to remove all records from the **Inventory** table other than the last one, remove all records in the **Sourcing** table and then add the new row as shown in Figure 8.

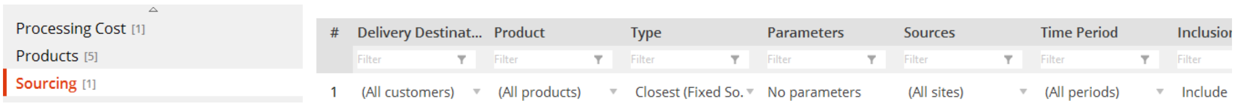


Figure 8: Inclusion type.

Every site has facility expenses. Find all records about Louisville distribution center-related costs in the redesigned supply chain scenario and then add them to the related tables. Figure 9 and Table 3 show the results.

Note: To accurately compare different runs, ensure each completed scenario has the same data, especially while converting the green field analysis or optimization results into a scenario. You should check the groups, paths and sourcing policies that make up the scenario you are converting from an experimental result.

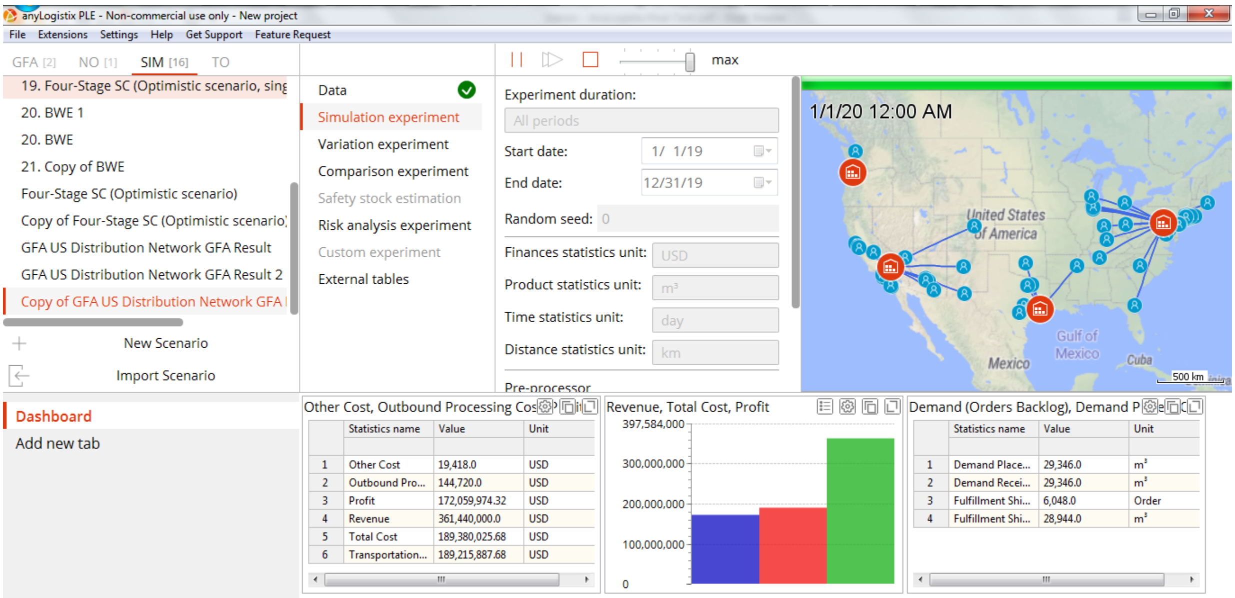


Figure 9: Redesigned supply chain with adapted green field analysis result.

Table 3: KPI Comparison

KPI	**AS-IS**	**Redesigned Supply Chain**	**Adapted GFA Result**
Financial DC performance:			
Other cost, $	**14 563.5**	**20 038.5**	**19 418.0**
Outbound processing cost, $	144 720.0	144 720.0	144 720.0
Profit, $	**133 555 056.38**	**165 923 155.39**	**172 059 974.32**
Revenue, $	361 440 000.0	361 440 000.0	361 440 000.0
Total cost, $	**227 884 943.62**	**195 516 844.61**	**189 380 025.68**
Transportation cost, $	**227 725 660.12**	**195 352 086.11**	**189 215 887.68**
Customer performance:			
Current backlog orders	0	0	0
Customer ordered items	29 346.0	29 346.0	29 346.0
Incoming replenishment items	29 346.0	29 346.0	29 346.0
Items shipped	28 944.0	28 944.0	28 944.0
Orders shipped	6 048.0	6 048.0	6 048.0
Outgoing replenishment orders	0	0	0

Figure 9 and Table 3 show the supply chain design that uses three current distribution centers and one new distribution center is even more efficient and profitable than the green field analysis result. You can see the explanation in the transportation policy (LTL) and expected lead time's effect on the number of deliveries and—by extension—the effect on transportation costs.

Are other improvements possible? If yes, where? If no, why? The fundamental problem with the green field analysis has been it only considers transportation costs during the facility location optimization only. The corresponding distribution center-related costs could be included in the simulation phase only.

As such, the green field analysis results are valid only for similar distribution center-related costs at different distribution centers. In the case the distribution center-related costs at different distribution centers are not equal, green field analysis results became sub-optimal and the search for supply chain design improvement is only possible on the "*what happens if* …" rule.

If we need to optimize supply chain design by considering transportation and distribution center-related costs, we need to use network optimization. We exemplify the network optimization and optimization-based simulation on an example of a smaller dimensionality to make our analysis more detailed.

Case Study 2: Network Optimization Approach and Optimization-based Simulation

Case Study

We'll use a U.S.-based beverage distributor that has six demand regions and five distribution centers. As a first step, create a simulation experiment, add their six customers and five sites, and then name them as shown in Figure 1.

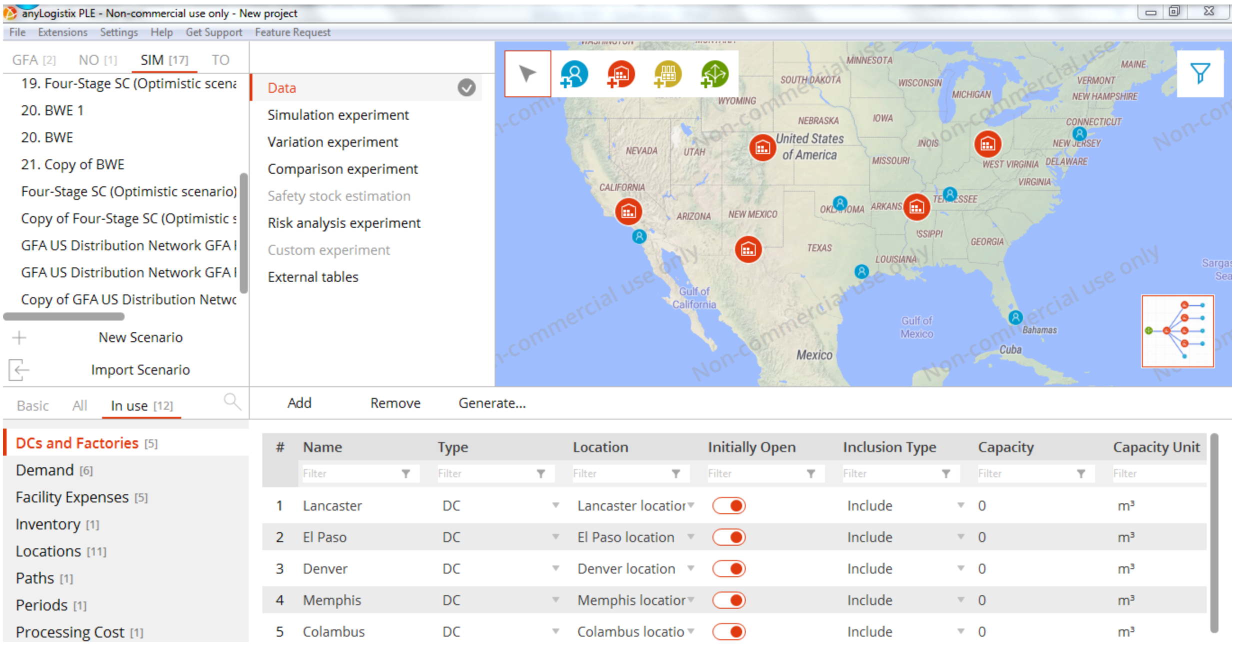
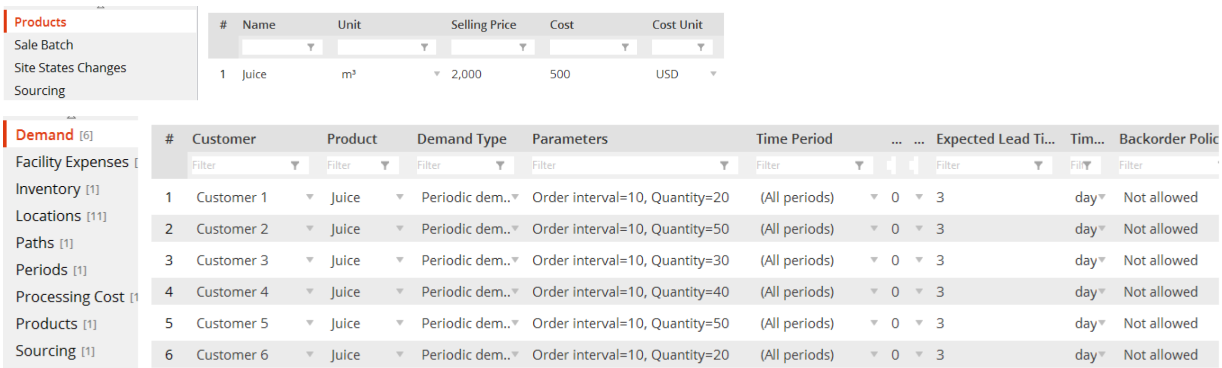


Figure 1. Distribution centers.

Now, create a new product ("Juice") and define each customer's periodic demandю



Define variable processing and fixed warehousing costs (Figure 2).

Facility Expenses [5] | Inventory [1] | Locations [11] | Paths [1] | Periods [1] | Processing Cost [1] | Products [1] | Sourcing [1]

#	Facility	Expense Type	Value	Currency	Time Unit	Product Unit	Time Period
1	Colambus	Other costs	12	USD	day		(All periods)
2	Denver	Other costs	13.3	USD	day		(All periods)
3	El Paso	Other costs	10	USD	day		(All periods)
4	Lancaster	Other costs	16.6	USD	day		(All periods)
5	Memphis	Other costs	14	USD	day		(All periods)

Paths [1] | Periods [1] | Processing Cost [1]

#	Source	Product	Type	Units	Cost	Currency	Time Period
1	(All sites)	(All products)	Outbound ship...	m³	5	USD	(All periods)

Figure 2. Distribution center-related costs for the existing supply chain. The additional inputs are:

- Sourcing policy: single sourcing (closest)
- Vehicle type: capacity 30 m^3, speed 50 km/h
- Transportation costs: $1.0 x product x distance
- Inventory policy: unlimited

Simulation Experiment

Figure 3 shows the simulation's results.

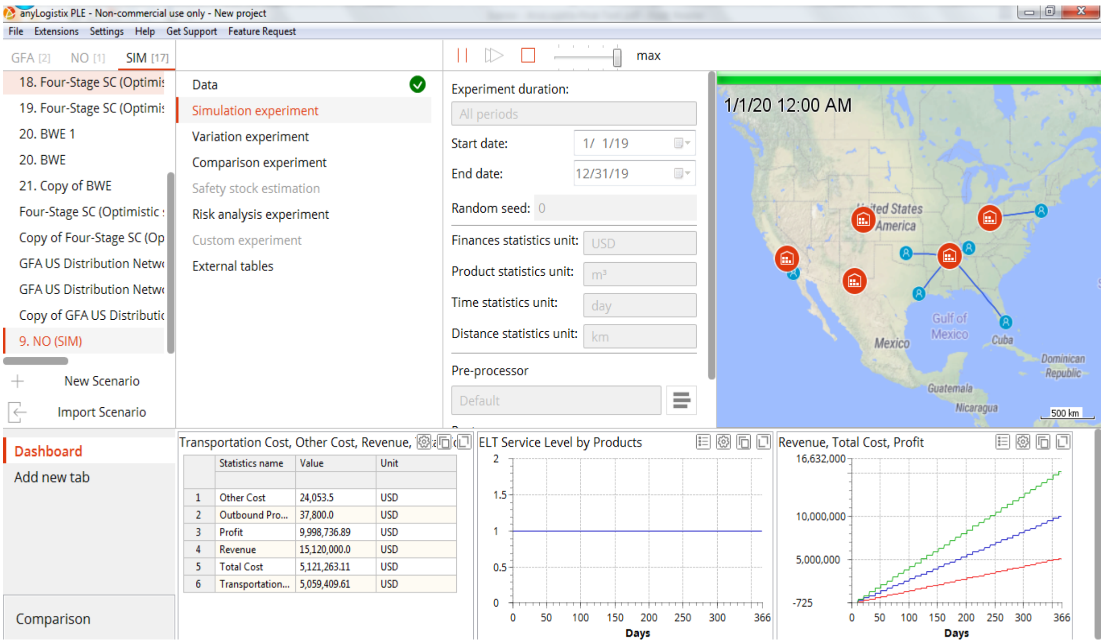


Figure 3. Simulation result for five distribution centers.

The company's CEO reviews the simulation and notes only three of the five distribution centers are used. But is it the optimal supply chain design with minimal total costs? Knowing the CEO wants to select supply chain design with minimal total costs (the sum of fixed and variable costs), he runs an optimization experiment to determine the costs of alternative supply chain designs with varying numbers of DCs.

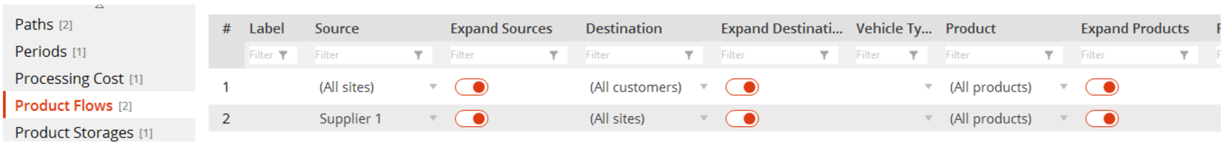
Optimization Experiment

To answer this question and determine the optimal supply chain design, we'll convert our simulation scenario to an NO scenario.

Change Inclusion type of all sites in the **DC** table and Factories to **Consider**.

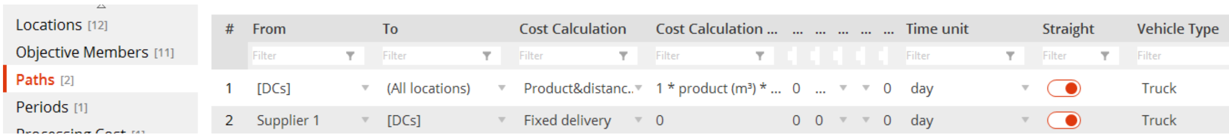
Since our distribution centers don't produce products, we need to add a Supplier that will provide our sites with a regular scale of Juice. It doesn't matter where our Supplier is located on the map. We will not compute costs related with the distribution center's sided purchases, so put the following data to related tables:

- Create a group named **DCs** (activate all objects in the **Sites** column);
- Update the **Product Flow** table
- Update the **Path** table



#	Label	Source	Expand Sources	Destination	Expand Destinati...	Vehicle Ty...	Product	Expand Products
1		(All sites)		(All customers)			(All products)	
2		Supplier 1		(All sites)			(All products)	

Figure 4. The **Product Flow** table



#	From	To	Cost Calculation	Cost Calculation ...	...	...	...	...	Time unit	Straight	Vehicle Type
1	[DCs]	(All locations)	Product&distanc..	1 * product (m³) * ...	0	...		0	day		Truck
2	Supplier 1	[DCs]	Fixed delivery	0	0	0		0	day		Truck

Figure 5. The **Path** table

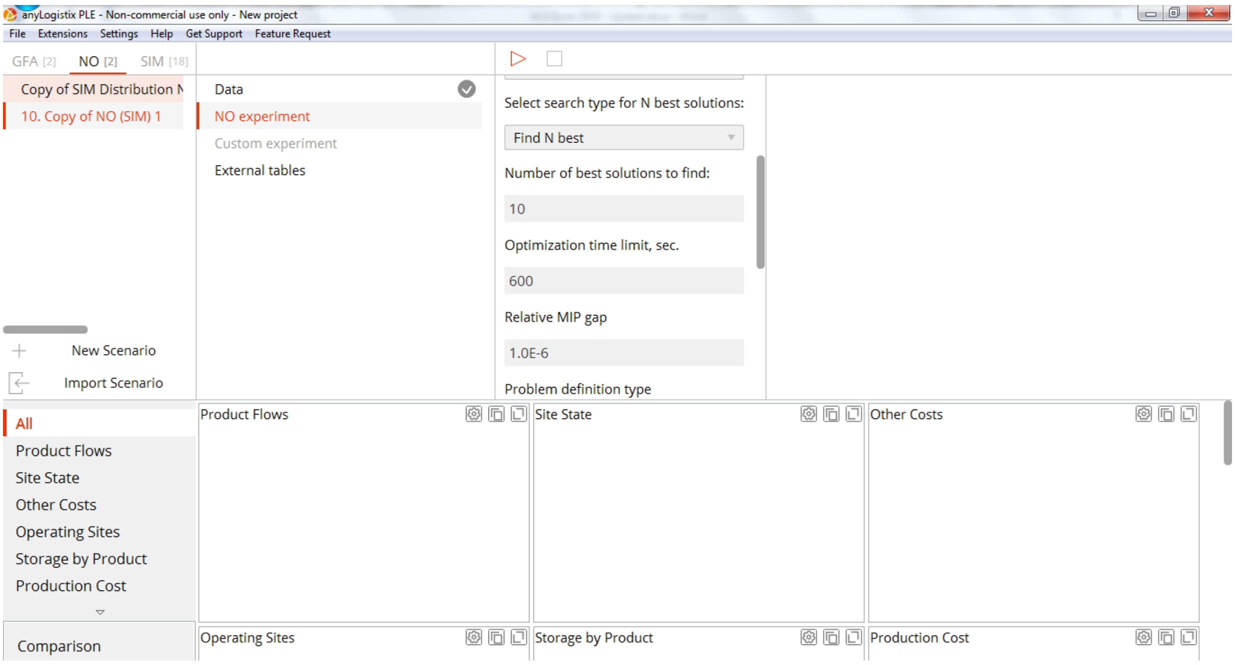


Figure 6. The Start dialog for the optimization experiment.

We run the optimization experiment (Figure 7).

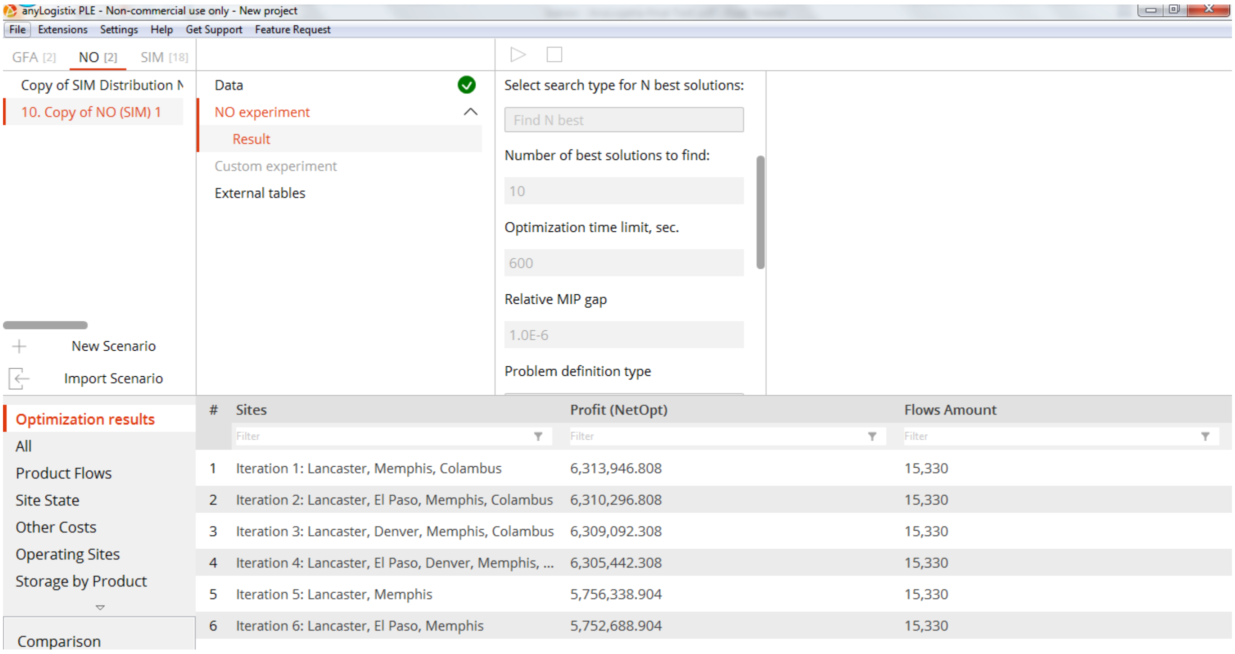


Figure 7. Solution to the network optimization problem in Network Optimization (CPLEX).

We can see our optimization result suggests three distribution centers–in Memphis, Columbus and Lancaster–would increase the supply chain's efficiency. Alexander will now use a simulation with three distribution centers to confirm these results.

Optimization-based Simulation Experiment

We'll use the results from our optimization experiment to perform a new simulation experiment that uses three distribution centers in Memphis, Columbus and Lancaster.

Convert the best NO experiment result to SIM scenario. In the scenario data under **DCs/Factories**, we need to change the **Inclusion Type** for Denver and El Paso from **consider** to **exclude**. Delete all rows in the **Inventory** table and add one record for All sites with **Unlimited Inventory Policy**.

Figure 8 and Table 1 show the simulation's results.

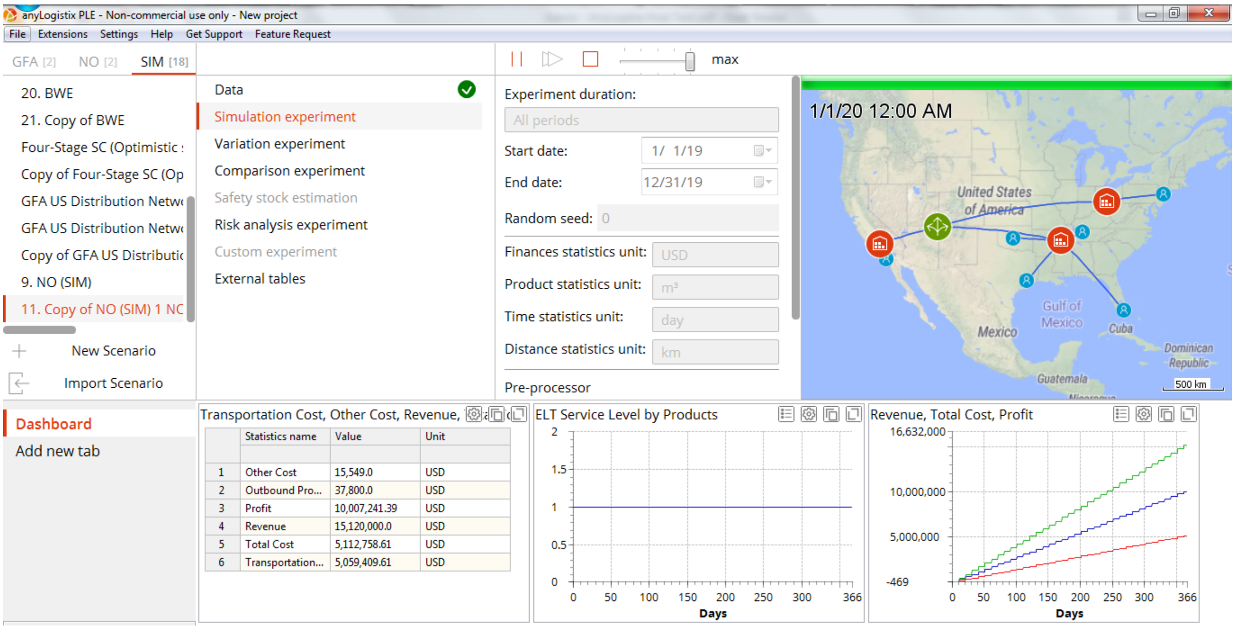


Figure 8. Simulation result for three distribution centers.

Note: In an optimization experiment, we compute optimal supply chain structure and minimum costs for a set of parameters. In a simulation experiment, we observe the structure's dynamic supply chain behavior and dynamics of different KPI over time.

Table 1. KPI Comparison

KPI	AS-IS (Five DCs)	Three DCs
Financial DC performance:		
Other cost, $	24 053.5	15 549.0
Outbound processing cost, $	37 800.0	37 800.0
Profit, $	9 998 736.89	10 007 241.39
Revenue, $	15 120 000.0	15 120 000.0
Total cost, $	5 121 263.11	5 112 758.61
Transportation cost, $	5 059 409.61	5 059 409.61
Customer performance:		
Service level, %	100	100

You can see in Table 1 that supply chain design with three distribution centers is more efficient and profitable. The lower fixed warehousing cost have increased the total supply chain's efficiency. This has proven that two distribution centers—one in El Paso, the other in Denver— have excess capacity in the supply chain.

Note: A **Comparison** experiment is a fast and convenient way to compare the KPI of supply chain designs with different policies and parameters. However, because this experiment compares scenarios, we would need to describe each design alternative as an individual scenario. We will learn how to use this option in Chapter 4, Risk Management.

Case-study 3: Simulation and network optimization

Consider the following example: A German-based supply chain includes one Supplier, three distribution centers and ten Customers (Figure 1).

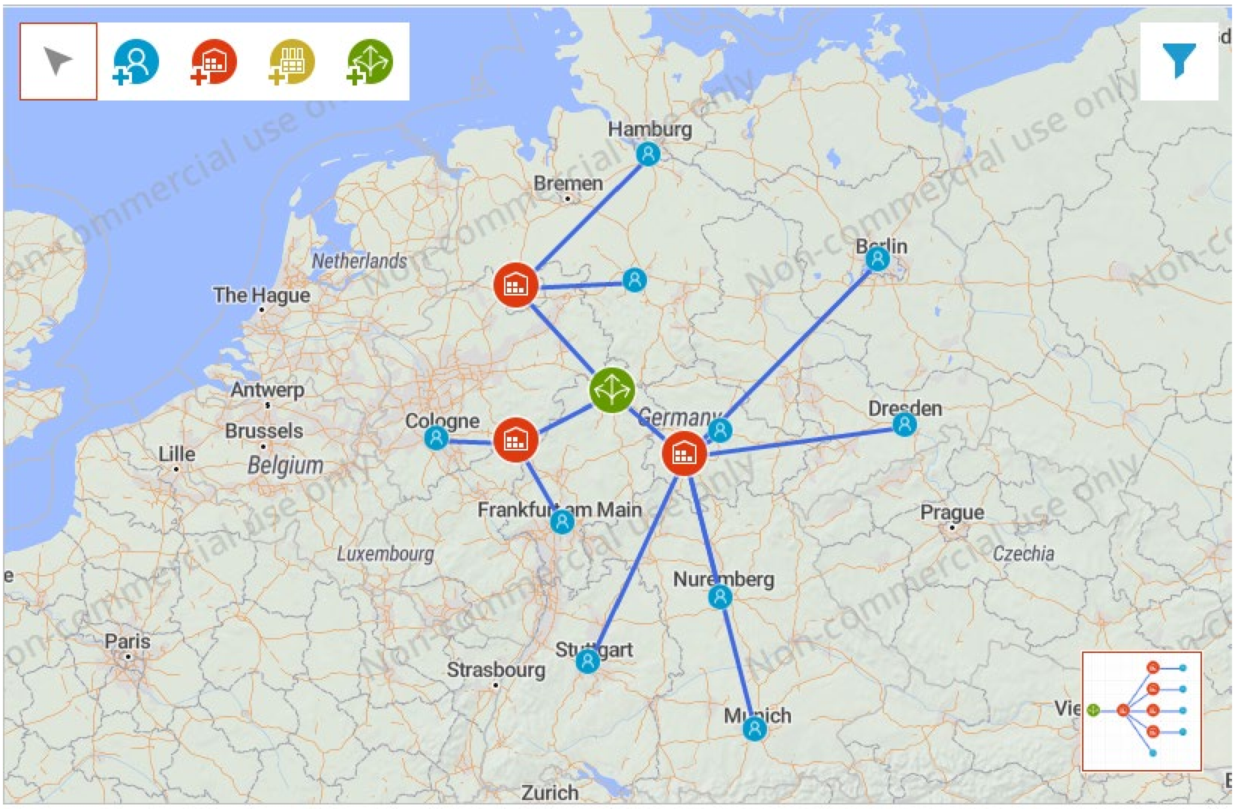


Figure 1. Supply chain structure.

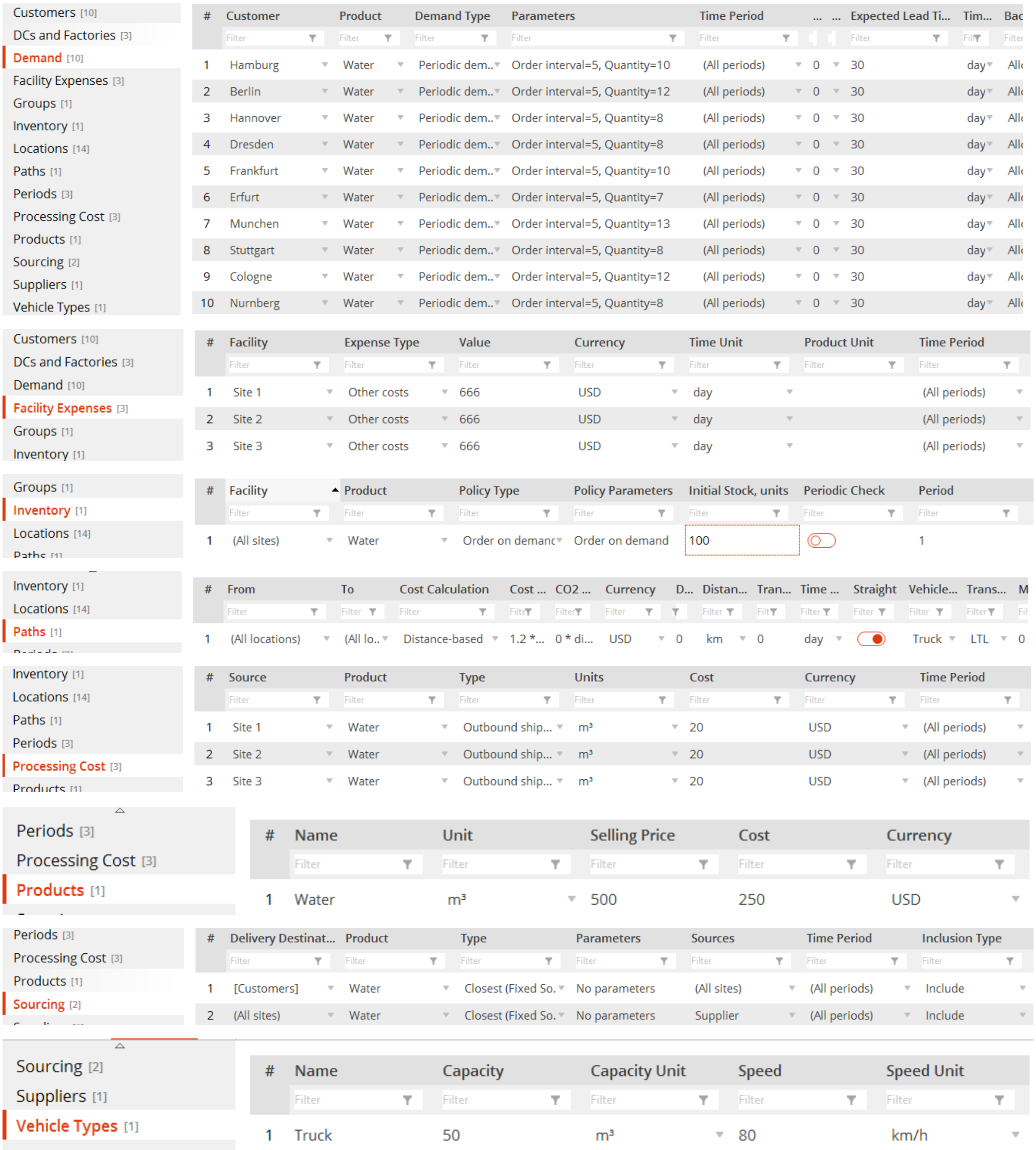
We use the following input data (Figure 2):

- Locations [14]
- Paths [1]
- Periods [3]
- Processing Cost [3]
- Products [1]
- Sourcing [2]

#	Name	Start	End	Demand Coeffici...
1	First period	1/1/19	4/30/19	1
2	Second period	5/1/19	8/31/19	1
3	Third period	9/1/19	12/31/19	1

- Customers [10]
- DCs and Factories [3]
- Demand [10]
- Facility Expenses [3]
- Groups [1]
- Inventory [1]

#	Name	Type	Location	Initially Open	Inclusion Type	Capacity	Capacity Unit
1	Site 1	DC	Site 1 location		Consider	0	m³
2	Site 2	DC	Site 2 location		Consider	0	m³
3	Site 3	DC	Site 3 location		Consider	0	m³



#	Customer	Product	Demand Type	Parameters	Time Period	...	...	Expected Lead Ti...	Tim...	Bac
1	Hamburg	Water	Periodic dem..	Order interval=5, Quantity=10	(All periods)	0	30		day	All
2	Berlin	Water	Periodic dem..	Order interval=5, Quantity=12	(All periods)	0	30		day	All
3	Hannover	Water	Periodic dem..	Order interval=5, Quantity=8	(All periods)	0	30		day	All
4	Dresden	Water	Periodic dem..	Order interval=5, Quantity=8	(All periods)	0	30		day	All
5	Frankfurt	Water	Periodic dem..	Order interval=5, Quantity=10	(All periods)	0	30		day	All
6	Erfurt	Water	Periodic dem..	Order interval=5, Quantity=7	(All periods)	0	30		day	All
7	Munchen	Water	Periodic dem..	Order interval=5, Quantity=13	(All periods)	0	30		day	All
8	Stuttgart	Water	Periodic dem..	Order interval=5, Quantity=8	(All periods)	0	30		day	All
9	Cologne	Water	Periodic dem..	Order interval=5, Quantity=12	(All periods)	0	30		day	All
10	Nurnberg	Water	Periodic dem..	Order interval=5, Quantity=8	(All periods)	0	30		day	All

#	Facility	Expense Type	Value	Currency	Time Unit	Product Unit	Time Period
1	Site 1	Other costs	666	USD	day		(All periods)
2	Site 2	Other costs	666	USD	day		(All periods)
3	Site 3	Other costs	666	USD	day		(All periods)

#	Facility	Product	Policy Type	Policy Parameters	Initial Stock, units	Periodic Check	Period
1	(All sites)	Water	Order on demand	Order on demand	100		1

#	From	To	Cost Calculation	Cost ...	CO2 ...	Currency	D...	Distan...	Tran...	Time ...	Straight	Vehicle...	Trans...	M
1	(All locations)	(All lo..	Distance-based	1.2 *...	0 * di...	USD	0	km	0	day		Truck	LTL	0

#	Source	Product	Type	Units	Cost	Currency	Time Period
1	Site 1	Water	Outbound ship...	m³	20	USD	(All periods)
2	Site 2	Water	Outbound ship...	m³	20	USD	(All periods)
3	Site 3	Water	Outbound ship...	m³	20	USD	(All periods)

#	Name	Unit	Selling Price	Cost	Currency
1	Water	m³	500	250	USD

#	Delivery Destinat...	Product	Type	Parameters	Sources	Time Period	Inclusion Type
1	[Customers]	Water	Closest (Fixed So.	No parameters	(All sites)	(All periods)	Include
2	(All sites)	Water	Closest (Fixed So.	No parameters	Supplier	(All periods)	Include

#	Name	Capacity	Capacity Unit	Speed	Speed Unit
1	Truck	50	m³	80	km/h

Figure 2. Input data.

First, we perform a simulation experiment for a supply chain design that uses three distribution centers. The result is shown in Figure 3:

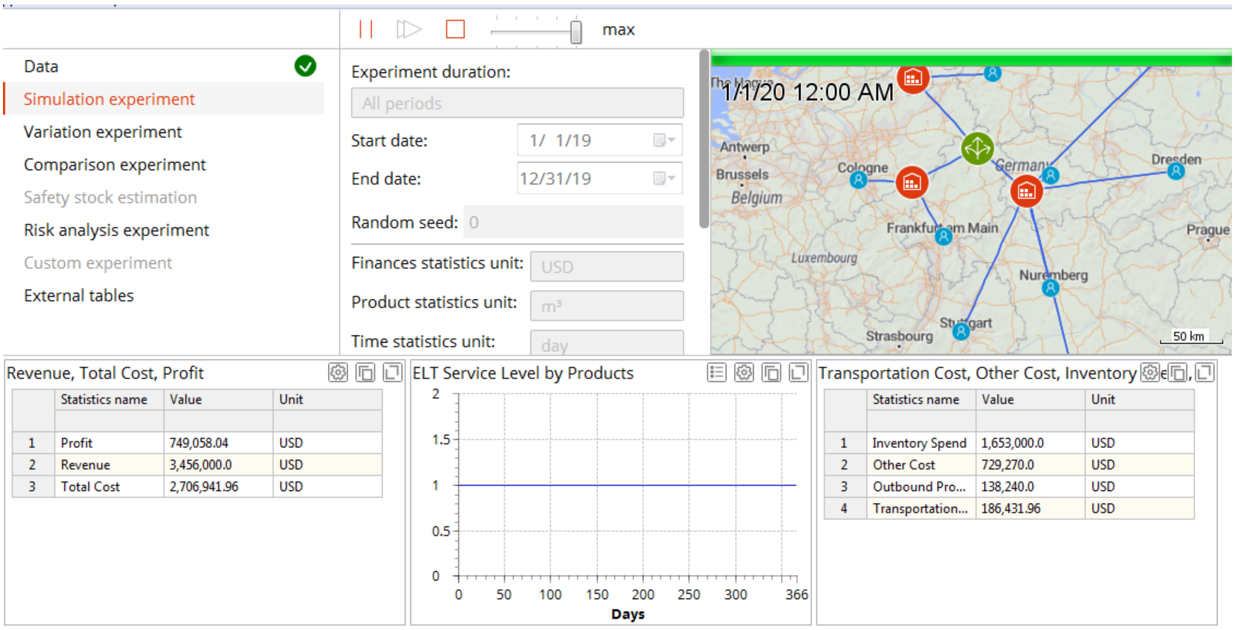


Figure 3. The performance of a supply chain that has three distribution centers.

Then convert current simulation scenario to NO scenario and enter the following data into the **Demand** table:

Table 1. Demand distribution

Customer	Product	Demand Type	Time Period	Revenue	Down Penalty	Up Penalty
Hamburg	Water	PeriodicDemand [period:5.0;quantity:10.0]	First	500	5000	5000
Berlin	Water	PeriodicDemand [period:5.0;quantity:12.0]	First	500	5000	5000
Hannover	Water	PeriodicDemand [period:5.0;quantity:8.0]	First	500	5000	5000
Dresden	Water	PeriodicDemand [period:5.0;quantity:8.0]	First	500	5000	5000
Frankfurt	Water	PeriodicDemand [period:5.0;quantity:10.0]	First	500	5000	5000
Erfurt	Water	PeriodicDemand [period:5.0;quantity:7.0]	First	500	5000	5000
Munchen	Water	PeriodicDemand [period:5.0;quantity:13.0]	First	500	5000	5000
Stuttgart	Water	PeriodicDemand [period:5.0;quantity:8.0]	First	500	5000	5000
Cologne	Water	PeriodicDemand [period:5.0;quantity:12.0]	First	500	5000	5000
Nurnberg	Water	PeriodicDemand [period:5.0;quantity:8.0]	First	500	5000	5000
Hamburg	Water	PeriodicDemand [period:5.0;quantity:13.0]	Second	500	5000	5000
Berlin	Water	PeriodicDemand [period:5.0;quantity:15.6]	Second	500	5000	5000

Hannover	Water	PeriodicDemand [period:5.0;quantity:10.4]	Second	500	5000	5000
Dresden	Water	PeriodicDemand [period:5.0;quantity:10.4]	Second	500	5000	5000
Frankfurt	Water	PeriodicDemand [period:5.0;quantity:13.0]	Second	500	5000	5000
Erfurt	Water	PeriodicDemand [period:5.0;quantity:9.1]	Second	500	5000	5000
Munchen	Water	PeriodicDemand [period:5.0;quantity:16.9]	Second	500	5000	5000
Stuttgart	Water	PeriodicDemand [period:5.0;quantity:10.4]	Second	500	5000	5000
Cologne	Water	PeriodicDemand [period:5.0;quantity:15.6]	Second	500	5000	5000
Nurnberg	Water	PeriodicDemand [period:5.0;quantity:10.0]	Second	500	5000	5000
Hamburg	Water	PeriodicDemand [period:5.0;quantity:8.0]	Third	500	5000	5000
Berlin	Water	PeriodicDemand [period:5.0;quantity:9.6]	Third	500	5000	5000
Hannover	Water	PeriodicDemand [period:5.0;quantity:6.4]	Third	500	5000	5000
Dresden	Water	PeriodicDemand [period:5.0;quantity:6.4]	Third	500	5000	5000
Frankfurt	Water	PeriodicDemand [period:5.0;quantity:8.0]	Third	500	5000	5000
Erfurt	Water	PeriodicDemand [period:5.0;quantity:5.6]	Third	500	5000	5000
Munchen	Water	PeriodicDemand [period:5.0;quantity:10.4]	Third	500	5000	5000
Stuttgart	Water	PeriodicDemand [period:5.0;quantity:6.4]	Third	500	5000	5000
Cologne	Water	PeriodicDemand [period:5.0;quantity:9.6]	Third	500	5000	5000
Nurnberg	Water	PeriodicDemand [period:5.0;quantity:6.4]	Third	500	5000	5000

In the second step, network optimization experiment is run (Figure 4).

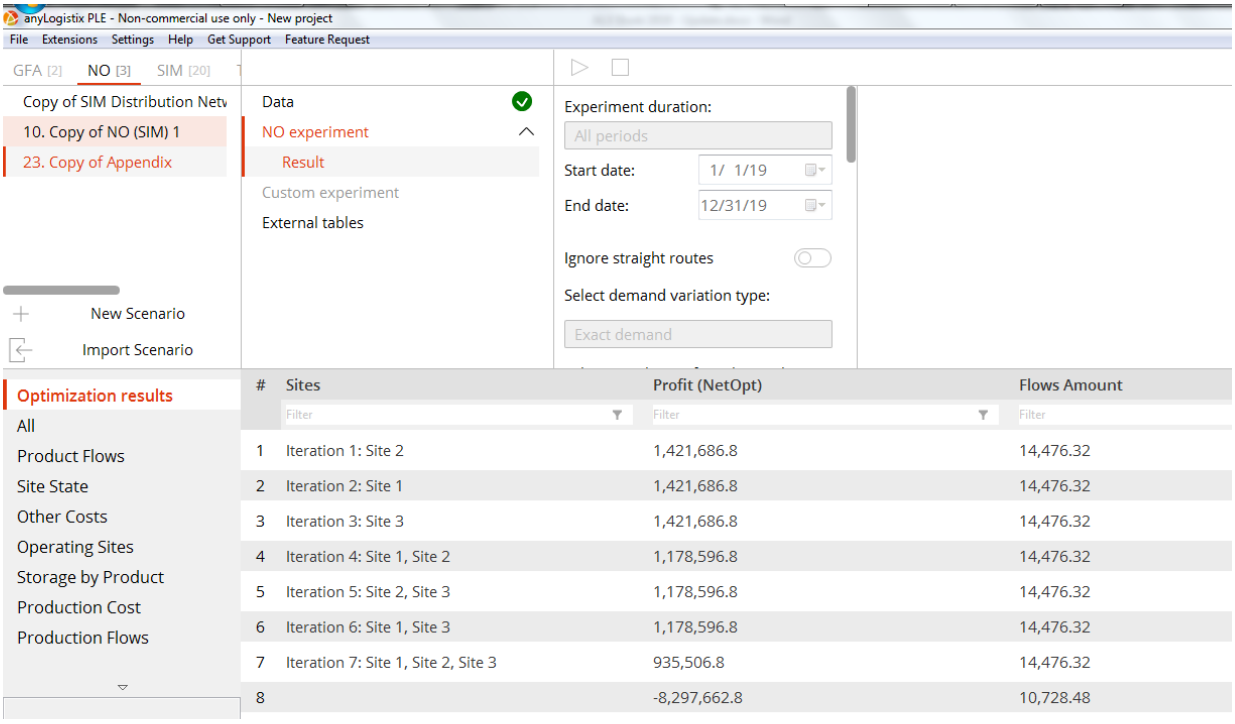


Figure 4. Network optimization experiment.

Third, we use the best result of the network optimization that suggests using one distribution center is the most profitable supply chain design (profit of $1,421,686.8). We convert it to the SIM scenario, change our input data (delete Supplier information and inventory policy) and run a simulation experiment with the optimal supply chain design subject to maximum profit (Figure 5).

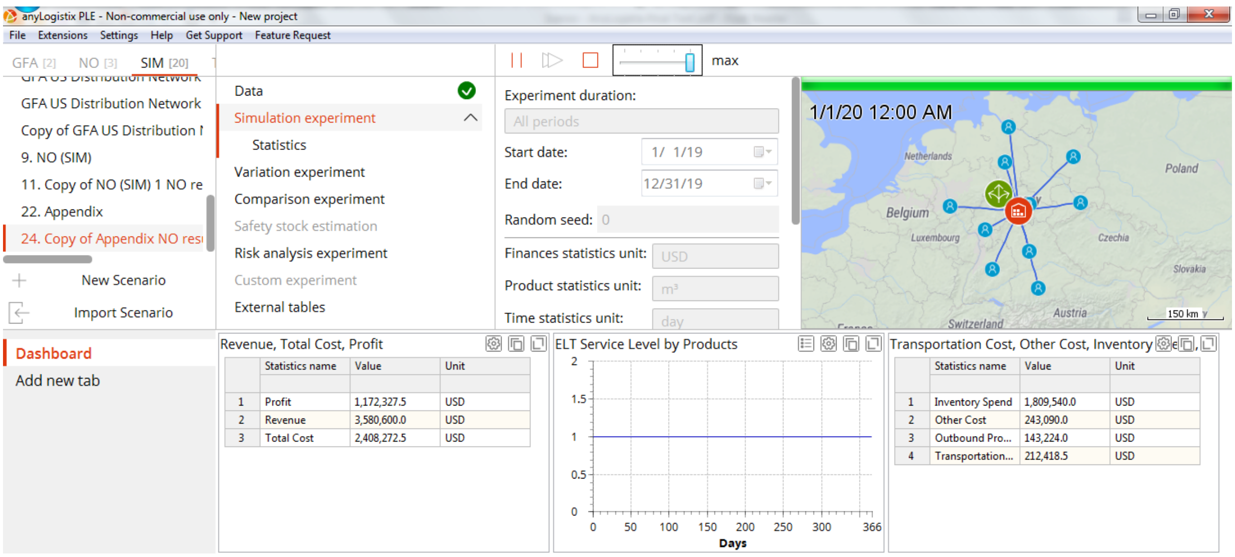


Figure 5. Simulation experiment with optimal supply chain design.

We can see the sum of fixed warehousing costs is $243,090.0 and variable transportation costs equals $212,418.5.

We use a **Comparison** experiment to compare the supply chain design that uses three distribution centers (scenario Appendix) with the design that uses one distribution center (scenario Copy of Appendix 1 NO results) (Figure 6).

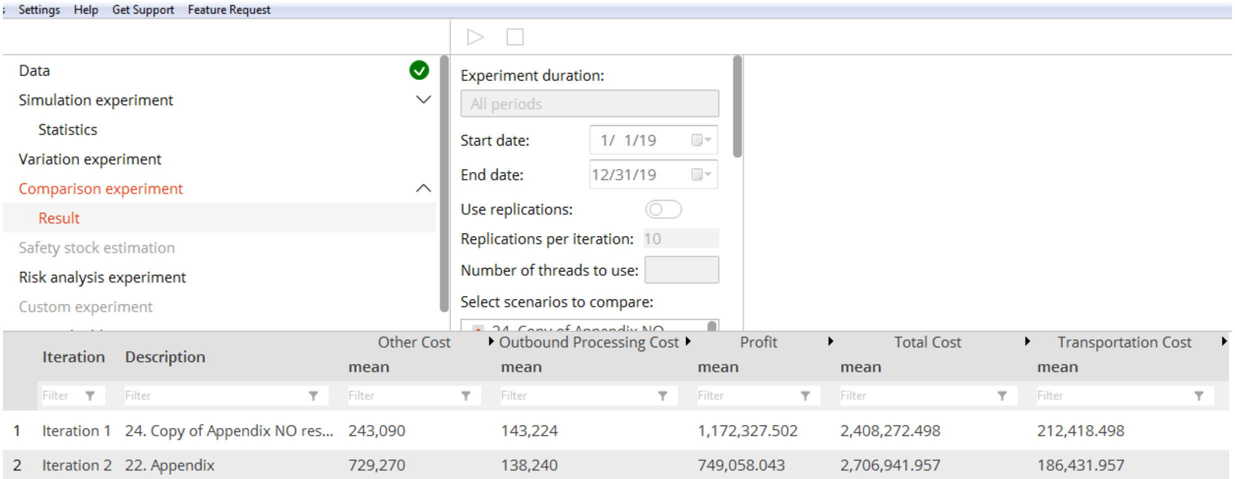


Figure 6. Comparison experiment

Figure 6 shows us the supply chain design that uses three distribution centers has lower transportation costs. However, the significant savings in fixed warehousing costs makes the design that uses one distribution center far more efficient and profitable.

Finally, we perform a variation analysis to analyze KPI sensitivity to the changes in transportation costs in range from $0.2 to $2.0 for a kilometer (Figures 7-10).

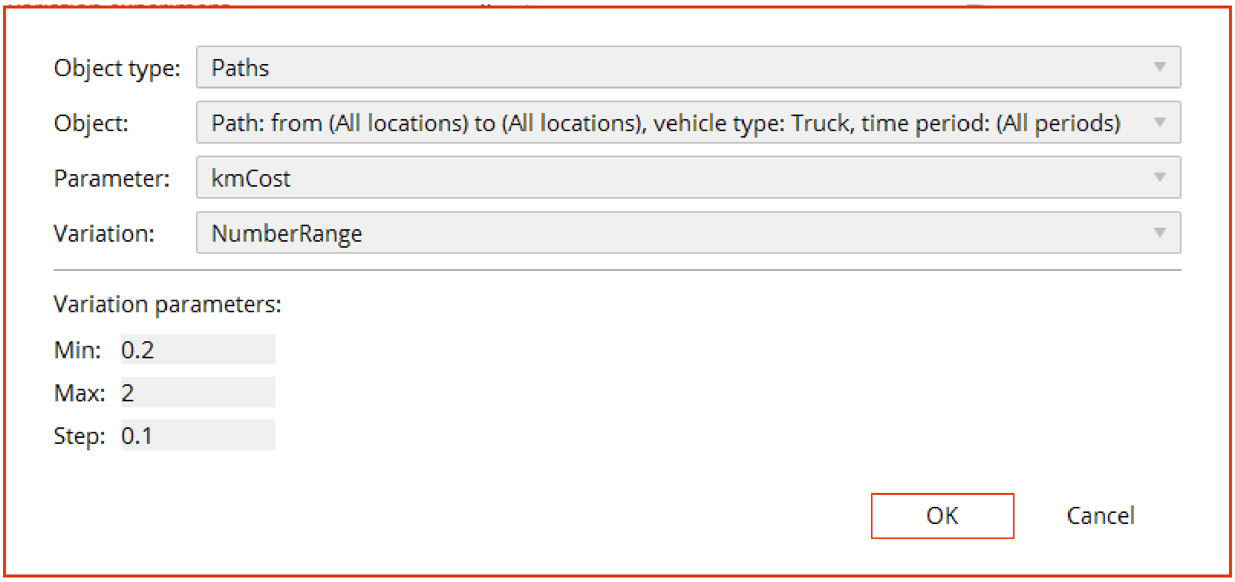


Figure 7. Setting the range for parameter change.

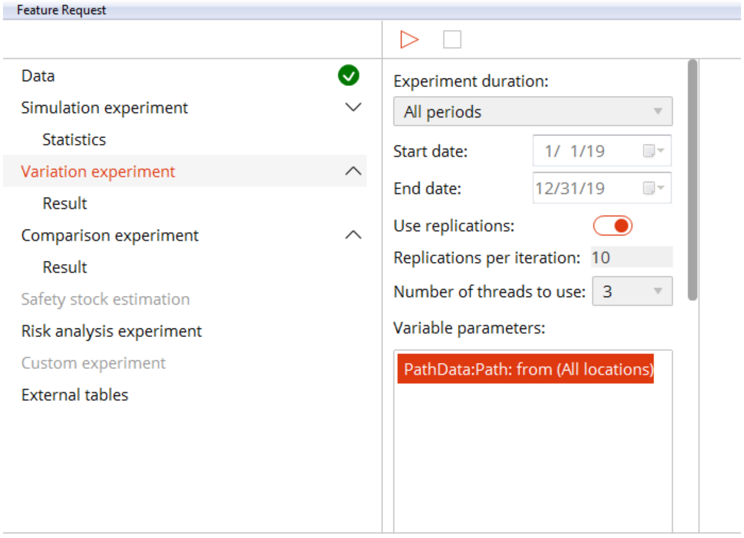


Figure 8. Setting the number of replications.

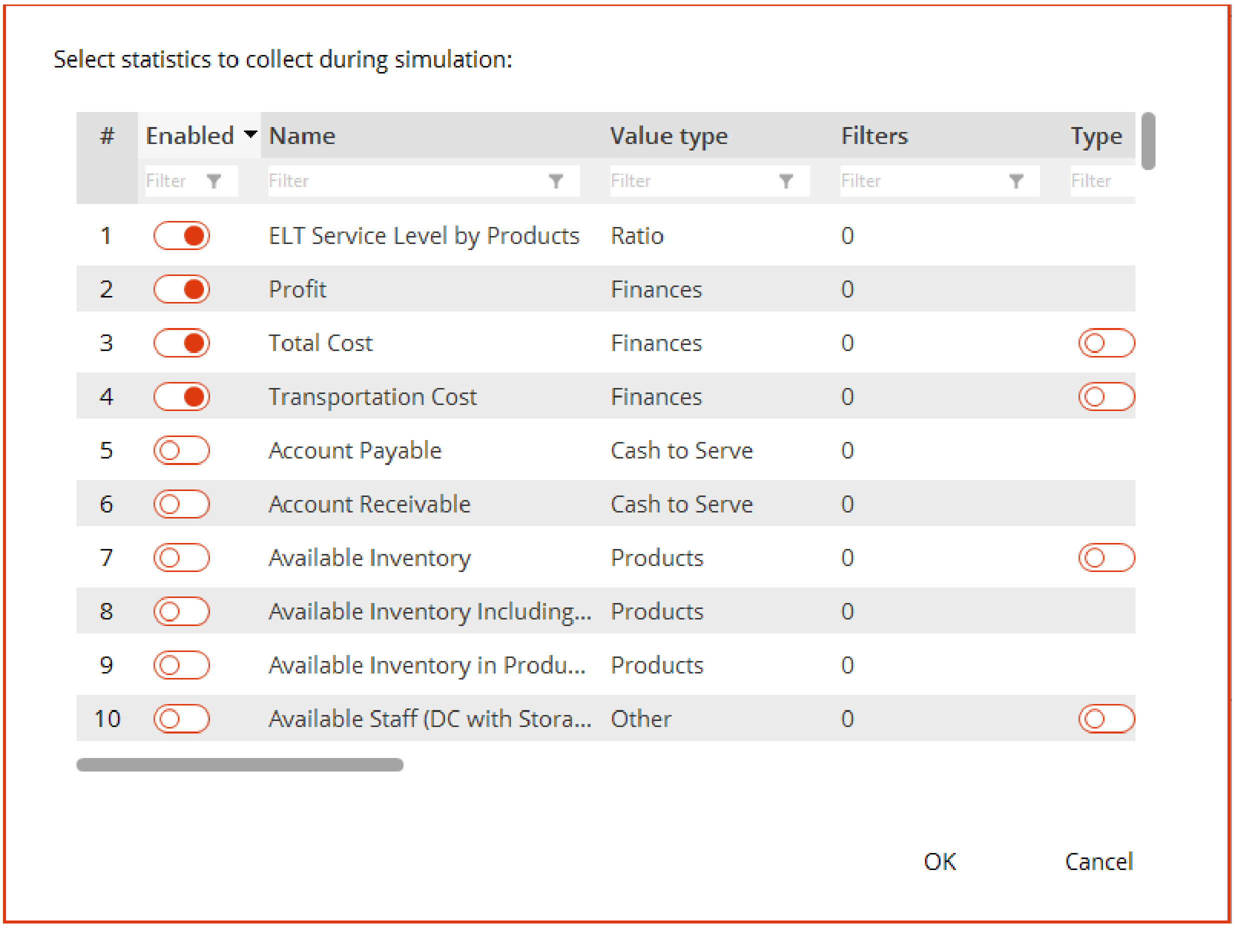


Figure 9. Configuring statistics.

	Iteration	Description	Transportation Cost mean	Total Cost mean	Profit mean	ELT Service Level by Pro(mean
	Filter	Filter	Filter	Filter	Filter	Filter
1	Iteration 1	kmCost: 0.2	35,403.083	2,231,257.083	1,349,342.917	1
2	Iteration 2	kmCost: 0.3	53,104.625	2,248,958.625	1,331,641.375	1
3	Iteration 3	kmCost: 0.4	70,806.166	2,266,660.166	1,313,939.834	1
4	Iteration 4	kmCost: 0.5	88,507.708	2,284,361.708	1,296,238.292	1
5	Iteration 5	kmCost: 0.6	106,209.249	2,302,063.249	1,278,536.751	1
6	Iteration 6	kmCost: 0.7	123,910.791	2,319,764.791	1,260,835.209	1
7	Iteration 7	kmCost: 0.8	141,612.332	2,337,466.332	1,243,133.668	1
8	Iteration 8	kmCost: 0.9	159,313.874	2,355,167.874	1,225,432.126	1
9	Iteration 9	kmCost: 1	177,015.415	2,372,869.415	1,207,730.585	1
10	Iteration 10	kmCost: 1.1	194,716.957	2,390,570.957	1,190,029.043	1
11	Iteration 11	kmCost: 1.2	212,418.498	2,408,272.498	1,172,327.502	1
12	Iteration 12	kmCost: 1.3	230,120.04	2,425,974.04	1,154,625.96	1
13	Iteration 13	kmCost: 1.4	247,821.581	2,443,675.581	1,136,924.419	1

Figure 10. Results of variation analysis.

Note: Figure 11 displays the unfiltered results of the variation analysis. If you want to make it easier to display the results, you can filter the results such as the **Total costs** column.

With the help of variation analysis, we can observe the KPI change in dependence on the input parameter changes. This is helpful for sensitivity analysis.

Case-Study 4: Three-stage, one-period supply network design

Problem statement

You are a supply chain manager at a company that produces beverages. Your task is to design a new supply chain with the highest possible profit. In the reports from different departments at the company you collected the following data:

- Potential locations of your distribution centers (DC) and factories
- Demand in the markets
- Factory production capacities
- Processing capacity at the DCs
- Product price
- Transportation, inventory holding and processing costs at the DCs

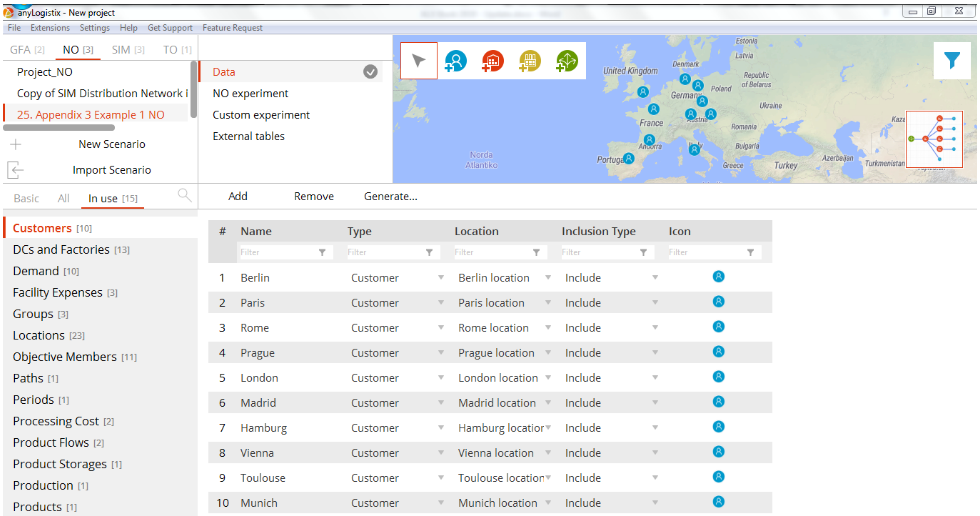
Table 1. Input parameter

Parameter	**Values**
Demand in the markets, in m^3	730
Transportation distances and time in between supply chain facilities	Determined automatically by actual routes*
Maximum inbound DC processing capacity, in m^3 per day	3,000
Maximum outbound DC processing capacity, in m^3 per day	3,000
Maximum production capacity at own factory, in m^3 per year	3,800
Penalties for overutilization of production capacity, in $	100,000
Unit price, in $ for m^3	3,000
Fixed facility costs, in $ per day	5,000
Transportation costs, in $ per km, per m^3	0.1
Production costs at own factories, per product unit (m^3), in $	250
Inbound processing costs at the DC, in $, per m^3	150
Outbound processing costs at the DC, in $, per m^3	100
Penalty for demand non-fulfillment, in $, per m^3	5,000

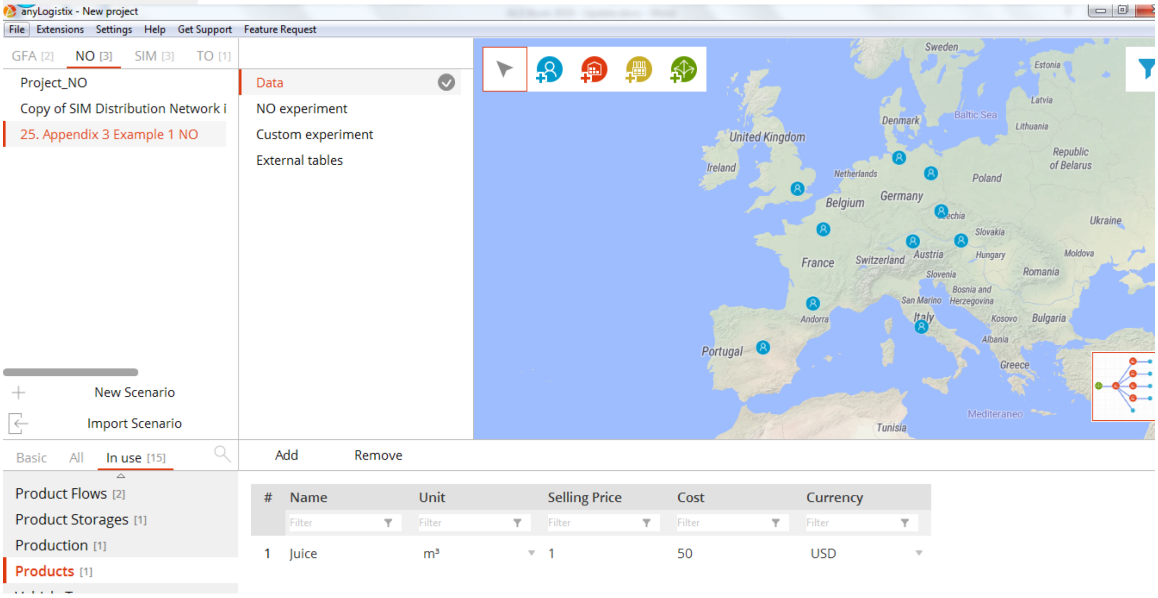
* Automated transportation distance and time determination are some advantages of anyLogistix. We do not need to determine a large-scale distance matrix. Both distances and times are determined automatically by the software using real routes and real truck speeds.

Input data

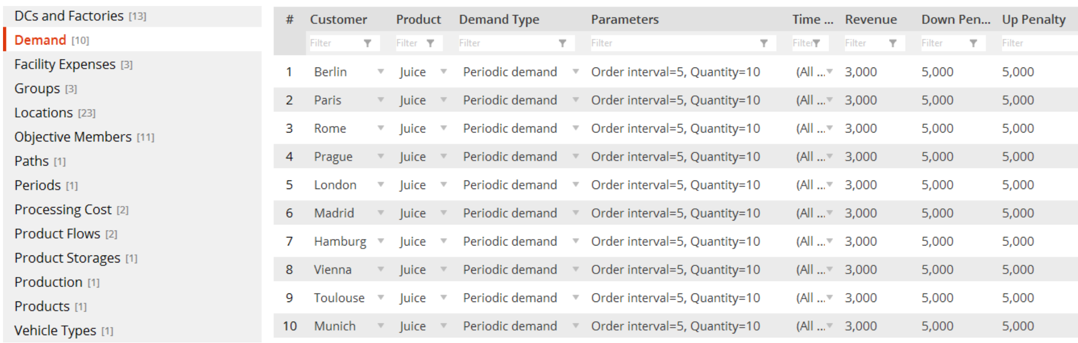
Customers and demand



#	Name	Type	Location	Inclusion Type
1	Berlin	Customer	Berlin location	Include
2	Paris	Customer	Paris location	Include
3	Rome	Customer	Rome location	Include
4	Prague	Customer	Prague location	Include
5	London	Customer	London location	Include
6	Madrid	Customer	Madrid location	Include
7	Hamburg	Customer	Hamburg location	Include
8	Vienna	Customer	Vienna location	Include
9	Toulouse	Customer	Toulouse location	Include
10	Munich	Customer	Munich location	Include

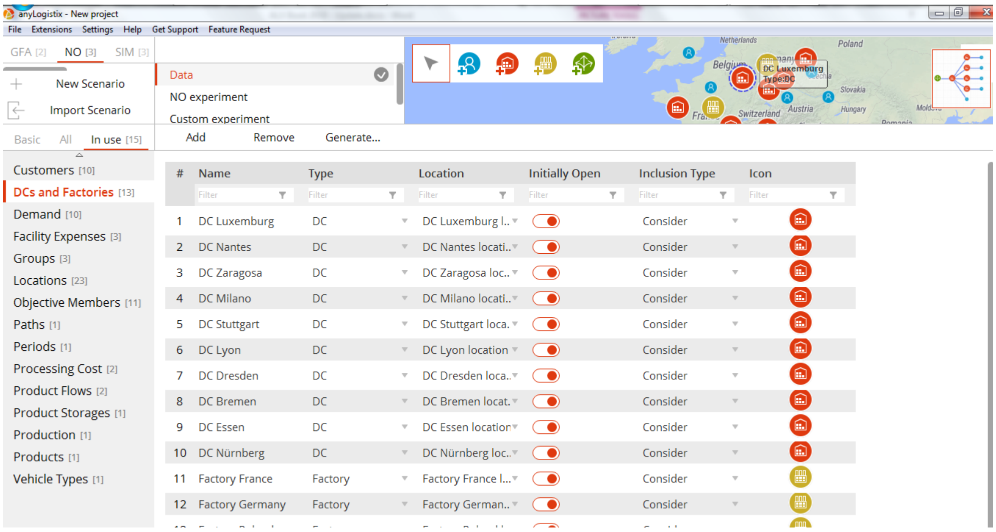


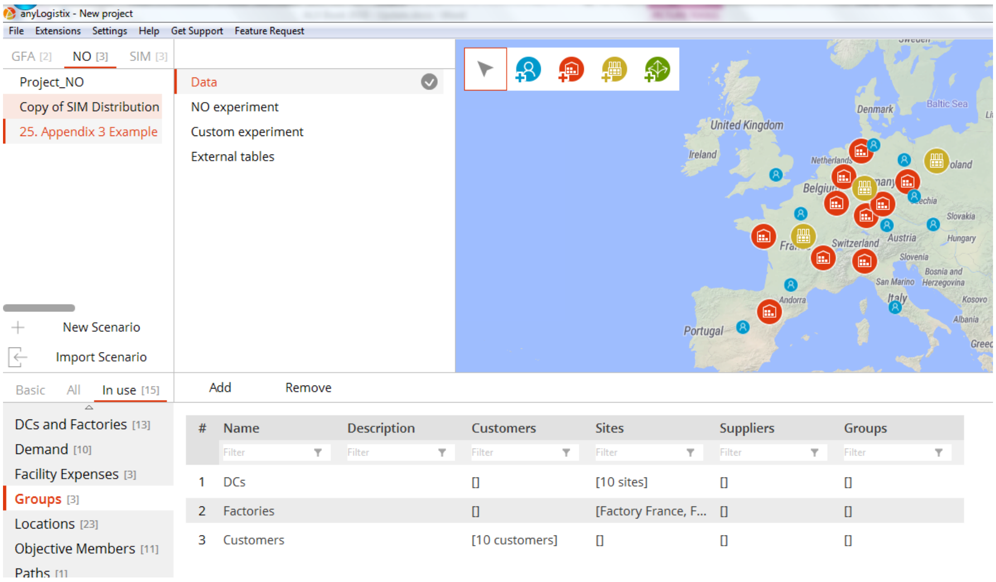
#	Name	Unit	Selling Price	Cost	Currency
1	Juice	m³	1	50	USD



#	Customer	Product	Demand Type	Parameters	Time ...	Revenue	Down Pen...	Up Penalty
1	Berlin	Juice	Periodic demand	Order interval=5, Quantity=10	(All ...	3,000	5,000	5,000
2	Paris	Juice	Periodic demand	Order interval=5, Quantity=10	(All ...	3,000	5,000	5,000
3	Rome	Juice	Periodic demand	Order interval=5, Quantity=10	(All ...	3,000	5,000	5,000
4	Prague	Juice	Periodic demand	Order interval=5, Quantity=10	(All ...	3,000	5,000	5,000
5	London	Juice	Periodic demand	Order interval=5, Quantity=10	(All ...	3,000	5,000	5,000
6	Madrid	Juice	Periodic demand	Order interval=5, Quantity=10	(All ...	3,000	5,000	5,000
7	Hamburg	Juice	Periodic demand	Order interval=5, Quantity=10	(All ...	3,000	5,000	5,000
8	Vienna	Juice	Periodic demand	Order interval=5, Quantity=10	(All ...	3,000	5,000	5,000
9	Toulouse	Juice	Periodic demand	Order interval=5, Quantity=10	(All ...	3,000	5,000	5,000
10	Munich	Juice	Periodic demand	Order interval=5, Quantity=10	(All ...	3,000	5,000	5,000

DCs and factories





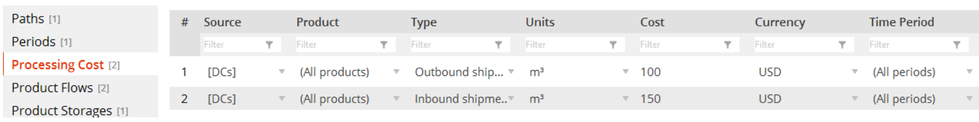


Figure 3. Input data for customers and demand

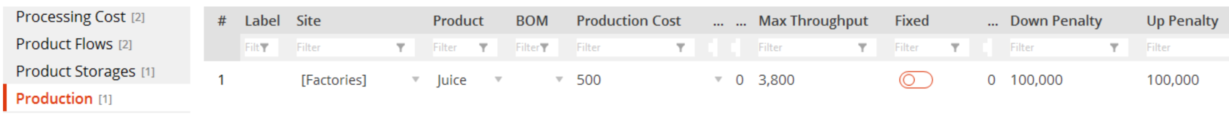


Figure 4. Production capacity and costs

In Figure 4, we depict how to set up the production capacity restriction at factories. The production capacity maximum needs to be entered in the column “**Max Throughput**” (if you need to restrict the minimum capacity level, please use the respective column).

Note: In order to activate this constraint, you need to setup any large number in the columns “**down penalty**” and “**up penalty**”.

Paths and flows

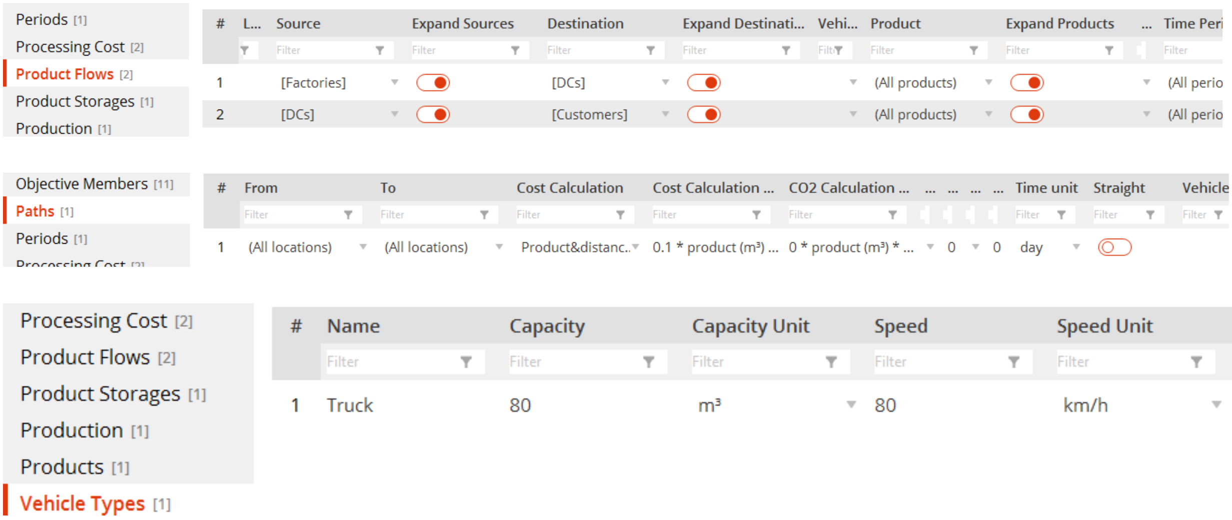


Figure 5. Path and flow settings

Network optimization experiments

In NO Experiment, we start the network optimization for the given data:

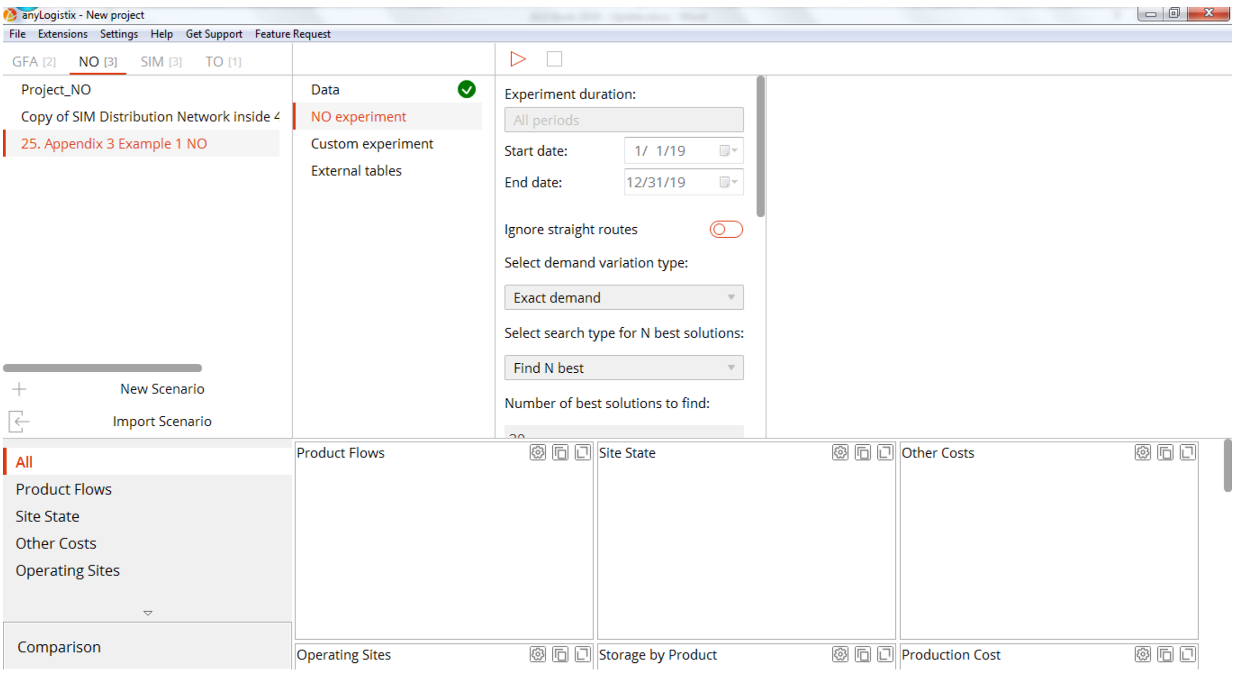


Figure 6. Start of network optimization experiment

The results are shown in Figs 7-10.

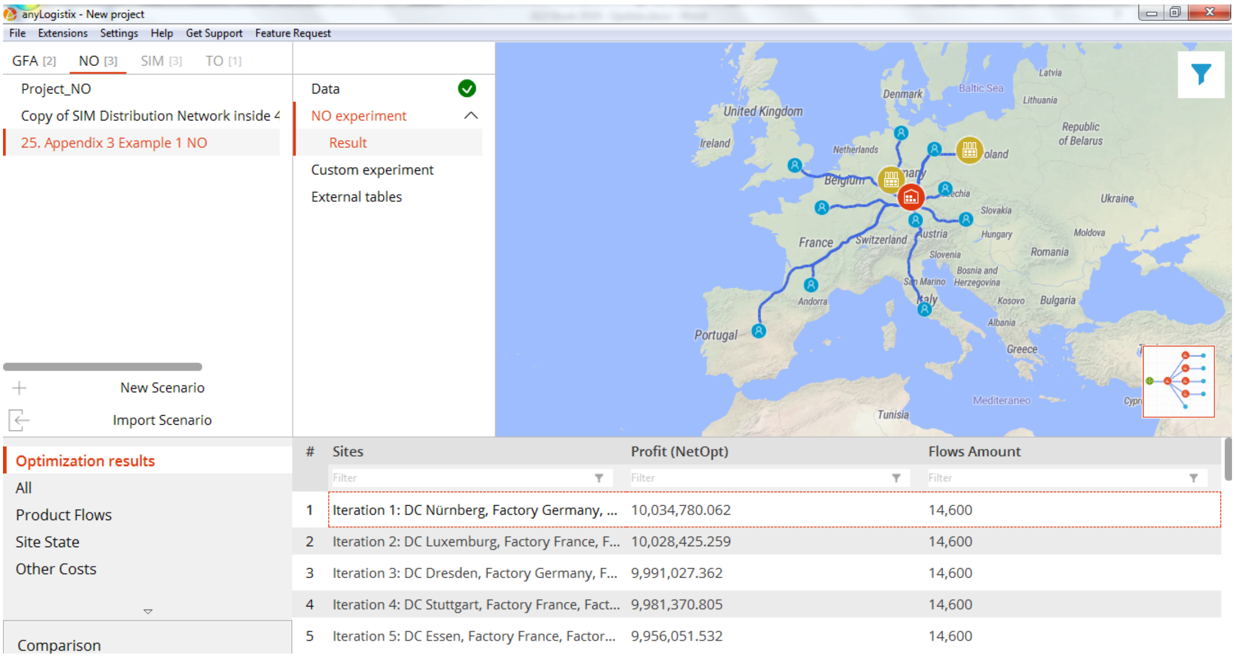


Figure 7. Network optimization results

It can be observed in Fig. 7 that the supply chain design with two factories in Germany and Poland and a DC in Nuremberg earns the highest profit.

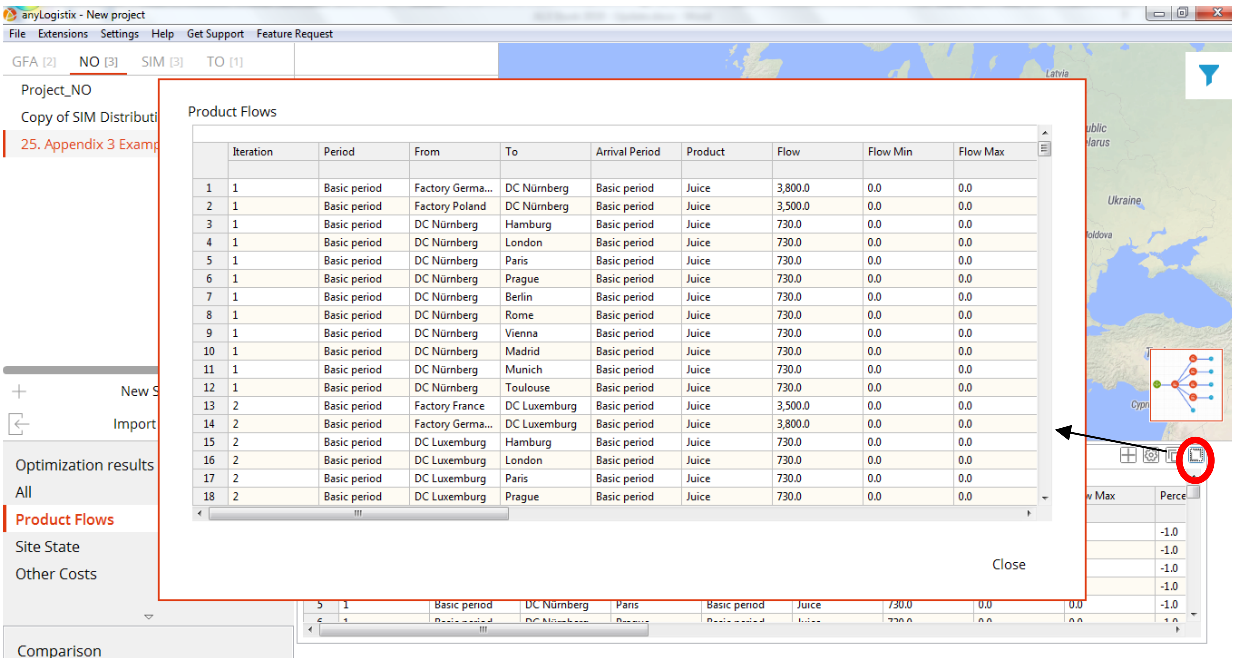
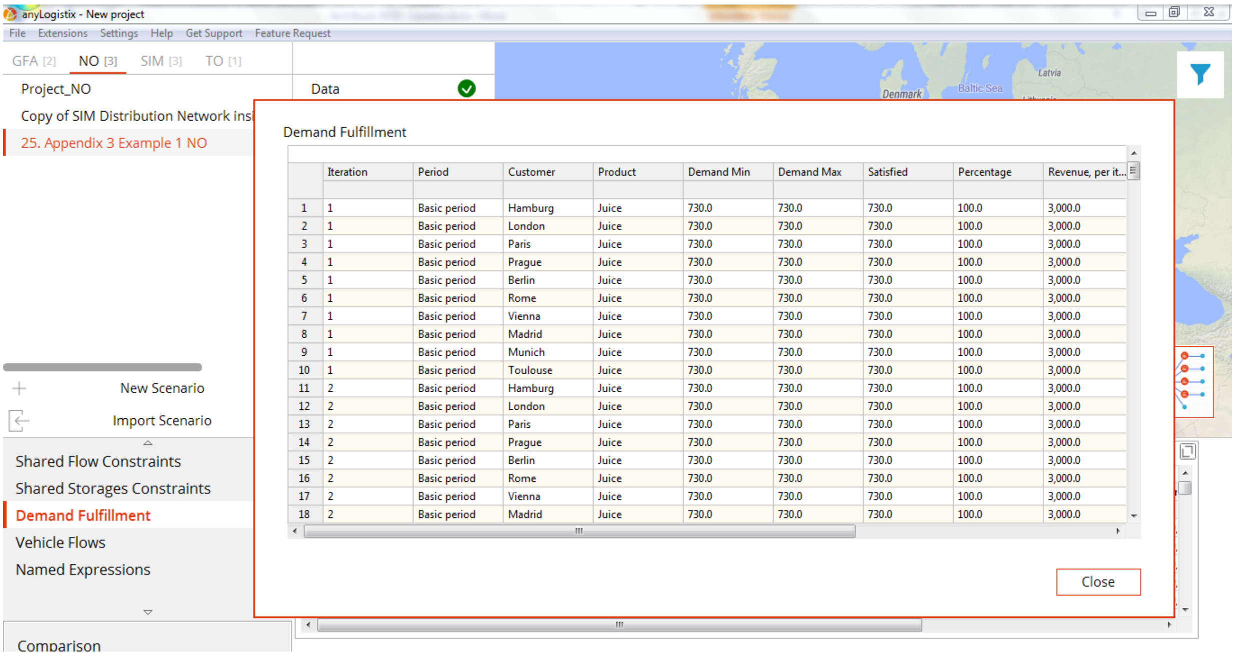


Figure 8. Optimal flows

In Fig. 8, supply chain material flows for the optimal and other possible design are presented.

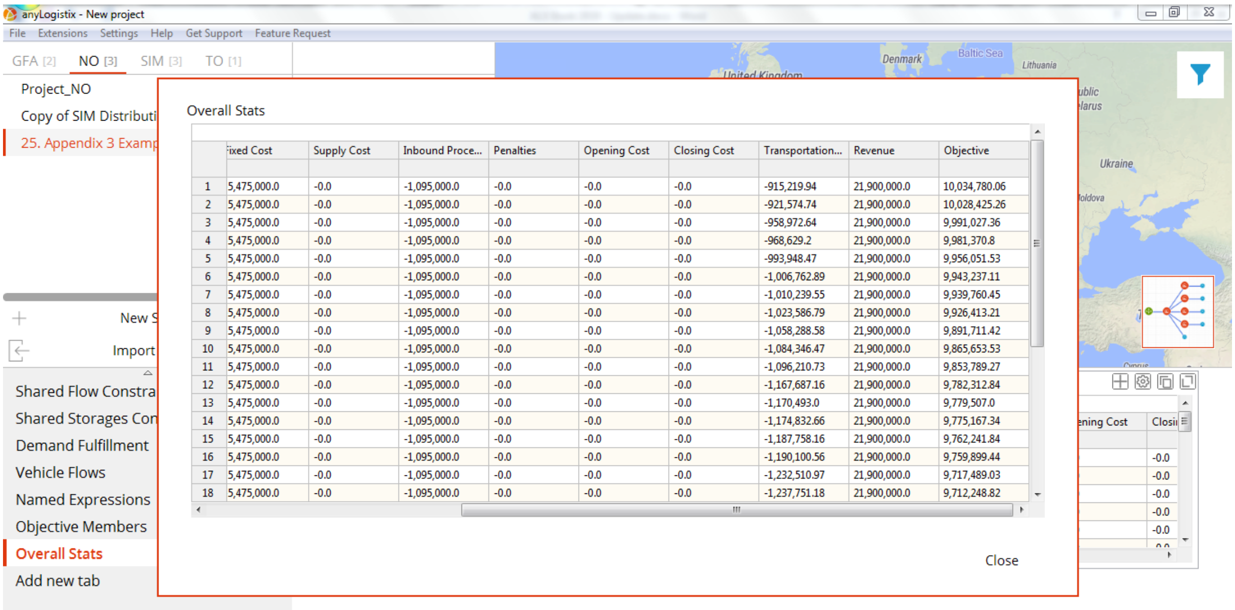


Demand Fulfillment

	Iteration	Period	Customer	Product	Demand Min	Demand Max	Satisfied	Percentage	Revenue, per it...
1	1	Basic period	Hamburg	Juice	730.0	730.0	730.0	100.0	3,000.0
2	1	Basic period	London	Juice	730.0	730.0	730.0	100.0	3,000.0
3	1	Basic period	Paris	Juice	730.0	730.0	730.0	100.0	3,000.0
4	1	Basic period	Prague	Juice	730.0	730.0	730.0	100.0	3,000.0
5	1	Basic period	Berlin	Juice	730.0	730.0	730.0	100.0	3,000.0
6	1	Basic period	Rome	Juice	730.0	730.0	730.0	100.0	3,000.0
7	1	Basic period	Vienna	Juice	730.0	730.0	730.0	100.0	3,000.0
8	1	Basic period	Madrid	Juice	730.0	730.0	730.0	100.0	3,000.0
9	1	Basic period	Munich	Juice	730.0	730.0	730.0	100.0	3,000.0
10	1	Basic period	Toulouse	Juice	730.0	730.0	730.0	100.0	3,000.0
11	2	Basic period	Hamburg	Juice	730.0	730.0	730.0	100.0	3,000.0
12	2	Basic period	London	Juice	730.0	730.0	730.0	100.0	3,000.0
13	2	Basic period	Paris	Juice	730.0	730.0	730.0	100.0	3,000.0
14	2	Basic period	Prague	Juice	730.0	730.0	730.0	100.0	3,000.0
15	2	Basic period	Berlin	Juice	730.0	730.0	730.0	100.0	3,000.0
16	2	Basic period	Rome	Juice	730.0	730.0	730.0	100.0	3,000.0
17	2	Basic period	Vienna	Juice	730.0	730.0	730.0	100.0	3,000.0
18	2	Basic period	Madrid	Juice	730.0	730.0	730.0	100.0	3,000.0

Figure 9. Demand fulfillment analysis

Fig. 9 shows that the demands in all the markets are 100% covered in the optimal solution.



Overall Stats

	Fixed Cost	Supply Cost	Inbound Proce...	Penalties	Opening Cost	Closing Cost	Transportation...	Revenue	Objective
1	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-915,219.94	21,900,000.0	10,034,780.06
2	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-921,574.74	21,900,000.0	10,028,425.26
3	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-958,972.64	21,900,000.0	9,991,027.36
4	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-968,629.2	21,900,000.0	9,981,370.8
5	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-993,948.47	21,900,000.0	9,956,051.53
6	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-1,006,762.89	21,900,000.0	9,943,237.11
7	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-1,010,239.55	21,900,000.0	9,939,760.45
8	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-1,023,586.79	21,900,000.0	9,926,413.21
9	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-1,058,288.58	21,900,000.0	9,891,711.42
10	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-1,084,346.47	21,900,000.0	9,865,653.53
11	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-1,096,210.73	21,900,000.0	9,853,789.27
12	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-1,167,687.16	21,900,000.0	9,782,312.84
13	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-1,170,493.0	21,900,000.0	9,779,507.0
14	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-1,174,832.66	21,900,000.0	9,775,167.34
15	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-1,187,758.16	21,900,000.0	9,762,241.84
16	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-1,190,100.56	21,900,000.0	9,759,899.44
17	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-1,232,510.97	21,900,000.0	9,717,489.03
18	5,475,000.0	-0.0	-1,095,000.0	-0.0	-0.0	-0.0	-1,237,751.18	21,900,000.0	9,712,248.82

Figure 10. Start of network optimization experiment

Finally, the financial performance report on the optimal and other possible supply chain designs is shown in Figure 10.

How to analyse the optimization results and make a management decision

The optimal solution to our problem is to open factories in Germany and Poland and a DC in Nuremberg. Imagine you need to report your results to the CEO. She may ask you some questions such as e.g.:

- is it possible to find a better supply chain design with an even higher profit?
- what happens if the demand in particular markets changes?
- what happens if facility costs grow and transportation costs decrease?
- what about disruption risks: if anything happens at the DC in Nuremberg, is there no second source or backup DC in the supply chain design?

Indeed, you would answer that, for the given set of parameters and their values, this is the best solution in terms of profit maximization. However, the changes in input parameters, e.g., in demand, fixed facility or variable transportation costs, or even in the production capacities may change the solution. For example, the solution changes if you assume a maximum production capacity of factories 8,000 m^3 a year instead of 3,800 m^3. The optimization result is shown in Figure 11.

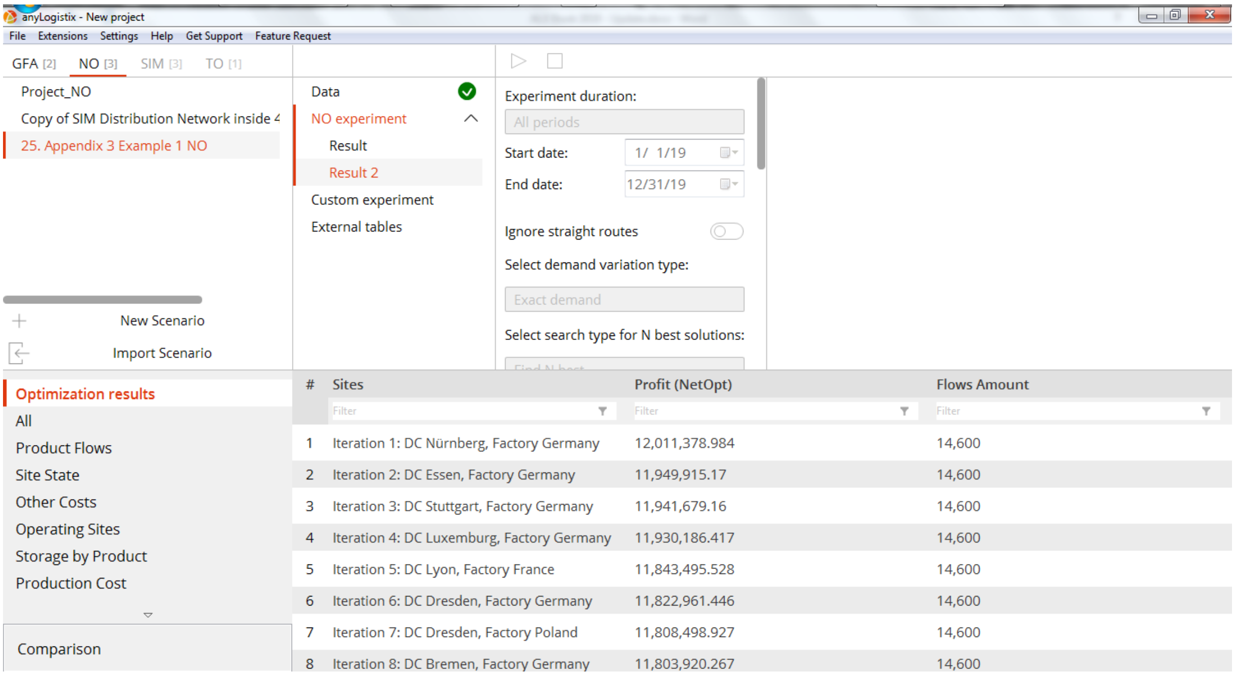


Figure 11. Optimization result for new production capacity maximum

It can be observed in Figure 11 that the new optimal solution is now a supply chain design with a factory in Germany and a DC in Nuremberg. This solution is even more profitable than the previous one. Why do you think this change occurred? Using the optimization results, you might also quickly answer the CEO's question about what the highest profit is that could be achieved in a supply chain design with two DCs (risk management!), see Figure 12.

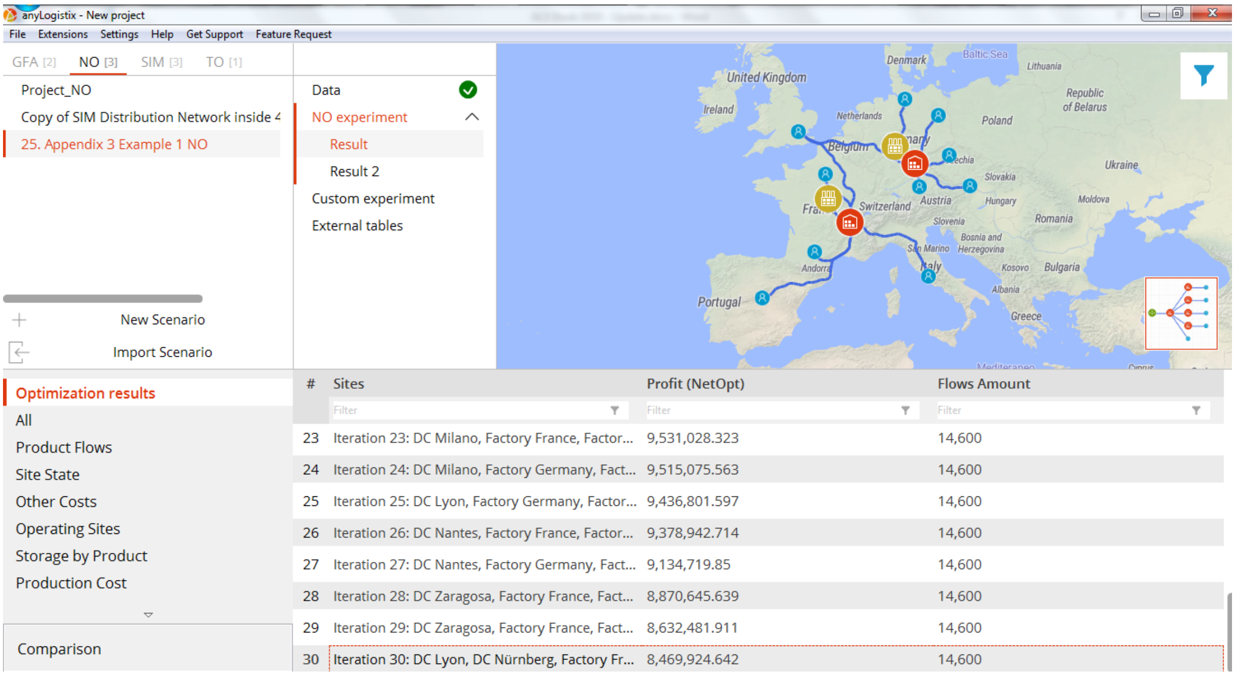


Figure 12. Selection of the best result with two DCs

We can observe in Figure 12 that the most profitable supply chain design with two DCs is the option with two factories in Germany and France and two DCs in France and Germany. However, the profit from this supply chain design would be lower than that of the optimal supply chain design. We call this the “costs of robustness” (Ivanov 2018).

Variation experiment

In order to answer the CEO’s questions about what happens if demands change, facility costs grow and transportation costs decrease, you can run the variation experiment (see details in Ivanov 2017). You might want to let the transportation costs range from 0.05 to 0.5, the fixed facility costs range from 50 to 300, and demand be changed by 20% up or down.

Note: the variation experiment is possible in the SIM mode of anyLogistix. There you will need to define additional policies, e.g., the inventory control policy.

Case-Study 5: Four-stage, multi-period supply chain planning with capacity disruptions, inventory, and transportation constraints

Problem statement

Additional features that will be added in this Chapter:

- Limited transportation capacity
- Many periods
- Capacity disruptions
- Inventory holding costs
- Limited storage capacity

Assume the following problem statement based in Ivanov et al. (2014). We investigate a multi-stage distribution network (DN) that displays the following characteristics: (i) system performance depends on the ability to operate despite perturbations; (ii) some system elements may become unavailable due to disruptions in the DN, and (iii) the system experiences performance degradation if some of its elements fail.

Consider the following supply chain design (Figure 1).

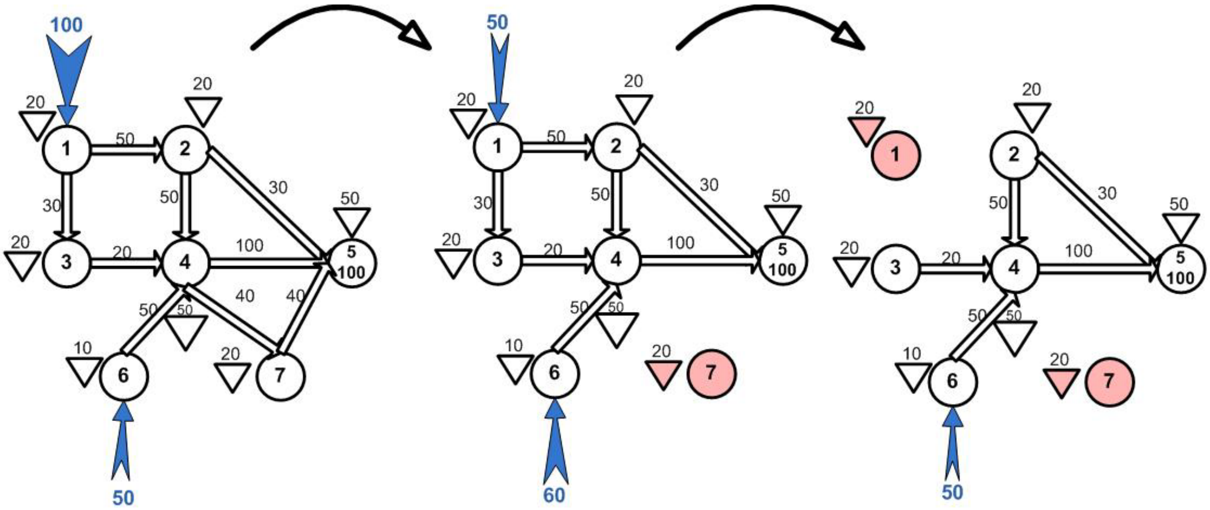


Figure 1. Supply chain design (Ivanov et al. 2014)

The DN is composed of two seaports (nodes 1 and 6), a central distribution hub (node 4), two intermediate warehouses (nodes 2 and 3), an outsourced warehouse (node 7), and a regional distribution center as a strategic inventory holding point (node 5). Execution in each of the nodes and transportation arcs is limited by maximal warehouse capacity, processing throughput, and transportation throughput, respectively.

The triangles represent warehouse capacity, and numbers on the arcs refer to maximal transportation throughput. Suppliers deliver certain order quantities at the beginning of each period at seaports 1 and 6. Then, the goods are processed in central distribution hub 4. The goods from hub 1 are additionally processed at intermediate terminals 2 and 3. From hub 4, the goods are moved to the regional distribution center 5, which has a demand in each of the periods (i.e., 100 units per period). We consider three periods. Inventory from previous periods may be used in the following periods. Profit is computed as revenue from goods delivered at node 5 minus the sum of sourcing, transportation, processing, fixed, and inventory holding costs which are assumed to be a linear function of the quantities.

The primary problem is to find the aggregate product flows to be moved from suppliers through the intermediate stages to the strategic inventory holding point subject to maximizing the service level and minimizing the total cost under (i) constrained capacities and processing rates and (ii) varying demand, supply, and DN structure for a multi-period case. In addition, the calculated plans should suggest ways to reconfigure product flows in the event of capacity disruptions. As shown in Figure 1, in period 2, node 7 becomes unavailable, and in period 3 we have disruptions at seaport 1 and node 7.

Setting the management problem in anyLogistix Network Optimizer

In Figs 2-7, the input settings and parameters for the problem considered are defined.

Supply chain design

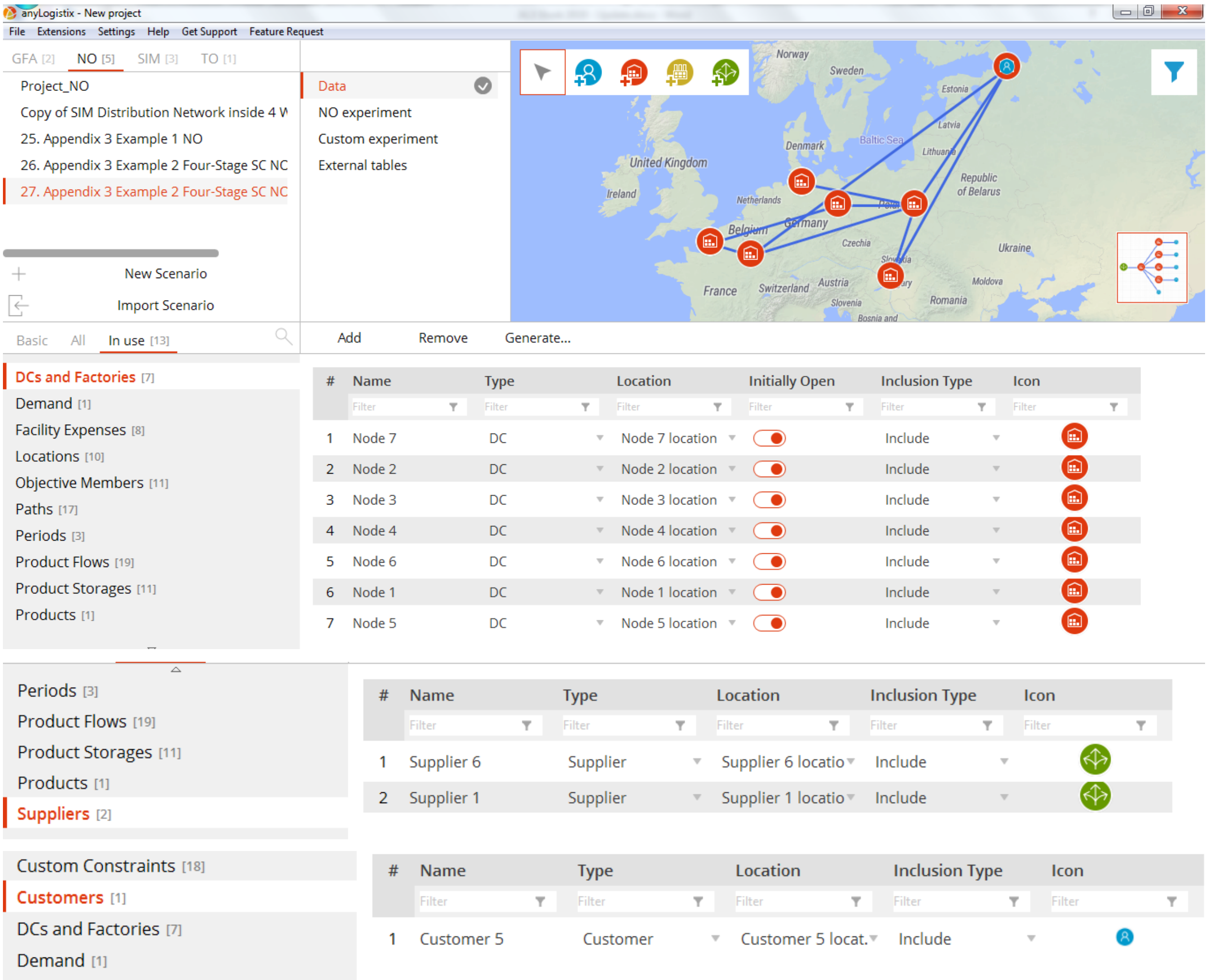
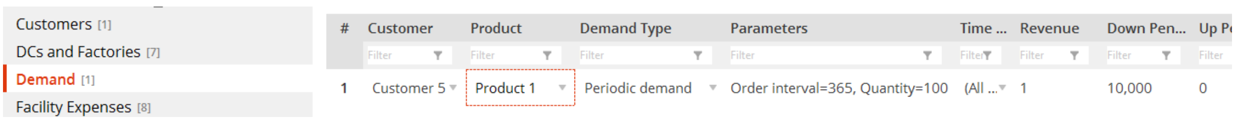


Figure 2. DN design

Note: In order to set up storage capacity at the customer, we define an auxiliary DC in the same location. This allows setup of storage capacity without any transportation costs or time. In order to setup the incoming flows to seaports 1 and 6 we set up auxiliary suppliers at the same locations as seaports 1 and 6.

Demand and periods



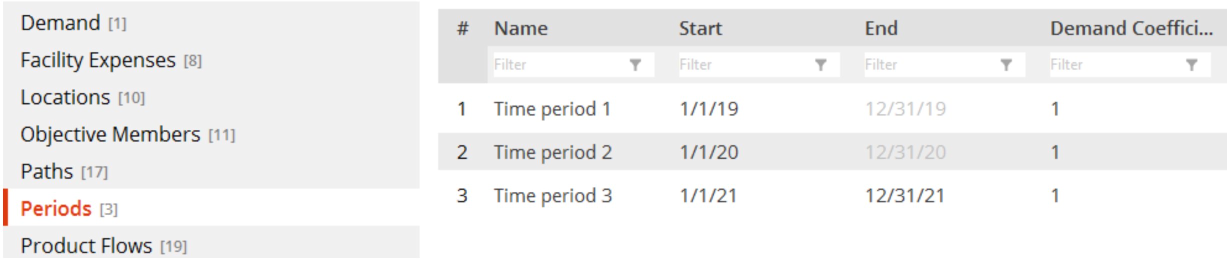


Figure 3. Demand and periods

Transportation capacities and disruptions

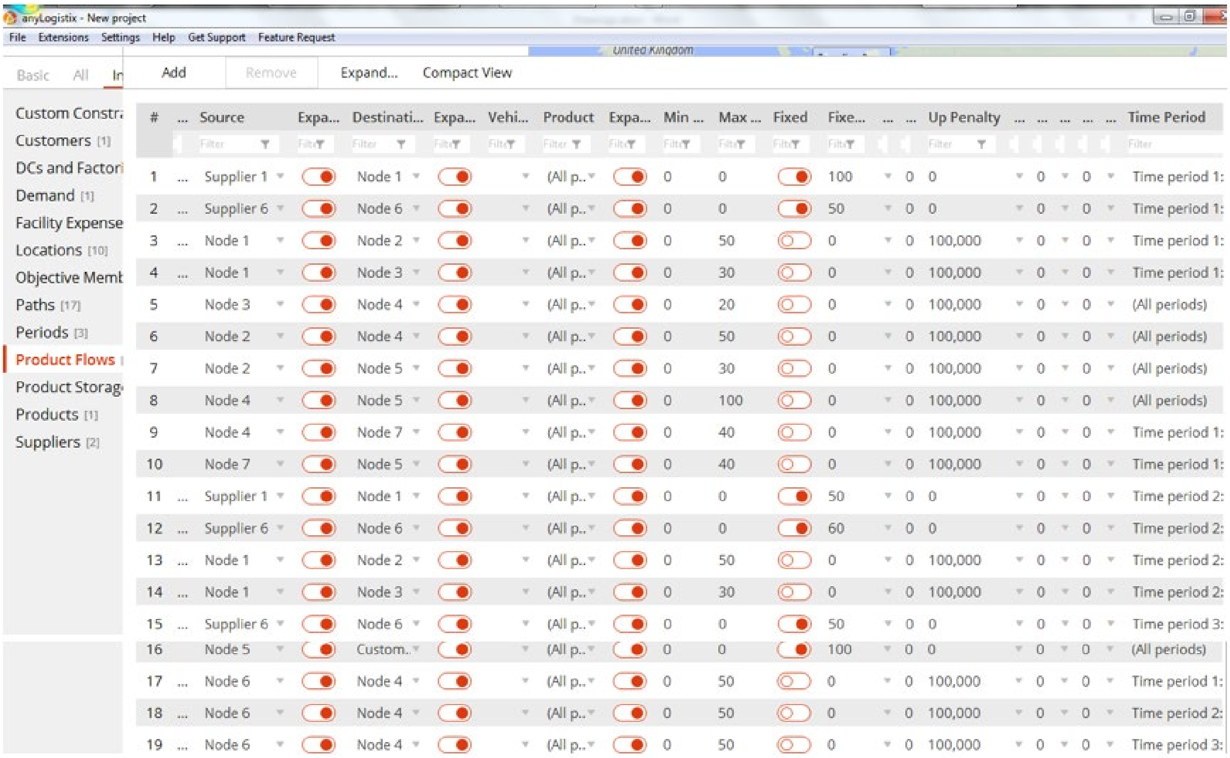


Figure 4. Product flows

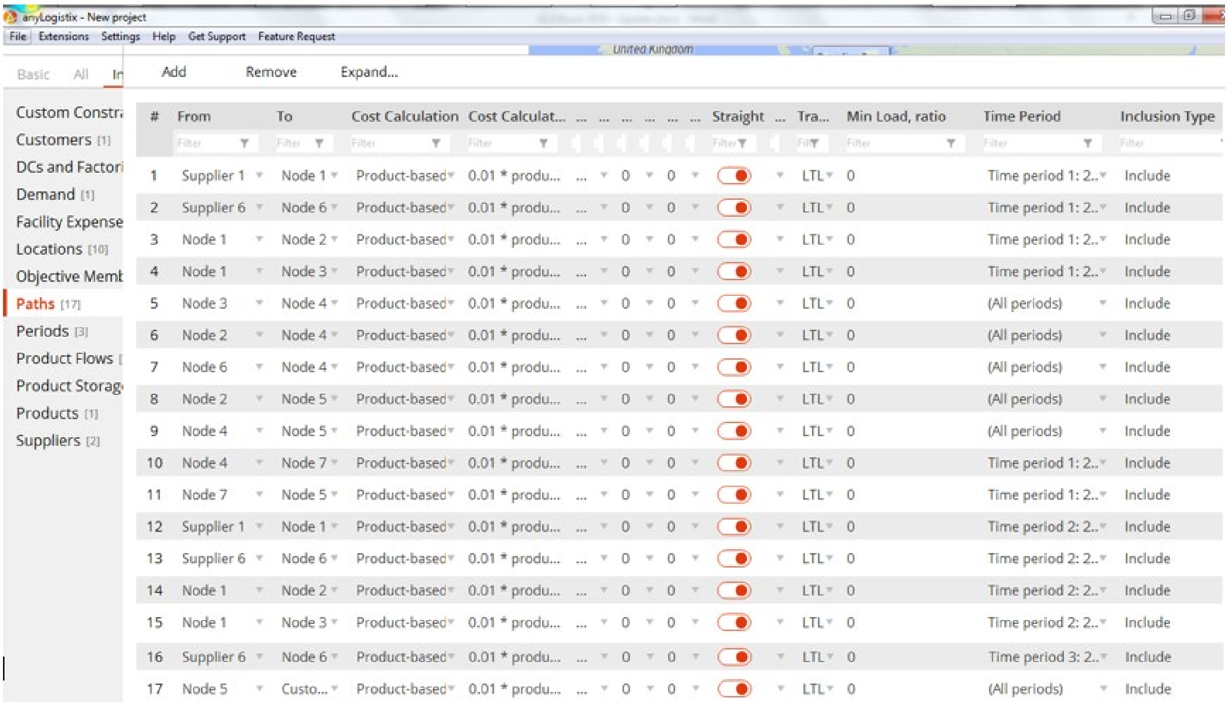
In “**Product flows,**” we set up the constraint on the limited transportation throughput in the column “**Max Throughput.**” Moreover, here we also set up the conditions of the incoming flows from suppliers at seaports 1 and 6. Finally, the disruptions in the supply chain are set up here by explicitly entering and not entering product flows in different periods.

Note: the constraints are activated by setting the **Up Penalty** as a large number. If the penalty is not set up, then two situations are possible:

1. Max >= min and min > 0, down penalty = up penalty = 0, then max throughput is considered fixed, i.e., the flows will exactly equal the value in the column “**max throughput**”. Fixed is the value that cannot be violated.
2. Max >= min and min = 0, down penalty = up penalty = 0, then the throughput constraint is ignored.

Note: In "**Product Storages,**" you need to define data separately for "DCs" and "Factories"; do not use the default setting "All sites". Do not forget to activate "**Expand sources.**" Do not use penalties if min and max throughputs are not defined.

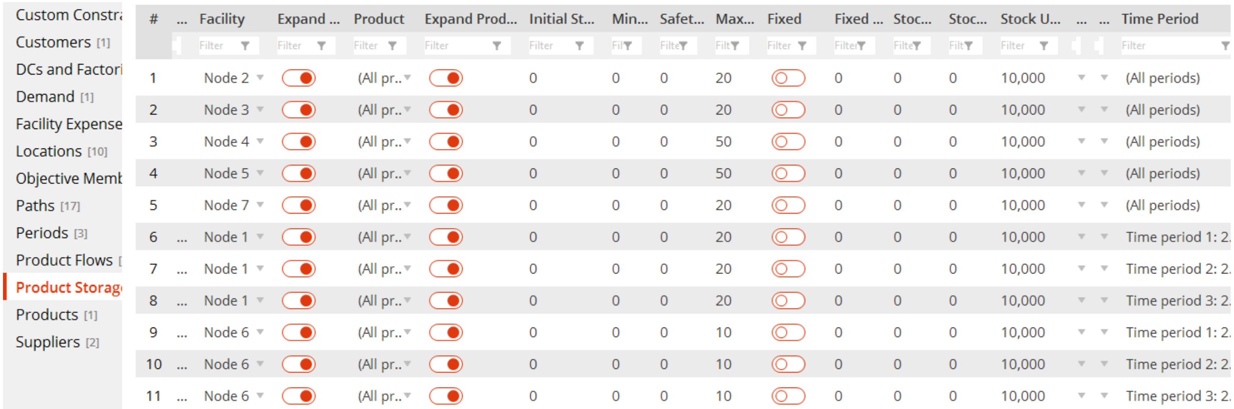
In Fig. 5, paths setting is illustrated.



#	From	To	Cost Calculation	Cost Calculat...	...	...	...	Straight	...	Tra...	Min Load, ratio	Time Period	Inclusion Type
1	Supplier 1	Node 1	Product-based	0.01 * produ...	...	0	0			LTL	0	Time period 1: 2...	Include
2	Supplier 6	Node 6	Product-based	0.01 * produ...	...	0	0			LTL	0	Time period 1: 2...	Include
3	Node 1	Node 2	Product-based	0.01 * produ...	...	0	0			LTL	0	Time period 1: 2...	Include
4	Node 1	Node 3	Product-based	0.01 * produ...	...	0	0			LTL	0	Time period 1: 2...	Include
5	Node 3	Node 4	Product-based	0.01 * produ...	...	0	0			LTL	0	(All periods)	Include
6	Node 2	Node 4	Product-based	0.01 * produ...	...	0	0			LTL	0	(All periods)	Include
7	Node 6	Node 4	Product-based	0.01 * produ...	...	0	0			LTL	0	(All periods)	Include
8	Node 2	Node 5	Product-based	0.01 * produ...	...	0	0			LTL	0	(All periods)	Include
9	Node 4	Node 5	Product-based	0.01 * produ...	...	0	0			LTL	0	(All periods)	Include
10	Node 4	Node 7	Product-based	0.01 * produ...	...	0	0			LTL	0	Time period 1: 2...	Include
11	Node 7	Node 5	Product-based	0.01 * produ...	...	0	0			LTL	0	Time period 1: 2...	Include
12	Supplier 1	Node 1	Product-based	0.01 * produ...	...	0	0			LTL	0	Time period 2: 2...	Include
13	Supplier 6	Node 6	Product-based	0.01 * produ...	...	0	0			LTL	0	Time period 2: 2...	Include
14	Node 1	Node 2	Product-based	0.01 * produ...	...	0	0			LTL	0	Time period 2: 2...	Include
15	Node 1	Node 3	Product-based	0.01 * produ...	...	0	0			LTL	0	Time period 2: 2...	Include
16	Supplier 6	Node 6	Product-based	0.01 * produ...	...	0	0			LTL	0	Time period 3: 2...	Include
17	Node 5	Custo...	Product-based	0.01 * produ...	...	0	0			LTL	0	(All periods)	Include

Figure 5. Paths

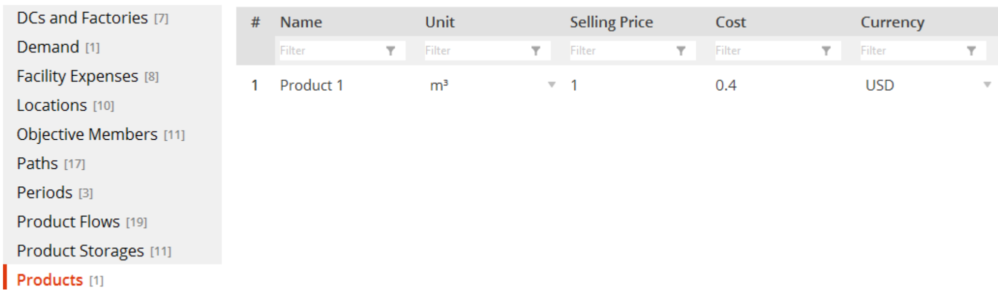
Warehouse storage capacities



#	...	Facility	Expand ...	Product	Expand Prod...	Initial St...	Min...	Safet...	Max...	Fixed	Fixed ...	Stoc...	Stoc...	Stock U...	...	...	Time Period
1		Node 2		(All pr...		0	0	0	20		0	0	0	10,000			(All periods)
2		Node 3		(All pr...		0	0	0	20		0	0	0	10,000			(All periods)
3		Node 4		(All pr...		0	0	0	50		0	0	0	10,000			(All periods)
4		Node 5		(All pr...		0	0	0	50		0	0	0	10,000			(All periods)
5		Node 7		(All pr...		0	0	0	20		0	0	0	10,000			(All periods)
6	...	Node 1		(All pr...		0	0	0	20		0	0	0	10,000			Time period 1: 2.
7	...	Node 1		(All pr...		0	0	0	20		0	0	0	10,000			Time period 2: 2.
8	...	Node 1		(All pr...		0	0	0	20		0	0	0	10,000			Time period 3: 2.
9	...	Node 6		(All pr...		0	0	0	10		0	0	0	10,000			Time period 1: 2.
10	...	Node 6		(All pr...		0	0	0	10		0	0	0	10,000			Time period 2: 2.
11	...	Node 6		(All pr...		0	0	0	10		0	0	0	10,000			Time period 3: 2.

Figure 6. Storage capacity setup

Costs and profits



#	Name	Unit	Selling Price	Cost	Currency
1	Product 1	m³	1	0.4	USD

DCs and Factories [7]
Demand [1]
Facility Expenses [8]
Locations [10]
Objective Members [11]
Paths [17]
Periods [3]
Product Flows [19]
Product Storages [11]
Products [1]
Suppliers [2]

#	Facility	Expense Type	Value	Currency	Time Unit	Product Unit	Time Period
1	Node 2	Other costs	0.02	USD	day		(All periods)
2	Node 3	Other costs	0.02	USD	day		(All periods)
3	Node 4	Other costs	0.02	USD	day		(All periods)
4	Node 7	Other costs	0.02	USD	day		(All periods)
5	Node 2	Carrying cost	0.001	USD	day	m³	(All periods)
6	Node 3	Carrying cost	0.001	USD	day	m³	(All periods)
7	Node 4	Carrying cost	0.001	USD	day	m³	(All periods)
8	Node 7	Carrying cost	0.001	USD	day	m³	(All periods)

Figure 7. Costs and profits

Network optimization results

Figure 8 presents network optimization results.

Product Flows

	Period	From	To	Arrival Period	Product	Flow	Flow Min	Flow Max	Percentage
1	Time period 1	Supplier 1	Node 1	Time period 1	Product 1	100.0	0.0	0.0	-1.0
2	Time period 1	Supplier 6	Node 6	Time period 1	Product 1	50.0	0.0	0.0	-1.0
3	Time period 1	Node 1	Node 2	Time period 1	Product 1	50.0	0.0	50.0	100.0
4	Time period 1	Node 1	Node 3	Time period 1	Product 1	30.0	0.0	30.0	100.0
5	Time period 1	Node 6	Node 4	Time period 1	Product 1	50.0	0.0	50.0	100.0
6	Time period 1	Node 3	Node 4	Time period 1	Product 1	20.0	0.0	20.0	100.0
7	Time period 1	Node 2	Node 4	Time period 1	Product 1	20.0	0.0	50.0	40.0
8	Time period 1	Node 2	Node 5	Time period 1	Product 1	30.0	0.0	30.0	100.0
9	Time period 1	Node 4	Node 5	Time period 1	Product 1	90.0	0.0	100.0	90.0
10	Time period 1	Node 5	Customer 5	Time period 1	Product 1	100.0	0.0	0.0	-1.0
11	Time period 2	Supplier 1	Node 1	Time period 2	Product 1	50.0	0.0	0.0	-1.0
12	Time period 2	Supplier 6	Node 6	Time period 2	Product 1	60.0	0.0	0.0	-1.0
13	Time period 2	Node 1	Node 2	Time period 2	Product 1	50.0	0.0	50.0	100.0
14	Time period 2	Node 1	Node 3	Time period 2	Product 1	20.0	0.0	30.0	66.67
15	Time period 2	Node 6	Node 4	Time period 2	Product 1	50.0	0.0	50.0	100.0
16	Time period 2	Node 3	Node 4	Time period 2	Product 1	20.0	0.0	20.0	100.0
17	Time period 2	Node 2	Node 4	Time period 2	Product 1	20.0	0.0	50.0	40.0
18	Time period 2	Node 2	Node 5	Time period 2	Product 1	30.0	0.0	30.0	100.0

Close

Storage by Product
Production Cost
Production Flows
Shared Flow Constraints
Shared Storages Constraints
Demand Fulfillment
Vehicle Flows
Named Expressions

Demand Fulfillment

	Iteration	Period	Customer	Product	Demand Min	Demand Max	Satisfied	Percentage	Revenue, per it...	Revenue Total	Under Cos
1	1	Time period 1	Customer 5	Product 1	100.0	100.0	100.0	100.0	1.0	100.0	10,000.0
2	1	Time period 2	Customer 5	Product 1	100.27	100.27	100.0	99.73	1.0	100.0	10,000.0
3	1	Time period 3	Customer 5	Product 1	100.0	100.0	100.0	100.0	1.0	100.0	10,000.0

Production Flows
Shared Flow Constraints
Shared Storages Constraints
Demand Fulfillment
Vehicle Flows
Named Expressions
Objective Members
Overall Stats
Add new tab

Overall Stats

	d Proce...	Opening Cost	Fixed Cost	Transportation...	Storage Cost	Outbound Pro...	Production Cost	Supply Cost	Revenue	Closing Cost	Objective
1		-0.0	-87.68	-12.1	-0.0	-0.0	-0.0	-124.0	300.0	-0.0	76.22

Figure 8. Network optimization results

It can be observed from Figure 8 that a total profit of 76.2 monetary units can be achieved whereby the demand is 100% met. The network optimal distribution plan has also been computed subject to the considered disruption scenario. This plan can be used as a contingency/recovery plan in the event of the real disruptions.

Additional features

In the given example, we applied some of the network optimization functionality of anyLogistix. Indeed, anyLogistix network optimizer can do much more. For example, you may extend the problem statements by adding new parameters or constraints in terms of processing time and costs at the DCs, considering demand and lead times not as fixed parameters but rather as stochastic variables, or by including sales batches. For more advanced application, custom constraints, indicator constraints, and linear ranges can be used to develop specific control policies, e.g., return flows in the supply chain. Moreover, it is always possible to customize the factory, warehouse, supplier, and customer agents in Any Logic and create any kind of network optimization model.