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20th Anniversary Invited Article

Impact of Tariffs on Global Supply Chain Network Configuration: Models, Predictions, and Future Research

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Abstract. The past three decades have witnessed tremendous growth of supply chain activities around the globe thanks to the lowered trade barriers and free trade agreements among countries. The global supply chain management literature developed during this time provided theoretical frameworks and decision support tools for operational and supply chain decisions in the global context. Recent development in trade barrier debates as well as increasing uncertainties in countries' trade policies have forced companies to rethink their global operational strategies. In this short paper, we draw insights from the existing global supply chain literature and in particular, focus on interpreting recent research contributions published in *Manufacturing & Service Operations Management (M&SOM)* on the topic to gain understanding of the implications of trade policies, especially tariffs, for firms' global facility network design decisions. We also provide a discussion of important dimensions that were absent from the existing literature but are pertinent to providing a richer understanding of implications of trade policies for today's interconnected supply chains. Future research that takes into consideration those previously less explored dimensions has the potential to offer insights not only to industry practitioners but also, to the policy makers. Developing an appreciation of potential reactions from complex connected supply chains in various industries would help policy makers better anticipate the impact of trade policy change.

History: This paper has been accepted for the *Manufacturing & Service Operations Management* 20th Anniversary Special Issue.

Keywords: tariffs • global supply chain • operational flexibility • network configuration

1. Introduction

The recently imposed U.S. 232 tariffs (based on Section 232 of the Trade Expansion Act of 1962) on steel (25%) and aluminum (10%) imports had serious and often unexpected implications for multinational firms and global supply chains. They immediately led to retaliatory tariffs by affected countries, including the European Union, Canada, Mexico, and China, and strategic reactions of firms to their new realized cost structures. These tariffs were motivated by the need to protect steel and aluminum producers in the United States, and they were expected to lead to increased regionalized production, with the hope of increased manufacturing employment in the United States. Thus far, we have seen that the implied predictions of single-firm microeconomic models do not necessarily explain some of the observed outcomes (e.g., closure of some U.S. factories in certain industries and shifting of their locations to Europe or Asia). Therefore, this begs the question about whether our more detailed operational modeling of supply chain networks better captures the impact of tariffs on global supply chains, production output, and firm profitability. Using recent

research papers that appeared in *Manufacturing & Service Operations Management (M&SOM)*, we will interpret modeling predictions of this research related to the impact of tariffs on global supply chains. We conceptually formalize the modeling results as applicable to tariff impact and then, interpret observed outcomes through them. Furthermore, we will identify issues not yet effectively captured in our supply chain network and location models and thus, naturally point to future research directions to help us better understand corporate implications of such trade issues in a highly interconnected global environment.

The other major tariff event of 2018 was the proposed Section 301 \$50 billion in tariffs on Chinese goods (based on Section 301 of the Trade Expansion Act of 1974 in response to unfair trade practices). The 232 and 301 tariffs led to retaliatory tariffs by China, including a 25% tariff on American soybeans and substantial tariffs on pork and pig offal imports. Again, the observed outcomes in both the soybean and pork industries are far from being explained through single-firm microeconomic models, and the richness of our global network models highlights missed insights and

meaningful predictions. However, there are still growing issues to be captured in our modeling works if we want to more effectively deal with the systematic and global supply chain impact of such phenomena (e.g., escalated tariffs) in complex, multiproduct, multistage supply chains. In this paper, at a first level, we show how simple models that build on existing insights can inform us on managerial decisions and provide an educated interpretation of observed outcomes. At a second level, we point to the surprising and unexplained issues as avenues to guide future modeling work that balances the need to depict relevant operational complexity while at the same time, abstracts a stylized setting amenable to meaningful analysis for insights and conceptual understanding. This is always the art of modeling, and our community has proven talented in mastering it.

There is a vast amount of research on factors impacting global supply chain network structure that could form the basis of an analysis about how escalated tariffs and trade wars might be affecting supply chains, firm outputs, and profitability. Because of the immediacy of these events, there are no custom-built research papers to directly address them. Our paper is uniquely positioned to serve this role. We use recent modeling work in *M&SOM* as the basis of a modeling platform to explain tariff impact on supply chain structure. The reasons for this choice are relevance to the topic, wide familiarity of the models within our community, and to better serve the special issue of *M&SOM* that the paper is written for. We will use the newsvendor network model studying supply chain structure in Lu and Van Mieghem (2009) as the benchmark model for early prediction on tariff impact in industrial supply chains. Getting beyond the fixed price setting of the newsvendor network and considering the strategic option of firms to respond to cost increase from tariffs on either input materials or shipped finished goods (FGs), we discuss the responsive pricing newsvendor network model under both demand and exchange rate uncertainty of Dong et al. (2010) as an advanced discussion platform for tariff implications.

Although it is outside the scope of this paper to have a detailed discussion of all relevant literature, we would like to point out seminal works that the interested reader should refer to as the basis of additional thinking on issues raised in this paper. The early framework research on global resource deployment analysis in facility networks by Cohen and Lee (1989) is a useful conceptual contribution. A structural mathematical programming approach to depict operational complexity in facility network choices is presented in Kouvelis et al. (2004), and a structural equations model using global sensitivity analysis is presented for factors influencing global facility network design in Kouvelis et al. (2013). For other relevant research references, we refer readers to the

research monograph by Kouvelis and Su (2008) and the reference list in Kouvelis et al. (2013).

The structure of our paper is as follows. In Section 2, using the newsvendor network model for the study of global facility network structure of Lu and Van Mieghem (2009), we discuss the main factors influencing facility network design and how tariffs on input materials may be affecting them. Our discussion highlights the advantages of a more detailed and complex operational model in deciphering observed tariff impact outcomes in certain industries over single-firm economic models. At the same time, we point out the limitation of these models and especially, the exogenous fixed prices for sold goods. Section 3 uses a responsive newsvendor network model of both price adjustment and ex post transshipment flexibility in forming the basis for interpreting tariff impacts at different stages of the chain either at the input level or in the finished goods duties. It will allow for an informed discussion of surprising outcomes in auto and motorcycle manufacturing, appliances, and the pork industry. Still, there are many unexpected issues behind strategic reactions of firms to escalated costs owing to tariffs that have to be outlined in order to address observed outcomes. These issues at a simple modeling level form the basis of Sections 4 and 5.

The logic that levying tariffs will help protect and strengthen the corresponding domestic industry is not that straightforward in today's global economy, where firms around the world are interconnected through multidirectional trading flows and multistage competitions and where firms can exploit their operational flexibility to ex post reoptimize their use of supply chains. The implications of the collective optimal responses are hard to predict. We will use simple models and examples to illustrate how the impact of tariffs can be affected by the presence of some of those factors mentioned above: in particular, the tariff policy uncertainty, operational flexibility, and competition.

More specifically, Section 4 looks into ex post product mix adjustments in product portfolios with substitute or complement products. We use a simple model to explain tariff impact on different products within complex product portfolios. We also discuss other substitution strategies at the material level that firms may use to react to increased costs owing to tariffs. Section 5 tries to understand how operating exposure to tariffs depends on the structure of competitive facility networks and the intensity of industry competition. Again, a simple model informs us, and our discussion interprets observed outcomes of tariff impact in a variety of industries. Finally, Section 6 uses our discussion of still relevant but unexplored issues in modeling research to present directions for future meaningful research on the topic.

2. Newsvendor Network Model and Tariff Implications

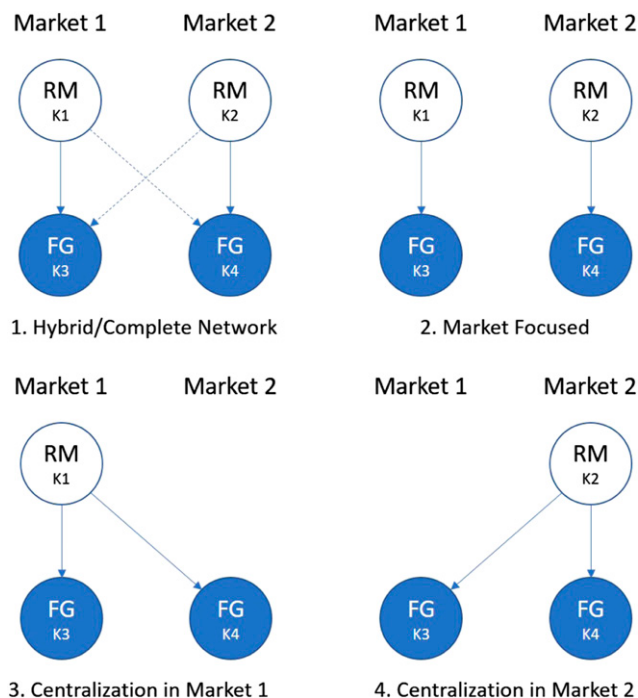
Lu and Van Mieghem (2009) consider a two-stage production system in which the upstream stage produces raw material (RM) for the downstream stage. The downstream stage performs final assembly of FGs. The RM can be produced in both the domestic market (Market 1) and the foreign market (Market 2); the FG production is dedicated to a specific market, and its facility is located in the corresponding market. RM produced in one market can be shipped to another market, incurring crossmarket transshipment cost (including shipping costs, tariffs, and duties). The network configuration decision includes the location decisions for the RM facilities and the capacity levels for the RM and FG facilities. Under this setting, four facility location configurations are possible (see Figure 1). The hybrid/complete configuration and the market-focused configuration have RM facilities located in each market. The hybrid configuration offers an ex post transshipment option, which is valuable to the firm if demands in two markets are uncertain. Under centralization configurations, the firm centralizes an RM facility in one of the markets and uses transshipment to supply RM to the other market. Adopting the newsvendor network framework of Van Mieghem and Rudi (2002), the authors establish thresholds of the transshipment cost below which centralizing the RM facility in one market is the optimal configuration. Otherwise, establishing RM facilities in both markets is optimal. What is important to recognize is that the transshipment thresholds are influenced by the market price difference and the manufacturing cost difference as well as the demand distributions of the two markets, reflecting the complex tradeoffs that the firm must balance between the revenue benefit and the cost implications in an uncertain world. We interpret their results related to transshipment costs to shed light on the discussion of the impact of tariffs on network design.

1. When transshipment costs are low, centralization configurations are viable choices. In this case, the market price difference and the demand uncertainty (mean, variance, and correlation) play an important role in deciding in which market to centralize the RM facility.

2. High transshipment costs drive the firm to establish RM facilities locally in each market. The market-focused configuration dominates the hybrid configuration when the transshipment cost (that is, the cost of exercising the ex post transshipment option) is prohibitively high.

Lowering trade barriers and economic reforms in the emerging economies have given rise to exploding growth of global supply chains. In the past three decades, many industries have witnessed drastic reorganization of supply chains around the globe, which

Figure 1. (Color online) Four Possible Configurations of a Multimarket Facility Network (Lu and Van Mieghem 2009, Dong et al. 2010)



often led to certain value-adding stages being concentrated in a specific country/region (i.e., the centralized configuration). For example, Asia has become the top sourcing destination (exporters) for, among others, textile and apparel as well as semiconductor and electronic circuit components, and it is the top producer for steel and iron. The United States is a top exporter of agricultural goods, aircraft, and automobiles.

According to these results, the model predicts that the levying of tariffs will discourage centralized production of the tariffed product categories and promote market-focused network configuration. At the raw material stage, the 232 tariffs will result in increased output and potentially, additional capacity investments of the U.S.-based steel and aluminum mills. For downstream manufacturers (automobiles, aircraft, appliances, canned fruits and vegetables, beverages, computer makers, etc.), even though at some increased input material costs, they may increase their local input material sourcing. In October 2018, the American Iron and Steel Institute reported that U.S. steel mills saw a 4.6% increase in shipment thus far in 2018 compared with 2017 (American Iron and Steel Institute 2018). However, the markets are concerned with how this may affect downstream manufacturers through increased costs, which may hurt their own demand if they increase prices, or they may strategically react to it through material substitution and/or shifting of their supply chains. Reflecting such concerns, stock prices of some of the

nation's biggest steel makers dropped by almost 50% in 2018 (Rapporteur 2019).

Limitations of the newsvendor network models for the study of global supply chains are the assumed fixed finished goods prices and not modelling input material substitution and/or product mix changes in response to the altered cost conditions. This seems to be clearly in full effect in the case of the automotive industry, with the amount of steel or aluminum input material heavily dependent on the type of car and its construction. Sedans are much lighter in such inputs relative to sport utility vehicles (SUVs) and pickups. In a plateauing U.S. car market, where more than 70% of vehicles sold are SUVs and pickups, increased cost owing to tariffs is very penalizing, with U.S. car manufacturers (Ford and GM) expected to see reduction of operating profits in the half a billion dollar range (Trivedi 2018). Adjusting prices and pushing some of the cost increases to consumers depending on the type of car and market segment (luxury vehicle demand is inelastic, and therefore, it is easier to push cost increases to consumers, whereas mass market sedans and small SUVs are more elastic, and therefore, it is hard to pass cost increases to the market) are the first levers to be pulled. Other strategic reactions include pushing attractive incentives to dealers to sell more sedans, working with their suppliers to substitute materials in their components, shifting the focus of their supply chain investments in serving growth markets in Asia, and reorienting their product portfolio toward electrical vehicle technologies with configurations less dependent on steel and aluminum inputs.

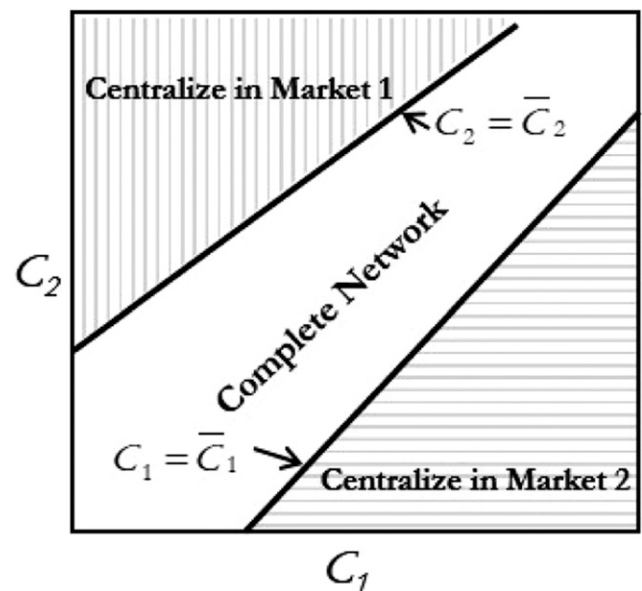
From the above discussion, newsvendor network models depicting multistage supply chain and location thinking (stylized two stages of input materials and final production/distribution) better reflect the reality of globalized supply chains, with cars produced all over the world—American cars are made with foreign parts, and European and Japanese cars are often made in the United States. However, a better modeling platform for tariff impact will have to at least reflect price adjustments to realized cost uncertainties. The more recent work of Dong et al. (2010), our next and more advanced model for discussing tariff impacts on supply chains, fits the requirement.

3. Responsive Pricing Newsvendor Network Model and Tariff Implications

Responsive pricing newsvendor network models allow prices to become part of the ex post decisions (Dong et al. 2017). Endogenizing prices enables the modeling of product interdependence (e.g., substitutes and complements), various forms of demand shocks (e.g., additive and multiplicative), and firm competition. Dong et al. (2010) adopt a responsive

pricing newsvendor network model to study the RM facility network design decision (assuming that FG facilities in both markets have ample capacities) under both demand uncertainty and currency exchange rate uncertainty. The authors characterize the optimal global facility network configuration by establishing thresholds of the unit production cost C_i in market i , $\bar{C}_i$, above which it is optimal that the firm centralizes the RM facility in market $j = 3 - i, i = 1, 2$ (see Figure 2). Let K_i represent the RM capacity level in country i ; superscripts C and F refer to specific network configurations: C for centralized, and F for complete ("full") network (see Figure 1) (networks 3 and 4 are centralized, and network 1 is full). Specifically, if $C_1 > \bar{C}_1$, then the firm centralizes RM production in Market 2 ($K_2^* = K_2^C > 0, K_1^* = 0$); if $C_2 > \bar{C}_2$, then the firm centralizes RM production in Market 1 ($K_1^* = K_1^C > 0, K_2^* = 0$). Otherwise, the firm produces RM in both markets ($K_1^* = K_1^F > 0, K_2^* = K_2^F > 0$). The paper provides comparative statics of the optimal capacities K_i^* and thresholds $\bar{C}_i, i = 1, 2$ with respect to the cost parameters and the demand and exchange change rate uncertainties. One interesting finding is that responsive pricing as a tool that the firm can use to maximize its ex post profit in response to the realized demand and exchange rate enables the firm's configuration preference to be less susceptible to changes in the unit FG production cost and changes in the mean demand than that of the newsvendor firm. Here, we interpret the comparative statics results to shed insight on the impact of tariffs on network design. Our most relevant results (Results 1 and 2) are as follows.

Figure 2. Optimal Configurations of a Multimarket Facility Network (Dong et al. 2010)



Result 1. Consider that the production of RM requires importing inputs from another country. That is, the unit production cost C_1 in Market 1 includes tariffs charged on the imported input. As the tariff increases, C_1 increases, and the optimal quantity produced in Market 1, K_1^C or K_1^F (depending on the optimal configuration), decreases. Moreover, when C_1 exceeds $\bar{C}_1$, if using Market 1's domestic input for RM production also results in a unit cost being higher than $\bar{C}_1$, then the firm should centralize its RM production in Market 2.

Result 2. Ex post transshipment of the produced RM enables the substitutability of RM produced in the two markets and can help the firm effectively cope with the fluctuating demands and currency exchange rate. Increasing the *inbound* transshipment cost of produced RM to market i , which may be the result of imposed tariffs on imported goods by market i , would decrease the firm's total RM production quantity but increase the RM production in market i . It also decreases the attractiveness of centralizing RM production in the other market (i.e., $\bar{C}_i$ increases in the transshipment cost into market i). Similarly, increasing market i 's *outbound* transshipment cost of produced RM, which may be the result of imposed tariffs by country j , would decrease the RM production in market i and increase the attractiveness in the other market.

The model clearly depicts the reality of global supply chains: that goods produced and sold in country i may involve inputs coming from country j , and those inputs may have required raw material coming from another country (potentially even country i). In looking at the impact of retaliatory tariffs by China on U.S. autos and components (as high as 40%), one has to account for the fact that autos produced in the United States may be using Chinese components that are exposed potentially to U.S. tariffs, and the final products exported to China are also exposed to Chinese tariffs. However, as the model would have predicted, the lower manufacturing costs in China and the high transshipment costs owing to tariffs from the United States to China result in U.S. auto manufacturers shifting most of their sourcing and final production to China. Actually, the level of Chinese tariffs on autos might be immaterial, because already, the vast majority of the world's cars are made there because of both manufacturing costs and low steel and aluminum input prices.

In June of 2018, Harley-Davidson announced the shifting of some of the production of its bikes overseas to avoid stiff retaliatory tariffs imposed by the European Union. Harley-Davidson saw its production costs increase in the United States owing to the 232 tariffs on steel and aluminum, and the European retaliatory tariffs increased its transshipment costs to Europe by adding, on average, \$2,200 per bike (Rappeport 2018). Worrying about the detrimental

impact on its business arising from any effort to pass a substantial portion of the cost to dealers and consumers and recognizing that most of the sales growth is driven by the European markets, the company shifted away from a centralized network with heavy investments of component facilities in the United States to a market-focused solution with regionalized U.S. and European supply chains. As our Results 1 and 2 imply, the impact of tariffs on upstream and downstream stages points to the same direction profitwise and remedial solutionwise. To manage cost increases and avoid hurting demand, moving production capacity outside of the United States is the rational corporate response.

Tariffs and the U.S.-China trade war have complicated corporate actions in the pork industry. Chinese retaliatory tariffs on soybeans heavily affected U.S. soy exports and lowered soy prices. Soy prices were further affected by a bumper crop in the United States, Brazil, and Argentina, the major soybean-sourcing locations. The good news on the input material side for U.S. pork producers was followed by the negative impact of Chinese-imposed tariffs on pork and offal products, especially when the Chinese market is the main export market for U.S. pork producers. It is reported that the share of China's pork imported from the United States shrank to 30% by November of 2018 (Shike 2018). Making matters worse, China has attempted to dramatically increase its own domestic pork production, with the resulting oversupply further depressing pork prices in the United States.

From the perspective of U.S. pork producers, the tariff wars are a mixed bag. Although Result 1 implies that an increase of pork production in the United States is the way to go, the rather saturated low margin nature of the U.S. pork market and the suspicion of unsustainability of the low soybean prices in the long run raise the importance of understanding the impact of retaliatory pork tariffs by China. Following the implication of Result 2 and with China facing the need to meet growing domestic pork demand at reasonable prices, it offers incentives for pork production investment in the country. Some U.S. pork producers are considering shifting their production capacity and regionalizing a Chinese pork meat and offal supply chain. The concerns about increased soybean input prices are easily ameliorated, because Brazil and Argentina have geared up to substitute for U.S. soybean sourcing at reasonable prices. Furthermore, regulation allowing for lowered protein content in hog feed and/or substitution of soy with other inputs in the feed has kept animal feed costs in China at reasonable levels. A persistent effect of tariffs on U.S. soybeans may be creating incentives for strong investments in soybean growing, storing, and further processing in South America (especially Brazil and Argentina),

where many of the major agricultural firms (Bunge, ADM, and Cargill) already have facilities and access; thus, there would be a more permanent shifting of soybean supply to China from the region. Although the soybean industry might be shifting toward independent supply chains (the United States, Europe, South America, and Asia) not easily influenced by a U.S.-China trade war, the pork industry might shift its heaviest hub to Asia, resulting in costlier pork for U.S. consumers.

In the above-described stories in both the automotive and pork industries, there are important issues that might be delaying implementation of some of the suggested actions and explain observed inertia of strategic responses to the imposed tariffs. The most important factors behind such inertia are as follows.

1. *Switching cost.* For many industries, switching suppliers takes a considerable amount of time and effort. Certain types of manufacturers—like automobile manufacturers—must go through time-intensive processes to qualify suppliers.

2. *Tariff policy uncertainty.* The uncertainty about the timing and the magnitude of future tariff policies as well as possible tariff retaliations from other countries can deter firms from making immediate drastic changes in sourcing strategies. This factor has been key in the pork producer reactions, with both the uncertainty of soybean prices and the outcome of the trade war on imposed tariffs on pork by China driving a wait-and-see attitude on magnitude of investments and locations of new capacity.

Some of the newsvendor network and responsive pricing with transshipment options modeling works address the multistage sourcing and production aspects of supply chains and reflect the reality of global product flows cutting across countries while exposed to multiple tariff and political/regulatory forces. However, there are still important unexplored issues to understand and explain observed outcomes in the recent tariff escalation and subsequent trade wars. Two of the important ones are as follows.

U1. Operational flexibility. Many firms have developed operational flexibility to cope with supply and demand sides' uncertainties and disruptions. When rising tariffs hamper firms' crossmarket transshipment flexibility, they will resort to other operational flexibility to mitigate the negative impact from tariff changes. For example, as we discussed above, passing cost increases owing to tariffs to the downstream customer through price increases is relatively easy to implement. Firms can also explore alternative bill of materials to reduce their reliance on the tariffed input. Firms with wide product portfolios can shift production and marketing focus to products that depend less on the tariffed inputs or products with demands that are inelastic.

U2. Competition. Global firms often face competition in multiple markets. A tariff increase on inputs of those firms will weaken their competitiveness and decrease their market shares in those markets. Thus, a firm's sensitivity to tariff policy depends on how connected it is to global markets and competitive situations in those markets.

Although in this section, we dealt to an extent with price adjustments in response to tariffs in a responsive newsvendor network model, other operational flexibility adjustments through input substitution or product mix sold to a market can be important strategic levers for a firm in responding to new tariff regimes. Additionally, the operating exposure of a firm to the tariffs is an important factor to consider, with the effects of tariffs on competitive cost structures and the nature of competition in an industry explaining strategic responses pursued when new tariffs are levied. In the next section, we present simple modeling efforts to capture such issues in a way that can sharpen our understanding of supply chain network implications of tariffs. Our objective was to offer insights through simple models rather than a comprehensive and complex modeling of situations. The latter might be something worthwhile to pursue in future research as we outline in Section 6.

4. Product Portfolio Flexibility: Substitutable and Complementary Products

We now explore how multiproduct firms and firms that can custom adjust their offerings in multiple markets respond to tariff-driven cost increases. We provide insights on the implications of tariff increase for those firms.

Many firms offer product portfolios consisting of substitutable or complementary products. A wider product offering not only enables a firm to cater to diverse customer needs but also, offers them flexibility to cope with changes in the business environment. For example, when changes in tariffs affect the cost of offering some products in the portfolio, the firm can adjust its pricing, production, and promotion effort over the entire portfolio to offset or mitigate the negative impact of the increasing cost.

To illustrate, let us consider a firm selling two products, product A and product B, with inverse demand functions that are given as follows:

$$p_A(q_A, q_B) = A_A - q_A - \beta q_B, \quad p_B(q_A, q_B) = A_B - q_B - \beta q_A,$$

where q_A and q_B are the selling quantities of product A and product B, respectively; $\beta \in (-1, 1)$ measures the degree of substitution and complementarity between the two products: $\beta > 0$ represents a substitution relationship, and $\beta < 0$ represents a complementary

relationship. The unit variable cost of product A, $\tilde{v}_A$, is affected by a tariff policy on an input component. We assume that the future tariff rate is uncertain and that $\tilde{v}_A$ follows a uniform distribution $[v_A, v_A + \Delta]$. The production of product B is not affected by the same tariff, and for simplicity, we assume that the unit variable cost of product B, v_B , is constant. The two products share one production facility. The firm must decide, before the uncertainty of the tariff is resolved, the capacity level of the facility, K , at unit cost c and then, decide the production quantities for the two products after the tariff uncertainty is resolved. The firm's two-stage problem can be formulated as follows:

$$\text{Time 0: } \max_{K \geq 0} \mathbb{E}\{\pi(K, \tilde{v}_A) - cK\},$$

$$\text{Time 1: } \pi(K, \tilde{v}_A) = \max_{\substack{q_A, q_B \geq 0 \\ q_A + q_B \leq K}} \{p_A q_A + p_B q_B - \tilde{v}_A q_A - v_B q_B\},$$

where $\mathbb{E}$ takes expectation over $\tilde{v}_A$.

It is straightforward to establish that the time 0 objective function is a convex function in K . We solve the optimal capacity K^* and obtain the corresponding expected production quantities and prices for products A and B, $\mathbb{E}[q_A^*]$, $\mathbb{E}[q_B^*]$, $\mathbb{E}[p_A^*]$, and $\mathbb{E}[p_B^*]$, respectively. Increasing Δ represents increasing both the mean and the variance of the unit cost $\tilde{v}_A$ for product A. To understand how the tariff uncertainty affects the multiproduct firm's capacity and selling decisions, Proposition 1 provides comparative statics of the optimal capacity and expected selling quantities and prices with respect to Δ .

Proposition 1.

- (a) $\mathbb{E}[q_A^*]$ decreases in Δ . $\frac{d^2 \mathbb{E}[q_A^*]}{d\Delta d\beta} < 0$ for $\beta > 0$, and $\frac{d^2 \mathbb{E}[q_A^*]}{d\Delta d\beta} > 0$ for $\beta < 0$.
- (b) $\mathbb{E}[q_B^*]$ increases in Δ if $\beta > 0$ but decreases in Δ if $\beta < 0$. $\frac{d^2 \mathbb{E}[q_B^*]}{d\Delta d\beta} > 0$.
- (c) $\mathbb{E}[p_A^*]$ increases in Δ , but $\mathbb{E}[p_A^* - \tilde{v}_A]$ decreases in Δ . $\mathbb{E}[p_B^*]$ is constant in Δ .
- (d) K^* decreases in Δ , and $\frac{dK^*}{d\Delta d\beta} > 0$.

Parts (a)–(c) of Proposition 1 state that an increase in the mean and the variance of the unit cost for product A would decrease the expected production quantity for product A. The demand interdependence between products A and B decides that product B, for which unit cost remains constant, is also affected. The expected production quantity for product B increases (decreases) in Δ if A and B are substitutes (complements). The quantity adjustment for the two products is accompanied by increasing the selling price of product A (i.e., passing the cost of a higher tariff to the downstream customer) while keeping the selling price of product B constant. The more interdependent product A and product B are (a stronger substitution or a stronger complementary relationship;

that is, higher $|\beta|$), the faster $\mathbb{E}[q_A^*]$ decreases in Δ and the faster $\mathbb{E}[q_B^*]$ increases (decreases) in Δ in the case of substitute (complements). Part (d) of Proposition 1 states that the optimal capacity level K^* decreases in Δ and decreases more slowly (faster) as products A and B become more substitutable (complementary).

Aluminum is an extremely important input component for the beverage can industry. In fact, nearly 100% of all cans in the United States to package beer, soft drinks, juices, and other nonalcoholic beverages are made from 100% aluminum. A 10% tariff on the price of imported aluminum gets passed through the production process from can sheet makers to can producers to beverage producers and to some extent, to consumers. The option to substitute away from products using aluminum cans to other packaging options, like plastics, aseptic packages, and glass bottles, is frequently exercised for many soft drinks and nonalcoholic beverages. For the beer industry, the reality is that 60% of all beer sold in the United States is in aluminum cans, and both consumer preferences and capacity constraints in the production process make it hard to substitute away from aluminum cans (see the white paper on the beer industry in John Dunham & Associates 2018). About 36% of the aluminum in beer cans is imported, and 64% is sourced domestically. It is expected that the 232 tariffs will impact in the range of one to two cents per beer can. Within a highly competitive market, it is hard to adjust prices for the high-volume beer brands, and efforts in adjusting prices by smaller producers of microbrews may drive some demand away. Vertically integrated producers, like ABInBev, with some aluminum capacity of their own can change their process for altered aluminum quantity in their cans for some products and adjust offered product portfolios to their vendor-managed inventory wholesalers. It is expected that ABInBev will better manage tariff impact on North American beer sales relative to competitors, like Molson-Coors, that rely on sourced cans from U.S. and Canadian suppliers. It is reported that the U.S. unit of Molson-Coors had a \$40 million cost increase in its operation owing to tariffs (IndustryWeek and Bloomberg 2019). For smaller craft brewers, like Oskar Blues in Colorado, tariffs would either result in delayed capital investments in a badly needed effort to match growing demand or some increase in prices that may hurt current and future growth.

As we discussed in previous examples, changing the product mix in the product portfolio is a frequent strategy in the automotive industry to counteract 232 tariffs and retaliatory tariffs on cars by other countries. Car manufacturers selling to the U.S. market are incentivized to focus on lighter usage of steel and aluminum products, such as sedans and small SUVs. For exporters of U.S.-made cars to other markets, the

flexibility of a product portfolio that has luxury and mid- to upper-market vehicles makes it possible to pass some of the cost increase via adjusted prices without hurting demand. Shifting production of the low-end vehicles to China is the only way to deal with this double-whammy effect of cost increases in both raw materials and assessed duties on exported goods to the sales region. We expect more reduced capacity and closed factory announcements, like the ones by GM or Harley-Davidson, as tariffs on imported cars are maintained by China or the European Union. Although some input material substitution may be possible by U.S. suppliers to the car industries, the uncertainty of the tariff amount and duration may be prohibitive to obtaining capital investment needed for a profound impact on cost structures, thus leaving supply chain shifting backed up by demand growth in the sales region as a more permanent and easy driver for such decisions.

5. Competition and Tariff Impact

In competitive business environments, the extent to which firms compete with rival firms in global markets influences the impact that tariffs can have on their profitability, strategic reaction, and long-term market share. In the next stylized example, we consider two firms, Firm 1 and Firm 2, producing substitutable products and selling in their respective domestic markets. We compare four competition scenarios (illustrated by the four network structures in Figure 3). Let q_{ij} be Firm i 's quantity selling to market j , $i, j = 1, 2$. Scenario A represents the case that each firm is a (local)

monopolist in its domestic market ($q_{12} = q_{21} = 0$). In Scenario B, Firm 2 exports to and competes with Firm 1 in Market 1 ($q_{12} = 0$). In Scenario C, Firm 1 exports to and competes with Firm 2 in Market 2 ($q_{21} = 0$). In Scenario D, two firms compete with each other in both markets. Firm i 's unit production cost is v_i , and it incurs shipping cost t_i for every unit shipped to another market. We assume Cournot competition in each market and study how an increase of unit variable cost for one firm, in this case Firm 1, affects the production quantity for the two firms. We assume a linear (inverse) demand function in each market:

$$\begin{aligned} p_1(q_{11} + q_{21}) &= A_1 - (q_{11} + q_{21}), \\ p_2(q_{12} + q_{22}) &= A_2 - (q_{12} + q_{22}). \end{aligned}$$

The Cournot game between these two firms is formulated as below:

$$\begin{aligned} \text{Firm 1: } \max_{\vec{q}_1} \pi_1(\vec{q}_1 | \vec{q}_2) \\ &= \max_{\vec{q}_1} p_1(q_{11} + q_{21})q_{11} + p_2(q_{12} + q_{22})q_{12} \\ &\quad - v_1(q_{11} + q_{12}) - t_1 q_{12}, \\ \text{Firm 2: } \max_{\vec{q}_2} \pi_2(\vec{q}_2 | \vec{q}_1) \\ &= \max_{\vec{q}_2} p_1(q_{11} + q_{21})q_{21} + p_2(q_{12} + q_{22})q_{22} \\ &\quad - v_2(q_{12} + q_{22}) - t_2 q_{21}, \end{aligned}$$

where $\vec{q}_1 \equiv (q_{11}, q_{12})$ and $\vec{q}_2 \equiv (q_{21}, q_{22})$ represent the production quantities of Firm 1 and Firm 2, respectively.

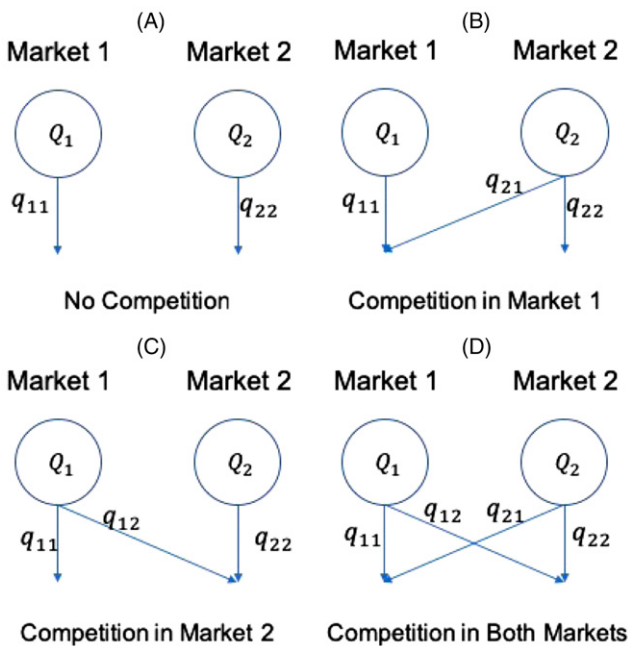
There exists a unique equilibrium for each of the four scenarios. Define the equilibrium total quantity produced by firm i by Q_i^* , $Q_1^* \equiv q_{11}^* + q_{12}^*$, and $Q_2^* \equiv q_{21}^* + q_{22}^*$. We consider the case where Firm 1's unit production cost v_1 is affected by a recently imposed tariff. A cost increase for one firm leads to a production decrease for that firm. How does the competition relationship (i.e., the way that firms are connected with each other in the network) affect the rate of decrease for that firm and affect the response of the other firm? Proposition 2 compares the rate of change in Firm i 's equilibrium total quantity in response to an increase in v_1 across all four competition scenarios, $i = 1, 2$.

Proposition 2. Let Q_{iX}^* be Firm i 's equilibrium total quantity in Scenario $X \in \{A, B, C, D\}$. Then,

$$\begin{aligned} 0 &> \frac{dQ_{1A}^*}{dv_1} > \frac{dQ_{1B}^*}{dv_1} > \frac{dQ_{1C}^*}{dv_1} > \frac{dQ_{1D}^*}{dv_1}, \\ 0 &= \frac{dQ_{2A}^*}{dv_1} < \frac{dQ_{2B}^*}{dv_1} = \frac{dQ_{2C}^*}{dv_1} < \frac{dQ_{2D}^*}{dv_1}. \end{aligned}$$

We make several observations from Proposition 2. A cost increase for Firm 1 has the least negative effect on Firm 1 and no effect on Firm 2 when two firms are

Figure 3. (Color online) Four Competition/Network Structures



not competing with each other (Scenario A). Competition enables a firm's opponent to take advantage of the firm's cost increase by selling more quantity in the competing market(s) and thus, escalates the negative effect on the firm. If Firm 2 enters into Market 1 and competes with Firm 1 in that market (Scenario B), then its presence aggravates Firm 1's quantity decrease in response to its own cost increase. If Firm 1 enters into Market 2 and competes with Firm 2 in that market (Scenario C), then Firm 1's marginal cost of selling to each of the two markets increases and negatively affects its quantity output levels in both markets, resulting in a faster quantity decrease rate than that when Firm 1 does not export but competes with Firm 2 in Market 1 only (Scenario B). When the firms compete in both markets (Scenario D), Firm 1 suffers from its cost increase the most, because its cost vulnerability is explored by Firm 2 in both markets. Thus, as the number of markets to which the firm exports increases and as competition intensifies in those markets, the negative impact of an increase of the firm's cost on its total quantity output exacerbates.

The situation depicted in Figure 3 comes close to the competitive picture in the appliance industry. Let us concentrate on washing machines, the perennial player Whirlpool (the United States), and its Korean competitors LG and Samsung. They are global firms selling in multiple markets but also, in each other's home country market. The 232 tariffs on steel increased the cost for Whirlpool washers, but the United States-imposed tariff of 20% on imported washers had severe effects for the Korean exports to the United States. All manufacturers passed their increased costs to U.S. consumers, which resulted in reduced demand (an almost 3% sales drop for washing machines) (Tankersley 2019). Whirlpool saw a decline in its sales not only because of the decrease in U.S. demand but also, because it was disadvantaged in all other markets, such as South Korea and Japan, which were supplied by transshipped goods from U.S. factories. LG and Samsung were able to weather the storm of the United States-imposed tariffs by adjusting product mix and prices for some of their upscale models in the United States while focusing their sales output to markets in which they had the increased cost advantage after the 232 tariffs over Whirlpool. The sales and profit decreases for Whirlpool were surprising given the motivation of the United States-imposed tariffs of 20% on the imported foreign goods.

The situation in the solar panel industry resembles Scenario B, with Market 1 being the United States and Market 2 being the Asian markets for the Asian competitors. In an effort to protect small-sized U.S. solar producers (e.g., Suniva and Solar World), the United States imposed a 30% tariff on all solar imports, which will decline by 5% a year until it goes away. Chinese

(e.g., Jinko Solar) and Korean (e.g., LG Electronics) firms have their manufacturing hubs in their countries and used their scale economies to ship cheap solar panels to the U.S. market in the past. The smaller U.S. solar panel producers were at a cost disadvantage and demanded protection. However, in an industry in which solar product prices are continuously falling because of technology improvements and oversupply, the temporary cost increases to the competitor's cost structure selling in multiple markets are not as high impact as one would expect. This aligns with the prediction of Proposition 2. The global manufacturers can adjust their production levels in their network of Asian factories for a better cost position and rely on already stored inventories in the U.S. market to temper the effect of tariffs in their short-term sales (see Gearino 2018, Silverstein 2018). Furthermore, they have the financial strength to switch to a complete network by investing in new facilities or expanding on the existing capacity of acquired U.S. producers to address the longer-term impact of sustained or renewed tariffs.

It is interesting to note that, although U.S. steel producers increased their profitability owing to the 232 tariff, this was not the observed outcome for U.S. aluminum producers. U.S. aluminum producers are still struggling with intense price pressures from Chinese and European producers. European producers capitalized on a relatively lower import tax compared with Chinese producers and exported more aluminum to the United States in 2018. U.S. imports grew by 17% (around \$1.8 billion) in 2018 compared with the previous year. The observed outcome fits our model prediction as in Scenario B, which fits the competitive situation.

6. Opportunities for Future Research

The global supply chain management literature offers a rich set of models and decision support frameworks for global firms' facility network design, production, inventory, and logistics decisions. Such models capture important global features, such as multiple markets, multiple supply sources, transportation lead times, and a multitude of uncertainties (demand, supply, currency exchange rate, and disruptions). Many of those models focus on the single-firm, single-product setting and work under a general presumption of a stable, open trade/low-trade barrier global environment. Although those models provide helpful insights on how to optimize a firm's facility investment and operational execution decisions to cope with intrinsic business uncertainties and risks, they reach their limits when making predictions about firms' response in a world where the crossborder trading costs become highly uncertain. In such a world, the optimal design of a global facility network should take several additional important dimensions into consideration.

First, tariff uncertainties can affect multiple stages of a supply chain. The directions and magnitudes of tariff movements are uncertain in terms of both the timing and the duration. Second, there is product interdependence. The impact of tariffs on a specific product category can be quite different for a single-product firm and a multiproduct firm. The latter has the flexibility to adjust production and selling decisions among its product offerings. Product demand interdependence, the structure of bill of materials, the substitution ability away from impacted material and components, and the production facility usage all influence how susceptible a multiproduct firm is to trade policy changes. Third, there is competition. Previous low trade barriers have opened the world's markets to many companies and encouraged competition in almost every industry and almost every stage of a value chain. Competitors will take advantage when opponents become (cost) vulnerable in serving a market. How to reduce a firm's vulnerability to trade policy is an especially important consideration in a firm's global facility network design. Fourth, supply chains are decentralized. It is not uncommon for a firm to own and operate only one stage of a value chain. When a trade policy hits its upstream suppliers or downstream customers, its supply chain partners will make strategic responses to optimize their self-interests. It is not obvious what equilibrium would result from a change in tariff policy. For example, a tariff increase on steel could immediately increase a domestic steel manufacturer's price without a significant capacity increase. This could be partly because of the lead time required to construct new production capacity or the uncertainty around the tariff duration, and it could be partly because of the uncertainty around the real long-term demand directed to the domestic steel, because the downstream manufacturers can resort to their operational flexibility to cope with the cost increase. A common thread of the above dimensions is interconnectedness. Upstream and downstream activities are connected through the value-adding processes, products are connected in the different ways that they serve customer needs, and firms are connected through horizontal and vertical competitions. Although it may seem like tariffs only impact a single part of the supply chain, their effects are felt by every company involved from creating the raw material to delivering the final product to consumers.

We believe that the operations and supply chain management community can help advance understanding of the interactions of the rich set of economic driving forces within models that depict some of the operational complexity and network structure of global supply chains. Although in practice, firms may well find all of the above (and more) factors relevant

to their decision making, tackling all of them in one model would lead to an intractable model with hard to disentangle tradeoffs. Carefully choosing a subset of factors that is most relevant and critical to the operations and supply chains of a specific industry could offer new insights and deeper understanding of the implications of trade policy for the industry. Those insights are not only helpful for industry practitioners but also, highly valuable to policy makers. For the latter, developing an appreciation of potential responses from complex, connected supply chains in various industries would help to better anticipate the impact of changing trade policy.

Appendix

Proof of Proposition 1. We first establish that $\mathbb{E}[\pi(K, \tilde{v}_A)]$ is concave in K . By checking the Hessian, we can show that the time 1 unconstrained profit $p_A(q_A, q_B)q_A + p_B(q_A, q_B)q_B - \tilde{v}_A q_A - v_B q_B$ is jointly concave in q_A and q_B . Thus, solving the first-order condition (FOC) yields the optimal unconstrained q_A^* and q_B^* :

$$q_A^* = \frac{A_A - \beta A_B + \beta v_B - \tilde{v}_A}{2(1 - \beta^2)}, q_B^* = \frac{A_B - \beta A_A - v_B + \beta \tilde{v}_A}{2(1 - \beta^2)}.$$

When $\tilde{v}_A < A_A + A_B - 2(1 + \beta)K - v_B$, we have $q_A^* + q_B^* > K$, in which case we can obtain the optimal constrained $q_A^*(K)$ and $q_B^*(K)$ by plugging $q_A + q_B = K$ into the time 1 profit function and solving the FOC:

$$q_A^*(K) = \frac{A_A - A_B + 2(1 - \beta)K + v_B - \tilde{v}_A}{4(1 - \beta)},$$

$$q_B^*(K) = \frac{A_B - A_A + 2(1 - \beta)K - v_B + \tilde{v}_A}{4(1 - \beta)}.$$

Substituting $q_A^*, q_A^*(K), q_B^*, q_B^*(K)$ into $\mathbb{E}[\pi(K, \tilde{v}_A)]$ and taking the second-order derivative with respect to K , $\frac{d^2 \mathbb{E}[\pi(K, \tilde{v}_A)]}{dK^2} = \frac{-(1 + \beta)(A_A + A_B - 2(1 + \beta)K - v_B - \tilde{v}_A)}{\Delta}$. The numerator must be negative for any reasonable K , because if $A_A + A_B - 2(1 + \beta)K - v_B - \tilde{v}_A \leq 0$, then at time 1, the firm will find $q_A^* + q_B^* < K$ for all realizations of $\tilde{v}_A$ (i.e., its capacity is never binding).

Next, we obtain the optimal K^* by solving the FOC of $\mathbb{E}[\pi(K, \tilde{v}_A)] - cK$ and taking the smaller root:

$$K^* = \frac{(A_A + A_B - v_A - v_B) - 2\sqrt{c\Delta}}{2(1 + \beta)}.$$

We can compute $\mathbb{E}[q_A^*]$ and $\mathbb{E}[q_B^*]$ by plugging K^* into $q^*(K)$ and $q^*(K)$ and utilizing the unconstrained q_A^* and q_B^* :

$$\mathbb{E}[q_A^*] = \frac{2A_A - 2(1 - \beta)c - 2\beta A_B - 2v_A + 2\beta v_B - \Delta}{4(1 - \beta^2)},$$

$$\mathbb{E}[q_B^*] = \frac{2A_B - 2(1 - \beta)c - 2\beta A_A - 2v_B + 2\beta v_A - \Delta}{4(1 - \beta^2)}.$$

We can compute $\mathbb{E}[p_A^*]$ and $\mathbb{E}[p_B^*]$ by plugging $q^*(K)$ and $q^*(K)$ and unconstrained q_A^* and q_B^* into the inverse demand function. We have

$$\mathbb{E}[p_A^*] = \frac{2A_A + 2c + 2v_A + \Delta}{4}, \mathbb{E}[p_B^*] = \frac{2A_B + 2c + v_B}{4}.$$

Taking derivative yields the desired results. $\square$

Proof of Proposition 2. Solving the Cournot game for each of the four scenarios, we obtain equilibrium quantities.

Scenario A:

$$q_{11} = \frac{A_1 - v_1}{2}, q_{22} = \frac{A_2 - v_2}{2}.$$

Scenario B:

$$q_{11} = \frac{A_1 - 2v_1 + v_2 + t_2}{3}, q_{21} = \frac{A_1 + v_1 - 2v_2 - 2t_2}{3},$$

$$q_{22} = \frac{A_2 - v_2}{2}.$$

Scenario C:

$$q_{11} = \frac{A_1 - v_1}{2}, q_{12} = \frac{A_2 - 2v_1 + v_2 - 2t_1}{3},$$

$$q_{22} = \frac{A_2 + v_1 - 2v_2 + t_1}{3}.$$

Scenario D:

$$q_{11} = \frac{A_1 - 2v_1 + v_2 + t_2}{3}, q_{12} = \frac{A_2 - 2v_1 + v_2 - 2t_1}{3},$$

$$q_{21} = \frac{A_1 + v_1 - 2v_2 - 2t_2}{3}, q_{22} = \frac{A_2 + v_1 - 2v_2 + t_1}{3}.$$

Computing Q_1 and Q_2 for each scenario and taking derivative with respect to v_1 yields the desired comparison results. $\square$

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