Improving Supply Chain Resilience through a Portfolio Approach to Multi-source Supplier Selection

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ABSTRACT

Recent disruptions to global supply chains have underscored the importance of supply chain resilience, prompting firms to increasingly adopt multi-sourcing strategies. The supplier selection process is key to ensuring secondary suppliers enhance supply chain resilience, yet most literature focuses on individual supplier resilience in isolation. This risks multi-sourcing from suppliers that are exposed to the same exogenous threats—such as being in the same city (natural disasters) or country (trade or currency risks). This paper explores a portfolio-based approach to supplier selection—identifying an optimal mix of suppliers for a material to minimise overall risk. A resilience hedging score was developed to quantify and compare the risk hedging provided by potential secondary suppliers. The resilience hedging score is an extension of Gower's Distance and utilises pairwise comparison of categorical and numerical supplier risk attributes, as well as a weighted consideration of geographic distance between suppliers. For our sponsor company, the resilience hedging score proved effective at recommending secondary suppliers with very dissimilar risk profiles to the primary supplier. It is relatively simple to deploy in a business, scalable, and easily explainable, potentially allowing firms to quickly implement resilient multi-sourcing strategies.

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1. INTRODUCTION

In recent years several high-profile global events have highlighted the value of supply chain resilience, or in some cases, the surprising costs firms can incur when their supply chains lack resilience. For example:

- Government responses to a viral pandemic in the form of intermittent factory and port closures during the Covid-19 lockdowns of 2020–2021, which caused considerable disruptions to both demand and supply of materials and finished goods globally (Xu et al., 2020).
- The temporary closure in March 2021 of the Suez Canal, a major global shipping route, due to the container ship *Ever Given* running aground and blocking traffic in both directions. The canal carries approximately 12% of global trade by volume (The Economist, 2021).
- Disruptions to exports from Ukraine, one of the world's major agricultural producers, due to deliberate targeting of export infrastructure by the Russian military during Russia's ongoing full-scale invasion. This severely impacted Ukraine's ability to export grain for many months, which had a significant impact on supply of grains and food oils to the global market (Breslin, 2023).
- Deliberate disruptions to shipping in the Straits of Hormuz beginning in 2023 due to Houthi militia attacking merchant vessels. Several merchant vessels have been seized or destroyed and others attacked with anti-ship missiles and drones. This has discouraged shipping from using the Suez Canal route and rerouted ships via the Horn of Africa, adding 10 days shipping time to typical Europe-Asia voyages.

These examples differ in geography, in root cause, and in the type of disruption – or mode of failure – they caused. However, what they have in common is that they were all unexpected events, they all caused major disruptions to supply chains around the world, and they all left companies and governments searching for ways to improve supply chain resilience.

1.1. Motivation

CGCo, a large consumer packaged goods (CPG) manufacturer and distributor, was also impacted by the supply chain disruptions caused by these events. Like many companies, prior to 2020 they had a supply chain relying primarily on single sourcing of materials. Each of 12,000 materials were supplied by only one of their 1,000 suppliers. This single source strategy minimised the number of suppliers, thereby simplifying supplier management. However, more recently, trade-offs inherent in this strategy have become apparent:

- Ongoing global supply chain disruptions of the past four years have highlighted that some suppliers of materials have become increasingly unreliable and unable to meet commitments.

- Increasing variability of demand has also highlighted that suppliers often lack the capacity to surge production to meet peak demand, causing stockouts and impacting CGCo's revenue and their reputation as a reliable partner for retailers.

With that in mind, CGCo has embarked on a program to move from a mainly single-source strategy to one of multi-source supply of materials – primarily chemicals, packaging, and electronic components – with the aim of improving supply chain resilience. However, several factors complicate the implementation of this strategy. First, not all materials can be multi-sourced immediately due to some having long-term minimum-spend contracts which expire sequentially over the next 2–3 years, necessitating a sequenced approach. Second, CGCo has three major product lines, each requiring a very different mix of materials and sourcing considerations. Third, the scope of the project is significant, with approximately 12,000 materials, 79% of which are still single-sourced.

CGCo is motivated to explore novel uses of algorithms or other methods to develop an optimal sequence of transitioning several thousand materials to a multi-sourced supply approach, at scale, and as rapidly as possible. In developing this strategy, they have also considered what other opportunities might be unlocked through a multi-source approach. Recent experience has highlighted that a multi-source approach may provide buyers with greater leverage, allowing for cost savings as well as the potential to improve resilience.

They also believe that, once multi-sourcing is in place for a category, there may be an opportunity to use technology to speed up buyers' purchasing decisions to take advantage of opportunities as they present – a dynamic sourcing approach. Thus, CGCo would also like to explore the use of technology to assist buyers in making rapid dynamic sourcing decisions that take advantage of a multi-sourced supply base and deliver further cost savings. Though this was not part of the scope, we conducted some preliminary research and discuss recommendations in Section 5.3.

1.2. Risk, modes of failure, and resilience – what is CGCo trying to be resilient against?

It is worth distinguishing between risk and resilience, terms which are often but incorrectly used interchangeably when discussing supply chain strategy or performance.

In a supply chain context, a risk is a future event that could disrupt the supply chain; if a supply chain is viewed as a system, then the disruption would cause a "mode of failure" of the system. For example, labour strikes or a shipping accident are both risks that could close a port and delay container shipments. Though both risks are different, the resulting impact on supply chains – delays to container shipments – would be the same. The result of both would be to cause the same "mode of failure" in the form of a loss of supply for companies relying on container shipments through that port.

Resilience is the "ability to bounce back from a disruption" (Sheffi & Rice, 2005). The specific cause of disruption is less important in this context; what is important is the type of mode of failure that the supply chain experiences, and whether the supply chain can bounce back from that mode of failure. Continuing the example of port closures and "loss of supply," a company could choose from a variety of measures to build resilience against a loss of supply due to port closure, one of which would be having secondary suppliers that are able to deliver by road transport.

CGCo is primarily interested in being resilient to a loss of supply of materials. They have realised that a supply chain relying mostly on single sources of supply leaves them exposed to the many sources of risk that each supplier is exposed to.

1.3. Problem statement

CGCo company established a product supply transformation team in early 2024 to improve supply chain resilience and deliver cost savings over 26 months, with an initial focus on one business unit selected to pilot the transformation initiatives. Our particular project is one of the projects contributing to this goal for the pilot business unit (PBU).

The first part of the problem is transitioning from single sourcing to multi-sourcing. For now, only 21% of materials are multi-sourced. The objective is to reach 70% to improve resilience while also delivering cost savings. The PBU product lines use approximately 12,000 materials from ~1,000 suppliers. The 1,000 suppliers are split into three categories of material: chemicals, packaging, and electronics. Each product category has challenges regarding resilience. For chemicals the qualification of a new supplier is time-consuming because of the many and stringent health regulations that apply to CGCo's products. In contrast, the qualification of cardboard and plastic packaging suppliers is straightforward, but quality can be difficult to guarantee because of a lack of quality control at the supplier's production centres. Finally, CGCo found that the supply of electronic parts needed for electric devices is highly consolidated, meaning that there is often only one suitable supplier, limiting multi-sourcing opportunities.

In that context, the question that arises is:

- How do we design a multi-sourcing algorithm for recommending secondary suppliers for each material?

1.4. Project goals and expected outcomes

Considering our primary focus on multi-sourcing, we anticipate our project may result in a multi-sourcing algorithm to recommend secondary suppliers for each material that is currently single-sourced. This tool may improve the purchasing team's daily decision-making about the sourcing process.

When considering our approach to developing a multi-sourcing algorithm, we noted that CGCo already considers the risk and resilience of potential suppliers during their supplier selection process, primarily relying on the Dun & Bradstreet Supplier Evaluation Risk (SER) score. These scores consider the intrinsic risks inherent in each supplier. Rather than replace these scores, we provide a complementary perspective on supplier selection that may help CGCo improve the resilience of their multi-sourced suppliers.

We therefore chose to help CGCo develop a portfolio of suppliers for each material that together provide resilient supply. Under this approach, our multi-sourcing algorithm is intended to consider exogenous risks that each primary supplier is exposed to and propose a resilience hedging score (RHS). This could allow quantitative comparisons between suppliers and recommend secondary suppliers that achieve improved "hedging" against exogenous risks.

2. STATE OF THE PRACTICE – MULTI-SOURCING

CGCo is pursuing a multi-sourcing strategy to improve supply chain resilience (SCR). Under this strategy, if there is a disruption of supply from a primary supplier, then pre-existing relationships with secondary suppliers will be used to replace the volume. The effect for the business will be to eliminate or at least minimise disruption to production. Critical to this strategy is the supplier-selection process for the secondary supplier so that the secondary supplier is not exposed to the same disruption risks as the primary supplier.

Our literature review therefore focused on the following:

2.1 Supplier selection to improve SCR, in the context of a multi-sourcing strategy

2.2 Supplier selection to improve SCR, with general applicability

2.1. Supplier selection to improve SCR in the context of a multi-sourcing strategy

Supplier selection in this context is relatively unexplored in the literature. Our review examined 22 studies in detail (see Table 1) that explored the use of Multi-Criteria Decision-Making (MCDM) to assist supplier selection, from a total of 50 studies reviewed. Only five studies explored techniques for supplier selection specifically as part of a multi-sourcing strategy.

Sawik (2015) explored the performance of single- and multi-sourced supply chains by using simulations and modelling the effects of disruptions to suppliers caused by local, regional, and global events. Local disruptions were defined as impacting individual suppliers, regional disruptions as impacting several suppliers, and global disruptions as impacting all suppliers. Multi-sourcing was found to be effective at reducing the impact of local disruptions. It was also found to be effective at reducing the impact of

regional disruptions, particularly where the secondary supplier was in a different region than that affected by the disruption.

Table 1

Review of studies exploring supplier selection methods to improve supply chain resilience

Study	Supply Chain Objectives	Multi-Criteria Decision-Making Methods	Industry or Type of Example
Supplier selection specifically in the context of multi-sourcing			
Sawik (2013)	Resilience	MILP	Illustrative example
Wang et al. (2023)	Resilience	MILP-LHS-SAA-SR	Manufacturing
Sawik (2015)	Resilience	Stochastic MIP	Illustrative example
Torabi et al. (2015)	Resilience	Stochastic programming, two-stage	Illustrative example
Namdar et al. (2017)	Resilience	Stochastic programming, two-stage	Illustrative example
Supplier selection with general applicability			
Piprani et al. (2020)	Resilience	AHP	Textiles
Hosseini & Barker (2016)	Resilience, Green	Bayesian network model	Automotive
Mohammed et al. (2021)	Resilience	DEMATEL-OCRA-TOPSISVIKOR	Steel
Amindoust (2018)	Resilience, Green	FIS-DEA	Alloy
Mari et al. (2019)	Resilience	Fuzzy Werner's fuzzy and operator	Garments
Pramanik et al. (2020)	Resilience, Green	Fuzzy AHP-ARAS	Automotive
PrasannaVenkatesan and Goh (2016)	Resilience	Fuzzy AHP-PROMETHEE	Numerical experimentation
Haldar et al. (2013)	Resilience	Fuzzy AHP-QFD	Hypothetical case
Kaur & Singh (2021)	Resilience	Fuzzy AHP-TOPSIS–DEA	Automotive
Pramanik et al. (2015)	Resilience	Fuzzy AHP-TOPSIS–QFD	General manufacturing
Xiong et al. (2020)	Resilience, Green	Fuzzy BWM-WASPAS-TOPSIS	Illustrative example
Hasan et al. (2020)	Resilience	Fuzzy DSS-MCGP	Logistics
Kayani et al. (2023)	Resilience, Green	Fuzzy MOMINLP	Pharmaceuticals
Sahu et al. (2016)	Resilience	Fuzzy VIKOR	Empirical example
Leong et al. (2022)	Resilience	GRA-BWM-TOPSIS	Food manufacturing
Parkouhi et al. (2019)	Resilience	Grey DEMATEL-SAW	Wood and paper
Mohammed et al. (2020)	Resilience, Green	Grey DEMATEL-VIKOR	Chemical manufacturing

Namdar et al. (2017) also highlighted multi-sourcing as being effective at managing risk, particularly high-impact, low-frequency (HILF) disruptions. Additionally, they found that as the likelihood of supply chain disruption increases, the attractiveness of multi-sourcing increases compared to single sourcing, as the benefits of resilience offset the increased costs of managing multiple suppliers. This finding was echoed by Torabi et al. (2015), who explored the use of backup suppliers as one of several resilience strategies. Wang et al. (2023) also found multi-sourcing to be an effective part of a resilience strategy, including other measures such as proactive management of inventory and planning of alternative DC (Distribution Centre) locations, though the use case they explored for multi-sourcing was reactive – seeking alternative suppliers after a disruption had already occurred.

While the five studies examining supplier selection specifically in the context of multi-sourcing highlighted the benefits of a multi-sourcing strategy, there are some limitations in their application to CGCo's problem. In most of these studies, multi-source supplier selection was considered as one of several strategies explored and was therefore not given explicit focus. Torabi (2015) and Wang et al. (2023) explored multi-sourcing as part of a set of strategies. Sawik (2015) and Namdar et al. (2017) focused on testing the effectiveness of multi-sourcing, rather than more deeply exploring supplier selection.

Sawik (2013) was the only study identified that treated supplier selection as a portfolio problem: exploring the resilience provided by a specific combination of suppliers, rather than the resilience of an individual supplier. Considering supplier selection as a portfolio problem appears to be underexplored, and this paper seeks to contribute to that area.

2.2. Supplier selection to improve SCR under other strategies

Our literature review found that most studies that explored supplier selection to improve supply chain resilience focused on the general concepts of selecting an individual supplier, rather than more specifically within the context of a multi-sourcing strategy. Reviewing this area of the literature was still useful in understanding the applications of different methods to supplier selection.

Resilient supplier selection often entails trade-offs of quantifiable measures such as cost and lead time against less quantifiable measures of resilience, and is often treated as a multi-criteria decision-making (MCDM) problem. Most studies used one or more MCDM methods to aid supplier selection (Table 1).

Fuzzy-based MCDM methods were the most common in our review. Of 22 studies reviewed in depth, 10 used fuzzy logic, a method that enables decision making and optimisation where "goals and/or constraints" are imprecise or "fuzzy in nature" (Bellman & Zadeh, 1970) as the basis for the methodology. Within this group, fuzzy Analytical Hierarchy Process (AHP) was the most common combination used for quantitative supplier assessment. It builds upon Saaty's AHP method (Saaty, 1980), which helps elicit the priority of different criteria from decision makers through the use of pairwise comparison and allows

priorities to be elicited in linguistic form – e.g. “more important,” “about the same,” or “far less important.” This approach is often practical where the measurement and comparison of criteria are not precise. Because of its usefulness in this context, fuzzy AHP has been widely used in supplier selection since at least 2006, when it was explored to assist in reviewing green/environmental considerations (Haldar et al., 2012). One of the first examples of fuzzy AHP application for resilient supplier selection is provided by Haldar et al. (2012), where fuzzy AHP was used in combination with Quality Function Deployment (QFD). Since then, fuzzy AHP has been paired with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to combine the advantages of TOPSIS (flexibility, scalability) with those of fuzzy AHP. Others also explored the use of fuzzy combined with other MCDM models, such as VIKOR (Sahu et al., 2016), the creation of a fuzzy Decision Support System (DSS) using Multi-Choice Goal Programming (MCGP), or fuzzy multi-objective mixed integer nonlinear programming (MOMIINLP) (Kayani et al., 2023).

Fuzzy MCDM is not ideal when information is incomplete. This can be a practical limitation, particularly when assessing potential new suppliers where information in the early stages of discussion is unknown and potentially time-consuming to collect. Several studies instead used Grey Decision Making as the basis for supplier selection models given its utility in evaluating and ranking alternatives under uncertainty (Deng, 1982). Grey Decision-Making Trial and Evaluation Laboratory (DEMATEL) was used in combination with Grey Simple Additive Weighting technique (Parkouhi et al., 2019), and in combination with VIKOR (Mohammed et al., 2020). Leong et al. (2022) used Grey Relational Analysis (GRA) combined with Best-Worst Method (BWM) and TOPSIS to assist in resilient supplier selection to allow for a wide range of resilience criteria to be incorporated into decision making.

Though the papers and methods in section 2.2 relate to resilient supplier selection in general, rather than considering a multi-source approach, reviewing this area of the literature was still informative to understand the wider variety of different methods to supplier selection methods.

3. METHODOLOGY

This methodology chapter presents the development of our multi-sourcing recommendation model, which is designed to help CGCo identify secondary suppliers that can enhance supply chain resilience. For our analysis and multi-sourcing model, we focused on one of the three material categories procured by the pilot business unit: packaging, chemicals and electronics. We selected chemicals because products made from those materials represent most of the pilot business unit’s revenue. Additionally, the supplier qualification process for chemicals is lengthy (9-10 months). Our model is intended to facilitate supplier qualification decisions by recommending suppliers with the greatest potential to improve resilience. This enables buyers to evaluate their potential impact before investing in the lengthy qualification process.

Central to our approach is the creation of a resilience hedging score, which measures each supplier's potential to mitigate the selected risks faced by the pilot business unit. This score enables buyers to prioritise which suppliers to qualify.

This chapter includes five main sections:

3.1. Selection of Exogenous Risks to be Hedged Against

3.2. Data Collection

3.3. Data Preparation

3.4. Selection of a Dissimilarity Scoring Method

3.5. Scoring Potential Secondary Suppliers and Filtering Recommendations

3.1. Selection of exogenous risks to be hedged against

Before developing a resilience hedging score, we first examined the Dun & Bradstreet Supplier Evaluation Risk (SER) assessment scores used by CGCo. We found that the SER almost exclusively assesses factors that are intrinsic to each supplier, such as liquidity ratio or past-due payments. To complement this, we developed a resilience hedging score focused on supplier attributes that can be used to indicate exposure to external risks, which we captured in the Exogenous Risk Matrix (Table 2). The resilience hedging score would be calculated through pairwise comparison of the primary and potential secondary supplier attributes defined in Table 2.

Table 2

Exogenous Risk Matrix

Risks external to the supplier (exogenous risks)

Supplier attributes	Factor	Natural disaster	Trade disputes	Armed conflict	Workforce strike	Corporate collapse	Financial collapse
Geography & politics	City	×					
	State/province	×					
	Country	×	×	×			
	Region	×					
Logistics	Logistics mode			×			
	Outbound port	×	×		×		
	Inbound port	×	×		×		
Organisation	Vendor name					×	
	Parent company name					×	×
Financial	Currency		×				×
	Bank, primary						×
Labour	Labour union				×		

The matrix captures 12 attributes are used as proxies for exposure to exogenous risks. In developing this list, we considered some of the likely causes of failure based on reporting and research (Arntzen, 2021).

3.2. Data collection

The development and practical application of the resilience hedging score relied primarily on data obtained from the procurement module of CGCo's enterprise resource planning (ERP) system. This data represents the base of our multi-sourcing model and consists of data pertaining to suppliers and third-party manufacturers, as well as data pertaining to CGCo's own manufacturing plants.

From CGCo's ERP system we received data for suppliers, manufacturers and plants participating in the pilot business unit's supply chain. Additionally, we obtained the unique identifier code for each supplier/manufacturer's bank. Sensitive account information was not sourced, only unique codes such as the SWIFT code which can be used to identify individual banks. The raw data consisted of four main files:

- Parent Company (parent entity of suppliers and/or manufacturers)
- Plant_Locations (plant_ID, plant_name, latitude, longitude)
- Suppliers (supplier_ID, supplier_name, parent_company, latitutde, longitude, financial_institution)
- Manufacturers (man_ID, man_name, parent_company, latitude, longitude)

3.3. Data preparation

To create a homogeneous database for our model we conducted data cleaning and data aggregation analysis. First, we analysed data relating to the parent entity of the suppliers and/or manufacturers. Out of a total of 324, we identified a total of 86 duplicate entities (a single parent entity incorrectly captured twice in the ERP, with different parent company IDs) and 21 parent companies without an ID number. The consolidation of duplicates reduced the quantity of unique parent companies from 324 to 217. One parent entity can have multiple suppliers and manufacturers spread around one or more regions.

Further, we aggregated the data of the 223 suppliers and 261 manufacturers to analyse them as unique active vendors. There as well we identified many duplicates, often the same supplier with multiple supplier ID numbers in the ERP. After removing duplicates, 367 unique vendors remained, 150 of which were inactive vendors that CGCo no longer procured from. After removing these, we obtained a total of 217 active unique vendors.

3.4. Selection of a dissimilarity scoring method

We searched for methods used in other fields that are effective at measuring dissimilarity among mixed data sets. We shortlisted both Gower's Distance (Gower, 1971) and Heterogeneous Euclidian-Overlap Metric (HEOM) (Wilson & Martinez, 1997). Both methods compare the differences in attributes in the same way but differ in how they present an overall final aggregation of differences. We chose to use

Gower's Distance as the basis for our resilience hedging score, as the final aggregation is simpler than HEOM, though both methods have equal validity in this application.

Neither method specifically considers geographic distance during comparison, so we developed an extension to Gower's Distance to incorporate geographical separation of suppliers. This allows further differentiation of suppliers in cases where potential secondary suppliers are very similar to the incumbent supplier.

Existing comparison methods treat incomplete data in different ways, often allowing pairwise comparisons involving incomplete data to contribute to the resilience hedging score. When analysing CGCo's data on existing suppliers, we found that there often were gaps in information even for existing suppliers. Additionally, we considered use cases where our algorithm would be used to assess potential new suppliers whose information was likely to be incomplete. This shaped our selection of dissimilarity scoring methods with a preference for using a method that excluded incomplete pairwise comparisons from contributing to the resilience hedging score. For example, if Supplier A uses Bank X, and Supplier B's bank is unknown, then this comparison would be excluded from the resilience hedging score, effectively contributing zero to the score.

It was important for our method to compare differences in categorical (nominal) attributes of incumbent and potential secondary suppliers. The majority of supplier attributes were categorical attributes, such as location data (country, state, city), financial information (primary bank), and logistics information (outbound port, inbound port).

When calculating the differences in categorical attributes, we used the following formula from Gower's Distance:

$$s_{ijk} = \begin{cases} 1 \text{ if } x_{ik} = x_{jk} \\ 0 \text{ if } x_{ik} \neq x_{jk} \end{cases}$$

where S_{ijk} is the similarity score (0 or 1) between categorical attribute k for suppliers x_i and x_j.

Though our selection of supplier attributes (Table 2) did not include numerical attributes, we considered it important to include in the model the capability to do so, so that numerical supplier attributes can be compared in future applications. To calculate the differences in numerical data, we made available in the model the following formula from Gower's Distance:

$$s_{ijk} = 1 - \frac{|x_{ik} - x_{jk}|}{R_k}$$

where S_{ijk} is the normalised numerical distance between numerical attribute k for supplier x_i and x_j, and where R_k is the range of attribute k across all suppliers, calculated as $R_k = \max(x_k) - \min(x_k)$.

Gower's Distance calculates an overall dissimilarity score as follows:

$$S_{ij} = \frac{\sum_{k=1}^{N} (s_{ijk} \cdot \delta_{ijk})}{\sum_{k=1}^{N} \delta_{ijk}}.$$

As an extension to Gower's Distance, we also incorporated geographic distance between pairs of suppliers. When calculating geographic distance between two points on a globe, the haversine formula is commonly used (Mahmoud & Akkari, 2016). The haversine formula can be inaccurate over long distances (>1,000km) due to the assumption that Earth is spherical, when in fact it has an equatorial bulge. Given that the purpose of our analysis is supplier comparison, rather than one where a precise distance is required, haversine is an adequate method for calculating geographic distance between pairs of suppliers. We used the formula as follows:

$$d = 2rsin^{-1}\left(\sqrt{sin^2\left(\frac{\Phi_2 - \Phi_1}{2}\right)} + cos(\Phi_1)\, cos\,(\Phi_2) sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)\right)$$

To combine the Gower's distance and geographical distance measures into a single score, we used:

$$D_{ij} = S_{ij}(1 - w) + d_{ij} \cdot w$$

where D_{ij} is the final dissimilarity between supplier i and j, S_{ij} is the Gower's Distance score between supplier i and j, d_{ij} is the geographic (haversine) distance between supplier i and j, and w is the weight given to the geographic distance ($0 \leq w \leq 1$).

3.5. Scoring potential secondary suppliers and filtering recommendations

We used Python to score and rank potential secondary suppliers, based on the degree of dissimilarity when compared to the primary supplier for each material. Our algorithm was built and tested with CGCo's data.

To ensure the maximum practical use of the resilience hedging score (RHS) recommendations, we built a selection of Microsoft PowerBI dashboards. These took the tables outputted by the Python model and presented them in a user interface for buyers that enabled them to answer practical questions such as:

- For a given material, what are the top five recommended secondary suppliers, based on their RHS? What are the attributes of the proposed secondary suppliers compared to the primary supplier?
- For a proposed secondary supplier, for what materials are they the ideal secondary supplier, based on their RHS?

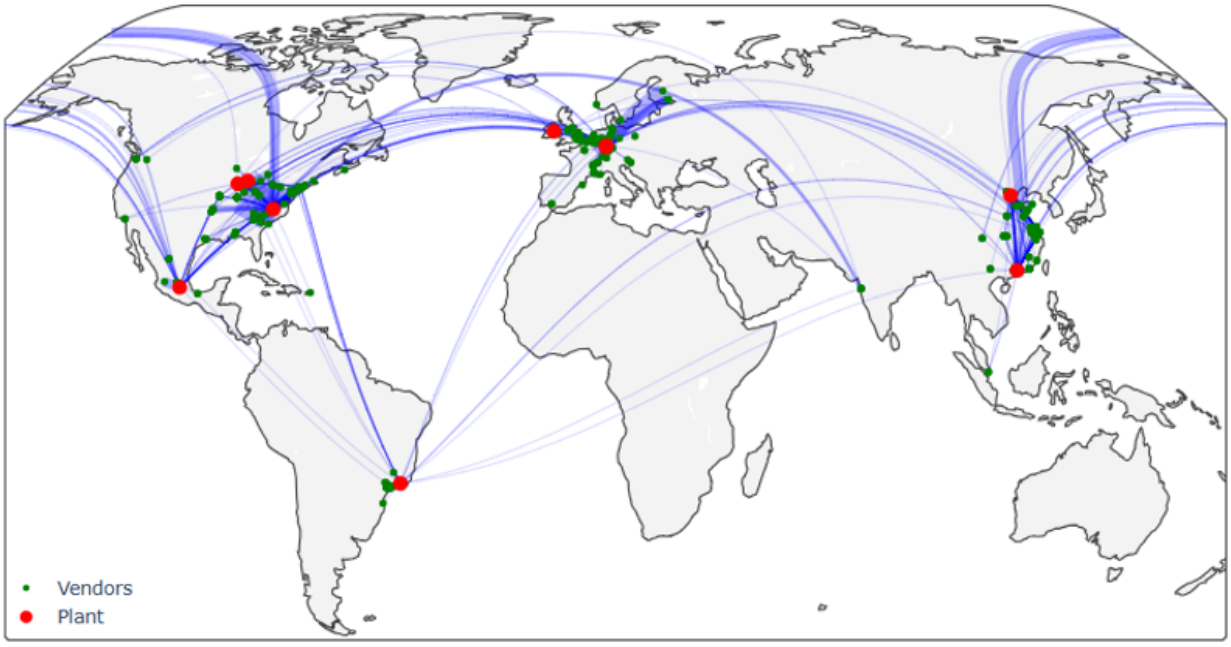
4. RESULTS AND DISCUSSION

This chapter presents the results and discussion from our data analysis and model. Section 4.1 refers to the primary findings we encountered through the data analysis and the initial sources of risk that were identified. Next, we discuss the analysis of the initial 20% of multi-sourced materials, the split between each of CGCo's 10 plants, and the risk exposure of the existing multi-sourcing. Then, we explain the results of the recommendation model, detailing the next steps and priorities of the multi-sourcing initiative. The chapter concludes with the limitations encountered in this research, mostly regarding data improvement and time limits that arose with the project.

To visualise the current flows from the vendors to the different plants around the world, we established a flow map (Figure 1), where the flow represents the spend on each vendor in USD per plant.

Figure 1

Map of flows between vendors and plants

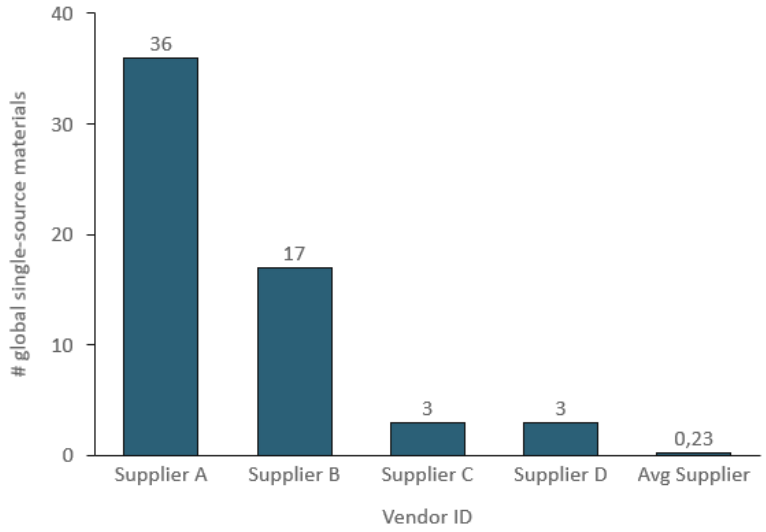


4.1. Results

During the data preparation process, two unexpected insights were uncovered. While cleaning the data to consolidate duplicate vendors, we discovered several unique vendors that were the global single-source vendor for specific materials. This was not previously obvious due to some vendors being listed with different vendor ID numbers. One unique vendor was identified as the global single-source supplier of 36 different materials (see Figure 2), representing a very high risk in the sourcing process in case of disruption for this supplier. Three other suppliers were identified as high-risk suppliers in this analysis. The average vendor, meanwhile, supplies only 0.23 single-source unique materials.

Figure 2

Global single point of failure suppliers (top 4): number of materials sourced from each supplier that have no global second source



The second vendor risk we identified is the number of plants supplied by a unique vendor, with some vendors supplying as many as eight out of CGCo's 10 manufacturing plants. A disruption to a vendor supplying eight of the pilot business unit (PBU) plants would impact CGCo's overall sourcing process. Table 3 presents the top 16 suppliers that supply six or more plants and which plants they supply. These suppliers are also considered high-risk because of a potential disruption's impact on the overall sourcing of this PBU.

Table 3

Highly connected vendors: Vendors supplying multiple plants

Vendor_id	Plant A	Plant B	Plant C	Plant D	Plant E	Plant F	Plant G	Plant H	Plant I	Plant J	Total Plants Supplied
A	1	1	0	1	1	1	1	1	1	0	8
B	1	1	0	1	1	1	0	1	1	0	7
C	1	1	0	1	1	1	0	1	1	0	7
D	1	1	0	1	1	1	0	1	1	0	7
E	1	1	0	1	1	1	0	1	1	0	7
F	1	1	0	1	1	1	0	1	1	0	7
G	1	1	0	1	1	1	0	1	1	0	7
H	1	1	0	1	1	1	0	1	1	0	7
I	1	0	0	1	0	1	1	0	1	1	6
J	1	1	0	1	0	0	1	0	1	1	6
K	1	1	0	1	1	1	0	0	1	0	6
L	1	1	0	1	1	1	0	0	1	0	6
M	1	1	0	1	1	1	0	0	1	0	6
N	1	1	0	1	1	1	0	0	1	0	6
O	1	1	0	1	1	1	0	0	1	0	6
P	1	1	0	1	1	1	0	0	1	0	6
Q	1	1	0	1	1	1	0	0	1	0	6

To establish an understanding of existing risk exposure of multi-sourcing at CGCo, we examined multi-sourcing of materials across CGCo's 10 plants (Table 4). The number of materials in the chemicals category sourced by each plant varies between 2 and 98. On average, plants multi-source 13% of materials, with the percentage varying from 0 to 21%. Plants A, B, D, and E have the highest quantity of materials, as well as the highest percentage of multi-sourced materials (15-21%).

Table 4 also summarises our analysis of the exogenous risk factor exposure of the multi-source suppliers. For example, for Plants B, D, and E, where multi-sourcing was most prevalent, most multi-source secondary suppliers are in the same country as the primary supplier and thus are exposed to the same exogenous risks (see Table 2). It was noted that plants that are most at risk are in China and Brazil, where materials are only sourced within their own country. Another factor where most secondary suppliers shared the same exposure as the primary supplier was currency. Parent company was also included, not only to highlight any exposure to events such as a supplier's parent company collapsing, but because CGCo's objective is to have secondary suppliers from different parent companies with the aim of maximising leverage during price negotiations. This analysis found several instances at a few plants where secondary suppliers in fact shared the same parent company, contrary to CGCo's stated aim.

Table 4

Multi-sourcing risk exposure analysis: Existing multi-source suppliers, by plant

Multi-sourcing overview by plant				Multi-sourcing risk exposure analysis					
Plant	# Materials	Multi-source materials	Multi-source %	Same Country	Same State	Same City	Same Currency	Same Bank	Same Parent Company
A	95	17	18%	33%	13%	9%	61%	32%	30%
B	98	20	20%	95%	25%	20%	95%	26%	15%
C	2	0	0%	0%	0%	0%	0%	0%	0%
D	79	16	20%	82%	10%	0%	82%	32%	26%
E	87	19	22%	95%	26%	15%	95%	22%	10%
F	44	5	11%	100%	80%	20%	100%	40%	0%
G	49	3	6%	33%	0%	0%	33%	33%	33%
H	21	3	14%	57%	0%	0%	57%	29%	29%
I	53	9	17%	46%	25%	25%	46%	25%	25%
J	3	0	0%	0%	0%	0%	0%	0%	0%
TOTAL	**531**	**92**	**17%**	**71%**	**21%**	**12%**	**77%**	**29%**	**21%**

Through the model, we have identified a potential to multi-source more materials for each plant (Table 5). For each material with only one supplier, we recommended a secondary supplier which differs as much as possible from the original one. This secondary supplier is likely to be from a different parent company and a different country, and to use a different currency, thus hedging potential risks for the plants. Since the recommended supplier has a different risk exposure than the initial vendor, potential disruptions are unlikely to affect both suppliers. Table 5 is a direct comparison of Table 4 and how the risk exposure would be improved if the second supplier recommendations were implemented.

Table 5

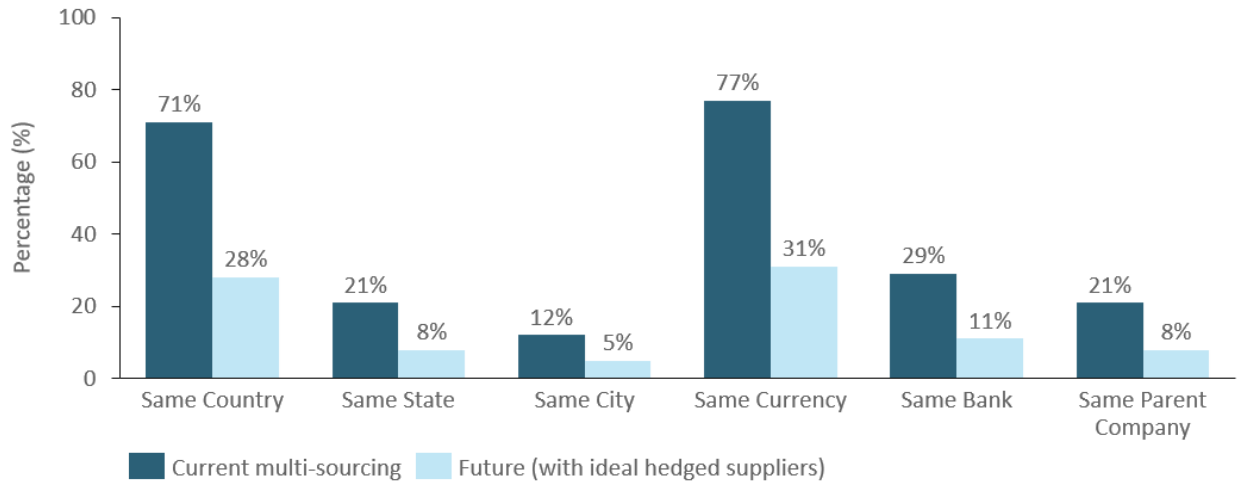
Multi-sourcing risk exposure analysis: Recommended multi-source suppliers, by plant

Multi-sourcing overview by plant				Multi-sourcing risk exposure analysis					
Plant	# Materials	Multi-source materials	Multi-source %	Same Country	Same State	Same City	Same Currency	Same Bank	Same Parent Company
A	95	95	100%	16%	6%	4%	29%	15%	15%
B	98	98	100%	40%	11%	8%	40%	11%	6%
C	2	2	100%	0%	0%	0%	0%	0%	0%
D	79	79	100%	34%	4%	0%	34%	13%	11%
E	87	87	100%	39%	11%	6%	39%	8%	4%
F	44	44	100%	11%	8%	2%	11%	4%	0%
G	49	49	100%	2%	0%	0%	2%	2%	2%
H	21	21	100%	4%	0%	0%	4%	2%	2%
I	53	53	100%	12%	6%	6%	12%	6%	6%
J	3	3	100%	0%	0%	0%	0%	0%	0%
TOTAL	**531**	**531**	**100%**	**28%**	**8%**	**5%**	**31%**	**11%**	**8%**

With the implementation of the multi-sourcing model, there would be an improvement in the company's risk exposure, as detailed in Figure 3. This summary assumes that the existing multi-sourced materials would not be updated and that multi-sourcing would be implemented on all other single-source materials. There is a net decrease of exposure in terms of suppliers being in the same country or using the same currency. Same state, city, and parent company are also at a new low point. Conversely, there is less impact on the evolution of the same bank exposure, which is probably due to the global scale of banking entities.

Figure 3

Multi-sourcing risk exposure summary with current and potential future multi-sourcing



The insights and results detailed in this section provide a better understanding of the current situation of CGCo's specific PBU and how the multi-sourcing recommendation model can reduce the risk exposure of the overall sourcing strategy.

4.2. Practical inclusion of the resilience hedging score into the supplier evaluation process

When considering a new primary or secondary supplier, CGCo's buyers currently assess the supplier based on price, lead time, and the Dun & Bradstreet Supplier Evaluation Risk (SER) score, which is the current measure of the intrinsic risks inherent in each supplier. In discussions with buyers, we proposed including the resilience hedging score as a fourth dimension in this assessment, which can be visualised as the Supplier Assessment Diamond shown in Figure 4.

Figure 4

Supplier Assessment Diamond



The three non-price factors included in the diamond provide buyers with a succinct but well-balanced summary of key considerations that determine whether the proposed secondary supplier is likely to improve the resilience of supply:

- The D&B SER score quantifies the intrinsic risks inherent in each supplier.
- The resilience hedging score quantifies how dissimilar, or hedged, the proposed supplier is to the incumbent primary supplier.
- The supplier's responsiveness can be thought of as the lead time. The lead time can also be compared to that of the primary supplier to determine whether there would likely be a gap in supply in the event of a disruption.

The objective of the Supplier Assessment Diamond is to provide buyers with a conceptual framework for how the resilience hedging score complements existing dimensions of supplier assessment and can provide a more comprehensive assessment of resilience under a multi-sourcing strategy.

4.3. Limitations

Given data security restrictions, we were not able to directly access CGCo's data or ERP system. This data might have allowed us to increase the number of attributes used to assess supplier dissimilarity. In addition, we did not have access to data such as unit cost per material, production costs and lead times. Adding these features to our model would allow us to include constraints in the resilience hedging score recommendations, such as respecting certain lead times or budget directives. Such additional metrics and constraints would make the model more robust and give more visibility to the buyers.

While the results from the model are promising in terms of improving resilience in CGCo's sourcing process, there are some limitations. The RHS recommendations provided by our model do not include constraints/filters. Including constraints/filters would allow CGCo or future users of the resilience hedging score to apply practical limitations to the recommended suppliers. Such as only recommending

suppliers within a certain distance of the plant being supplied, or suppliers able to supply within a certain lead time. Another potential consideration may arise when the model recommends that a plant located in a country with a weak currency, sources from a supplier in a country with a stronger currency. The resulting cost increase can be significant. When CGCo implements the model in their system, they will be able to make adjustments according to their procurement strategy.

5. CONCLUSION

CGCo's motivation was to move from a single-source strategy to one of multi-source supply of materials with the aim of improving supply chain resilience. They needed assistance in creating a method to evaluate the level of resilience provided by each potential secondary supplier.

We took a portfolio approach to supplier resilience, seeking to help CGCo develop a portfolio of suppliers for each material that together have the potential to provide resilient supply. Given that 80% of CGCo's materials were single-sourced, the move to a multi-sourced resilient portfolio of suppliers required assessment of potential secondary suppliers compared to the current single-sourced suppliers. Our novel resilience hedging score provided a quantifiable assessment of each potential secondary supplier, enabling effective comparison and selection of secondary suppliers that could make the portfolio of supply options more resilient. Comparison was based on a pairwise comparison of 12 supplier attributes that were used as proxies for exogenous risk exposure. The use of readily available supplier attributes and the choice of Python for completing the analysis made the process scalable.

5.1. Management recommendations

We recommend that CGCo consider adopting the portfolio approach to supplier selection and use the resilience hedging score (RHS) to assist in facilitating the selection of secondary suppliers that improve the overall resilience of supply. Existing supplier selection processes considered potential suppliers in isolation, which often resulted in multi-source suppliers with exposure to similar risks. A portfolio approach would help address this challenge and should improve the resilience of supply. We recommended that the RHS be used to support the move to a portfolio approach in three ways:

- CGCo first prioritise addressing the small number of suppliers that are the global single source of supply for a significant number of materials. These suppliers represent critical vulnerabilities in the material supply chain, and identifying a secondary supplier with dissimilar risk exposure should allow CGCo to significantly reduce their risk exposure. CGCo could use the RHS score to evaluate existing suppliers of other materials as potential secondary suppliers, as this gives CGCo the greatest potential to move quickly to address these critical vulnerabilities.

- Secondly, we recommended incorporating the use of the multi-sourcing algorithm into the supplier search and selection processes. The RHS algorithm can be used to inform buyers of the ideal profile of potential secondary suppliers, possibly improving the efficiency and effectiveness of the supplier search process. Additionally, the RHS algorithm has a direct application during the supplier assessment process, by highlighting the resilience potentially provided by each proposed secondary supplier.
- Lastly, we recommended that CGCo continues to update the attributes that the resilience hedging score algorithm uses, to ensure that the attributes remain relevant as new risks emerge. The RHS has the potential to significantly contribute to CGCo's supply chain risk management capability. Incorporating it into existing quarterly risk reviews and updating the attributes used to represent exogenous risk exposure as required will ensure that it continues to help CGCo hedge supply chain risks, as those risks evolve over time.

5.2. Future work – further applications of the resilience hedging score

Our method is very effective at recommending ideally hedged suppliers (see Table 4), and it has the flexibility to consider numerical, categorical, and distance attributes of suppliers. The most obvious extension of this paper is to explore the integration of the portfolio approach and RHS into AI-assisted supplier scouting algorithms. Currently, the "potential of AI is untapped in many procurement activities, including supplier scouting" (Guida et al., 2023). Using the RHS to provide parameters for supplier scouting algorithms could assist those algorithms in identifying or prioritising new secondary suppliers based on the resilience they can potentially provide to a portfolio of suppliers.

A second area of extension would be to explore the integration of the resilience hedging score with risk-identification algorithms. Event risk-identification algorithms involve the early identification of disruptive events before their disruptive impact is realised on the supply chain (Shahsavari et al., 2004). Typically, an alert is issued when an event is detected, and staff then investigate the potential supply chain impact. Integrating the RHS and risk-identification algorithms could speed investigations of potential supply chain impact after an alert is issued, by highlighting suppliers that are exposed to the disruption and prioritising them for investigation based on whether or not the secondary supplier is exposed to the same event.

5.3. Future work – applications of dynamic sourcing

Our primary focus for the project was multi-sourcing. However, as part of its future strategy, CGCo aims to leverage its multi-sourced supplier portfolio by developing a dynamic sourcing algorithm that will allocate volumes to the most cost-efficient and resilient suppliers. Specifically, CGCo wants to dynamically

split volumes between primary and secondary suppliers to reduce risk while optimising for cost and lead time. Although dynamic sourcing was outside the formal scope of this project, we conducted initial research on the topic to explore how CGCo could apply it in practice. We believe a dynamic sourcing algorithm would be effective for assessing, in real-time, the effects of splitting volume between the primary and secondary suppliers. The algorithm would enable buyers to evaluate the impact of these changes on costs and lead times, improving the overall supplier selection decision-making experience.

In this initial research, we identified different mathematical approaches to volume allocation. Yousefi et al. (2019) build a multi-objective mixed-integer nonlinear programming model that through two optimisation functions "allows the buyer to change the supplier selection criteria and add or remove them in different conditions." Unlike our model, there is no pre-selection of the suppliers; the selection and allocation decisions take place within the same model. Further, we found the mathematical model approximate dynamic programming used to find the optimal solution for volume allocation (Fang et al., 2013). Through the approximate dynamic programming algorithms, Fang et al. (2013) establish a reliability rating for each supplier, similar to the supplier risk profile of our multi-sourcing approach. In an environment under recurrent disruptions, they recommend splitting the volume between two suppliers to reduce supply risk. Mafakheri et al. (2011) similarly propose a two-stage multiple criteria dynamic programming approach that integrates supplier selection and order allocation over time, considering cost, quality, and delivery performance. Aziz and van Hillegersberg (2010) go a step further and add to their optimised volume allocations model what-if scenarios to allow buyers to simulate the results to guide them through their decision.

While existing studies provide valuable models, they also have limitations: most focus solely on quantity allocation or cost efficiency and often struggle to compare multiple suppliers effectively. Additionally, many rely on pre-disruption assumptions rather than addressing sourcing in environments of continuous disruption. In our initial research, we did not find any existing approach that fully matches CGCo's ambition for dynamic sourcing that integrates resilience, real-time adaptability, and interactive decision support. For CGCo, we recommend developing a dynamic sourcing algorithm that incorporates all constraints and uses dynamic inputs such as the resilience hedging score established in the multi-sourcing phase. This score would impact the volume allocation of materials across the pilot business unit's suppliers. Ideally, buyers would access an interactive tool to input variables such as demand, supplier capacity, and lead time. By comparing these scenarios, buyers could select the optimal option before executing decisions. As live purchasing data is commercially sensitive, the recommendation would be to build this solution offline in a sandbox, for CGCo to implement in the live environment later.

Volume allocation has long been a challenge in procurement, where the goal is to balance sourcing risk while minimising purchase costs. This echoes the core issue we addressed around supply chain

resilience and cost-efficiency for CGCo's pilot business unit. Therefore, we recommend that CGCo's volume allocation strategy builds directly on the results of multi-sourcing and incorporates the supplier resilience hedging score as a dynamic input. This future work would lay the foundation for integrating dynamic sourcing into CGCo's broader multi-sourcing strategy. By enabling real-time evaluation of cost and lead time impacts, the proposed algorithm will enhance supplier selection decisions and help buyers optimise volume allocation with greater confidence and flexibility.

5.4. Conclusion

There are very few quantitative measures that assist companies in implementing a portfolio approach to multi-sourcing strategy. The resilience hedging score makes a notable contribution in this regard and can allow companies to very rapidly make a quantifiable assessment of how potential secondary suppliers could improve their resilience of supply. The score is practical and easily explainable, which is not often true of many mixed-criteria decision making methods which are commonly used in supplier assessment. Additionally, the resilience hedging score complements, rather than seeks to replace, existing resilience considerations such as measures of supplier intrinsic risk (like the D&B SER score) or supplier lead time. This is a significant practical advantage, as it allows companies to quickly supplement existing supplier selection processes and avoid lengthy retraining that might be inherent in alternate approaches.

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