Risk Mitigation to Increase Time to Survive

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SUBMITTED TO THE PROGRAM IN SUPPLY CHAIN MANAGEMENT
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE IN SUPPLY CHAIN MANAGEMENT
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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May 2023

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ABSTRACT

In our increasingly interconnected global economy, businesses confront heightened risks of supply chain disruptions. This capstone project, sponsored by Tempur Sealy International Inc., a leading manufacturer in the mattress industry, focuses on evaluating and enhancing supply chain resilience to mitigate these disruptions. The project introduces a unique methodology that combines Time to Survive (TTS) analysis and procurement optimization. This dual approach quantifies the cost of resilience measures, providing a tangible value to efforts often viewed as abstract or precautionary. In addition, this methodology supports key decision-making processes within the company, particularly in relation to storage capacity investments, inventory planning, and procurement strategy. By analyzing scenarios and potential disruptions, we offer valuable insights that not only highlight areas of potential risk but also suggest viable solutions for improvement. Our findings demonstrate that through the optimal allocation of resources and strategic procurement practices, Tempur Sealy can maintain its existing levels of supply chain resilience while also achieving cost savings. This balance is crucial in ensuring the company can effectively manage potential disruptions without compromising financial performance. Finally, we posit that the tools and methodology developed during this project have broader applications beyond the specific case presented. We believe these methods can be generalized and utilized by other companies across various industries. This approach enables businesses to justify investments into risk mitigation measures, providing a clear, quantifiable value to these often overlooked yet crucially important efforts. This study, therefore, contributes to the literature on supply chain management and resilience, offering practical tools and insights for businesses navigating the complexities of the global supply chain.

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ACKNOWLEDGMENTS

We would like to express our gratitude to Tim Russell, our capstone project advisor, for his time and guidance over the past 10 months, as his valuable feedback and support were instrumental in completing this project and contributed to our personal and professional growth.

Also, a special thanks to Pamela Siska for her support, encouragement, and meticulous attention to detail throughout the editing process of our drafts.

We would like to thank our classmates and the MIT Center for Transportation & Logistics community for their continuous support throughout the creation of this capstone report and for making the program an unforgettable experience.

Finally, we extend our sincere gratitude to Tempur Sealy for providing us with such an interesting and challenging project, and for the amazing team consisting of Jimmy, Erica, Sam, Sara, and Tom, who offered valuable expertise, timely assistance, endless patience, and significant insights throughout our journey. We appreciate the chance to work on the best capstone project we could have asked for.

Gabriel Szuma and Szuya (Silvia) Huang

I would like to express my gratitude to my capstone partner, Gabriel Szuma, for his brilliant ideas, collaboration, and unwavering commitment throughout the capstone project. With all the efficient and high-quality discussions that we had; it has been a pleasure to work alongside him.

Moreover, I would like to show appreciation to my dearest family, friends and especially my partner for all the support, love, and encouragement they provided throughout my journey. Their unconditional support and belief in me have been crucial in helping me navigate through the challenges and achieve my goals. I could not have done this without them.

Szuya (Silvia) Huang

First, I would like to express my sincere gratitude to my parents for their love and support, allowing me to explore the world and pursue my dreams. Their values are the bedrock upon which I stand.

To my wife, who selflessly put her career on a break and moved with me across the ocean so that I could chase my dreams. Thank you for always standing by my side.

I am profoundly grateful to my colleagues at Oriens, my second family, whose heartfelt support was instrumental in my journey to MIT.

Finally, to Silvia, my capstone partner, the best teammate, who never shied away from an all-nighter when it was most needed. Your partnership and friendship made this journey truly enjoyable.

Gabriel Szuma

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1. INTRODUCTION

As international trade has continued to grow over the past several decades, firms have increasingly relied on complex global supply chains to stay competitive in their industries. While international trade has led to lower costs and increased innovation, it has also introduced the potential for global supply chain disruptions. In addition to global supply reliance and lower costs, one side effect of this globalization is that supply chain disruptions often reverberate on a worldwide scale. Several major disruptions during 2019-2022 created a difficult environment for individuals, firms, and nation-states alike. First, the United States−China technology trade war gave us a flavor of how global trade and supply chains can be disrupted in a specific industry. Later, events such as the coronavirus pandemic, the war between Russia and Ukraine, and the Ever-Given cargo ship obstructing the Suez Canal showed how easily regional disruptions extend across industries and impact trade and supply chains at the global level. All these “black swan events” are random, unexpected, unpredictable, and with severe consequences around the globe (Aggarwal & Bohinc, 2012). Natural disasters like hurricanes, floods, ice storms, or anthropogenic events like fires and machine breakdowns can also cause disruptions. The impact can sometimes last for months or even years when disruptions happen. The disruptions directly impact companies’ ability to manufacture products and fulfill their customer’s needs, thus jeopardizing revenue, profitability, and long-term growth.

1.1 Motivation

The increasing frequency and scale of supply chain disruptions has not prevented some companies from growing aggressively, which is the case of Tempur Sealy, a global-leading mattress manufacturer headquartered in the United States (US). Tempur Sealy operates 71 manufacturing facilities globally, 34 in North America (Tempur Sealy International, Inc., 2023).

To deliver products to consumers in over 100 countries, the firm is highly reliant on a stable supply chain for polyurethane chemicals (PU chemicals). The key ingredient for mattress production is polyurethane foam (PU foam) which is manufactured by controlled reactions of chemicals. Raw materials for production are also limited to a few locations globally. Moreover, the key precursor chemicals needed to produce Tempur's raw materials require specialized transportation which is costly. The chemicals are usually produced close to petrochemical industry hubs, which are clustered in a few locations around the globe. Because the chemicals come from a limited number of suppliers, it might be difficult or even impossible for the company to find a suitable replacement supplier in case of a regional disruption of the chemical supply chain. This situation can significantly impact the company's operational ability both on the local and global scale.

To mitigate the above-mentioned uncertainties of key raw material supplies, Tempur Sealy has taken a series of risk mitigation steps, but these were acted upon on an ad-hoc basis for a specific chemical and/or as a reaction to a disruptive event. The mitigation steps included dual and multi-sourcing chemicals and adding inventory capacity. However, the multi-sourcing strategy is difficult and can be limited due to minimum volume requirements, proprietary/specialty chemicals, and supplier processes. In addition, since the raw materials often come from a few suppliers located in a single region, multi-sourcing might not help the company secure enough supply for manufacturing if a natural disaster disrupts production in that region. Moreover, since the manufacturing process requires precisely controlled and timed chemical reactions, there is little room for variations in the sourced chemicals.

Therefore, in addition to the dual and multi-sourcing strategies, the company also holds an increased inventory level. The additional inventory level varies from three to eight weeks, depending on the firm's internal risk assessment level of each chemical. Aside from this on-site storage, they also utilize multiple offsite storage options to accommodate more inventory. External storage options for chemicals are available at two main locations. The first is near US entry ports for chemicals imported from abroad, and these options include shore tanks and ISOtainer tank[1]. The second location is near manufacturing sites, where storage options include railcar storage and traditional warehouses.

The company's product portfolio consists of thousands of SKUs, but each product usually includes only 25-30 components. However, to ensure the readiness of each product, and to maintain a continuous manufacturing process, all components must be available at the same time. This capstone project focuses on reviewing applicable supply chain risk management, supply chain resilience and network optimization methods to help develop cost-effective strategies to mitigate the potential risk and impact of various disruptions.

Lastly, based on discussions with company managers responsible for its supply chain, a major obstacle to approving investments in risk management initiatives is quantifying the

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[1] The ISO tainer tanks are held at the depot that leased by Tempur Sealy

beneficial effects of such actions. This is especially true if the risk mitigation works as intended and nothing goes wrong: at first sight, only the additional implementation costs may be visible, while the benefits (avoided downside) are overlooked. This capstone aims to answer the question: What are the hidden benefits of the money spent on risk mitigation?

1.2 Problem statement and research questions

The company is looking to better understand the trade-off between risk mitigation and the opportunities of an optimized supply chain, and thus be able to improve decision making. More specifically, the project will assess the inventory and its balance across different chemicals, strategic procurement, supplier, and source location diversification in an effort to increase “Time to Survive.”

In that context, the questions to be answered include:

1. What are the state-of-the-art methodologies of risk mitigation?
2. What general strategies can Tempur Sealy apply to mitigate risk and disruption?
3. What is the current time to survive for Tempur Sealy?
4. What is the time to survive of a cost optimal procurement strategy?
5. How to increase the time to survive for Tempur Sealy to mitigate the risk?
6. What are the opportunities to lower the cost while improving the time to survive?

1.3 Project goals and expected outcomes

The project’s overall goal is to provide the company with a method to better understand how their current approach deals with potential disruptions and to develop suggestions on the most cost-efficient way to prolong their time to survive while facing disruptions. Furthermore, as several factors of supply chain change continuously, the goal is to provide models that are adjustable and can be updated quickly to adapt to supply chain changes (Simchi-Levi et al., 2014).

Tempur Sealy is currently mitigating risks at the level of individual raw material inputs but does not have a holistic overview of the system performance as a whole. The method proposed in this capstone will help the company overcome the risks stemming from a narrow and highly specialized, concentrated supplier base to secure uninterrupted production to support growing demand from customers. The analysis focuses on the impacts to US factories; however, because the company is currently sourcing globally, disruptions across all regions will be considered.

The deliverables to the company will include:

1. Analysis of current network (baseline model) and its performance.
2. Methodology to evaluate TTS and suggestions to inform which TTS of which nodes should be improved and how to improve the nodes.
3. Procurement optimization model to identify lowest cost allocation of purchasing volumes to suppliers.
4. Model to review the result (cost reduction/ change in TTS) after improvement.
5. Sensitivity analysis to evaluate how performance can be improved at various nodes of the supply chain network.

With the analysis and the suggested model, the company can make well-informed decisions to secure the desired inventory level under predicted disruption scenarios and prolong the time to survive. The company will be able to continue to manufacture and fulfill customers' orders to ensure revenue and growth with a better understanding of the main levers to maintain business continuity.

2. STATE OF THE ART

Network improvement and risk mitigation have been widely discussed topics in the supply chain field. To lay the theoretical foundations necessary to address this capstone's main problem, we start by reviewing literature on risk mitigation, specifically in supply chains. We continue with exploring the current state of research on supply chain resilience, including ways to quantify resilience. Next, we look at previous applications of the introduced concepts by companies in different settings and provide an overview of research on various potential failure modes and disruptions of supply chains. We conclude by providing an overview of research on procurement optimization.

2.1 Supply Chain Disruption

Supply Chain researchers and practitioners have different definitions of the term disruption, one of them is "Supply chain disruptions are unplanned and unanticipated events that disrupt the normal flow of goods and materials within a supply chain" (Craighead et al., 2007). Similar to this definition, some scholars have categorized disruption as an operational risk, which refers to expected operational issues and disruption risks, which refers to events that have low frequency but high impacts (El Baz & Ruel, 2021). Disruptions are difficult to measure and quantify, but they often impact and increase operational costs (Manhart et al., 2020). Furthermore, Manhart et al. (2020) explained that as a supply chain becomes more complex, the impact of the disruption will be amplified.

It is more challenging for firms that have a complicated supply chain network to manage the disruption.

2.2 Failure modes

In their work on maritime transportation systems, Berle et al. (2011) define failure modes as “loss of the key functions and capabilities of the supply chain, loss of any such would reduce or remove the ability of the system to perform its mission.” According to Rice (2021, p.4), when a supply chain fails, the result can be categorized in seven ways, which he calls “failure modes”:

1. The capacity to acquire materials (maintain supply).
2. The capacity to ship and/or transport products.
3. The capacity to communicate.
4. The capacity to convert (internal manufacturing operations).
5. The human resources (personnel) capacity.
6. The capacity to maintain financial flows.
7. The capacity to distribute products to customers including consumers.

Although the exact nature of the disruptions is unpredictable, their effects are limited to the above-mentioned seven failure modes. In other words, when the disruption result is predictable, firms can arrange a preventive move and control the drivers to prevent failure mode.

2.3 Supply Chain Risk Mitigation

The US Computer Security Resource Center defines risk mitigation as “Prioritizing, evaluating, and implementing the appropriate risk-reducing controls/countermeasures recommended from the risk management process.” (USCSRC, n.d.) Nowadays, an increased number of firms are paying attention to risk management as they encounter more disruptions in their operations and find risk management crucial to their overall performance. However, although many firms try to access risk management, they often struggle to efficiently manage the risks (Manhart et al., 2020). The reasons include, but are not limited to, difficulty achieving supply chain transparency necessary to investigate the risks, the scope and scale of the supply chain being too large to be measured, and proprietary concerns limiting the information visibility (Bailey et al., n.d.). To better manage risk, studies identify a few significant strategic capabilities including flexibility, reliability, resilience, robustness, agility, adaptability, alignment, and responsiveness. Although the capabilities are different, they possess a common goal: to mitigate the risk for the firm (Vishnu et al., 2020).

Many scholars have suggested various approaches to guide firms to mitigate risk. For example, keeping buffer stock (Barros et al., 2021; Jüttner et al., 2003), encouraging cooperation between supply chain actors and increasing a supply chain’s strategic capabilities such as agility. (Betts & Tadisina, 2009). Two kinds of risk mitigation strategies are often discussed – redundancy and flexibility. The redundancy strategy puts more focus on leveraging additional product availability to mitigate the risk of stocking out. The common methods include maintaining safety stock and building relationships with multiple suppliers. On the other hand, flexibility strategies encourage firms to build up capabilities to sense and response to potential threats (Chang et al., 2015).

2.4 Supply Chain Resilience

According to the National Academy of Sciences, resilience is “the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events.” (National Research Council, 2012). Rice (2021) pointed out that “resilience is about creating the ability for the supply chain to continue operating in the face of a risk event or disruption.” With the intention to mitigate the risk, resilience should be designed into a supply chain and will be enhanced by building the risk management culture in the organization (Christopher & Peck, 2004). Much research suggests that there are different dimensions of supply chain resilience such as agility, flexibility, anticipation, preparation, robustness, recovery, absorption and adaptive (Namdar et al., 2021), (Christopher & Peck, 2004).

In recent years, two basic approaches to resilience have been developed – the proactive approach focuses on protection and considers risk without taking the recovery process into account; the reactive approach focuses on improving supply chain process while dealing with disruptions (Ivanov et al., 2017). Much of the literature emphasizes the value of the proactive supply chain resilience approach. However, managers should invest in both approaches to reduce vulnerabilities and quickly recover from disruption (Namdar et al., 2021).

One approach that has gained widespread adoption to manage disruptions and improve supply chain resilience is Time-to-Recover (TTR) and Time-to-Survive (TTS) metrics. These metrics can help reduce risk exposure (Simchi-Levi et al., 2014). Time-to-Recover is an essential part in defining supply chain resilience (Miklovic & Witty, 2010). TTR is defined as the time that the organization takes to fully recover its original capacity following a disruption and is usually measured by historical experience of interacting with the organizations' counterparts such as suppliers. It provides a quantitative method to evaluate a supplier's risk level (Simchi-Levi et al., 2014). On the other hand, TTS represents the time that the organization can survive with their resources on hand without a negative impact on its service level.

To calculate TTS, a node is removed to simulate a disruption, and then the organization observes how long they can provide their service uninterrupted. By comparing the TTR and TTS for each node, the organization can learn if its operations are in danger and identify the sources of vulnerability in its supply chain. If the TTS is longer than TTR, it means the organization has sufficient resources to keep the operation working normally before the disruption impact is recovered. On the other hand, if TTR is longer than TTS, then the organization might experience various financial and operational problems (Simchi-Levi, 2015). For the nodes with low TTS value, they might need a closer TTR evaluation, as TTR is formed with subjective evaluations and might be inaccurate due to optimistic assessments. Otherwise, the organization will need take approaches to improve the TTS to mitigate the risk of impacting by the disruption. For nodes with high TTS value, the organization can evaluate whether they spend too many resources on securing the nodes and thus led to unnecessary resource waste (Simchi-Levi et al., 2015). TTR and TTS guide organizations to make strategic decisions to improve their supply chain resilience and help their response to disruptions.

2.5 Case studies of previous TTS/TTR applications

With the increasing awareness of the importance of implementing supply chain risk management and supply chain resilience measures, we identified many cases where businesses adopted TTR/ TTS metrics. These cases provide an overview view of how the metrics can be applied in the business under different goals and approaches. Table 1 summarizes five cases that illustrate the relevance, usefulness, and importance of these measures across industries (automotive, telecommunication, networking, fashion retail, pharmaceuticals, and consumer packaged goods).

Table 1:

Overview of applied risk management cases

Company	Industry	Goal	Result	Source
Cisco	Networking SW & HW	De-risking Cisco's supply chain	Implemented Business Continuity Planning (BCP), as an essential part of the organization. Supply Chain Design is not concerned with specific potential disasters but creating a resilient system. Introduced resilience metrics for key products.	Harrington, 2009; Miklovic & Witty, 2010
Ford	Automotive	Understanding where to tackle risk with 10 tiers of suppliers and 50,000 parts	Using a quantitative approach, the initiative helped the firm to identify the weak links in its supply chain and defined the time to survive metric.	Simchi-Levi, 2015
Verizon	Telco	Enhancing service through identifying critical parts	Adapted the TTS and TTR methodology for a service provider. Identified parts critical for the provision of service and established necessary levels.	Golany, 2014
NIKE	Fashion Retail	Identifying risk exposure	Applied the concept of TTS measurement using discrete event simulation and Monte Carlo simulation to identify nodes most impacted by potential disruptions.	Xu, 2021

			Provides alternative definitions such as Risk Exposure Time (RET).	
Toyota	Automotive	Increasing resilience	Following the Fukushima Daiichi disaster, Toyota realized its increasing dependency on chips. It strategically increased their inventory levels and established closer cooperation with suppliers. In the aftermath of Covid19 induced chip shortage, Toyota benefited from un-interrupted production and gained market share.	Rice, 2022
"ABC"	Pharma & CPG	Assessing resilience investment options	Developed a framework combining options theory from finance and quantification of risk to identify allocation of investments into supply chain.	Clark & Pan, 2022

2.6 Procurement optimization

Optimization in procurement is a crucial aspect of supply chain management, as it ensures cost efficiency, timely delivery, and overall effectiveness. The four articles discussed here provide different perspectives and approaches to optimization in procurement logistics. Manerba (2015) focuses on specific optimization models and algorithms, such as linear programming, mixed-integer programming, and metaheuristic algorithms, which can be applied to procurement logistics problems, offering valuable insights into solving complex issues like supplier selection, transportation, and inventory management.

Crama et al. (2004) delve into optimal procurement decisions in the presence of total quantity discounts and alternative product recipes, highlighting the importance of considering multiple factors when making decisions. Benson (2005) investigates optimal pricing and procurement strategies in a supply chain with multiple capacitated suppliers, emphasizing the need for a well-balanced approach that considers both supplier capacity and pricing. Lastly, Sawik (2014) compares single vs. multiple sourcing strategies in the context of cost and service level optimization amidst supply chain disruption risks.

Together, these articles provide a comprehensive understanding of optimization in procurement, shedding light on several factors, models, and strategies that contribute to successful supply chain management.

This capstone will apply the Time-to-Survive (TTS), Time-to-Recover (TTR) and procurement optimization approaches to the supply chain network of Tempur Sealy. As shown above, we believe this approach is flexible to be applied in various industries, in our case it will be mattress manufacturing, and at the same time it can provide valuable insights to make better risk mitigation decisions.

3. DATA AND METHODOLOGY

This chapter first introduces the preparatory steps we took before starting our analysis and how necessary data was collected. It continues by describing the actual steps taken exploring the provided data and current characteristics of the supply chain, mapping the current supply chain network, quantifying baseline TTR and TTS and identifying opportunities for improvement. We decided to follow this order as the steps are sequential and build on top of each other.

After reviewing the literature and the feedback from Tempur Sealy, we focused on TTS calculation to help us understand the current operation decision of the company and guide us in deciding on the opportunities to improve. Quantification of TTR is more subjective in nature than TTS, as it is based on either supplier self-assessment (biased) or historical precedents (small sample). Therefore, we opted to approach it through qualitative lens guided by historical events that affected the company. We collected data from Tempur Sealy primarily through weekly meetings with management teams who are responsible for sourcing, transportation, and logistics. Data requests resulting from the meetings included information characterizing parts of the business relevant for this project, such as: input materials, annual volumes of inputs, buffer stock target levels, historical inventory levels, suppliers, procurement price breaks, modes of transportation, storage location and capacities. In addition to these discussions, the team conducted a site visit of a factory and transloader to better understand the actual operations.

3.1 Mapping the current supply chain network

We started by creating a map of the current supply chain network (see Figures 1-3), which serves as a simplified model of the actual physical network. The map captures the location of the main nodes, edges (including transportation modes), storage capacities and material requirements (chemicals). An important simplification assumption is a scope reduction to only include the upstream supply chain (from suppliers to production), because the company maintains a sufficiently large buffer stock of finished goods. Geographically, our analysis is limited to the sites in North American region and 3 main production sites in (Site #1, Site #2, Site #3). Through mapping we develop a detailed understanding of the supply chain network, including suppliers, production facilities, transportation routes, and customer locations.

Figure 1:

Tempur Sealy's North American supply chain

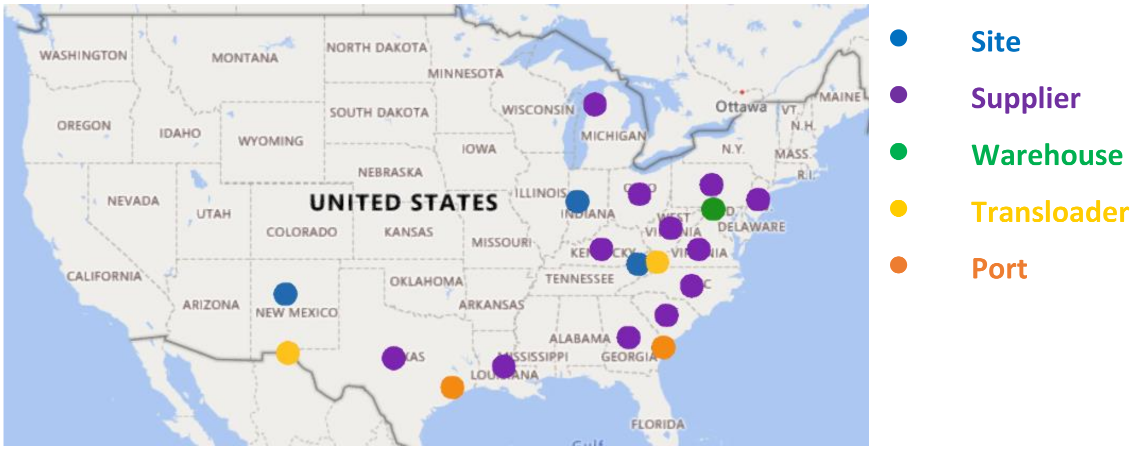

Figure 2:

Tempur Sealy's European supply chain

Figure 3:

Tempur Sealy's Asian supply chain

3.2 Identifying strengths and vulnerabilities

We continued by analyzing the current supply chain to identify potential risks and vulnerabilities. Specifically, for each material we investigated supplier concentration levels, share of multi-region sourcing and adequacy of available storage capacities compared to company defined buffer stock requirements.

3.3 Cost comparison of current and cost-optimal procurement strategies

To be able to attach a financial value to the current level of resilience of the supply chain, we compared the costs of the current procurement strategy and the costs of a cost optimal allocation of procurement volumes to suppliers. First, we calculated the current total annual procurement cost using the latest demand forecast for each site and chemical, as well as the expected allocation of purchasing volumes to suppliers and their prices. Second, we calculated the costs for a procurement strategy focusing solely on minimizing costs. The detailed methodology is described in 3.3.1.

In addition to the cost difference between current and optimal procurement, which we used as an estimate of the company's investment into resilience, we also looked at the changes in the supplier concentration and regional diversification of the cost optimal procurement strategy compared to the current system.

3.3.1 Optimization of procurement volume allocations for minimum cost

We developed a Mixed Integer Linear Programming (MILP) model in Python (Szuma & Huang, 2023) using the commercial Gurobi solver to optimize the cost of supplying materials to production sites while satisfying constraints of forecasted demand, general volume thresholds for price rebates and in case of one supplier specific minimum volume thresholds related to three specific chemicals.

The code starts by importing the required libraries and reading data from Excel files, which contain the price, demand, minimum volume thresholds, special thresholds, and supplier group data. Suppliers are assigned into groups such that, if a supplier has discounts, each discount level is treated as a virtual supplier and is placed into a group together with the original and all virtual suppliers. For example, if supplier "Lion[2]" has three volume thresholds for increasing magnitude of rebate, then suppliers Lion, Lion1, Lion2, Lion3 will be placed

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[2] All suppliers and products have been renamed to maintain confidentiality

together in a single group. Dictionaries are then created to store the input data more efficiently for the optimization problem.

Sets:

I: Set of materials

J: Set of suppliers

K: Set of locations

L: Set of containers

M: Set of sites

N: Set of regions

H: Set of supplier groups

OLV: Set of specific chemicals (Orange, Lime, Olive)

Parameters:

D_{im}: Demand for material i at site m.

C_{ijknlm}: Price of material i, supplied by supplier j, from location k, in region n, in container l, to site m.

V_j : Minimum quantity threshold for supplier j (across all chemicals, locations, containers etc.).

T_j : Specific threshold for supplier j (minimum volume of specific chemicals OLV for supplier j).

G_h : Set of suppliers in group h.

default_max_percentage1: maximum share of supply by single supplier for chemicals with more than 1 supplier.

default_max_percentage2: maximum share of supply by single supplier for chemicals with more than 2 suppliers.

default_max_region_share : maximum share of supply from a single region for each chemical with more than 1 region.

Decision variables:

x_{ijknlm} : Integer variable representing the volume of material i, supplied by supplier j, from location k, from region n,in container l, to site m.

y_{jh} : Binary variable indicating if supplier j from group $G[h]$ is active (supplying)

z_{ji} : Continuous variable representing the maximum share of supplier j for material i, given there are more than 1 suppliers.

w_{ji} : Continuous variable representing the maximum share of supplier j for material i, given there are more than 2 suppliers.

r_{in} : Continuous variable representing the maximum share of region n for material i, given there are more than 2 regions.

Objective function:

The objective is to minimize the total cost, given by the formula:

$$\text{Minimize} \quad \textstyle\sum_{(i,j,k,n,l,m)} C_{ijknlm} \cdot x_{ijknlm} \text{ , } \forall i, m \in D$$

Constraints:

1. Demand constraint: The sum of the supplied volume x must be greater than or equal to the demand D for each material i at site m.

$$\sum_{j,k,l,n} x_{ijklmn}\, y_{jh} \geq D_{im}, \quad \forall i \in I, m \in M$$

2. Supplier group constraint: For each group h, there can be at most one active supplier j.

$$\sum_{\mathrm{j} \in \mathrm{G[h]}} y_{jh} \leq 1, \quad \forall h \in H$$

3. Maximum share supplied by single supplier: For each material i and supplier j, the supplied volume x should be less than or equal to the product of the corresponding variable z_{ji} or w_{ji} and the total demand for material i.

$$\sum_{\mathrm{k,\, l,\, m,\, n}} \mathrm{x_{ijklmn}} \leq \mathrm{z_{ji}} \cdot \sum_{\mathrm{m \in M}} \mathrm{D_{im}}, \quad \forall\, \mathrm{i} \in \mathrm{I},\ \mathrm{j} \in \mathrm{J}$$

$$\sum_{k,l,m,n} x_{ijklmn} \leq w_{ji} \cdot \sum_{m \in M} D_{im}, \quad \forall i \in I, j \in J$$

4. Maximum share supplied from a region: For each material i and region n, if the material is available from more than one region, the supplied volume should be less than or equal to the product of the corresponding variable r_{in} and the total demand for material i.

$$\sum_{j,k,l,m} x_{ijklmn} \leq r_{in} \cdot \sum_{m \in M} D_{im}\,, \quad \forall i \in I, n \in N$$

5. Minimum quantity: For an active supplier j in group h, the supplied volume must be greater than or equal to the minimum quantity threshold V_j.

$$\sum_{i,k,l,m,n} x_{ijklmn} \geq V[j] \cdot y_{jh}, \quad \forall j \in G[h], h \in H$$

6. Specific minimum quantity: If supplier j has a specific minimum quantity T_j, then the sum of the amount supplied from chemicals OLV (Orange, Lime, Olive) must be greater than or equal to the threshold T_j for supplier j.

$$\sum\nolimits_{k,l,m,n} x_{ijklmn} \geq T[j] \cdot y_{jh}, \quad \forall j \in T, h \in H, i \in OLV$$

3.4 Quantifying TTR and TTS

We assessed the company's resiliency to supply disruptions by quantifying the TTS (time to survive) of the current system using a Python code (Szuma & Huang, 2023) described below. By iterating over each supplier and turning them off, we calculated how long each production location can continue to operate using inventory and supply from remaining suppliers to cover its demand. We assumed there is no flow of chemicals between the sites and suppliers / chemicals are not interchangeable between sites. For the inventory, we used average levels of inventory for each chemical. We also disrupted entire defined regions based on supplier clustering, such as Texas, Northeast US, Western Europe…etc. The results served as our baseline representing current system performance under a theoretical disruption of supply. The result was a TTS value in weeks, for each chemical and production site. We also calculated a TTS for the procurement cost optimal system. We compared the costs and TTS values of the current and cost optimal system to obtain a dollar value per additional unit of TTS. The gap of TTS between the current and optimal system represents the cost of extra resiliency that the company put in the current system.

We calculated the impact on TTS during a disruption by removing the supply from the affected supplier or region (all suppliers in the region). Then, we determined TTS by dividing the total inventory on hand by the difference between weekly demand and weekly supply (please see the formula below). If weekly supply exceeds weekly demand, the company will experience a "surplus supply," and the disruption will not affect the company's ability to meet demand. Thus, in this case, inventory will not be depleted. However, if weekly demand exceeds weekly supply, the company will start to deplete its inventory, and the TTS will represent the weeks that the company can survive under the disruption.

TTS calculation

$$\boldsymbol{TTS = \frac{Total\ Inventory\ on\ Hand}{Weekly\ Demand - Weekly\ Supply}}$$

During scenario planning, the company informed us that they have a contingency plan to stretch supply from the current supplier by an additional 20%. Therefore, to simulate the actual business environment more accurately, we also incorporated scenarios in which the current suppliers are stretched by 20% and we evaluated the resulting impact on TTS. In such a scenario, we assumed that the supply of every other supplier providing a particular chemical would be stretched by 20% if one of the suppliers stopped supplying that chemical. For example, if supplier, Lion, experienced a disruption and can no longer supply chemical Orange, Tempur Sealy would stretch all the other suppliers who provide chemical Orange by an additional 20%. Moreover, we simulated all the scenarios under two different inventory position strategies – current strategy and cost optimal purchasing volumes allocation strategy. Based on the different focus of the strategy, we combined the cost effect and risk mitigation result for the business to better understand how their effort improve supply chain resiliency.

Figure 4:

TTS scenario simulation

Current Strategy	Optimized Inventory Allocation
• Without disruption	• Without disruption
• Turn off supplier, no change in supply	• Turn off supplier, no change in supply
• Turn off supplier, stretch supply for 20%	• Turn off supplier, stretch supply for 20%
• Turn off region, no change in supply	• Turn off region, no change in supply
• Turn off region, stretch supply for 20%	• Turn off region, stretch supply for 20%

For TTR, we defined, together with the company, three distinct scenarios based on historical events of various magnitude, which have affected the company in the past. These are to serve as archetypical examples of potential unpredictable disruptions. The goal is to quantify "the time it would take for the site (*chemical*) to be restored to full functionality" (Simchi-Levi et al., 2014, para. 6).

The scenarios are:

- Texas ice freeze: In February 2021, the winter storm Uri struck Texas. Temperatures dropped as low as 6 degrees and the state was covered in ice and snow causing widespread blackouts. The result was zero supply from sites in the affected area for 5-6 weeks, followed by limited operations for 2-3 months and full restoration only after 6 months. We consider this a one-off, irregular event and geographically limited to a state.
- Hurricane Harvey: Hurricane Harvey hit Houston and surrounding areas in August 2017. All operations ceased at the port of Houston and Houston airport due to severely damaged infrastructure. Compared to the Texas ice freeze, hurricanes are more common in the gulf area and occur seasonally. The expected disruptions from a hurricane in the gulf area is 2-3 weeks of no supply and fast recovery thereafter.
- Asian lockdown – In the wake of the global Covid pandemic in 2020 – 2022, many countries introduced strict lockdown measures to contain the virus. One of the strictest policies were introduced in China, which is also a major supplier for many raw materials. The lockdowns caused factories and ports to pause operations. This type of disruption is very unpredictable and could last from a few weeks up to a year (or more).

By identifying the possible disruptions and their duration, we can gain a better sense of how increasing TTS can aid in risk mitigation. We defined the TTR scenarios to illustrate the range of potential disruption durations and magnitudes. Combining this knowledge with an understanding of TTR, the company can take proactive measures to minimize the impact of potential disruptions on its operations.

3.5 Identifying and analyzing opportunities for improvement

The resulting TTS values of the current system were plotted to see the chemicals with the shortest TTS. These chemicals require the most attention as they pose a threat to disrupt the manufacturing of the company. On the other hand, we expected some chemicals to have excessively high TTS values due to surplus storage capacity or too many suppliers. The goal was to help the company level-set the various chemicals to TTS values that correspond to their respective importance levels or risk categories. For easier evaluation, we also grouped the chemicals by their risk categorization and compared their TTS levels to the desired buffer levels.

In this section, we outlined the data and methodology we employed to analyze the supply chain resilience. First, we created a map of the current supply chain network, identified strengths and vulnerabilities, and compared the costs of the current procurement strategy to a cost-optimal approach. To estimate the TTR, we defined three scenarios based on historical events and quantified the time it would take for the site to be restored to full functionality. Furthermore, we developed a Mixed Integer Linear Programming model to optimize the cost of supplying materials to production sites while satisfying demand constraints. In the next section we provide the results and discussion.

4. RESULTS AND DISCUSSION

In this chapter, we start by exploring the data provided by the company and mapping the current supply chain network. Next, we start our analysis by comparing the risk categorization of chemicals to actual storage capacities and evaluate supplier diversification. Then, we present the results of the procurement optimization and TTS calculations. Finally, we conclude by an overview of potential improvement opportunities.

4.1 Data exploration

Data were obtained in Excel files as agreed upon during discussions with the company management. As the project progressed, there were requests for updates or additional data points, which were promptly delivered. The most important data sources for our analysis were:

- Price list of chemicals by supplier, supplier location, container type, production site
- Forecast demand for 2023 for each chemical and site
- Historical volumes and prices for material deliveries to production sites for 2019-2022
- Storage capacities and average inventory levels for each chemical and site
- Risk categorization of chemicals including buffer stock policies

After exploring the provided data, we were able to build an initial picture of the company's supply chain characterized as:

- 3 production sites (Manufacturing Site #1, #2 and #3)
- 51 chemicals from 22 suppliers and 20 locations (on 3 continents) delivered in 5 container types
- 1 transloading facility, 2 entry ports and 1 warehouse

For the purposes of safe data handling and avoiding the leakage of sensitive information, the names of the suppliers, chemicals and manufacturing sites were encoded as animals, trees and in numbers.

4.2 Mapping the current supply chain

Based on the available data, we mapped the nodes of the supply chain to get a better understanding of their dimensions and flows. The map is broken down into three snippets for easier visualization: US, Europe, and Asia (see Figures 1, 2, and 3).

Based on the mapping, we were surprised to see that there are no West Coast facilities usage, even though there are imports of chemicals for Asia and the Port of Los Angeles is one of the main entry points for Asian suppliers. Moreover, the distance to the New Mexico site seemed shorter compared to Houston, TX. However, we learned from the company that due to the nature of the chemicals, special handling equipment and specialized transportation providers are required, which are only available at ports around the Gulf. Therefore, the ports in Houston, TX and Savannah, GA are used.

From the ports, chemicals are transported to the sites directly by trucks, from Houston to Site #2, and from Savannah to Site #1 and Site #3. In the case of Site #1, the company also uses rail transport from the port to a transloading facility located in close proximity. A new transloading facility in close proximity to Site #2 is planned to begin operating in May 2023. The transloading facility offers three advantages. First, the rail transport to the nearest vicinity of the site is cheaper. Secondly, the transloader effectively alleviates driver shortage issues caused by long hauls. The available drivers have increased due to the shorter hauls needed. Finally, the transfer of ownership is a form of risk mitigation of chemicals that are stored in the shore tank - when the chemicals reach the transloading facility where the chemicals are stored, Tempur Sealy acquires possession of the chemicals at an earlier stage in the supply chain. All material in the shore tank is supplier owned and subject to allocation rules under a Force Majeure situation even if already on the way to a customer (Tempur Sealy). However, this is not possible when chemicals are parked at the transloader. A similar risk mitigation strategy is storage of ISOtainers at the port, which are owned by the company once they arrive and clear customs.

4.3 Comparison of chemical risk categorization to actual storage capacities

As part of its risk mitigation activities, the company introduced a risk categorization of its chemicals. There are three categories of risk (Low, Medium, High) and each has a prescribed buffer inventory (3, 5, 8 weeks respectively). The risk categories are qualitative. The main risk assessment criteria focus on the number of available sources, whether the supply has been constrained and has limited production, and what share of the products use the given chemical. About 10% of the chemicals are ranked low risk, 20% ranked as medium risk, and 70% ranked as high risk. However, at the same time they represent 62%, 32%, and 6% of the procurement volumes. Low risk chemicals are similar to commodities, purchased in large quantities, in contrast to the high-risk chemicals, which are very specialized and purchased in small quantities. At the same time, these special chemicals, even though small in quantity, can be essential to produce almost all SKUs; hence, their shortage might lead to the entire production being stopped.

To understand the inventory level in actual operation, we calculated how long (weeks) the most recent average inventory levels[3] would last in the absence of any supply and compared the result to the required buffer stock levels (weeks). As can be seen in Figure 6, for high-risk chemicals, Site #1 has 13 chemicals under the buffer stock, while only 2 for Site #2. For medium and low risk chemicals, Site #1 has more chemicals below buffer stock than Site #2. In general, Site #1 has 57% chemicals and site #2 has 89% chemicals meeting the requirement.

We noticed that some chemicals do not meet the buffer stock requirement in both sites such as Hemlock and Olive. There are also chemicals that have inventory levels well above their buffer stock requirement. From the discussions with the company, we learned that there are limited storage capacities at the sites, and additional storage expansion is difficult and expensive. Therefore, to add safety and flexibility, they hold extra inventories at a warehouse and transloaders. These outside inventory options provide an extra 10 and 9 railcars of capacity for Site #1 and Site #2 respectively. For chemicals that Site #1, and Site #2 cannot hold at the transloader, Tempur Sealy should explore reducing inventory levels of chemicals which are far above the required buffer and allocate storage to chemicals below the required threshold.

Figure 5 summarizes the total volume of chemicals needed to reach the required buffer level (shortfall) as well as the total volume of chemicals that are above the buffer level (excess). The values are indexed based on “current inventory = 100” for each location. For both Site #1 and Site #2 the excess volume is higher, which means that if the company was able to

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[3] The inventory levels are based on 6-9 months of historical data

reallocate storage capacities between chemicals, it should be able to reach its target buffer levels without increasing total storage capacity. The optimal inventory shows the volume of chemicals to be stored to reach the buffer level policy and is 15% and 23.6% lower for Site #1 and Site #2 respectively. It excludes chemicals with zero demand.

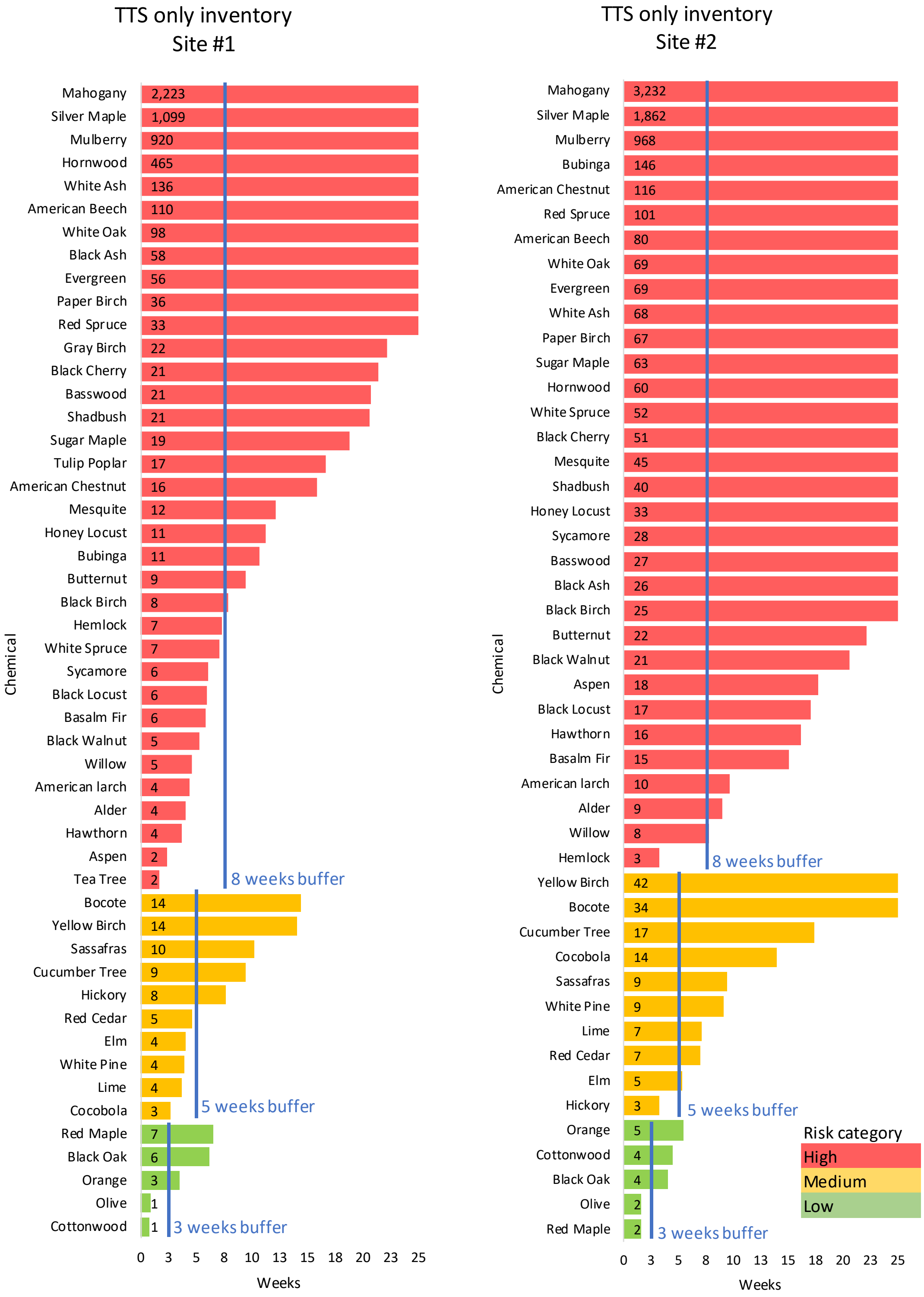
Figure 5:

Comparison of inventory to buffer level requirement

current inventory = 100	**Site #1**	**Site #2**
Current inventory	100	100
Shortfall	18	14
Excess	33	37
Optimal inventory	85	76
Change %	*-15.0%*	*-23.6%*

Figure 6:

TTS of Site #1 and Site #2 with average inventory



4.4 Supplier diversification per chemical

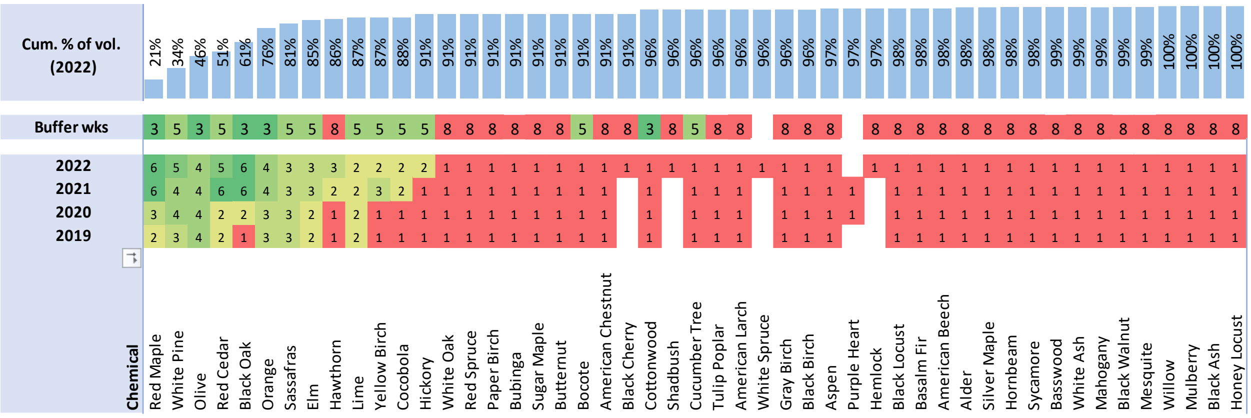
One risk mitigation strategy outlined in previous chapters is diversification of supplier base. This means sourcing the same material from multiple suppliers and/or multiple geographical locations and known as dual- or multi-sourcing. We looked at historical procurement data from the company to see if there were any changes in the number of suppliers by chemical or number of sourcing regions to understand the current procurement strategy.

Overall, we noticed that the company increased both the number of suppliers and the sourcing regions for the purchased chemicals. In 2019, only 2 chemicals (Olive, Sassafras), representing 21.3%, were regionally dual sourced from within USA and internationally in meaningful volumes (at least 10% from outside the USA). Three years later, in 2022, 10 chemicals are sourced from both within U.S. and outside U.S., representing 86% of total purchased volumes. The share of chemicals sourced from US suppliers decreased from 92.6% to 72.2% between 2019 – 2022 representing Tempur Sealy's effort to diversify the supplier location.

When considering the number of suppliers, the share of single sourced chemicals decreased from 27% to 9% and multi-sourced (3+ suppliers) increased from 42% to 86% between 2019 – 2022. When looking also at the relative importance of the chemicals (the share of products containing the chemical), we see that the effect is even more pronounced for the most important chemicals, which are needed for all production. This can be seen in Figure 7, which shows for each chemical, the count of suppliers by year, buffer required in weeks and the cumulative share of total procurement volume. We see that for most high-risk chemicals, the number of suppliers has not increased, the only exception is Elm. For medium risk chemicals, the company was able to secure dual or multi sourcing for all except Bocote and Cucumber Tree. The chart also links the previously mentioned fact that high risk chemicals represent 70% of the count but represent only 6% of volume. At the same time, most of them have only 1 supplier. By interpreting Figure 6 and Figure 7, we can pinpoint the chemicals that might face higher risk and prioritize the risk mitigation effort. For example, chemical Willow is classified as a high importance chemical while its TTS is below buffer stock requirement and is still single sourced. To mitigate the risk of Willow shortage under disruption, Tempur Sealy could either increase the number of suppliers or store more inventory of Willow.

Figure 7:

Supplier count, buffer levels and chemical volumes in 2019-2022

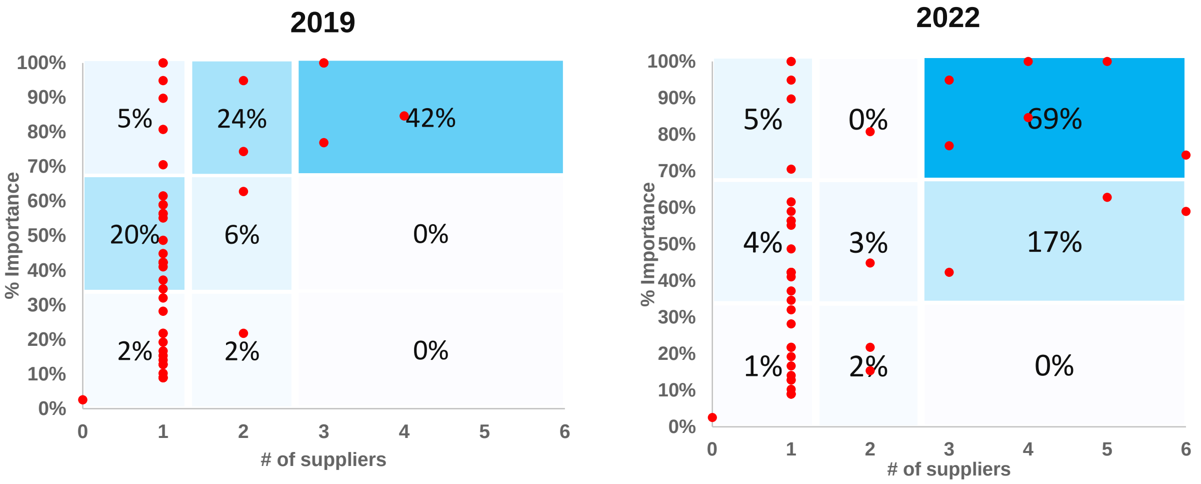


Chemical	Cum. % of vol. (2022)	Buffer wks	2022	2021	2020	2019
Red Maple	21%	3	6	6	3	2
White Pine	34%	5	5	4	4	3
Olive	46%	3	4	4	4	4
Red Cedar	51%	5	5	6	2	2
Black Oak	61%	3	6	6	2	1
Orange	76%	3	4	4	3	3
Sassafras	81%	5	3	3	3	3
Elm	85%	5	3	3	2	2
Hawthorn	86%	8	3	2	1	1
Lime	87%	5	2	2	2	2
Yellow Birch	87%	5	2	3	1	1
Cocobola	88%	5	2	2	1	1
Hickory	91%	5	2	1	1	1
White Oak	91%	8	1	1	1	1
Red Spruce	91%	8	1	1	1	1
Paper Birch	91%	8	1	1	1	1
Bubinga	91%	8	1	1	1	1
Sugar Maple	91%	8	1	1	1	1
Butternut	91%	8	1	1	1	1
Bocote	91%	5	1	1	1	1
American Chestnut	91%	8	1	1	1	1
Black Cherry	91%	8	1			
Cottonwood	96%	3	1	1	1	1
Shadbush	96%	8	1			
Cucumber Tree	96%	5	1	1	1	1
Tulip Poplar	96%	8	1	1	1	1
American Larch	96%	8	1	1	1	1
White Spruce	96%		1			
Gray Birch	96%	8	1	1	1	1
Black Birch	96%	8	1	1	1	1
Aspen	97%	8	1	1	1	1
Purple Heart	97%			1	1	
Hemlock	97%	8	1			
Black Locust	98%	8	1	1	1	1
Basalm Fir	98%	8	1	1	1	1
American Beech	98%	8	1	1	1	1
Alder	98%	8	1	1	1	1
Silver Maple	98%	8	1	1	1	1
Hornbeam	98%	8	1	1	1	1
Sycamore	98%	8	1	1	1	1
Basswood	99%	8	1	1	1	1
White Ash	99%	8	1	1	1	1
Mahogany	99%	8	1	1	1	1
Black Walnut	99%	8	1	1	1	1
Mesquite	99%	8	1	1	1	1
Willow	100%	8	1	1	1	1
Mulberry	100%	8	1	1	1	1
Black Ash	100%	8	1	1	1	1
Honey Locust	100%	8	1	1	1	1

In addition to the number of suppliers, we also evaluated chemicals based on their *importance*, which is the share of the finished goods that contain them. Figure 8 shows the split of procurement volumes based on chemical importance (y axis) and the number of suppliers (x-axis), red dots each represent one chemical. Ideally, the distribution of the red dots would be around diagonal line, meaning that as the importance of the chemical increases, the number of suppliers increases. The dots under the diagonal line indicate overinvesting in extra suppliers, and conversely, the dots over the diagonal line indicate that they do not have a sufficiently diversified supplier base. However, how many suppliers need to be acquired for the corresponding importance of chemicals should still be decided not only based on the chemical importance but also multiple considerations such as inventory holding volume, capacity and shelf life. The most important takeaway is that the company was able to move away from the top left corner towards the right direction – closer to the diagonal line, but there are still some particularly important chemicals that are single-sourced (Alder, Black Locust, Cottonwood, Cucumber Tree, and Honey Locust). These represent 5% of total procurement volume as seen in the top left corner of the 2022 chart.

Figure 8:

Supplier count, importance and chemical volume contribution in 2019 and 2022



4.5 Cost optimal allocation of purchasing volumes to suppliers

To find the optimized inventory allocation under lowest cost while fulfilling procurement requirement such as contractual amount commitment, we ran the MILP python model developed to generate the solution. As a natural side-effect of an increasingly diversified supplier base, we expected procurement (unit) costs to increase for three main reasons. First, the average volume allocated to a supplier is lower, thereby weakening the negotiation power of Tempur Sealy. Second, it becomes increasingly difficult for the company to manage its supply chain, thereby creating additional costs (including additional transaction costs). However, some suppliers offer additional rebates based on total annual purchase volumes. However, with many additional suppliers, it becomes difficult to assign the volumes in a way to maximize rebates and achieve the lowest possible purchasing costs.

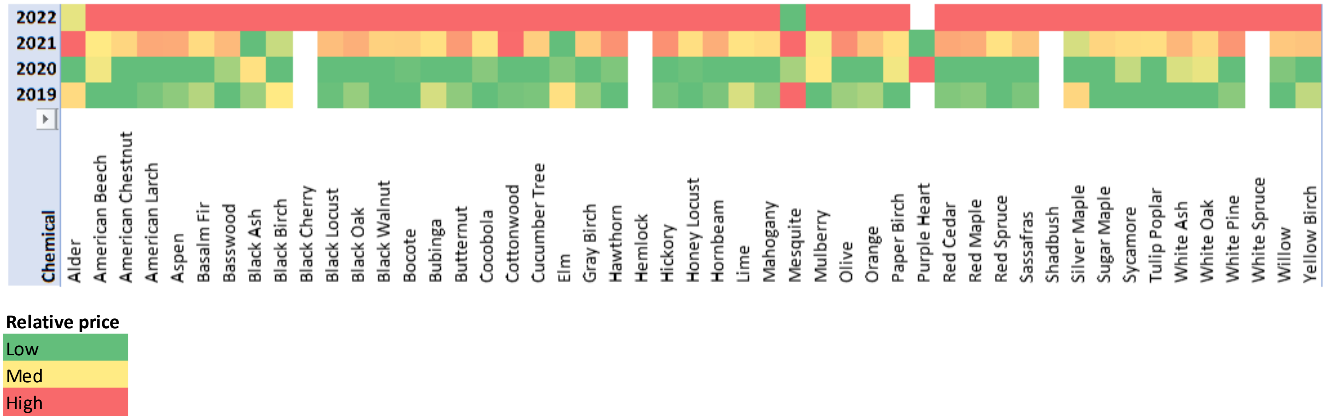
On the actual operation perspective, from our discussions with the company, we also learned that while the listing of new suppliers and chemicals is coordinated centrally, the operational procurement of chemicals is done at the sites independently (from the approved list of suppliers).

Given the increased supplier diversification, we ran an optimization model with the goal of minimizing total procurement costs to see the impact on the supplier diversification. Figure 10 and Figure 11 show the historical and forecast volumes, procurement costs and average prices per pound. All values have been indexed to 2019 = 100. The most recently estimated spend for the 2023 procurement was 183 with an average price per pound at 135. The average prices increased significantly in 2021 and 2022. Tempur Sealy mentioned that they believe the spike in 2022 was due to increased logistics costs, acute supply shortage and Ukraine war. To verify if this increase was in any way linked to the ongoing diversification of the supplier base, which as previously discussed, occurred in the same time period, we took below steps:

First, to confirm that the change was indeed a price effect and not a mix effect, which would be caused by shift in the mix of the procured chemicals towards more expensive ones, we fixed the chemical volumes at 2019 levels and applied prices in the following years to come up with the new average prices. The results of our analysis showed that the average prices were almost identical (<1% difference) to the actual ones for 2020 – 2022. This suggests that the average price increase was driven by a change in prices and not by a different mix. Figure 9 also shows that the prices for the chemicals increased across the board between 2019 – 2022.

Figure 9:

Price development of chemicals in 2019 - 2022



Next, we ran the MILP code in python to find the optimized allocation that would yield the lowest possible procurement costs without any dual sourcing requirements. We found that the optimal procurement cost would be 169, which is 14 points lower compared to the company forecast. These costs already include the rebates and additional logistics costs in both cases. However, the optimized cost allocation case results in a purely single-sourced strategy. The main reason is that for each chemical, the model selects the supplier with lowest cost to fulfill the demand, and if the supplier does not have enough capacity, the model selects the supplier with second lowest cost. In the optimized case, since most of the suppliers have enough capacity that the company needs, the result of the model becomes a single-source strategy. The optimized result, all except two chemicals (Orange, Black Oak) come from a single supplier. In terms of regions, all are single region sourced except (Orange). We think the difference in the cost is a good proxy to the price paid for the current resilience level of the company.

To see if it is still possible to achieve some cost savings while preserving some of the resilience of the system, we also ran another three optimization scenarios with additional constraints. The three scenarios used the following additional constraint: (1) using at least two suppliers for each chemical, (2) using at least 2 different regions per chemical (3) using minimum of 2 suppliers and 2 regions per chemical. As a side note, the constraints were only applied to chemicals where additional suppliers or regions were available. The results, summarized in Figure 10 and Figure 11, show that even with the third scenario, which is most restrictive but resilient, there are potential savings of up to 10 points of cost.

Figure 10:

Total cost and volume of purchased chemicals in 2019 - 2023

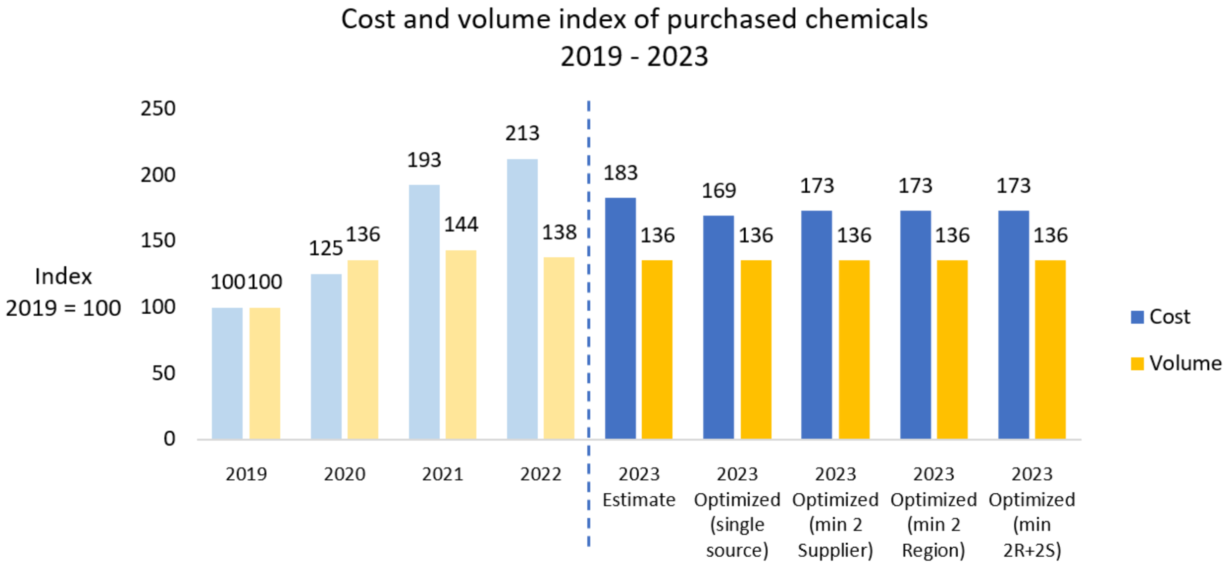
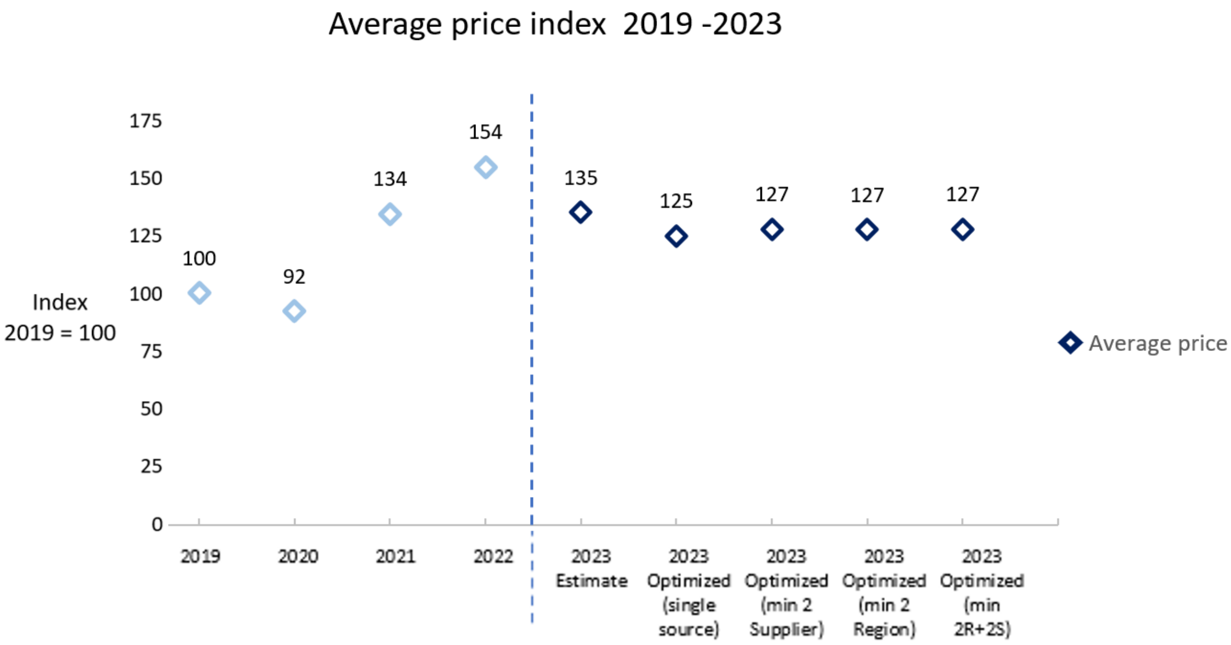


Figure 11:

Average price index of chemicals in 2019 - 2023



4.6 TTS result under disruptions

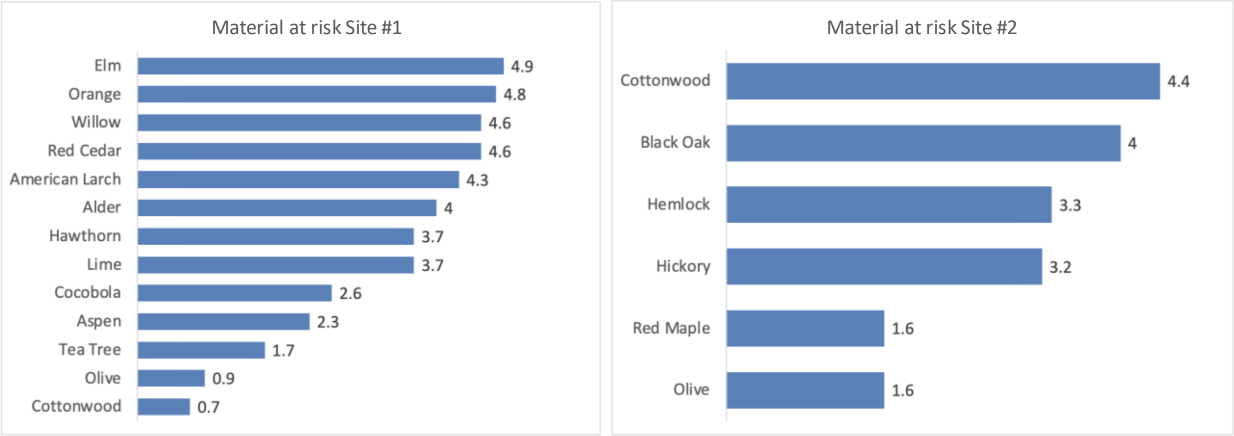
We calculated the TTS for different scenarios, compared the results and identified the lowest TTS under each scenario. Furthermore, we quantified the Time to Survive of the current system and compared it to the cost optimal system to obtain a dollar value per additional unit of TTS, which represents the cost of extra resiliency. Finally, we identified and analyzed opportunities for improvement by plotting TTS values and grouping chemicals by their risk categories to level-set their TTS values.

By identifying the lowest TTS or the TTS lower than the company's expectation, we can not only find the area to improve but also quantify the company's effort in increasing supply chain resilience by comparing the changes in TTS and the cost spent. There are multiple ways to interpret the TTS result under different scenarios. For example, based on the company feedback that the rule of thumb is to keep five weeks of inventory at any time, we looked at the chemicals that have TTS that is lower than five weeks under any kind of scenarios (see Figure 4 for all the scenarios). The result is shown in Figure 12. For Site #1, 13 chemicals have TTS lower than five weeks and account for 25% of chemical count; while in Site #2 it is 6 and 12%. Furthermore, since the chemical Olive showed up in charts for both sites, its' shortage would impact both sites under the worst scenario. Thus, the company should prioritize the risk mitigation effort on this chemical.

During our discussion with Tempur Sealy, we learned that they were not surprised to know that chemicals Cottonwood and Olive were identified as material at risk and that they are actually working on increasing the storage capacity of the chemicals. However, Tempur Sealy were surprised to see that chemical Orange was identified as being below the buffer level, since they already increased inventory capacity for it. By combining the TTS result and the company's inventory policy, the company could easily verify if the current inventory position meets expectations and quickly identify areas to improve. In the case of Orange, it turned out to be an error in the reporting of inventory levels. After correction, the chemical is meeting its buffer levels (although still below the five weeks rule of thumb). This case shows the usefulness of the methodology for identifying potential issues.

Figure 12:

Material under 5 weeks for Site #1 and Site #2



To understand how the TTS changes in different scenarios, Table 2 and Table 3 show the lowest TTS of 4 scenarios after the regional disruptions for each site. We can see in Table 2, under current strategy, when region Korea is disrupted, the minimum TTS is 25.7 weeks (about 6 months) without stretching remaining suppliers and 36.9 weeks (about 8 and a half months) when other suppliers are stretched. Because the chemical Sassafras is supplied by 3 suppliers, the TTS will be maintained after we stretch other suppliers, indicating that the other suppliers are in regions outside Korea, and the multi-source strategy is helpful to mitigate the regional risk.

With the optimal strategy, the company's lowest TTS of the chemical Sassafras can be extended up to 88 weeks (about 1 year 8 months), and a situation of surplus supply can be achieved if we stretch other suppliers. However, when we look at the region East Coast US in Table 2, we can see that the lowest TTS remains at 0.7 weeks for the chemical Cottonwood among all the scenarios. Since the chemical Cottonwood is single sourced, TTS remains unchanged due to a lack of alternative supplier. The solution to increase the TTS is either to increase the inventory or to consider adding more suppliers.

Lastly, we suggest that stretching remaining suppliers is not necessarily helpful in increasing TTS. Figure 13 and Figure 14 build on Figure 6 to include the effect of remaining suppliers on TTS. To avoid confusion, we recap that there could be three different ways to look at TTS: (1) inventory only; (2) inventory + supply without disruption; and (3) inventory + supply with disruptions. Figure 6 showed the first case when only inventory was considered to calculate TTS for both sites. We verified the second case in our code, and the result showed that indeed in the absence of disruption, supply is meeting demand and inventories are not being depleted. For the third case, we looked at the additional TTS (on top of inventory only) provided by the remaining (undisrupted suppliers). We visualized this additional TTS in Figure 13 and Figure 14, with the darker colored bars. Based on these figures, we concluded that most of the benefits of multi-sourcing accrue to chemicals that are already above or near the buffer level. Cases when the remaining supply helps to reach the buffer level are Elm and White Pine for Site #1; and Olive and Red Maple for Site #2. Since all the chemicals (that have alternative supply in disruption) are above the buffer level, stretching those suppliers is not the most effective and cost-efficient way to mitigate the risk of disruption. Therefore, the company should be conscious about the cost-effectiveness of stretching suppliers to increase TTS for chemicals that are already meeting the buffer stock requirement. Efforts to increase TTS should be focused on the high-risk and single sourced chemicals which are under the buffer level and do not benefit from any supply during a disruption.

Table 2:

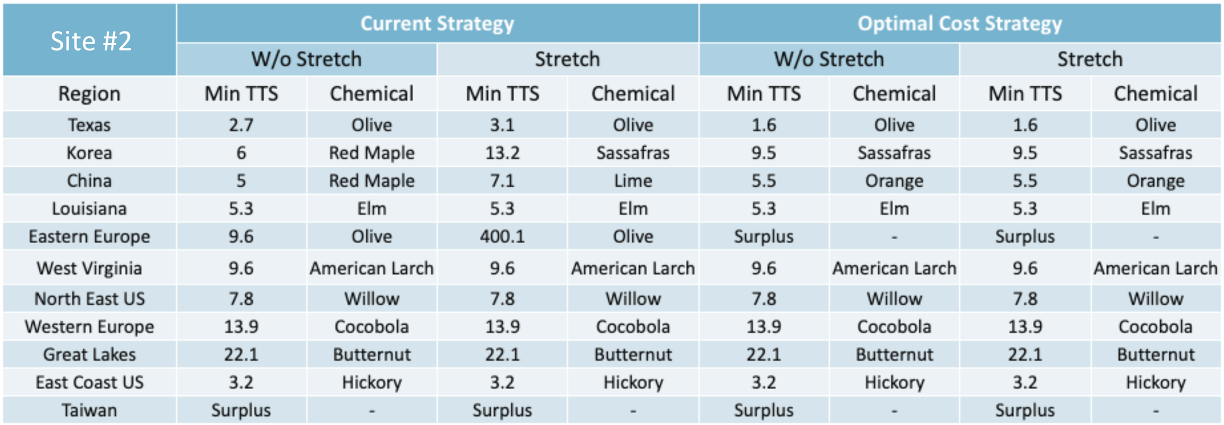
Lowest TTS under different scenarios and disruption of each region for Site #1

Site #1	Current Strategy				Optimal Cost Strategy			
	W/o Stretch		Stretch		W/o Stretch		Stretch	
Region	Min TTS	Chemical	Min TTS	Chemical	Min TTS	Chemical	Min TTS	Chemical
Texas	2.3	Olive	2.3	Aspen	2.3	Aspen	2.3	Aspen
Korea	25.7	Sassafras	36.9	Sassafras	88.1	Sassafras	Surplus	-
China	3.7	Lime	3.7	Lime	7.1	White Spruce	7.1	White Spruce
Louisiana	1.5	Olive	1.9	Olive	4.4	Lime	4.5	Lime
Eastern Europe	7.7	Olive	Surplus	-	0.9	Olive	0.9	Olive
West Virginia	4.3	American Larch	4.3	American Larch	4.3	American Larch	4.3	American Larch
North East US	1.7	Tea Tree	1.7	Tea Tree	1.7	Tea Tree	1.7	Tea Tree
Western Europe	5.2	Black Walnut	5.2	Black Walnut	5.2	Black Walnut	5.2	Black Walnut
Great Lakes	9.4	Butternut	9.4	Butternut	9.4	Butternut	9.4	Butternut
East Coast US	0.7	Cottonwood	0.7	Cottonwood	0.7	Cottonwood	0.7	Cottonwood
Taiwan	2.6	Cocobola	2.6	Cocobola	3.5	Cocobola	3.7	Cocobola

Note: “Stretch” means to stretch all the other suppliers who provide the chemical by an additional 20%

Table 3:

Lowest TTS under different scenarios and disruption of each region for Site #2

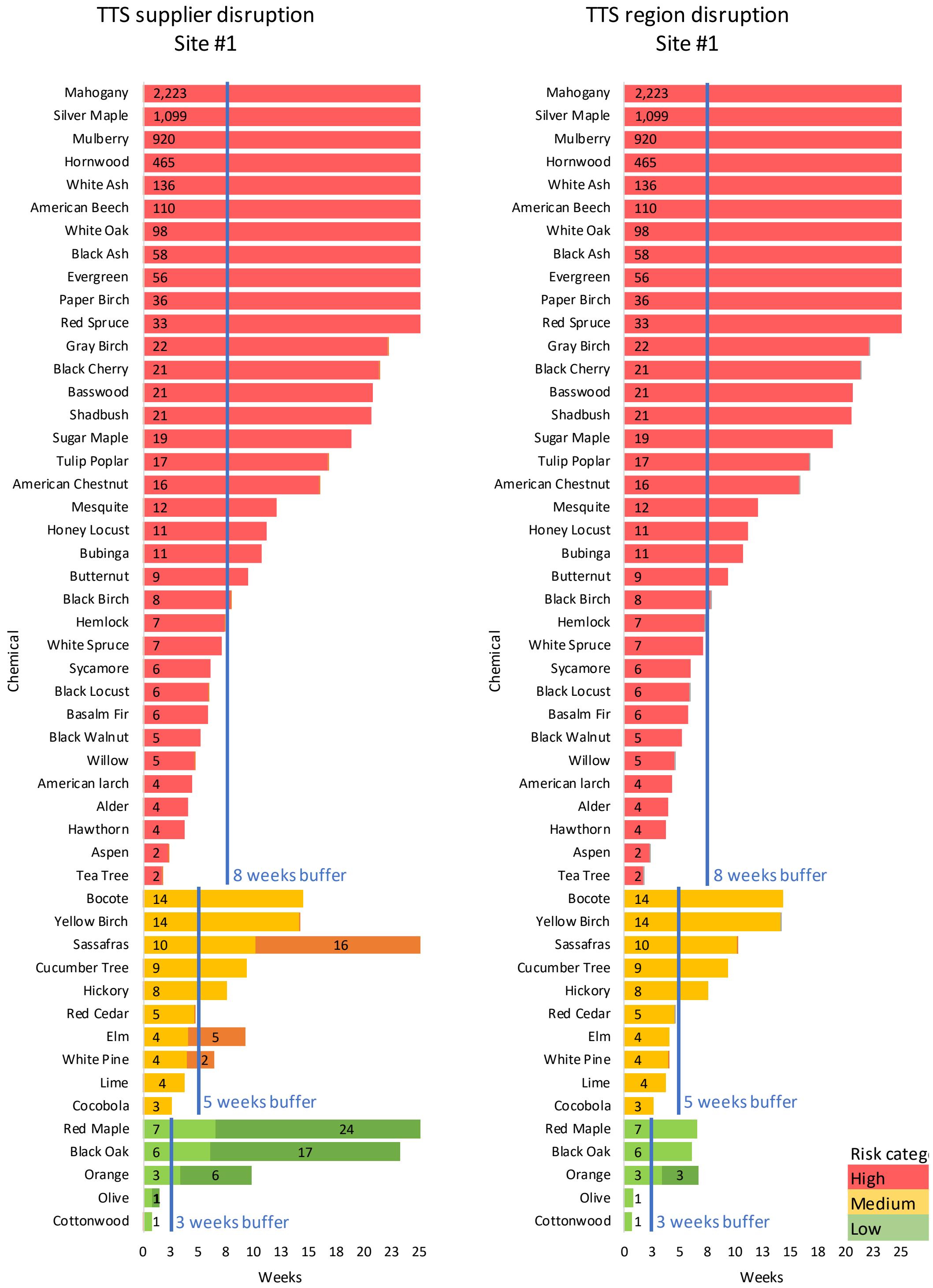


Site #2	Current Strategy				Optimal Cost Strategy			
	W/o Stretch		Stretch		W/o Stretch		Stretch	
Region	Min TTS	Chemical	Min TTS	Chemical	Min TTS	Chemical	Min TTS	Chemical
Texas	2.7	Olive	3.1	Olive	1.6	Olive	1.6	Olive
Korea	6	Red Maple	13.2	Sassafras	9.5	Sassafras	9.5	Sassafras
China	5	Red Maple	7.1	Lime	5.5	Orange	5.5	Orange
Louisiana	5.3	Elm	5.3	Elm	5.3	Elm	5.3	Elm
Eastern Europe	9.6	Olive	400.1	Olive	Surplus	-	Surplus	-
West Virginia	9.6	American Larch	9.6	American Larch	9.6	American Larch	9.6	American Larch
North East US	7.8	Willow	7.8	Willow	7.8	Willow	7.8	Willow
Western Europe	13.9	Cocobola	13.9	Cocobola	13.9	Cocobola	13.9	Cocobola
Great Lakes	22.1	Butternut	22.1	Butternut	22.1	Butternut	22.1	Butternut
East Coast US	3.2	Hickory	3.2	Hickory	3.2	Hickory	3.2	Hickory
Taiwan	Surplus	-	Surplus	-	Surplus	-	Surplus	-

Note: “Stretch” means to stretch all the other suppliers who provide chemical by an additional 20%

Figure 13:

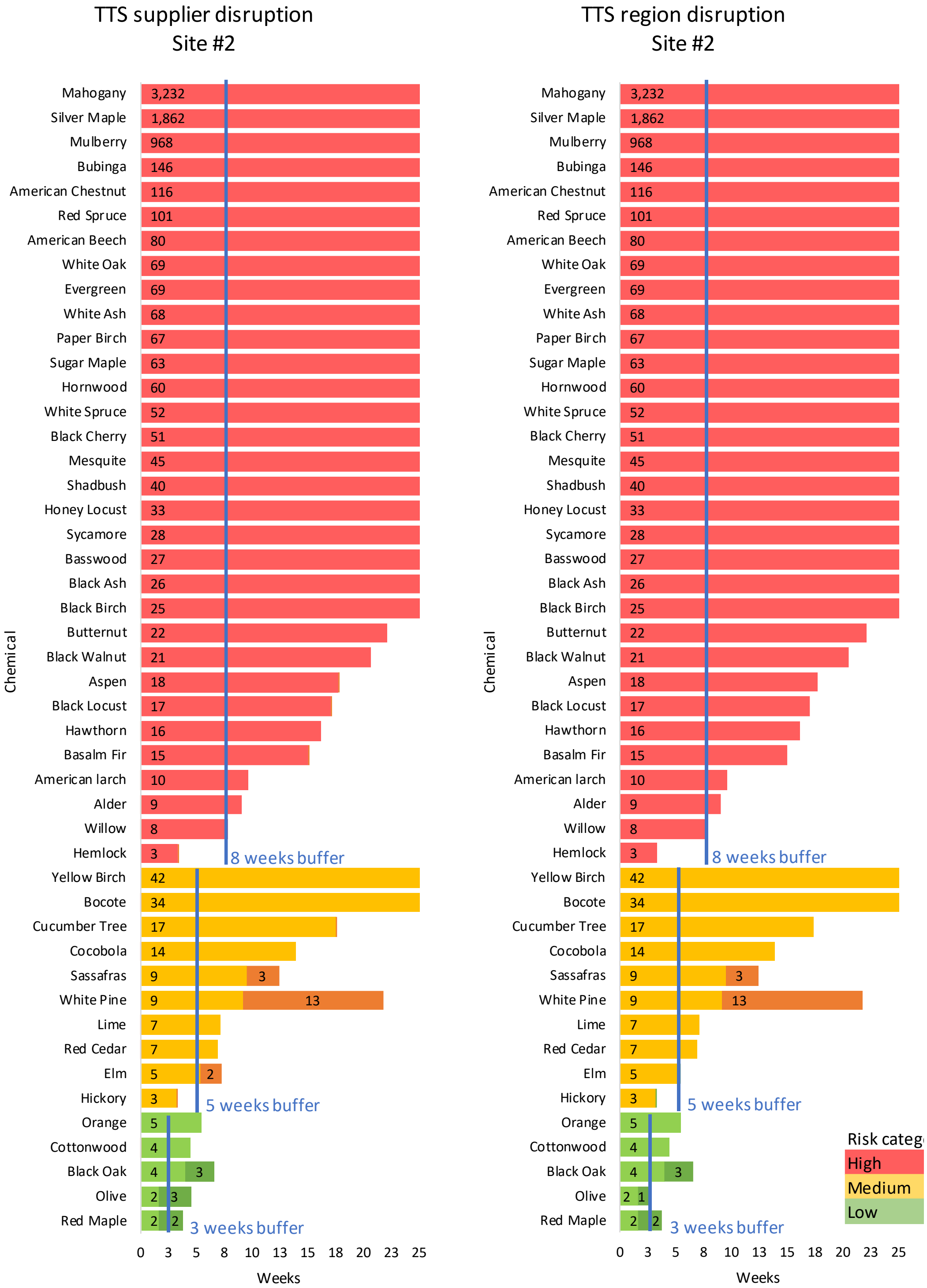
TTS under supplier and region disruption for Site #1



Note: The darker color appending on the bar represents additional TTS from remaining supply after a disruption of supplier or region

Figure 14:

TTS under supplier and region disruption for Site #2



Note: The darker color appending on the bar reflects the effect of TTS after turning off nodes (Supplier/ Region)

4.7 TTS result with optimized procurement strategy

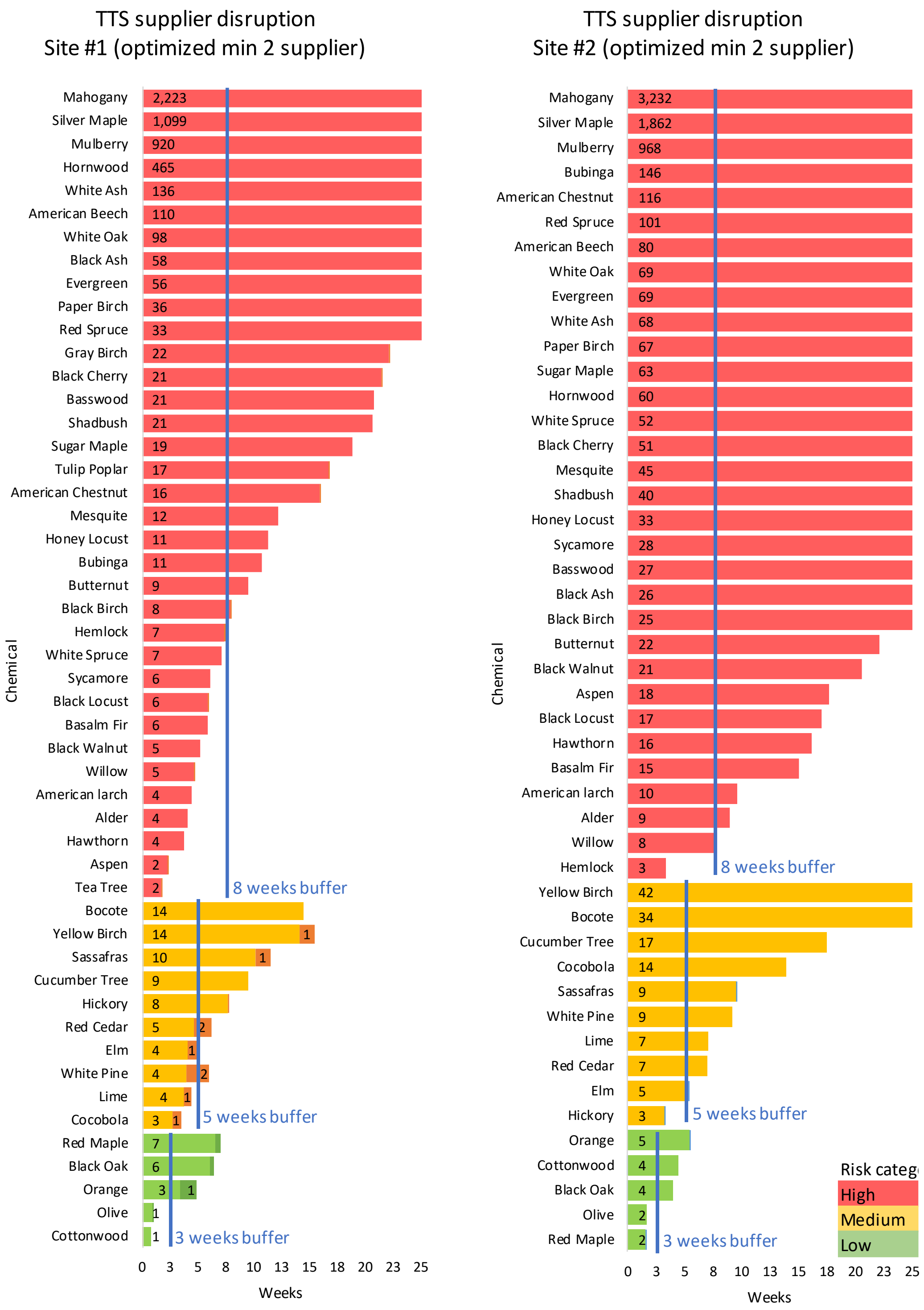
This strategy is the best option in terms of balancing cost savings and benefiting from dual sourcing (both supplier and regional level). In Figure 10, we can see that choosing optimal strategy of limiting at least two suppliers and two regions to procurement for each chemical can save Tempur Sealy around 10 points of cost with the same volume. Currently, even though the company added suppliers over the years, the actual number of active suppliers for 2023 is lower than the count shown in Figure 7. At the same time, multi-sourcing is mostly pursued at low and mid-risk chemicals. The only multi-sourced high-risk chemical is Hawthorn.

However, the second supplier of Hawthorn actually accounts for only less than 10 percent of Tempur Sealy's demand and thus has limited risk mitigation effect. In the 2023 procurement plan, Hawthorn is again single sourced from Beaver. To mitigate the risk, we recommend dual source Hawthorn, ideally with an even split.

Since most of the benefits from multi-sourcing accrue to chemicals that are already above or near buffer stock levels (Figure 13 and Figure 14), we argued that the cost-optimized procurement has little negative impact on the risk-mitigation of the company. The scenario with at least two suppliers (if available), maintains the small risk mitigation advantage while allowing for large savings. We illustrate the scenario in Figure 15, which shows small improvement of TTS maintained for Site #1. Site #2 has no additional TTS (dark bars) but is already meeting buffer levels much better compared to Site #1. The only exception could be Olive, where keeping multiple suppliers and stretching them allows us to reach the buffer level.

Figure 15:

TTS with supplier disruption and optimized 2 supplier procurement



4.8 Identification of opportunities

In this research, we identified a few areas that represent improvement opportunities to review. First, we suggest reviewing whether a re-allocation of storage capacities is possible for the chemicals which have an excessively high inventory level and for chemicals which have an insufficient inventory level. Secondly, we recommend continuing to mitigate the risk of ownership pull-back effect. By transferring the chemicals to Tempur Sealy's own facilities, containers and transloaders, Tempur Sealy currently alleviates the risk of suppliers calling force majeure for chemicals already on the way. However, it's important to regularly review the cost and the effect of this strategy, to ensure that it remains the most cost-effective and efficient approach to mitigate this risk. Additionally, we recommend Tempur Sealy to keep focusing on its supplier diversification efforts, especially for high-risk chemicals. Finally, we covered the analysis at plant level to discuss inventory level and supplier selection. As a future work, the analysis could be expanded to analyze how to optimize inventory further if the chemicals / suppliers supplying certain sites could be used across different sites to further increase resilience. For example, if the surplus chemical of Site #1 can be transported to Site #2, then Site #2 could store less inventory. Considering the storage capacity and transportation cost, the possible optimal solution could lead to an even lower total cost.

We recommend Tempur Sealy to keep leveraging the tool we built to review the company's procurement costs and its effect on resiliency. The TTS calculation tool enables the company to monitor the inventory capacity allocation between chemicals on a regular basis and the optimization model, can be used on an annual basis to plan a cost optimal allocation of purchasing volumes among suppliers. By using these two tools together, the company can ensure that the cost optimal result does not lead to a decline in risk mitigation. This approach enhances supply chain resilience and helps achieve cost savings.

5. CONCLUSION

In conclusion, we found the TTS method is a highly valuable tool for companies to evaluate their resiliency when facing supply chain disruptions. Based on our analysis, the company has done an excellent job in increasing its resiliency in recent years, with only a modest increase in procurement cost. The good data quality and mitigation measures in place provide a solid foundation for Tempur Sealy to evaluate the past work and continue with future improvements. Additionally, by incorporating additional constraints into the cost optimization, the company may discover alternative strategies that balance cost and resiliency. We recommend conducting the analysis regularly to review and evaluate the impact and tradeoff of risk mitigation efforts.

We believe the approaches and tools developed in this capstone project are also generalizable to other companies and industries. The cost optimization can be used to find the optimal procurement strategy which can be compared to the current spending to find the additional spending which might be related to risk mitigation efforts. TTS can be used to measure resiliency under both current and optimized scenarios. Finally, the combination of cost optimization and TTS measurement allows for a way to quantify the cost of current resiliency measures of businesses. We think the tools provide valuable information since the justification of risk mitigation spending can be exceedingly difficult because when properly executed, the disruptions never take place and only the cost remains to be seen and not the actual benefits.

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