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Managing Risks in Supply Chains with Digital Twins and Simulation

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White paper

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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 a recipient of many prestigious international awards. He co-edits the International Journal of Integrated Supply Management. His research record includes around 300 publications, with more than 60 papers in prestigious academic journals and the leading books "Global Supply Chain and Operations Management" and "Structural Dynamics and Resilience in Supply Chain Risk Management".

He has been teaching and presenting his research for more than 20 years in disciplines related to operations and supply chain management at different universities worldwide.

Introduction

According to the Business Continuity Institute¹, 65% of companies experienced at least one supply chain disruption in 2017. The consequences of these disruptions were a loss of productivity, a decrease in customer service, and loss of revenue. Between 2000 and 2018, supply chain disruptions, caused by both natural and man-made disasters, occurred more frequently and with greater intensity². Their consequences were severe.

Sophisticated management practices (lean manufacturing, just-in-time inventory, and so on) together with globalization, make supply chains more complex and interconnected, and consequently they are more vulnerable to disruption. Statistics show that the impact of disruption on global business is, on average, increasingly costly³. Production downtimes, unfulfilled demand, lost revenues, and the loss of customers are among the consequences.

An important phenomenon connected to disruption is the ripple effect. The ripple effect occurs when disruption at one tier or site propagates and affects performance across the whole network. Research shows that the ripple effect is a frequent problem in today's global logistics networks⁴.

Companies struggle to make their supply chains resilient – to be both low risk and able to adapt quickly to disruption. To handle risk and disruption, and especially to be able to foresee and prepare for the ripple effect, managers need to have complete visibility of the complex interdependencies in their supply chains. The modern techniques of predictive and prescriptive analytics, such as optimization and simulation modeling, are proving to be the only ways capable of achieving this.

What is more, these techniques, together with data analytics and IoT, make possible the creation of a supply chain digital twin – a special model that represents the state of the supply chain as it is now, allowing it to be examined for risk resilience.

This paper will define supply chain disruption, discuss what the ripple effect is, show different risk types and mitigation strategies, and explain the supply chain resilience concept. Finally, it will present a methodology to minimize the ripple effect – through the creation of a digital twin and the use of simulation and optimization.

1 BCI Supply Chain Resilience Report 2017. <https://www.thebci.org/news/bci-supply-chain-resilience-report-2017.html>

2 Dolgui, A., Ivanov, D., Sokolov, B. (2018). Ripple Effect in the Supply Chain: An Analysis and Recent Literature. International Journal of Production Research, 56(1-2), 414-430.

3 "Counting the Cost of Calamities," The Economist, January 14, 2012 (www.economist.com/node/21542755)

4 Ivanov D., Sokolov B., Dolgui A. (2014). The Ripple effect in supply chains: trade-off 'efficiency-flexibility-resilience' in disruption management, International Journal of Production Research, 52(7), 2154-2172

Risks in Supply Chains

To better understand the ripple effect, let's take a closer look at risks. Supply chain risks can be classified into operational and disruptive risks.



Operational, or recurrent, **risks** come from within the supply chain itself. They are related to business processes, especially the uncertainties of supply and demand. These risks often involve the [bullwhip effect](#), when shifts in demand and supply increase the intensity of inventory variability upwards through the supply chain.

Usually such risks impact operational parameters, such as lead time and inventory. Current performance metrics can decrease due to daily or weekly stock-out/overage costs. To handle this, time-efficient coordination to balance demand and supply is required. Prevention steps may include improving the flow of information along the value chain with better customer and supplier collaboration.



Disruptive risks are often exceptional. They are distinguished by rare occurrence and high performance impact. These risks disturb network structures and critical performance metrics like annual revenues or profits. They can be both natural and man-made and might include fires or floods at distribution centers or production facilities, supplier legal conflicts, strikes at airlines or railway companies, and much more. Once a disruption occurs, its effects tend to propagate down the supply chain. This is known as the ripple effect.

Usually such risks require short-term stabilization actions followed by a mid- to long-term recovery process. The consequences usually demand a lot of time, effort and investment to overcome. To prevent the ripple effect, companies need to proactively ensure supply chain redundancy and agility.

Disruptive risks represent a major challenge for supply chain managers, as they affect the integrity of the supply chain. Consider some real-world examples⁵.



The earthquake and resulting tsunami in Japan on March 11, 2011 rippled quickly through supply chains worldwide. As a result, Toyota lost its position as a major car manufacturer in terms of production volumes for that year. Many other industries worldwide were also hard hit by the shortage of chemicals and components produced in Japan.



A fire in the Phillips Semiconductor plant in Albuquerque, New Mexico, caused its major customer, Ericsson, to lose \$400 million in potential revenue.



The floods in Thailand in 2011 had a serious impact on the high-tech sector. Intel claimed to have lost \$1 billion in sales during the fourth quarter of 2011 because computer OEMs were unable to source hard drives for new computers and, therefore, were not buying chips from Intel.



As a result of the Volkswagen and Prevent Group contract dispute in the summer 2016, six German factories faced a production halt on parts shortage. 27,700 workers were affected, with some sent home and others moved to short-time working.

Let us now dig deeper into how severe disruptions can cause the ripple effect, and how the effect can be managed and prevented.

⁵ Dolgui, A., Ivanov, D., Sokolov, B. (2018). Ripple Effect in the Supply Chain: An Analysis and Recent Literature. *International Journal of Production Research*, 56(1-2), 414-430.

Ripple Effect

The ripple effect occurs in supply chains if a disruption cannot be localized and its effect on network structure and parameters cascades downstream, affecting the logistics system performance. Metrics such as sales, on-time delivery, service level, costs, and total profit may be affected⁶.

The ripple effect is common and can have serious consequences beyond just a short-term decrease in performance – Toyota’s loss of market share, as outlined above, for example.

How does the ripple effect occur? Following a disruption, its effect ripples through the supply chain. Missing capacity or inventory at the disrupted facility may then lead to a lack of materials and a decrease in production at the next tier in the supply chain. Furthermore, even greater consequences may follow in the next tiers. That’s why ripple effect is also known as the “domino effect” or “snowball effect”. The scope of the rippling and its impact on economic performance depends both on the robustness of reserves (e.g., redundancies like inventory or capacity buffers) and the speed and scale of recovery measures.

The reasons for the ripple effect are easily identifiable. With increasing supply chain complexity and greater demands for speed and efficiency, industries are becoming both more globally distributed and more concentrated into dense industrial districts. In addition, globalized logistics networks depend heavily on the availability of transportation infrastructure. As supply chains have become more complex, geographically spread, and more interconnected, they have



become more vulnerable to disruptions, and problems in a particular tier now inevitably lead to problems in the next.

As a result, managers have to proactively estimate risks and supply chain resilience when designing their networks and planning operations. In addition, at the operational level they are required to quickly react to disruptions by executing contingency plans (e.g., using alternative suppliers or shipping routes) to expedite stabilization and recovery, ensuring continuity of supply, and avoiding long-term impact. Companies must be prepared with strategies aimed at mitigating disruptions and avoiding their spread through the ripple effect.

⁶ Ivanov D., Sokolov B., Dolgui A. (2014). The Ripple effect in supply chains: trade-off ‘efficiency-flexibility-resilience’ in disruption management, International Journal of Production Research, 52(7), 2154-2172.

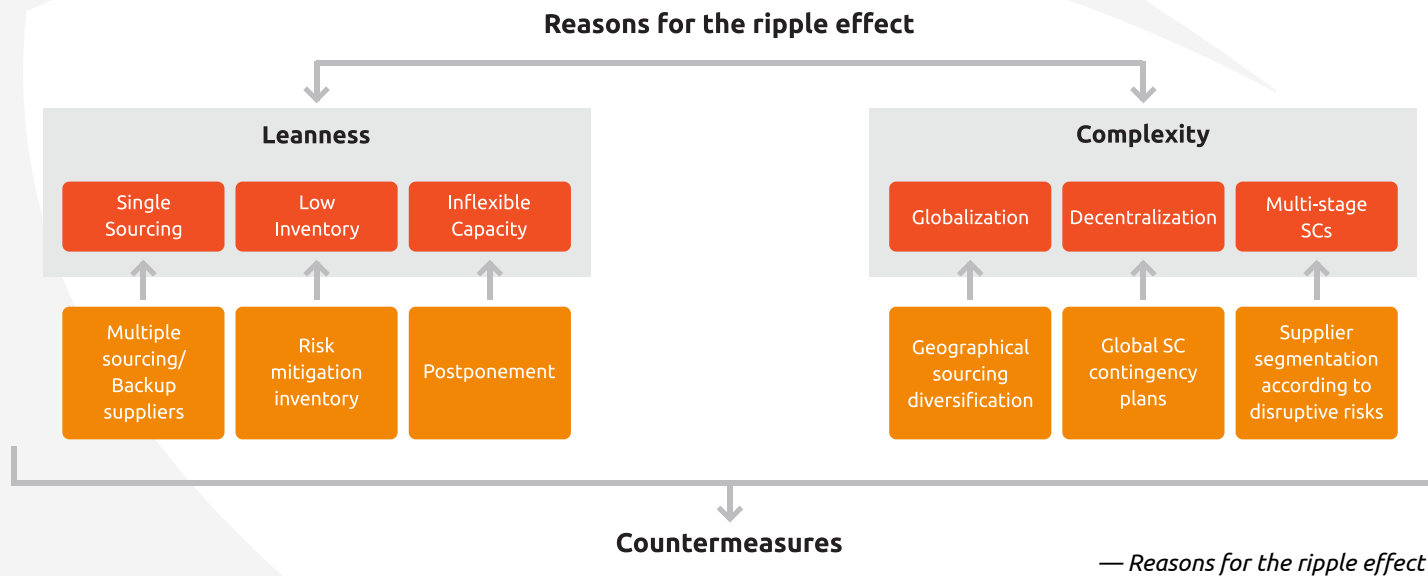
Protecting Against the Ripple Effect

To safeguard against the ripple effect, a supply chain must be resilient. This means that it must possess two critical capacities: robustness and agility. These capacities provide operations continuity, durability, recoverability, and the maintenance of supply chain processes and structure.

Robustness is a supply chain's ability to protect against disruptions and reduce their impact once they occur. To achieve it, managers have to proactively build in redundancy, such as risk mitigation inventory, additional capacity, or backup sourcing. For **agility**, this redundancy must be used jointly with reactive contingency plans for parametric, process, and structural adaptation of the network⁷.

Reasons for the ripple effect can often result from the **leanness** of a supply chain or its **complexity**. Depending on the nature of the problem, typical countermeasures include the creation of various redundancies⁸. Examples can be seen in the figure below.

It goes without saying that creating redundancies comes at a cost. Potential disruptions have to be weighed against the costs and effects of a contingency plan's redundancies, and alternative scenarios evaluated. For this, managers need tools that allow them to predict scenario outcomes, calculate metrics, and test hypotheses.



7 Dolgui, A., Ivanov, D., Sokolov, B. (2018). Ripple Effect in the Supply Chain: An Analysis and Recent Literature. International Journal of Production Research, 56(1-2), 414-430.

8 Dolgui, A., Ivanov, D., Sokolov, B. (2018). Ripple Effect in the Supply Chain: An Analysis and Recent Literature. International Journal of Production Research, 56(1-2), 414-430.

Tools to Improve Resilience: Simulation and Optimization

Dynamic simulation modeling and analytical optimization are the two dominating technologies in supply chain risk management. With the help of [optimization and simulation approaches](#), companies can generate new knowledge about the influence of disruption propagation on network output performance by considering disruption location, duration, and recovery policies.



Optimization models describe the network in terms of flows of goods between facilities. These models apply linear or non-linear mathematical programming approaches, as well as mixed-integer programming. By varying parameters like site openings and closures, these models enable analysis of the impact of disruptions on supply chain performance. Optimization models for multiple products and many periods can help evaluate the introduction of redundancies, such as backup suppliers, reserved capacity, and risk mitigation inventory. These satisfy demand at higher prices when a disrupted facility is not in operation. Optimization can be used to develop resilient network topologies that enable quick reaction and recovery when faced with disruption. This kind of analysis is effective at the strategic decision-making level.



Simulation models are used to study disruption propagation and the ripple effect across multiple tiers. One of its main advantages is that simulation models consider real time operation, and thus the length of disruption, when evaluating recovery policies. By adding dynamics to the model, such as situational behavior changes, simulation models allow a more in-depth view of network operations than with optimization.

Simulation gives analysts the possibility to change parameters dynamically during the experiment and to observe the performance impact of these changes in real time. This allows them to solve business challenges that could not be addressed otherwise, including:

- Disruption propagation in the SC – time and echelons.
- Dynamic recovery policies.
- Gradual capacity degradation, as the disruption propagates, and recovery.
- Multiple performance impact dimensions, including financial, service level, and operational performance.

Instead of flows that are used in optimization models, simulation models describe the interactions in the network as algorithms, like in real life. This

allows simulation models to consider additional **logical constraints**, such as inventory, production, sourcing, and shipment control policies, as well as capacity degradation and recovery over time. They can also consider **randomness constraints** such as randomness in disruptions.

Simulation studies have been widely carried out to model and measure phenomena that cannot be captured using optimization or spreadsheet-based modeling, for example:

- Transportation disruption in multi-echelon supply chains to reveal the ripple effect impact on fulfilment rate and inventory fluctuations.
- Supplier capacity disruption with or without recovery policies and their impact on the SC service level.
- Manufacturing capacity disruption, with quantitative estimation of disruptive risks, calculating costs and weeks of recovery.

Which technique is better?

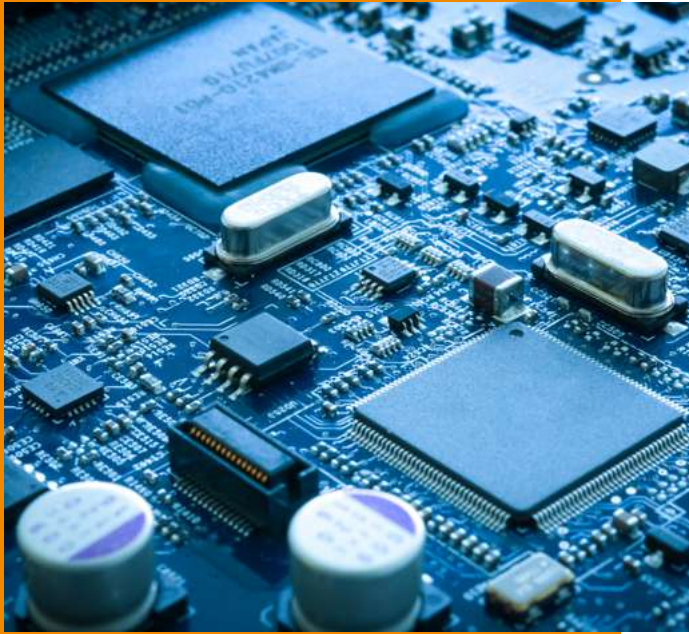
There is no definite answer. Optimization is strong in its particular field of risk-free network design, but for complex problems with ad-hoc network behavior changes, simulation can be more powerful.

Typically, optimization models of disruptions only consider a particular network element (for example, site) and assume that other elements are not affected by disruption, continuing to operate as planned. This means real-world complexity is significantly reduced in order to obtain feasible mathematical solutions in a reasonable time. By nature, randomness and time-related aspects of disruptions and recovery actions are difficult to represent within the closed forms of mathematical equations. They can only be represented using dynamic simulation modeling.

The combination of simulation and optimization can extend the scope of each of them. Combining the methods enables:

- Network optimization towards minimizing total supply chain cost.
- Dynamic analysis of ordering, production, inventory, and sourcing control policies using simulation.

Simulation is the newer tool and it is especially powerful when combined with optimization. More supply chain managers are now adopting the practice of using these techniques together.



Case study: Planning Backup Sites for a Semiconductor Logistics Network

Infineon, a semiconductor manufacturing company, operates a complex, agile supply chain. Products are manufactured at designated frontend and backend sites. To produce particular products at an alternative site, special equipment and technologies are required before product transfer. This process is time-consuming, which makes it challenging to switch to an alternative site following a disaster.

Analysts needed to evaluate four types of backup sites to facilitate recovery in case of a disruption: mirror site (the most prepared site type for a production transfer in terms of equipment and technology availability), hot site, warm site, and cold site (the least prepared type). They developed a simulation model to assess the overall impacts of disruptions and performance trade-offs.

Four scenarios with different disruption lengths and severity were analyzed:

- Strikes
- Infrastructure destruction
- Industrial accident
- Long-term cyber-attack

Each of the scenarios had different severity in terms of capacity disruption, from 40% (long-term cyber-attack) to 100% (infrastructure destruction). The performance impact was measured by fill rate recovery time, while the financial performance included operational costs (backorder costs, sales loss, plus multiple costs for customers and customers of customers during long disruptions) and investment costs.

The results showed that the fastest recovery time provided by mirror sites came at an extremely high expense. A hot site could be a good alternative, showing robust overall performance. Unexpectedly, a warm site gave satisfying results, except for short-term disruptions like strikes. Furthermore, the cold site also exhibited some benefits, especially for shortening the recovery time of long-term disruptions (e.g., infrastructure destruction).

Overall, the project showed that it was not cost-effective to use alternative sites when dealing with short-term disruptions at all. In addition, the simulation demonstrated the tangible benefits of non-mirror sites, which had not been obvious before. These findings were to be used to support the development of Infineon's backup site strategy⁹.

⁹ Chen, Y., Ponsignon, T., Weixlgartner, R., Ehm H. (2017). Simulating recovery strategies to enhance the resilience of a semiconductor networks. Proceedings of the 2017 Winter Simulation Conference, W. K. V. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. Page, eds.

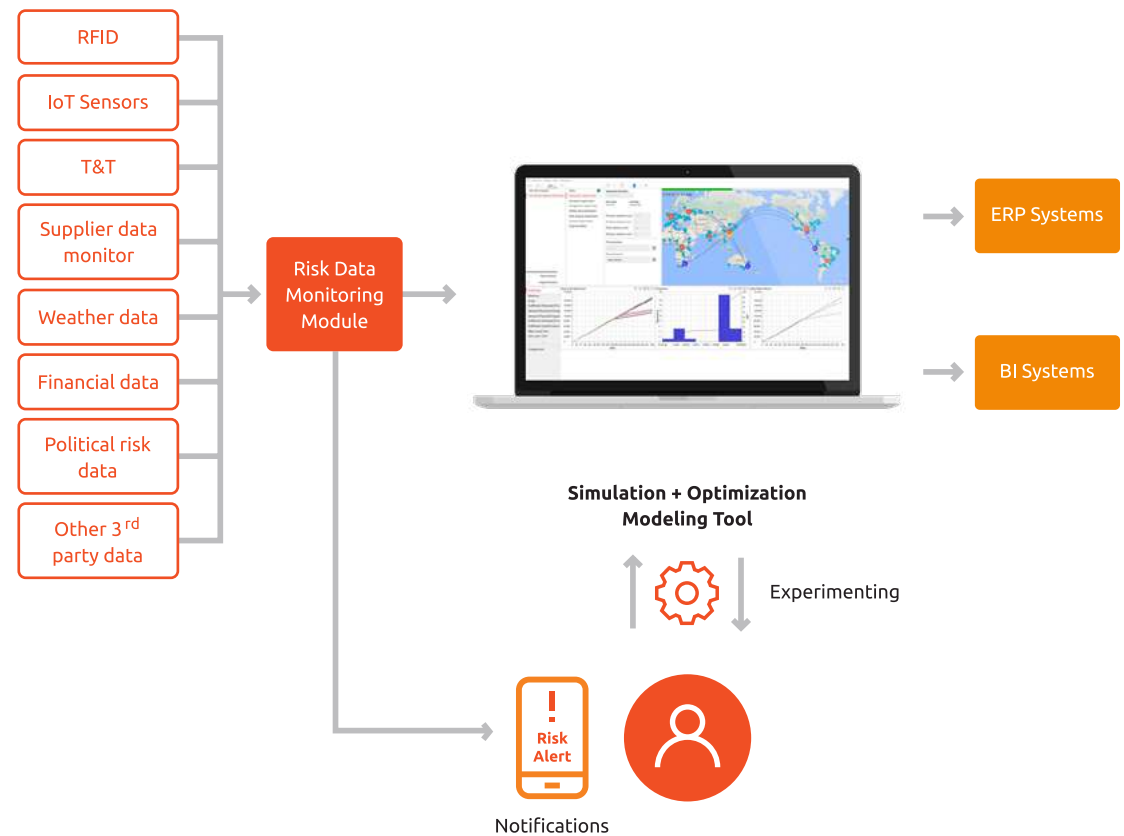
Digital Twins: Simulation + Optimization + Data Analytics

The combination of simulation, optimization, and data analytics constitutes the full stack of technologies needed to create a model for a supply chain digital twin. Integrating this model with a live data stream would represent the state of the network as it is now. Let us look at how this concept can be used in risk management.

Optimization and simulation have, so far, mostly been applied for **strategic planning** ("offline" planning). However, the quality of decision making, when dealing with risks, crucially depends on the timely availability of up-to-date data because decisions often have to be made immediately.

Today's technologies allow for the gathering of lots of supply chain data online: route disruption probabilities, supplier data (such as financial health and the production viability of suppliers), and on-the-go disruption detection data. This is possible because of online risk databases, IoT (Internet of Things) sensors, track and trace systems (T&T), and RFID. These monitoring technologies allow for the identification of critical hotspots and timely alerts about incidents that could disrupt the supply chain.

All of this real-time disruption data can be embedded into a simulation model, along with third-party real-time data about natural, financial, or political risks. The integration of simulation and optimization with live data allows for the use of models for **operational planning**. Such a real-time supply chain risk modeling system constitutes a digital twin.



— How a supply chain digital twin works

A digital twin represents the current state of a supply chain, with the actual transportation, inventory, demand, and capacity data. For example, if there is a strike at an international logistics hub, this disruption can be spotted by a risk data monitoring tool and transmitted to the simulation model as a disruptive event. Then, simulation in the digital twin can help show disruption propagation and quantify its impact. In addition, simulation enables efficient recovery policy testing and the adaptation of contingency plans according to the situation – for example, reconsidering alternative network topologies and back-up routes on-the-fly.

The output data from a simulation inside a digital twin can be transferred to an ERP system or a business intelligence (BI) tool to analyze the performance impact of the disruptions. Additionally, a simulation model can activate BI algorithms. For example, if a service level in a simulation model decreases to a certain level, the digital twin might activate a BI algorithm to search for the reasons for the problem.

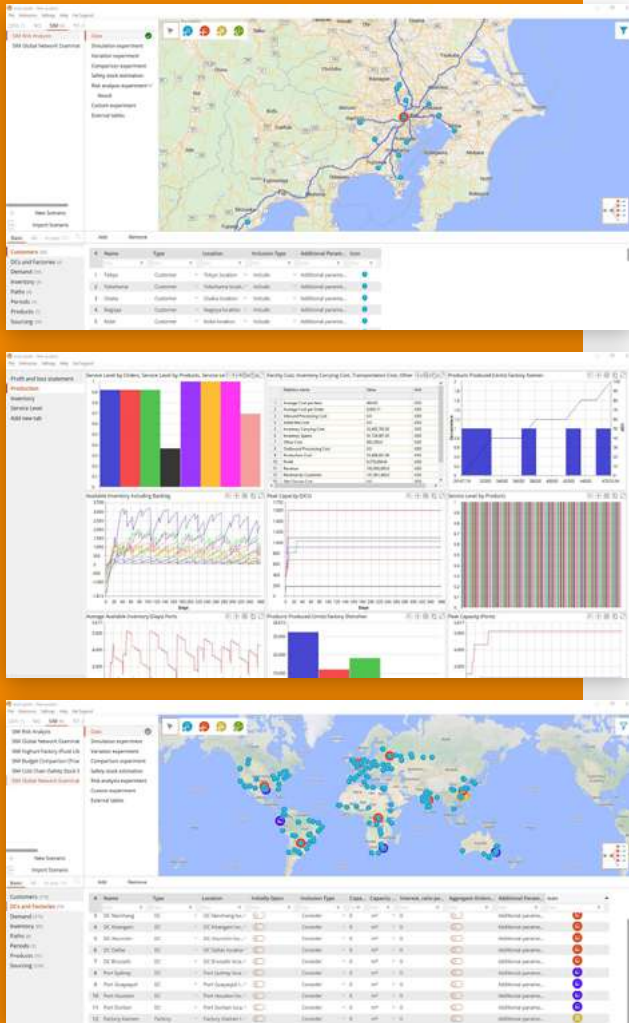
Interacting with other SCM tools, a digital twin provides a control tower for end-to-end supply chain visibility.

Using digital twins, managers can holistically evaluate their supply chains for risks and resilience and improve their agility. Gartner predicts that by 2021, half of all large industrial companies will employ digital twins, resulting in those organizations gaining a 10% improvement in effectiveness¹⁰. Supply chain management will be no exception to this mass adoption.

¹⁰ Prepare for the Impact of Digital Twins 2017, Christy Pettey
<https://www.gartner.com/smarterwithgartner/prepare-for-the-impact-of-digital-twins/>



What Does a Supply Chain Simulation Model Include?



While using optimization is common practice in many companies, simulation has only been gaining more attention in recent years, along with the rise of modern easy-to-use software tools. What can a typical supply chain simulation model include, and what factors can it consider when working on risk analysis?

Network design and geographical information

Network design, with regard to the geographical location of sites, is the core of most supply chain simulation models. GIS maps are used in simulation models to locate the sites, calculate distances, routes, and travel times along real roads. Besides geospatial calculations, they provide visualization and transparency in a model. These screenshots are taken from [anyLogistix™](https://www.anylogistix.com) software and show map-based model animation and the model-building editor.

Operational parameters

Inventory control policies, back-order rules, production batching, and scheduling algorithms, as well as shipment rules and policies, need to be defined in the model and balanced with each other for both normal and disrupted operation modes. Modern supply chain simulation tools allow the visual modeling of these policies and do not require programming skills.

Disruptions and recovery

Random or scheduled disruption events can be modeled with a probability distribution in regard to their duration. As to recovery, analysts can set up individual recovery policies for different sites and define the rules of policy activation depending on when it occurred, the expected duration, and the severity of the disruption.

Performance impact

The direct impact of the ripple effect is reflected in the changes of KPIs. Revenue, sales, service level, fill rate, and costs are typically calculated. Unlike analytical models, that usually focus on a particular metric (e.g., costs/profit), simulation allows all of these metrics to be measured in the same model. Their values can be checked at any chosen moment of the modeled time. This way, disruption duration can be modeled, performance impact measured, and mitigation policies evaluated for efficiency.

A simulation model that considers all of these factors can become the basis for building a successful digital twin that can be used for the complex analysis of supply chain risks, the development of contingency plans, and more efficient operational management.

Conclusion

Building a resilient supply chain means finding a balance of robustness and agility. Both of these can act as cushions against uncertainties and need to be taken into account when planning.

Robustness comes through upfront costs that increase redundancy: increased inventory, additional production capacity, alternative transportation provision, and more. In return, these redundancies secure uninterrupted sales and stable service levels, lowering the cost of disruption. Additionally, elements of robustness facilitate schedule execution, in this way lowering the risk of disruption. As a result, achieving targets such as on-time delivery can be more easily accomplished, which also positively influences sales and service levels. Redundancy in a supply chain may also correspondingly improve agility and positively affect service level and costs.

Simulation and optimization are the two methods that can strengthen supply chains in terms of their ability to mitigate the impact of uncertainty and maintain robustness. They enable the testing of management strategies under disruptive risks and ripple effect.

Different problems need different solutions, and no single technique can be universally applied with the same effect. Optimization is best applied during the stages of network design and planning. These strategic design and tactical plans can be improved through simulation models that imitate the dynamics of operations, including execution and recovery. In addition, simulation models allow a dynamic observation of important risk-related KPIs, such as supplier reliability, time-to-recovery, ripple effect performance impact, fill rate, and overall system resilience.



Managerial insights from simulation modeling of the ripple effect can provide decision support for the following questions:

- When does a failure trigger follow-on failures?
- Which network structures are particularly sensitive to the ripple effect?
- What ripple effect scenarios should be expected, and what is the most efficient way to react in each of these scenarios?

Simulation modeling methods allow us to consider the details and specific traits of supply chain elements. This not only allows the visualization of network operations, but also for tracing every process inside. In addition, using simulation enables us to observe the impact of different disruptions and recovery policies in time, and to consider gradual capacity degradation and recovery. By making changes to a simulated supply chain, it becomes possible to understand the dynamics of the physical network.

At the **tactical decision-making level**, analysis based on simulation models is of great importance for supply chain operation planners and dispatchers. At the same time, optimization methods provide rigorous decision-making support for supply chain executives at the **strategic level**.

Moreover, the instant availability of data from across the whole supply chain makes it possible to expand the usage of simulation and optimization models to the operational level. This is achieved with a supply chain digital twin, which can be developed using the combination of simulation, optimization, and live data.

A digital twin can represent the network state for any given moment in time and allow for complete end-to-end supply chain visibility to improve resilience and test contingency plans. The adoption of digital twins is set to increase greatly in the near future and significantly improve supply chain management efficiency.

Overall, the greatest benefits come from supply chain design and analysis tools that feature both analytical optimization and dynamic simulation modeling methodologies, as well as allowing for easy integration with other systems.

Additional resources

- White papers
 - [Supply Chain Optimization and Simulation: Technology Overview](#)
 - [Simulation-Based Inventory Planning for the Digital Supply Chain Era](#)
 - [Supply Chain Digital Transformation: Insights and Tools](#)
- [anyLogistix Webinar](#)
- [anyLogistix Demo Video](#) – tutorials
- [anyLogistix PLE](#) – free version for self-study and education
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