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Supplier-Selection Practices for Robust Global Supply Chain Networks:

A Simulation Of The Global Auto Industry

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SUMMARY

How can companies develop and maintain global supply chain networks that are robust—that is, capable of maintaining an uninterrupted flow of goods and materials—when confronted with a geographically spreading disruption that could cause the shutdown of multiple suppliers at once? To answer this question, this article combines an empirical analysis of supply chain networks of three global automotive manufacturers with computational experiments. The results reveal that even when a small fraction of buyers adopt regionalizing supplier-selection practices—those in which a buyer chooses geographically proximate suppliers, whether to the buyer or its current suppliers—the supply chain network becomes more robust.

KEYWORDS: networks, supply chain, supply chain management, global supply networks, computer-based modeling

The COVID-19 pandemic caused immense disruption to global production and supply networks (GPSNs), leading to the shutdown of numerous manufacturing facilities and interrupting shipping routes between them. The associated ripple effects adversely affected industries that heavily rely on GPSNs.[1] For example, in late March 2020, 93% of all auto production in the United States was offline, leaving only two plants in the entire nation operational.[2] Similarly, 69% of electronic companies

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experienced shipment delays, with 15% experiencing delays of six weeks or longer.[3] And yet, at the same time, some companies withstood the crisis significantly better. Quick-turn manufacturers with flexible supply chains, such as ProtoLabs and Essentium, proved able to ramp up production to capitalize on the urgent demand for COVID-19-related medical components, including test kits, ventilators, and respirators.

While the world was still reeling from COVID-19, GPSNs were hit by another major supply chain disruption: the weeklong blockage of the Suez Canal by the *Ever Given*, a massive container ship, which delayed 350 other ships carrying more than $50 billion dollars' worth of goods and supplies. Downstream delays in shipments created difficulties for GPSNs, although less significant than the disruptions associated with the COVID-19 pandemic. This shock was followed by the worldwide shortage of computer chips, which forced multiple global automakers and their suppliers to cut production drastically. And future disruptions of more significant proportions are unfortunately not out of the realm of possibility: scientists are worried about the next pandemic[4] and the next mega natural disaster,[5] both of which carry the risk of wreaking havoc on global supply chains.

Designing Robust GPSNs in the Global Automotive Industry

This study is motivated by the question of how companies can design and implement practices that would result in more robust GPSNs. In supply chain research, robustness is commonly defined as "the ability of the supply chain to maintain its function despite internal or external disruptions."[6] Comparable definitions of robustness can be found in other supply chain studies.[7] Consistent with this and related research on complex systems,[8] we define network robustness as the GPSN's capacity to sustain an uninterrupted flow of goods and materials through the supply network in the face of significant disruptions.

Our operationalization of disruption involves a concurrent shutdown of a large number of GPSN participants,[9] which could occur due to pandemics, natural or human-made disasters, social or political unrest, or other major shocks. Furthermore, in accordance with this area of research, we conceptualize robustness as the system's near-term capability to withstand the impact of a shock while relying on its existing characteristics. We do not consider the medium- and long-term responses to and recovery from a disruption by the actors within a GPSN. (Our definition of robustness is, therefore, distinct from the concept of resilience, which considers the affected entities' adaptive capacities and, thus, the systems' ability to respond to a given shock.)

The task of building a robust GPSN is exceptionally challenging for three key reasons. First, contemporary GPSNs are extremely complex: they are multi-tiered, with an enormous number of organizations at each level dispersed across geopolitical regions. Our analysis of supply chain networks in the global automotive industry reveals that companies have thousands of suppliers with manufacturing facilities spread across 67 countries.

Second, most companies do not design their entire supply chains; they have limited authority to manage or observe their supply chain networks beyond their direct (tier-1) suppliers.[10] Given the limits to vertical integration,[11] this condition constitutes a seemingly insurmountable challenge for global manufacturers, forcing them to operate as constrained architects of their GPSNs. Indeed, global manufacturers manage only the most immediate tier of suppliers, yet they must try to ensure the robustness of a multitiered GPSN in which suppliers' failures at any tier can prove debilitating for the entire network. In the empirical case we consider in the present study, the automotive industry, tier-2 and especially tier-3 suppliers were the most adversely affected GPSN entities during the COVID-19 pandemic. Those disruptions were outside the managerial reach of the automobile manufacturers, and they hampered the ability of tier-1 suppliers to maintain uninterrupted operations.[12] At times, the automotive companies were stuck in the role of passive observers of a collapsing GPSN.

Third, unlike banks—which are now legally required in many countries to run regular stress tests and issue annual stability reports[13]—companies in the automobile sector face no such regulations. Thus, the industry lacks a coherent framework or process for conceptualizing or measuring robustness.

In a broad sense, a supply chain's robustness can be defined and measured with respect to four types of disruptions:

- failures of suppliers or manufacturing facilities within the network, such as when a fire or labor strike shuts down a component manufacturer;
- environmental and economic shocks, such as when the 2011 earthquake in Japan shut down the Onahama plant, the sole global provider of Xirallic, a pigment used in black and red car paints (indeed, this remains front of mind for many automotive executives nearly a decade later)[14];
- the distribution of inventory levels and delivery times, such as those resulting from, for example, the slowdowns at bridge crossings between the United States and Canada following the 2001 terrorist attacks that disrupted global automotive supply chains[15] or the 2021 computer chip shortage that forced some automotive manufacturers to drastically reduce their production[16]; and
- debilitating internal dynamics related to decision making and feedback, which are all too familiar to anyone who has participated in the "beer distribution game" simulation, in which demand fluctuations often produce chaos.[17]

A robust GPSN maintains functionality in response to each type of disruption singly and, sometimes, in combination.

Study Objectives

In this work, we seek to assist managers who have limited observability and managerial control over the global supply network in building GPSNs that are robust to geographically spreading disruptions. In other words, how can hundreds of buyers and suppliers—who collectively constitute a GPSN and make independent purchasing decisions—ensure that those decisions, in the aggregate, enhance rather than undermine the robustness of the entire GPSN?

We focus on GPSNs' robustness to disruptions that spread through a geographic space. Notable examples of such disruptions include pandemics, political and social unrest, as well as human-made or natural disasters. The geographic reach and duration of these disruptions vary. An electric power grid failure may affect just the suppliers in the focal country and last for a few days; whereas the consequences of an earthquake, hurricane, or flood can affect multiple countries and be felt for months. And, as we now know all too well, global pandemics can reverberate through most of the world and inflict consequences from which companies can take years to recover.

Given that any single player in a GPSN network, including the original equipment manufacturer (OEM), has limited control over and even knowledge of the GPSN beyond its immediate suppliers,[18] we approach building a robust GPSN as a collective endeavor that lacks a central planner. In other words, rather than being designed by a global manufacturer, a GPSN emerges from hundreds if not thousands of decisions to form and break relationships across the network. Thus, in our analysis, we do not prescribe specific network designs. Instead, we compare how different practices for forming connections across companies result in GPSNs with varying degrees of robustness. Stated differently, we demonstrate how hundreds of buyers and suppliers who collectively construct the GPSN through decentralized purchasing decisions can, in the aggregate, produce more or less robust GPSNs.

In the models we construct, we assume that individual buyers and suppliers pursue their individual objectives by choosing the most economically attractive options while collectively sharing the responsibility for developing a robust GPSN. Our main goal, therefore, is to identify simple and realistic supplier-selection practices which, if followed by at least some GPSN participants, produce more robust GPSNs. By simple, we mean that the information required for execution must be readily available to the suppliers and the requisite action easily determined. By realistic, we mean that these practices do not put an undue burden on the suppliers' individual priorities.

To carry out our analyses, we leverage both empirical data on GPSNs and a series of computational experiments. In particular, we use data on three leading global automakers (General Motors [GM], SAIC Motor Corporation [SAIC], and Volkswagen [VW]) to produce approximations of these companies' GPSNs. We then subject these networks to computational experiments that examine the effects of various supplier-selection practices (i.e., node replacement) on the emergent GPSN network's robustness to geographically spreading disruptions.

Building Robust Supply Chain Networks

GPSN as a Complex System

A GPSN can be formalized as a network in which suppliers (nodes) are interlinked by buyer-supplier relationships (edges). In this view, the network's edges represent the arteries through which goods and materials flow, ensuring the vitality of the supply chain network. Rather than being designed by a master planner and then built in a top-down fashion, in the case of automotive GPSNs, the network emerges from the actions of hundreds of independent buyers—spread over multiple tiers—who make decisions regarding which suppliers to renew, add, or terminate.[19] These decisions, when taken collectively, aggregate to form intricate network properties of the multitiered supply chain network. Such properties, in turn, determine the robustness of the network. In our formulation, this means how well the network can sustain an uninterrupted flow of goods and materials when a large number of suppliers must shut down their operations.

The scope of the managerial challenge should now come into focus. The organization is not choosing or constructing a network but is rather engaging in, or perhaps just encouraging, a set of practices for making connections with the goal that the network that emerges will be robust. Rather than having the direct authority to construct its GPSN, a company has only an indirect influence on the self-organization of its GPSN.

The Impact of Shocks

As noted, multiple types of shocks can afflict geographically proximate businesses. These include pandemics, social and political unrest, as well as natural and human-made disasters. For example, in response to the austerity measures triggered by the sovereign debt crisis in Europe, protests and strikes spread across the continent in 2012, eventually affecting business operations in multiple European countries.[20] Similarly, after the first wave of COVID-inflicted shutdowns in China in early 2020, the spread of the virus caused numerous disruptions in business operations and supply chains in neighboring Hong Kong, South Korea, and Japan in February and March of 2020 before spreading to the rest of the world.[21] Shocks such as pandemics spread with human-to-human contact, which are amplified by travel.[22] Thus, most nations' responses to the COVID-19 pandemic involved restricting air travel.

To account for these facts, we examine how supply chain networks withstand those shocks that primarily spread geographically, adversely affecting suppliers in countries sharing land borders or countries connected by multiple air travel routes. In addition to these general modes of shock diffusion, in supplementary analyses, we explore network robustness to strategic attacks (such as targeted terrorist attacks) and to the special case of a shock whose spread follows the exact trajectory of workplace shutdowns worldwide as a result of the COVID-19 pandemic.

Building Robust GPSNs

Given that GPSNs emerge from the buyers' supplier choices, we construct a model to examine the interplay between buyers' supplier-selection practices and the robustness of the emergent GPSN. To construct such a model, one must consider a key empirical regularity: GPSNs change constantly. Supplier churn is a prominent feature in any GPSN, with existing suppliers being replaced and new ones being added. If these supplier replacement decisions are determined only by price and supplier reputation, managers are placing a huge bet on GPSN robustness emerging through a fortuitous correlation between sellers' attractiveness and their contributions to robustness.

Our starting assumption is that, in many situations, multiple suppliers would feature sufficiently similar product prices and company reputation to allow for buyer discretion. That discretion can and should include considerations of features that contribute to GPSN robustness. Given this "robustness features as a tie-breaker" assumption, we consider a variety of practices of supplier selection based on the suppliers' geography and evaluate how these practices affect the robustness of the emergent GPSN to geographic shocks. First, we investigate the impact of *globalizing* supplier-selection practices on network robustness. In these practices, buyers select more *geographically distant* suppliers with respect to their current suppliers. We then examine the impact of *regionalizing* supplier-selection practices, in which buyers instead choose more *geographically proximate* suppliers with respect to the buyers themselves or the buyers' current suppliers.

The choice between proximate and distant suppliers is one of the fundamental choices in developing a supply chain. In practice, the variation in buyers' preferences for choosing globalizing versus regionalizing practices could stem from different managerial views on the degree to which supply chains could be regional versus global,[23] the varying degrees of buyers' reliance on trust and referrals in choosing suppliers,[24] the distinct levels of market pressures to innovate and search for new knowledge,[25] the differences in the distribution of expertise among local versus foreign suppliers,[26] the varying emphasis companies place on developing their local business communities,[27] or the level of economic protectionism and the associated regulatory restrictions placed on doing business with foreign companies, among other factors.[28] Importantly, in implementing any of these practices, the buyers work under the quotidian constraints of managing large GPSNs. Namely, the buyers have information only about their direct suppliers, and they thus cannot base decisions on the structure of the global supply chain network or attempt to coordinate with other buyers.

In addition to modeling the impact of globalizing and regionalizing supplier-selection strategies on the robustness of the emerging supply network, we test the impact of a random supplier-selection strategy as a baseline. In this strategy, buyers choose new suppliers irrespective of the suppliers' geographic location.

Before undertaking our analysis, we expected that globalizing supplier-selection practices would improve GPSN robustness for geographically diffusing disruptions relative to the robustness of real supply chain networks, whereas regionalizing supplier-selection practices would diminish it. Our intuition was that the near-simultaneous knockout of a large group of geographically co-located companies would prove disastrous for the ability of a GPSN to sustain uninterrupted operations, and that the globalizing practices—by diversifying the network geographically—would improve GPSN robustness, preventing any given shock from impacting the heavily geographically concentrated parts of the network.

This effect is not obvious, however, because a geographically diversified supply chain can be exposed to a larger number of disruptions, which could originate in various parts of the world. In this case, a supply chain's broader geographic presence creates the potential to touch hotbeds of epidemics, political unrest, and other types of disruptions, thus feasibly making the supply chain more vulnerable. Furthermore, many suppliers—especially those in tier 1—have a manufacturing presence in multiple countries, and the cumulative resultant geographic exposure of regionalizing and globalizing practices can therefore vary.

Our analysis considers both average effects and variation. Examining only the average levels of network robustness across a wide range of disruptions masks potentially catastrophic outcomes associated with outlier adverse events. Our expectation in this respect was that globalizing supplier-selection practices should result in networks that are more robust with respect to the worst possible outcomes. In contrast, regionalizing supplier-selection practices may leave supply chain networks particularly vulnerable to major disruptions that could quickly wipe out significant segments of the supply chain.

Analytical Strategy

Empirical Networks

We employed a three-step, multimethod analytical approach that combined the analysis of archival data on supply chain networks in the global auto industry with agent-based computational modeling. In the first step, using Bloomberg Supply Chain, SPLC <GO>,[29] we collected data on the first three tiers of suppliers for three global automotive manufacturers: GM, headquartered in Detroit, USA; SAIC, headquartered in Shanghai, China; and VW, headquartered in Wolfsburg, Germany. To select these three auto manufacturers, we started with the list of 23 global automakers featured in the most recent Fortune Global 500 list. Using this list, we clustered these manufacturers into the three supracontinental geographic areas: the Americas, Asia Pacific, and Europe, which are commonly used to classify markets and production in the automotive sector. We subsequently chose these three manufacturers to represent each of these geographies to account for possible geographic and national-cultural variations in the structure of GPSNs. The decision to limit our analysis to three global automakers and to the first three tiers of their suppliers was dictated in part by the need to keep data collection manageable.[30] The suppliers in this study reflect only those suppliers for which the buyer-supplier relationships are quantified on Bloomberg in terms of the buyer's cost of goods sold (COGS). As evidenced in Table 1, only

TABLE 1. Summary Statistics of GM's, SAIC's, and VW's Supply Chains.

Supply Chain Characteristic	GM	SAIC[a]	VW
No. of unique tier-1 suppliers[b]	193	51	213
No. of unique tier-2 suppliers[b]	899	408	1,026
No. of unique tier-3 suppliers[b]	2,875	1,476	2,901
%COGS accounted for at tier 1	47.58%	6.58%	31.43%

Note: GM = General Motors; SAIC = SAIC Motor Corporation; VW = Volkswagen; COGS = cost of goods sold.
[a]The significantly smaller fraction of COGS accounted by SAIC's suppliers is likely to be explained by the large (over 60%) proportion of tier-1 suppliers domiciled in China. Many of these suppliers do not have to publicly disclose detailed information about their major customers. They are also less likely to be listed as a major customer by a company that is required to publicly disclose the identity of its major customer, thus making it difficult for Bloomberg to estimate COGS.
[b]These counts of suppliers reflect only those suppliers for which the buyer-supplier relationships are quantified on Bloomberg in terms of the buyer's COGS. Only a fraction of such relationships is quantified as evident in %COGS accounted for at tier 1.

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Supplier-Selection Practices

In the second step, we designed a computational model of GPSN change, in which a small fraction of buyers select suppliers using one of the seven practices previously described (i.e., three globalizing practices, three regionalizing practices, and the random [baseline] practice). In each time period, 5% of buyers would replace *one* of their suppliers using the examined practices. We benchmarked that assumption on an S&P Global Market Intelligence report that established the probability of default on its debt in the auto industry to be about 5%.[31] We treat 5% as a very conservative starting point because suppliers could be replaced, of course, for many other reasons than default alone. By making such a small fraction of buyers abide by the rule and only with respect to one of their suppliers, we emphasize the primacy of other criteria that could drive supplier choice, namely, economic costs.

We tested these practices with three different starting network conditions, which represent the three empirically observed networks (i.e., GM, SAIC, and VW). Each of the starting networks evolved with a given supplier-selection practice for 10 time periods, which resulted in a 3 (starting scenarios) × 7 (supplier-selection practices) factorial design of the computational study. For each of the 21 conditions, we simulated 100 network runs, resulting in an overall sample of 2,100 simulated networks. See the Technical Appendix for details of the computational procedure.

In the final step, we subjected each of the 2,100 simulated networks across seven network conditions and the three empirically observed networks to shocks in the form of multistage supplier shutdowns (i.e., network node knockouts).

Each shock starts with the shutdown of all suppliers' facilities in a chosen "outbreak" country, subsequently proceeding to affect other countries either through adjacent land borders or via air travel. Recognizing that many suppliers have their manufacturing facilities spread across multiple locations, we removed a supplier from the network only when more than half of the countries in which the supplier had manufacturing facilities were knocked out.

The Geographic Diffusion of a Shock through Adjacent Land Borders

As noted, there are two general ways in which shocks can diffuse from country to country: through adjacent land borders and through air travel. In the first variant, we assume the contagion occurs from one originating country to its geographically proximate neighbors. Under this assumption, the initial shock spreads to the suppliers' facilities located in countries adjacent to the outbreak country (i.e., the country's geographic neighbors). We denote this stage as the "outbreak country +1 degree." Then, at "outbreak country +2 degrees," the shock spreads to all countries adjacent to those countries (i.e., the neighbors' neighbors of the outbreak country), and so on.

The disruption continues to spread from country to country until it cannot spread anymore across land borders. Such a shock trajectory is designed to represent the spreading impact of pandemics, social or political unrest, or natural or human-made disasters across national borders, leading to the shutdown of suppliers' manufacturing facilities located in each affected country.

Each geographically spreading scenario started with one of the 177 possible outbreak countries, from which the shock then diffuses across land borders.[32] For each of the 2,100 simulated and 3 observed networks, we simulated all 177 disruption scenarios. In total, our study thus covered 372,231 tests (2,103 networks × 177 disruption scenarios). See the Technical Appendix for additional details. As an illustration, in one run, China could be the outbreak country, wherein the disruption would first shut down the suppliers in China. The disruption would subsequently spread to and shut down suppliers' manufacturing facilities in each of the 14 countries that border China in the "outbreak country +1 degree geographic neighbors" scenario (i.e., India, Kazakhstan, Pakistan, Russia, etc.). In the next phase, the shock would spread to the 17 countries that border those 14 countries in the "outbreak country +2 degrees" scenario (i.e., Finland, Poland, Turkmenistan, Ukraine, etc.), disabling all suppliers' facilities in those countries, and so on. In the next disruption scenario, China could no longer be selected, but any of the remaining 176 countries could instead be chosen as the outbreak country.

The Geographic Diffusion of a Shock through Air Travel

In the second variant of shock diffusion, we assume that contagion occurs probabilistically by virtue of people flying from the outbreak country directly to other countries. Such a contagion trajectory is most likely to approximate the spread of pandemics. To carry out these tests, we obtained comprehensive airport-to-airport level route information from the OpenFlights/Airline Route Mapper Route Database (https://openflights.org/data.html). The 2014 version of this database, which is the most recent publicly available version, covers 67,663 routes between 3,321 airports on 548 airlines spanning the globe.

Using airport-to-airport flight data, we counted the number of direct flight routes (excluding code shares) between every pair of countries. We subsequently modeled the probability of a shock spreading from country A to country B as a function of the share of the number of direct flight routes from country A to country B over the total number of country A's outbound, international flight routes. This approach is based on the premise that the more people are flying from countries where infection rates are high to other countries, the more likely the suppliers in those countries will be adversely affected.

The spread from the outbreak country to a country connected by direct flight routes is denoted as "outbreak country +1 degree." Then, at "outbreak country +2 degrees," the outbreak country continues to affect other previously unaffected countries with which the outbreak country has outbound direct flight routes. In addition, countries that got "infected" by the originating country at the previous stage now begin to "infect" other countries to which they have direct outbound flight routes. From this stage and beyond, a country can get infected through multiple pathways, just like countries that have inbound flights from many different countries are inherently exposed to a higher risk of being infected.

Each scenario started with an outbreak in one of 222 countries. (After removing code share routes from the entire roster of flight routes, there were 222 unique countries that had at least one outbound flight route to a different country.) For each of the 2,100 simulated and 3 observed networks, we simulated 222 disruption scenarios. The second study thus covered 466,866 tests (2,103 networks × 222 disruption scenarios). From a randomly chosen outbreak location, the shock then spreads to other locations through flight routes. A supplier is removed from the network when more than half of the countries wherein the supplier has manufacturing facilities are afflicted by the spreading disruption.

As an illustration, in one run, China could be the outbreak country; the disruption would thus first shut down the suppliers in China. Subsequent to that, in "outbreak +1 degree," 63 countries that receive at least one of 1,015 outbound flight routes from China would be at risk of infection and supplier shutdown. For example, there are 12 outbound direct flight routes from China to Canada and 111 from China to Hong Kong. We thus expect the probability of China infecting Canada would be 12/1,015 = 1.182% and Hong Kong 111/1,015 = 10.936% in "outbreak +1 degree." In "outbreak +2 degrees," China would continue to infect 63 countries. Furthermore, now countries that were infected from "outbreak +1 degree" can infect others. The procedure for a given network finishes when each of the 222 locations has been chosen once as the outbreak country, thus exhausting all 222 disruption scenarios.

The Geographic Diffusion of a Shock: Supplementary Analyses

In the online appendix, we report supplementary analyses, testing how our proposed supplier-selection practices performed against the trajectories of diffusion that followed strategic attacks and the actual sequence of workplace shutdowns worldwide as a result of the COVID-19 outbreak. For modeling strategic attacks, we used the worldwide release schedule of the Disney animated film *Frozen*, which approximated a targeted terrorist attack on the countries sharing similar cultural or economic characteristics, and the targeted shutdowns of all suppliers in countries with the largest numbers of automotive suppliers.

Outcome: Changing Size of the Main Component of a GPSN

As a shock unravels from the focal country to its geographic neighbors and then to the neighbors' neighbors, we tracked the changes in the connectivity of the supply network, which is one of the central facets of each GPSN's robustness.[33] Consistent with prior work on robustness,[34] we measured *the percentage of companies remaining in the main component of the supply chain network* as the measure of the robustness of a GPSN. The main component of the supply network is defined as the largest interconnected segment of the supplier network in which each participating company can reach any other participating company through the network of buyer-supplier relationships, either directly or indirectly, through other suppliers. The variable's maximum value is 100%, which presents that the size of the main component of the supply network remained unchanged before and after the outbreak. A GPSN with a high percentage of companies remaining in the main component will be able to support an uninterrupted flow of goods and materials. A robust GPSN would also register less significant declines in the percentage of companies remaining in the main component as the shock engulfs more and more countries, indicating the network's ability to withstand the exit of multiple suppliers.

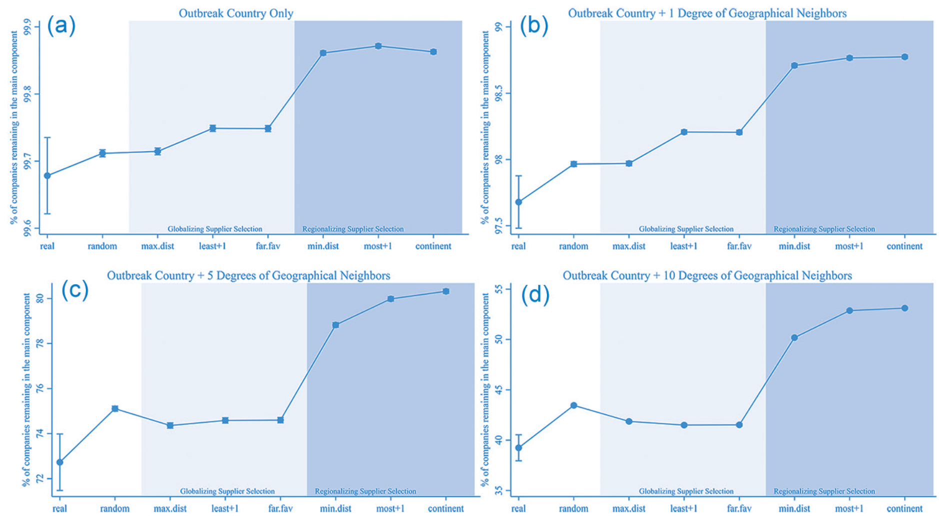
In reporting the study's results, we use "outbreak country only" and "outbreak country +1 degree" to show how robust the networks are to localized disruptions that do not spread too far beyond the originating country. By reporting network robustness in the scenarios of "outbreak country +5 degrees" and "+10 degrees," we assess network robustness to global disruptions that spread to numerous nations. Note that in our model, disruptions spread through a gradual diffusion process, in which countries are affected sequentially by the unfolding disruption. Our results, however, generalize to instantaneous global disruptions, in which large numbers of adjacent countries are affected concurrently.

Findings and Managerial Implications

Robustness of Observed Empirical Networks

Our results indicate that the supply networks of the three global automakers examined in this study are, on average, *robust to localized disruptions*, in which the disruption does not spread too far beyond the country in which it originated. Results in Figures 1(a, b) and 2(a, b) for the three observed automotive supply chain networks indicate that the main components of those networks remain

FIGURE 1. Supply chain network robustness to localized (a, b) and global disruptions (c, d) diffusing through adjacent land borders: (a) Network robustness to localized disruptions in which suppliers of only the outbreak country are shut down, (b) network robustness to localized disruptions in which suppliers of the outbreak country and its direct geographic neighbors are shut down, (c) network robustness to global disruptions in which suppliers of the outbreak country and all its geographic neighbors from first to fifth degree are shut down, and (d) network robustness to global disruptions in which suppliers of the outbreak country and all its geographic neighbors from first to tenth degree are shut down. Around each value, the bars reflect ±1 standard errors of the mean.



Note: real = Real networks of global automakers (no supplier-selection strategy applied); random = A buyer chooses a supplier randomly, irrespective of its geographic location. max.dist = A buyer chooses a supplier that maximizes the geographic distance from its current direct suppliers; least+1 = A buyer chooses a supplier from the least represented country among its direct suppliers; far.fav = A buyer chooses a supplier that is most distant from the country with the most direct suppliers in its network; min.dist = A buyer chooses a supplier that minimizes the geographic distance from its current direct suppliers. most+1 = A buyer chooses a supplier from the most represented country among its direct suppliers. continent = A buyer chooses a supplier from the buyer's continent.

largely intact when the geographic shutdown is limited to the outbreak and outbreak +1 countries. On average, the main component of the network preserves 97.7% to 99.7% of the participating companies in the main component when faced with localized disruptions.[35]

Our results reveal that the automakers' supply networks are *not* nearly as robust, on average, to global disruptions whose impact spreads beyond the borders of the outbreak country, such as would be the case in a global pandemic. The percentage of companies remaining in the main component of a GPSN in an instance of a global shock does not exceed 72.9% (outbreak country +5 degrees, for shocks spreading via air travel; Figure 2c), and it drops all the way to 9.9% in some cases (outbreak country +10 degrees, shocks spreading via air travel; Figure 2d).

These findings carry important managerial implications. Most centrally, they reveal that considering single-supplier (single node) knockouts is insufficient: *managers should focus foremost on improving robustness to global disruptions.* Doing so requires developing a set of scenarios in which the shock reverberates through scores of geographic neighbors and then developing metrics to assess the functionality of the supply chain network in those circumstances. When conducting stress tests, central banks have long focused on financial systems' robustness to cascading failures.[36,37] Manufacturers should do the same. By the same token, risk assessments should focus on the potential for events whose impact could spread more easily across geographic borders, such as global pandemics, escalating military conflicts, or nuclear catastrophes.

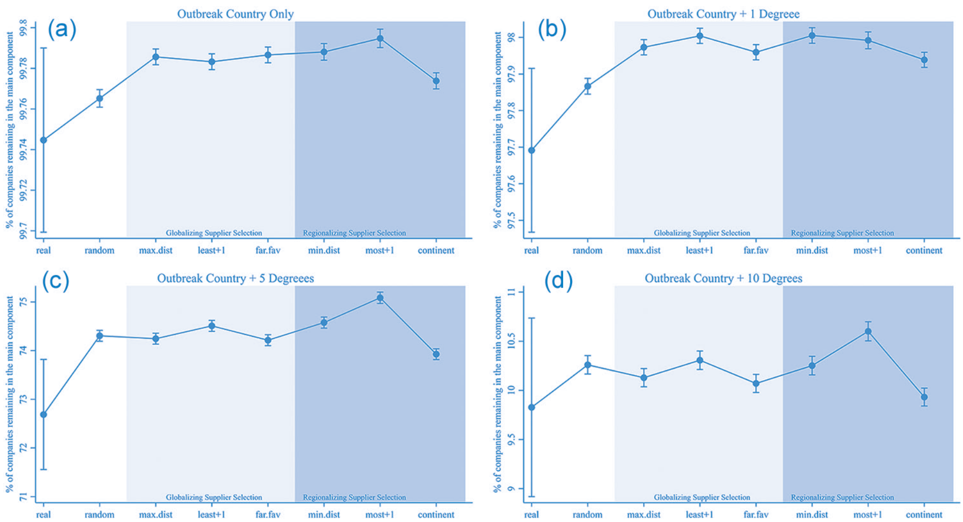
Furthermore, even for events that can engender seemingly localized consequences—such as wars involving one or a couple of countries, regional political and social unrest, earthquakes, tsunamis, or volcano eruptions—it is important to anticipate and plan for their potential global impact. For example, governments of countries that are not directly affected by the crises may nevertheless enact martial law and emergency orders to reorient production in order to enhance their armed forces, to boost border protection, or to accommodate the influx of refugees from neighboring countries. Such a reorientation of production may effectively result in initially localized disruptions affecting suppliers in a broad set of countries.

In terms of managing preparedness for local shocks, managers should identify and plan for shocks that could cause major supply chain disruptions. Although networks appear robust to local crises on average, some manufacturers are particularly vulnerable to disruptions originating in certain countries. A closer look into each of the 177 knockout scenarios revealed that some scenarios were much more catastrophic than others depending on the origin of the localized disruption. For example, for GM, shocks involving the shutdown of suppliers in Germany and all of Germany's geographic neighbors result in the loss of 5.92% of the main component. Similarly, for VW, disruption originating in Vietnam and spreading to the neighboring nations eliminates 12.38% of companies from the main component. Both of these scenarios are likely to be debilitating for their respective global supply chain networks.

These findings imply that a manager should not think, "we have only a 3% chance of a major disruptive event," but instead think, "we have identified five countries for which a local disruptive event could be catastrophic, so we must plan for those contingencies." The disruptions spreading via air travel can be even more debilitating to GPSNs, as an outbreak from a country with major hub airports can quickly seed multiple epidemic outbreaks across the world. For example, shocks originating from Japan will eliminate 6.30% of the main component for the three auto manufacturers. That number skyrockets to 27.25% of the main component if we consider shocks spreading from Japan to the first degree of countries via air travel.

Globalizing supplier-selection practices increase the average supply chain network robustness. Consistent with our expectations, our results reveal that all of the three globalizing supplier-selection practices—in which buyers select distant suppliers with respect to their current supplier networks—improve the robustness of the emergent global supply chain networks relative to the empirical networks. The

FIGURE 2. Supply chain network robustness to localized (a, b) and global disruptions (c, d) diffusing through air travel: (a) Network robustness to localized disruptions in which suppliers of only the outbreak country are shut down, (b) network robustness to localized disruptions in which suppliers of the outbreak country and its direct (first degree) flight destination are shut down, (c) network robustness to global disruptions in which suppliers of the outbreak country and its flight route from first to fifth degree are shut down, and (d) network robustness to global disruptions in which suppliers of the outbreak country and all its flight route from first to tenth degreeare shut down. Around each value, the bars reflect ±1 standard errors of the mean.



Note: real = Real networks of global automakers (no supplier-selection strategy applied); random = A buyer chooses a supplier randomly, irrespective of its geographic location; max.dist = A buyer chooses a supplier that maximizes the geographic distance from its current direct suppliers; least+1 = A buyer chooses a supplier from the least represented country among its direct suppliers; far.fav = A buyer chooses a supplier that is most distant from the country with the most direct suppliers in its network; min.dist = A buyer chooses a supplier that minimizes the geographic distance from its current direct suppliers; most+1 = A buyer chooses a supplier from the most represented country among its direct suppliers; continent = A buyer chooses a supplier from the buyer's continent.

networks that emerge as a result of globalizing practices are better, on average, at withstanding the impact of both local and global disruptions than the automakers' real networks (see Figures 1 and 2).

This said, the robustness advantage gained by our supplier-selection practices relative to the real networks is small. In localized shocks (outbreak to outbreak +1 countries), the networks stemming from the globalizing supplier-selection practices retain an additional 0.2 to 0.5 percentage points of the companies in the main component compared with real networks. In global shocks (outbreak to outbreak +10 countries), these gains increase to about 0.3 to 2.7 percentage points relative to the empirically observed networks. The recommended globalizing supplier-selection practices, on average, lag the robustness levels produced by a random supplier-selection strategy.

Regionalizing supplier-selection practices increase average supply chain network robustness (more than globalizing supplier-selection practices). The most surprising result of our research is that regionalizing supplier-selection practices—in which buyers choose geographically proximate suppliers with respect to the buyers themselves or the buyers' current suppliers—increases network robustness to geographic disruptions. In particular, two of these strategies—a buyer choosing a new supplier in a way that minimizes the geographic distance from its current direct suppliers [min.dist] and a buyer choosing a new supplier from the most represented country among its direct suppliers [most+1]—emerged as consistently outperforming the robustness levels produced by real network, random supplier-selection practices, or globalizing supplier-selection practices.

Robustness gains were particularly significant with respect to withstanding the impact of global shocks that diffuse through land borders and engulf higher degree geographic neighbors of the outbreak country. In these cases, the associated increases in robustness for resulting supply chain networks were substantial. For example, for shocks diffusing by land, regionalizing supplier-selection practices allow the GPSN to retain 78.8% to 80.3% of all suppliers if the global disruption reaches the fifth-degree geographic neighbors of the outbreak country (Figure 1c). By the same token, if the global disruption reaches the tenth-degree geographic neighbors of the outbreak country, a network built through regionalizing practices retains, on average, from 50.2% to 53.1% of the companies in the main component (Figure 1d). These numbers reflect a 6.1 to 13.9 percentage point advantage in the number of companies retained in the main component compared with the empirically observed real networks under similar circumstances. The networks built through regionalizing supplier-selection practices similarly offer a salient advantage over a network in which suppliers are chosen at random, which amounts to as much as 9.6 percentage points in some cases.

In light of these findings, our central advice to managers aiming to reduce the average exposure of the global supply chain networks to geographic shocks is to encourage more regional supplier focus when replacing existing suppliers. Such regionalization creates additional protection from disruptions that spread across geographic borders.

We offer this advice with the following notes and caveats. First, the most consistent of the regionalizing supplier-selection practices in terms of improving robustness across various shock scenarios appears to be the one in which a buyer chooses a supplier that minimizes the geographic distance from its current direct suppliers [min.dist]. Choosing a new supplier from the buyer's continent underperforms both globalizing and random supplier-selection strategies in situations of shocks diffusing by air. Choosing a new supplier from the most represented country in terms of the number of the buyer's current direct suppliers leads to lagging robustness in the case of a strategic attack or when retracing COVID-19-related workplace shutdowns (see the online appendix for detailed results).

Second, while the gains in GPSN robustness are small in terms of withstanding shocks diffusing by air travel (ranging from 0.1 to 2.2 percentage points), it is important to keep in mind that they result from infinitesimal changes in buyers' behaviors. Specifically, the discussed improvements in network robustness stem from only 5% of suppliers changing only one of their suppliers at any given time period based on the regionalizing supplier-selection practices, and the network evolving for a total of ten time periods with this dynamic.

Third, in interpreting these percentages, one must be aware that the effect of reductions in the size of the main component on the GPSN's ability to sustain uninterrupted operations may be nonlinear and even have threshold effects. For example, a GPSN that retains 80% of its nodes may be able to function with high probability, whereas one that retains only 75% may have little chance of doing so.

Finally, regionalizing supplier-selection practices produced more robust networks than the globalizing supplier-selection practices in three out of the four disruption scenarios we tested in the main and supplementary analyses: shocks spreading via land borders, shocks spreading by air, and strategic attacks. The one exception to this pattern of results is the shock whose diffusion trajectory retraced the sequence of workplace shutdowns during the COVID-19 pandemic. In these tests, networks built through globalizing supplier-selection practices emerged as more robust. However, even in these tests, the networks built through the recommended regionalizing supplier-selection practices registered higher levels of robustness than the real GPSN networks.

Implementing Supplier-Selection Practices for Building Robust Networks

Our analysis also reveals that small shifts toward regionalizing supplier-selection practices produce significant gains in enhancing GPSNs' robustness to both localized and global shocks. At their core, these regionalizing practices involve choosing suppliers that are close geographically to the buyers or the buyers' current base of suppliers. These regionalizing supplier-selection practices can also reduce the emergent network's vulnerability to adverse outlier events, such that even the worst possible disruptions become only a little disruptive to the supply network.

In implementation, these practices could be positioned to suppliers as recommendations for building socially sustainable supply chain networks. Note that all of these practices are centered on a particular buyer and the buyer's decisions only with respect to its own direct network of suppliers. As such, they require no coordination or other forms of collective action among buyers, which would be much more difficult to attain. Similarly, these practices require little to no knowledge of the overall state of the global supply chain network.

The implementation of the regionalizing supplier-selection practices could be coupled with encouraging buyers to invest in and develop their local communities, all under the rubric of building socially sustainable business operations that are also robust to a range of major disruptions. To this end, a communication campaign involving an OEM's direct suppliers and a few key allies in other tiers of the network may be a useful start.[38] While it may be difficult for OEMs to identify individual suppliers in higher tiers of the GPSN, the regions the suppliers represent may be better known. We anticipate that local governments will support regionalizing supplier-selection practices and, as such, could be engaged as useful advocates in the adoption process. Similarly, the regionalization of supplier selection is likely to resonate with NGOs and social movements supporting regional economic development.

In the absence of managerial fiat or major incentives for adoption, it is reasonable to be concerned that these recommendations will not be widely adopted throughout the global supply chain network. Yet, according to our analysis, even minuscule changes in buyers' behaviors can result in noticeable gains in robustness. To put our results in real terms, even if only 5% of buyers change only one supplier per year following these practices, the resultant gains in network robustness in 10 years are significant. In some cases, they exceed 50% improvement in robustness in relation to real supply chain networks.

Toward a Comprehensive Strategy for Network Robustness and Resilience

As noted in the introduction, the robustness of supply chain networks should be assessed comprehensively with respect to the failures of suppliers or manufacturing facilities, environmental and economic shocks, distribution of inventory levels, and debilitating internal dynamics related to participating firms' decision making. In this conceptualization, *network robustness* is defined as the network's ability to reduce the disruption's immediate adverse impact on the network's functionality, such as sustaining an uninterrupted flow of goods and materials in the case of supply chain networks. In a supply network that is perfectly robust, failures of suppliers or environmental disturbances have limited or no discernible impact on the network's functionality. As such, building *network robustness* hinges on *proactive* strategies so that disruptions are less crippling.

In reality, attaining perfect robustness of a supply chain network to various types of disturbances would be extremely challenging, if not impossible. And by some accounts, doing so may not always be advisable because it could limit the GPSNs members' abilities to learn and adapt.[39] As a result, when a disturbance compromises a network's functionality, it may be useful to talk about *network resilience*, which is defined as "the ability of a supply chain to return to normal operating performance, within an acceptable period of time, after being disturbed."[40] As such, it focuses on *reactive strategies* to the focal disturbance that enable agile responses of individual organizations to disruptions that could collectively recover the network's outcomes.[41]

Importantly, however, such recovery need not aim to return the system to the pre-shock state in terms of the GPSN's network architecture, the participating companies' collaboration strategies, or the companies' strategic pursuits. Rather, significant disturbances may enable the GPSN's members to transform to a different, new, and potentially higher performing state.[42]

The latter point is particularly important and deserves elaboration. Often framed as the debate between the "engineering" and "ecological" (or "socio-ecological") conceptions of resilience, it focuses on whether complex systems need to return to the pre-shock state or transform to a new and more desirable state.[43] In this conception, the notion of "state" could describe a distribution of actors on some observable characteristics, relationships among the actors, or the actors' behaviors.

The engineering perspective focuses on recovery to the pre-disturbance state. In ecological reasoning, resilience is frequently viewed as the amount of disturbance that a system can withstand before it shifts to another stable configuration or behavioral regime.[44] An example is the amount of fire a forest ecosystem can absorb before shifting to the alternative state of a grassland. The ecological views on resilience have subsequently been extended to explore whether and when a system would not need to recover to the previous state, but instead would be better off transforming to a different state.

Applying this to GPSNs, we suggest that such transformation could be more desirable under the following two conditions. First, if the disturbance fundamentally affects the external economic, political, or social environment of the GPSN. For example, one can envision a disturbance that, in addition to disrupting global automotive supply chains, also affects customer preferences for alternate modes of transportation. Should that be the case, rebuilding a supply chain toward delivering obsolete products would hardly be effective.

Relatedly, if the disturbance requires a fundamental change in design, we anticipate that transitions to new states would be more fruitful on more "rugged" performance landscapes, which are characterized by complex interdependencies and hence feature multiple local performance optima.[45] Under these circumstances, disturbances can activate a distant search for new strategies and collaborators, which could result in a GPSN finding a higher local or a global performance peak. Importantly, studying these questions requires identifying how the focal GPSN interacts with, is affected by, and influences the critical elements of its external environment, including other GPSNs, as well as expanding the focus on the value created by a given GPSN.[46]

Second, the disturbance enables the collaborating organization to disengage from dysfunctional lock-ins in their inter-organizational relationships. Extant research highlights how collaborating organizations often allow commitment and attachment imperatives to dominate economic considerations[47]; furthermore, the difficulties of exiting from inter-organizational relationships are also well known.[48] Under these circumstances, the disruption of existing relationships could position a GPSN for strategic renewal, rather than the recreation of the pre-disturbance status quo.

Should managers devote limited organizational resources to building up a network's robustness or to mastering strategies that elevate the network's resilience? Intuition might suggest that investing in network robustness may be preferred to investing in network resilience; indeed, an ounce of prevention is better than a pound of cure. In reality, this presents a difficult choice, which may necessitate investing in both robustness and resilience. The set of possible disruptions may be so large and diverse that the best strategy may include organizations building the capacity for agile responses. Constraints on managerial discretion in making network choices can limit how much organizations can improve network robustness and master network resilience. In addition to market forces, leadership commitments, long-term inter-organizational relationships with difficult exit provisions, and conservative risk management orientation can all restrict proactive action to adapt the network to future shocks.[49] Limitations of human capital and the inability to observe and control the extended supplier network can further limit an organization's ability to engage in an effective reactive strategy to a given supply chain network disturbance.[50]

Thus, building a comprehensive strategy for supply chain network robustness and resilience should be among the firm's central organizational objectives. Unfortunately, both research and practice on network robustness and resilience are fragmented and have yet to be interconnected.[51] Future research can thus explore how a comprehensive strategy in this area could rest on such key formative elements as: a company's inter-organizational relationships (the focus of the present study), both active and potentially available as substitutes; the depth and breadth of its human capital; formal systems and procedures; cultural readiness; and the organization's financial and physical resources.

Based on our analysis, we advance three recommendations as most impactful toward building a comprehensive strategy for network robustness and resilience. First, *practice*. The organizational capacity to adopt contingency plans, which could be developed through simulation training, is of paramount importance. Implementing a contingency action plan to deal with the shutdown of a single production facility or port without prior training would surely result in mistakes, but those mistakes are unlikely to be catastrophic for business operations. For these types of normal disruptions, developing human capital—communication abilities, expertise in cost-benefit analysis, and practice in group decision making—alongside some basic procedures may be sufficient.

Second, because many disruptions spread regionally, engage in *stress testing in critical regions*. Simulated flare-ups by region would reveal network weaknesses that differ from those discovered through random knockouts. A network with four independent suppliers for a critical component may appear incredibly robust to random disruptions. However, if all four of the suppliers are located in Hamburg, Germany (because German firms have a technological competitive advantage in manufacturing that component), the four firms may as well be one for a geographically spreading disruption.

Third, when building GPSN networks, *include the regional value of suppliers when making choices*. Related to the point articulated just above, make supplier choice decisions with an eye toward regional stress testing. As shown in our analysis, the regional value of an employer includes its impact on the robustness of the network to geographically spreading shocks. Adding suppliers from a new continent or geographically distant part of the same continent, not just from a new country that might neighbor an existing supplier country, also provides information that can complement the first two strategies. Through stress testing, firms can learn if, when, and how much thinking regionally matters.

Conclusion

The increased connectedness of the global economy means that any number of environmental, political, economic, and public health disruptions could disable multiple suppliers through a contagion-like process that spreads geographically. Such disruptions could threaten the functionality of global supply chain networks, which in turn could debilitate economic growth, prosperity, and firms' ability to function. In this article, we examined how companies can build robust global supply chain networks in situations when no single company or group of companies has control or authority over the actions of all the other companies in the supply network.

Our central contribution lies in uncovering that promoting even a small shift toward regionalizing supplier-selection practices—in which even a handful of buyers choose suppliers that are geographically proximate to the buyers or to the buyers' current suppliers—results in significant gains in supply chain network robustness. We anticipate that the proposed recommendations for supplier selection and management can immediately inform practice to improve how GPSNs withstand a range of disruptions, including those resulting from pandemics, social and political unrest, as well as natural and human-made disasters. More broadly, we hope to stimulate a conversation about a collective approach to the health of GPSNs and how all supply chain participants can contribute to and share the responsibility for their robustness.

Technical Appendix

Empirical Data

We formalized global production and supply networks (GPSNs) as networks in which companies (nodes) are connected by buyer-supplier relationships (edges). To populate the network, we used the data on the tier-1, tier-2, and tier-3 supply networks of three global automotive manufacturers: General Motors, SAIC Motor Corporation (SAIC), and Volkswagen (Source: Bloomberg Supply Chain). This resulted in a sample of 5,330 unique companies and 20,309 quantified relationships connecting them. From this sample, we omitted the relationships between companies that are not related to the cost of goods sold (i.e., those associated with CAPEX, R&D, and SG&A). The resultant sample comprised 12,132 relationships connecting 3,289 unique companies. For each of these companies, we identified geographic locations using Bloomberg data and an extensive manual Internet search.

The Model of Supply Network Change

Supplier-selection practices. In each model tick, 5% of edges of a network are rewired using one of the supplier-selection practices. Specifically, an edge selected for rewiring will have the same buyer, but a different supplier from the same tier as the "rewired" supplier. The supplier to which the edge is being rewired is chosen from the empirical pool of actual suppliers of all three automakers from the appropriate tier. In our empirical data, 24.35% of suppliers are featured in two distinct tiers, and 4.87% are featured in all three tiers. In those cases, the supplier is featured in the selection pool for all tiers in which it operates. The rewiring procedure enables us to keep the overall density of the evolving GPSN network constant, thus eliminating a potential confound of network robustness.

Each of the three empirically observed networks evolves for 10 ticks using each one of the supplier-selection practices (separately), which results in the 3 (networks) × 7 (supplier-selection practices) factorial design of the computational experiment. We ran the model 100 times for each of the nine conditions, resulting in a total of 2,100 networks. Our study additionally used the three empirically observed networks in their real-life manifestations (i.e., without any simulated changes) for a total of 2,103 networks used in our analyses.

The three empirical networks evolved using the following seven supplier-selection practices.

Description of examined supplier-selection practices	
Baseline: random	A buyer chooses a supplier randomly, irrespective of the supplier's geographic location, from all suppliers available in a given tier. For example, if a tier-1 buyer is substituting for a tier-2 supplier, only tier-2 suppliers would be eligible as replacements.
Globalizing supplier-selection practices	
max.dist	A buyer chooses a new supplier (randomly) from a country that *maximizes* the mean distance from the countries of its existing direct suppliers. For example, for an OEM, this rule would maximize the mean distance from each of its tier-1 suppliers to the new supplier. To calculate distances between countries, we applied the spherical distance formula to the countries' centroid locations.
least+1	A buyer chooses a new supplier (randomly) from the *least represented* country in terms of the number of the buyer's current direct suppliers. For example, if a buyer has 10 suppliers, where two are from Mexico, three are from the United States, and five are from China, the new supplier will be from Mexico.
far.fav	A buyer chooses a new supplier from a country that is *most distant* from the country that is most well-represented by the buyer's current direct suppliers.
Regionalizing supplier-selection practices	
min.dist	A buyer chooses a new supplier (randomly) from a country that *minimizes* the mean distance from the countries of its existing direct suppliers. For example, for an OEM, this rule would minimize the mean distance from each of its tier-1 suppliers to the new supplier. To calculate distances between countries, we applied the spherical distance formula to the countries' centroid locations.
most+1	A buyer chooses a new supplier (randomly) from the *most represented* country in terms of the number of the buyer's current direct suppliers. For example, if a buyer has 10 suppliers, where two are from Mexico, three are from the United States, and five are from China, the new supplier will be from China.
continent	A buyer chooses a new supplier (randomly) from those that are located on the *same continent* as the buyer.

Note: OEM = original equipment manufacturer.

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