Location Choices of Multi-plant Oligopolists: Theory and Evidence from the Cement Industry

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August 7, 2023

Abstract

This paper studies spatial interdependencies in multi-plant production. I develop a model in which each firm decides locations of plant set and variable markups where its plants sell. Such location decision is guided by two competing forces: amplification of a firm's competitive advantage through plant expansion and diminishing marginal benefits due to cannibalization. Despite a combinatorial discrete choice problem, the model is estimated efficiently provided the location game is submodular and aggregative. With this framework, I investigate the spatial organization of cement firms responding to environmental policy changes, and show that neglecting the interdependencies biases the estimate of carbon leakage.

Keywords: Multi-plant, oligopoly, interdependent entry, combinatorial discrete choice, submodular games, carbon leakage, Greenhouse Gas Pollution Pricing Act.

*School of Economics, Singapore Management University. 90 Stamford Road, Singapore 178903. Email: cyyang@smu.edu.sg. This paper combines the first and second chapters of my dissertation entitled "Decisions of Multinational Firms: Plant Location and Sourcing". Many thanks therefore go to my advisors Keith Head, John Ries, Sanghoon Lee, Álvaro Parra, Hiro Kasahara, and other faculty members at Sauder School of Business, University of British Columbia. I also would like to thank Pol Antràs, Costas Arkolakis, Jonathan Dingel, Hanwei Huang, Kala Krishna, Shenggang Liu, Volodymyr Lugovskyy, Eduardo Morales, Steve Redding, Robert W. Staiger, Daniel Xu, and seminar participants at various institutions and conferences for very helpful comments and suggestions. Support for this research from the Productivity Partnership as funded by SSHRC and SMU MOE Tier 1 Grant is also gratefully acknowledged.

1 Introduction

Firm-level adjustments to regulatory changes can undermine the intended purpose of a policy and impose costs on the economy. A classic example is a regional carbon tax that increases the local operating costs relative to unregulated rivals. Firms respond by moving production and associated emissions to jurisdictions with laxer standards, leading to losses in the taxing economy and limited changes in total emissions. The recurrent concerns about carbon leakage prompt a need to understand the spatial organization of firms, especially multi-plant firms which are prevalent and dominant in many industries.

Evaluating how multi-plant firms operate spatially is a complex problem. In industries with high fixed costs and tradable goods, a multi-plant firm strategically decides on the number and location of its *set* of plants, taking into account competition with rivals and cannibalization of its own. The spatial interdependency among these plants shapes the flow of goods, prices, and markups in each market, affecting global welfare in respond to local shocks.

This paper addresses three key questions related to multi-plant production: (1) how do multi-plant firms determine the number and location of their plants, (2) how does the spatial allocation of plants affect markups and prices, and (3) what is the impact of allowing for multi-plant production and interdependent entry of plants? To answer these questions, I first develop a quantitative model of oligopolists that characterizes firms' extensive and intensive margins of multi-plant production. The model generates precise mechanisms of how plant locations affect pricing and profitability of firms. Then, I propose a method to simplify the high dimensional interdependent location problem and estimate the model's key parameters. Finally, I use the model to analyze the effects of multi-plant production on the geographical distribution of economic activity and welfare under the Greenhouse Gas Pollution Pricing Act (the Act) in Canada.

The model embeds head-to-head price competition (Bernard et al., 2003, hereforce BEJK) in a Ricardian trade framework (Eaton and Kortum, 2002; Tintelnot, 2017) with an initial combinatorial discrete entry stage. It builds upon existing research in two key aspects. Firstly, by endogenizing entry and variable markups, this model offers an opportunity to reexamine the connection between extensive and intensive margins in the context of multi-plant firms. A firm with more plants will be able to charge higher markups and captures a larger fraction of the market. Secondly, solving an interdependent entry game with strategic substitutes is a hard permutation problem, yet the model entails two properties such that it can be solved less computationally intensive.[1] One is that a firm's profit exhibits submodularity in the decision set. The other is that a firm's profit depends on its own action and an aggregate of all firms' actions. These two properties guarantee the existence of pure-strategy Nash equilibrium (PSNE), and also allow one to solve the combinatorial discrete choice (CDC) problem by iteratively eliminating non-optimal decision sets, as in Arkolakis et al. (2021).

The model yields countervailing forces that determine the optimal set of production locations. On one hand, a large plant set enhances the firm's competitive advantage against rivals. On the other hand, cannibalization between its own plants decreases the marginal benefit. Therefore, plants are strategically added until the marginal payoff can no longer cover the fixed costs of construction.

I estimate the model in three steps using aggregated and easily obtained data. In the first step, I use gravity regressions to estimate a composite of local productivity and input costs across locations, and trade elasticity which regulates competition intensity among plants. In the second step, I estimate demand via the generalized method of moments (GMM) using data on consumption and market characteristics. In the third step, I estimate the fixed costs of construction by fitting moments to the observed plant locations. A notable advantage is that the multi-plant firm model in this paper can be estimated without micro data on firm or plant-level market shares.

To demonstrate the policy implications of the framework, I investigate the impacts of the Canadian Greenhouse Gas Pollution Pricing Act on the cement industry in the US and Canada. The cement industry is one of the largest industrial sources of carbon emissions, and commonly assessed to be emissions-intensive and trade-exposed with high risk of carbon leakage (European Commission white paper, Europejska, 2009). With actively traded cement in North America by a few giant multi-plant manufacturers, the model provides a realistic characterization of the industry. Three different carbon pricing schemes are evaluated, specifically a carbon tax with and without border tax adjustment (BTA), as well as an output-based pricing system (OBPS). Results demonstrate that the implementation of a carbon tax alone leads to the most significant changes in plant locations. For a carbon tax of \$50 per tonne of CO_2, the carbon leakage rate—increase in unregulated regions' emissions relative to domestic emission reduction—amounts to 26 percent. BTA is the most effec-

[1] When there are L possible production locations, a firm faces 2^L possible choices. A game with F number of players further complicates the combinatorial discrete choice problem, since it now involves 2^{FL} combinations.

tive strategy for combating carbon leakage, with 7.6 percent leakage rate when imposing the same level of carbon tax to imported cement. However, BTA cannot entirely eliminate leakage, as many Canadian plants that previously exported to the US still lose their competitive advantage against US plants. OBPS is effective in preserving the competitiveness of the domestic cement industry by reducing the effective carbon tax rate through rebates. Nonetheless, the carbon abatement achieved with this policy is only a quarter of that attained with a \$50 carbon tax. From a welfare standpoint, imposing a carbon tax alone on a concentrated industry is undesirable, as it exacerbates losses from domestic market distortion without achieving the desired environmental benefits due to carbon leakage. Instead, the output-based pricing system is preferred when emissions are less damaging, while a carbon tax augmented by the border tax adjustment is more welfare-improving once the social costs of carbon hit \$59 per tonne of CO_2.

How important is incorporating interdependencies among plants when studying multi-plant firms? In the last part of the paper, I compare baseline estimates obtained from the multi-plant model to an approximation in which each plant is assumed to enter separately. Abstracting spatial interdependencies significantly underestimates the fixed cost of plant construction for North American cement producers, resulting in an overstatement of leakage under a carbon tax. Additionally, the magnitude of bias varies by firm size.

This paper contributes to several strands of the literature. First, it extends the existing trade models that study oligopolists, such as BEJK and Atkeson and Burstein (2008), by clearly distinguishing between plants and firms. Such distinction is crucial considering the mounting evidence that highlights differences between the two economic entities (Rossi-Hansberg et al., 2021; Hsieh and Rossi-Hansberg, 2023; Aghion et al., 2019; and Cao et al., 2017). My multi-plant firm model, as an extension of BEJK, derives distributions of costs and markups that nest those in single-plant settings.[2] As such, the model yields more generalized insights on firm-level decisions, encompassing single- or multi-plant owners.

Second, this paper adds to the growing literature that explores interdependencies along the extensive margins of multinational firms, a group of firms that can be captured using my model. Due to computational challenges, most papers in this topic refer to complementarities in firms' sourcing, production, and export decisions.[3] The closest to my work

[2] Bernard et al. (2003) described markup distribution as being impervious to any characteristics of market structure. Subsequent papers by Holmes et al. (2011, 2014) and De Blas and Russ (2015) generalized the model to incorporate the effects of a finite number of firms in a market. My model is closer to the latter development that recognizes the granularity of firms.

[3] Antràs et al. (2017) featured complementarity across global input sourcing because adding an extra

is Tintelnot (2017), who studied substitutabilities in multinational production facing the potential for export platform sales. However, his work evaluated all possibilities in a small location set, and the method is not easily scalable. I overcome these challenges by combining theoretical properties from the submodular game with a solution algorithm for a combinatorial discrete choice problem. Additionally, unlike these papers that model firms as infinitesimal with constant markups, I consider a small group of sizable firms competing oligopolistically and exploiting geographical advantages to increase markups. This key difference makes my model more suitable to analyze policy questions in industries that are dominated by a few large firms.

Third, this paper joins the literature in the field of industrial organization that analyzes how retailers establish distribution networks in space, building on the works of Jia (2008) and Holmes (2011). The technique to solve CDC problems was first introduced by Jia (2008), who focused on positive spillovers among chain stores and supermodularity of the firm's return function. However, extending the method to a game where players are strategic substitutes is theoretically demanding and less straightforward. Holmes (2011) can only partially identify the parameters using a revealed preference approach, and Oberfield et al. (2023) approximated the discrete location set by choosing continuous density of plants. Recently, Arkolakis and Eckert (2017) developed a repetitive fixed point search algorithm to solve both supermodular and submodular problems, and it was further refined by Arkolakis et al. (2021) to allow for a continuum of monopolistically competitive firms over a monotonic type space. In this paper, I adapt their solution algorithm to heterogeneous oligopolies.

Fourth, this paper contributes to the literature on environmental policy design for multi-plant firms. It shows that neglecting interdependent plant relocation leads to an overestimation of carbon leakage. Carbon leakage has been extensively studied in previous research, such as Ryan (2012) and Fowlie et al. (2016). These works measured carbon leakage using an aggregated demand shift in imports without factoring in the foreign market structure or the interconnections between domestic and foreign markets through multi-plant firms. The proposed framework in this paper offers a more nuanced understanding of the carbon leakage phenomenon, highlighting the need to consider the strategic behavior of multi-plant firms in response to environmental policies.

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country in the set of active importing countries reduces expected costs of the firm. The recent paper, Antràs et al. (2022), added complementarity in both assembly and sourcing through fixed cost sharing. Jiang and Tyazhelnikov (2020) introduced complementarity in the production of pairs of inputs. Alfaro-Urena et al. (2022) added the time dimension to the combinatorial choices of export destinations.

The remainder of the paper is structured as follows. Section 2 presents the model and propositions derived from it. Section 3 describes the dataset and present important facts of the cement industry. The model is structurally estimated in Section 4. Counterfactual policy analysis on different carbon pricing schemes is conducted in Section 5, followed by the importance of incorporating interdependent plant locations in Section 6. Finally, Section 7 concludes the paper.

2 A Model of Multi-plant Firms

This section presents a theory on location of production, export, and pricing for multi-plant firms. Firms and plants are distinct, albeit related, economic entities. A plant can potentially serve the demand locally and elsewhere. A firm internalizes cannibalization within itself and competition with rivals by making strategic decisions on production locations and pricing of all its plants. Firms are heterogeneous in fixed costs of construction. Once the fixed costs are paid, plants are differentiated by production and trade costs associated with their locations, and a stochastic productivity measure. Each firm selects its optimal set of plant locations to maximize expected single-period profits. I consider a partial equilibrium setting, concentrating on interdependent entry and price competition between oligopolies in a single industry.

The model features a static simultaneous entry game with complete information. I identify the competition and cannibalization effects from the plants' spatial distribution pattern. With the objective of analyzing long-run spatial adjustments of multi-plant firms under different policy regimes, this approach abstracts from a number of dynamic considerations to simplify the computational burden of solving combinatorial discrete choice problems.[4] Formally, there is a finite number of discrete geographical units, $m \in \mathcal{M}$, and a given finite number of firms, $f \in \mathcal{F}$. A firm chooses a subset of locations $\mathcal{L}_f \subseteq \mathcal{M}$ to establish plants, where a plant is indexed by $\ell \in \mathcal{L}_f$.[5] The firm owns a number $N_f = |\mathcal{L}_f|$ of plants.

[4]For example, the model does not accommodate preemptive entry (Igami and Yang, 2013; Zheng, 2016), nor does it incorporate any learning process by firms (Arkolakis et al., 2018). Considerations such as how sunk costs and scrap values can deter relocation of a plant (Ryan, 2012) are also beyond the scope of this paper. With a static model, I slightly abuse the terminologies and use "relocation" or "change in plant locations" to indicate different spatial allocation of plants between two equilibria: pre- and post-policy implementation, rather than transitional dynamics.

[5]I assume a firm cannot have more than one plant at a location. Essentially, a firm choosing a set of plants is equivalent to choosing a set of locations to produce.

2.1 Demand

Demand is characterized for a single product bought by a continuum of consumers $i \in \mathcal{D}_m$ on a unit interval in m. The aggregated local demand is Q_m units of the good. I assume an isoelastic demand at the location level, given by

$$Q_m = A_m P_m^{-\eta}, \tag{1}$$

where $-\eta < -1$ is the price elasticity of demand to be consistent with profit maximization of monopolists. The local price index of the good is P_m, and the exogenous demand shifter is A_m. Demand is formulated at the location level as firms, ex-ante, perceive consumers within the same location as identical. Firms only acquire knowledge on consumer differences and set prices accordingly post-establishment of plants. Consequently, consumer-specific demand is superfluous for calculating a firm's expected profits.[6]

2.2 The multi-plant firm's problem

A multi-plant firm determines its production locations and how to serve consumers across all locations. Its plants produce an identical product, subject to the aforementioned demand function.[7] The timing of the game is as follows: at $t = 1$, firms simultaneously choose the set of plant locations to maximize expected profits, incurring the associated fixed costs. At $t = 2$, firms learn about the realized productivity of plants and decide plants' pricing and consumers to serve. For simplicity, I posit no fixed cost for exporting and every plant can be a potential supplier of all consumers.[8] I solve the model by backward induction.

[6] One can incorporate more complex structures, such as CES preferences—a specific form of isoelastic demand—among goods per consumer, then aggregating to a location. However, these additional demand parameters offer no advantage in resolving the firm's problem and merely complicate the model.

[7] I follow BEJK by assuming firms produce a homogeneous good. I acknowledge that this assumption may limit the scope of industries where the framework can be applied, of which cement is a suitable candidate. However, estimating the model requires less firm-level data compared to the distinct goods setting in Atkeson and Burstein (2008).

[8] Fixed costs of exporting at firm level can be incorporated, as in Tintelnot (2017), but they are omitted for simplicity and would require additional data to identify. However, if the fixed costs of exporting are associated with the set of plants, then a firm would not necessarily select the least cost plant to serve a consumer, and the model would lose tractability.

2.2.1 Production decisions given plant locations

Each location $m \in \mathcal{M}$ is characterized by an exogenous productivity level T_m, as well as local equilibrium characteristics that firms take as given, namely the demand shifter A_m and costs of input w_m. Inputs to produce the good are immobile across locations. Trade between any two locations bears an iceberg trade cost, $\tau_{\ell m}$.

Conditional on firm f producing at a set $\mathcal{L}_f$ of locations, for each $\ell \in \mathcal{L}_f$, the firm converts one bundle of inputs into a quantity $Z_{f\ell i}$ of the good for consumer $i \in \mathcal{D}_m$ at constant return to scale. The term $Z_{f\ell i}$ represents an idiosyncratic shock specific to a plant-consumer pair. Examples of such factors include relationship specificity and internal distance between consumers at m to its centroid. Rather than dealing with each $Z_{f\ell i}$ separately, I assume they are realizations of independently and identically distributed random draws from a Fréchet distribution,[9] according to

$$F_\ell^{draw}(z) = \Pr[Z_{f\ell i} \leq z] = \exp(-T_\ell z^{-\theta}).$$

Dispersion of productivity is represented by θ. The bigger θ is, the more similar are the productivity draws.

Combining productivity, input and trade costs, the marginal cost of supplying the good from a plant at ℓ to consumer i at m is therefore

$$C_{f\ell im} = \frac{w_\ell \tau_{\ell m}}{Z_{f\ell i}}, \forall \ell \in \mathcal{L}_f, i \in \mathcal{D}_m. \tag{2}$$

It is distributed as

$$F_{\ell m}^c(c) = \Pr[C_{f\ell im} \leq c] = 1 - \exp\left(-\phi_{\ell m} c^\theta\right),$$

where $\phi_{\ell m} = T_\ell (w_\ell \tau_{\ell m})^{-\theta}$ indicates the capability of location ℓ serving location m.

Note that plants at the same location are ex-ante identical regardless of ownership. This setup mirrors Antràs et al. (2017), where firm-specific factors are suppressed in the productivity distribution. One may argue to include a firm's core productivity parameter to shift its plants' productivity, as in Tintelnot (2017), such that more productive firms build more productive plants on average. As demonstrated in the online Appendix (Section B),

[9]The assumption of Fréchet distributed productivities is handy in later derivations due to its grounding in the extreme value theory. While technical advantages dictate this choice, empirical distributions of productivity are typically bell-shaped in the literature, which also favors the Fréchet specification.

it is straightforward to incorporate additional firm-level heterogeneity into the benchmark model. However, estimating the model becomes considerably more data intensive.[10] Although firms lack inherent productivity differences, I will demonstrate later that a firm having more plants at efficient locations is more productive overall. Therefore, ex-ante firm heterogeneity is entirely encapsulated by the differing fixed cost of plant construction and diverse sets of plant locations.

Plants engage in Bertrand competition in a nested structure. Each consumer within a location is served by its lowest-cost supplier. Under single-plant firms, the winning firm is constrained not to charge more than the second-lowest marginal cost, the standard setting in BEJK. In the case of multi-plant firms, a firm's headquarter coordinates prices for all its plants such that the winning plant will not undercut its *sister* plants under the same firm, unless the next-lowest-cost plant belongs to a competitor. Pricing is bound by the marginal cost of the lowest-cost plant owned by the second-lowest-cost firm. Rather than characterizing the cost ranking across all plants, the focus lies on the lowest-cost plant within a firm and the two lowest-cost firms.

First, I define the kth lowest-cost plant owned by firm f for consumer i in m as $C_{k,fi(m)}$. The lowest marginal cost follows the distribution

$$F^{c}_{1,fm}(c) = \Pr[C_{1,fi(m)} \leq c] = 1 - \exp(-\Phi_{fm} c^{\theta}), \tag{3}$$

where $\Phi_{fm} = \sum_{\ell \in \mathcal{L}_f} \phi_{\ell m}$ refers to the capability of a firm f serving location m. Therefore, the expected firm-level marginal cost to consumers in m is

$$E\left[C_{1,fi(m)}\right] = \Gamma\left(\frac{\theta+1}{\theta}\right)\Phi_{fm}^{-\frac{1}{\theta}}. \tag{4}$$

Having more plants at favorable (high $\phi_{\ell m}$) locations lowers a firm's marginal cost.[11] Intuitively, each additional production location provides the firm with another cost draw, leading to fiercer internal competition and reduced firm-level marginal costs. More plants also reduce the average shipping distance to consumers, resulting in further savings on trade costs. The benefit of an extra plant is greater when it is situated closer to consumers and

[10]To identify the set of firm core productivity parameters, I would need each firm's market share in every location which is not commonly available. I welcome researchers who have the relevant data to use the extended version of the model in the Appendix.

[11]This contrasts with Oberfield et al. (2023), which focuses on the span-of-control cost and more plants will reduce a firm's efficiency.

in locations with lower production costs. The properties of a multi-plant firm's lowest cost distribution underpin the following result (the proof is straightforward and omitted in the main text).

Proposition 1: *An additional production location to the firm's active location set strictly decreases its lowest expected cost of supplying the good to all consumers.*

Second, I define $C_{1,i(m)}$ and $C_{2,i(m)}$ as the lowest and second-lowest marginal costs across all firms for consumer i in m. Suppose $C_{1,i(m)} \equiv C_{f\ell i(m)}$ and $C_{2,i(m)} \equiv \min_{g\neq f, g\in\mathcal{F}}\{C_{1,gi(m)}\}$, I show in the online Appendix (Section A.1) that the conditional joint distribution of the lowest and second-lowest costs of supplying the good to a consumer at m is

$$F^c_{12,m|f}(c_1, c_2) = 1 - e^{-\Phi_m c_1^\theta} - \frac{\Phi_m}{\Phi_{fm}}\left(1 - e^{-\Phi_{fm}c_1^\theta}\right)e^{-\left(\Phi_m - \Phi_{fm}\right)c_2^\theta}, \tag{5}$$

for $c_1 \leq c_2$, where $\Phi_m = \sum_{f\in\mathcal{F}}\sum_{\ell\in\mathcal{L}_f}\phi_{\ell m}$ denotes the sourcing potential of location m over all plants. Incorporating multi-plant production and firm granularity generalizes BEJK-style models in literature. As the number of firms approaches infinity, the limit distribution of equation (5) aligns with the BEJK joint distribution of the two lowest costs. When firms are finite but single-plant, equation (5) takes the form of the joint distribution in Holmes et al. (2011).

I now describe the price and markup distributions. The competition structure implies a strategy similar to limit pricing, where the lowest-cost plant charges a minimum between the monopoly price and the lowest marginal cost of its head-to-head competitors. Mathematically, the price charged to consumer i in m is $P_{i(m)} = \min\{\bar{\mu}C_{1,i(m)}, C_{2,i(m)}\}$, where the monopoly markup $\bar{\mu} = \eta/(\eta - 1)$.

Conditional on sourcing from firm f, the firm sets the price to consumers in location m following the distribution,

$$F^p_{m|f}(p) = F^c_{12,m|f}(p,p) + \frac{\Phi_m}{\Phi_{fm}}\left(1 - e^{-\Phi_{fm}\bar{\mu}^{-\theta}p^\theta}\right), \tag{6}$$

and the expected price charged by firm f to consumers in m is

$$E\left[P_{m|f}\right] = \Gamma\left(\frac{\theta+1}{\theta}\right)\frac{\Phi_m}{\Phi_{fm}}\left(\left(\Phi_m - (1-\bar{\mu}^{-\theta})\Phi_{fm}\right)^{-\frac{1}{\theta}} - \left(\Phi_m - \Phi_{fm}\right)\Phi_m^{-\frac{\theta+1}{\theta}}\right). \tag{7}$$

Derivations are in relegated to the online Appendix (Section A.2). Firms' pricing exhibits incomplete pass-through. Furthermore, price distribution is invariant across plants within a firm, which implies the sourcing probability from any of its plants (quantity share) equals the expenditure share, as illustrated in Eaton and Kortum (2002). This enables standard firm-level gravity trade regression if plant sales to every market are observable. Yet, the same result cannot be drawn at the market level across different firms.

Firm f's markup in location m is the realization of a random draw from a shifted Pareto distribution truncated at the monopoly level,

$$F^{\mu}_{m|f}(\mu) = \begin{cases} 1 - \frac{1}{(1-s_{fm})\mu^{\theta}+s_{fm}} & 1 \leq \mu < \bar{\mu} \\ 1 & \mu \geq \bar{\mu} \end{cases}, \tag{8}$$

where the relative competitiveness of firm f against its rivals, $s_{fm} = \Phi_{fm}/\Phi_m$, is the sole shifter of the markup distribution. See the online Appendix (Section A.3) for the derivation. Given the distribution, a firm owning more plants in favorable locations charges higher markups and is more likely to exploit the maximum monopoly markup. Additionally, having more dispersed plants, indicated by smaller θ, also widens the cost gap between firms and increases the likelihood of charging the monopoly price.

The markup distribution extends single-plant firm models, yielding richer implications on how markups vary across firms. With infinite firms competing head-to-head, the markup distribution converges to equation (11) in BEJK. The markup distribution in Holmes et al. (2011) is also a special case of equation (8) when firms are single-plant owners. I summarize the results in the following proposition.

Proposition 2: *Holding the competitors fixed, (i) an additional production location to the firm's active location set weakly decreases its average price charged to all consumers; and (ii) an additional production location to the firm's active location set weakly increases its average markup charged to all consumers.*

Lastly, I aggregate firms' decisions to bilateral trade across locations. With firms' cost distributions in equation (3), the probability that firm f supplies a consumer in m is

$$s_{fm} = \int_0^{\infty} \prod_{g \neq f . g \in \mathcal{F}} \left(1 - F^c_{1,gm}(c)\right) dF^c_{1,fm}(c) = \frac{\Phi_{fm}}{\Phi_m}. \tag{9}$$

The probability equals the firm's relative competitiveness in supplying the good against all other competitors. Given uniformly distributed consumers in a unit interval, the probability of serving a consumer equals the expected fraction of consumers served in m.

Proposition 3: *An additional production location to the firm's active location set strictly increases the share of consumers sourcing from it, holding the competitors fixed.*

Suppose N_ℓ number of firms produce at ℓ, the probability that location ℓ exports to a consumer in m is

$$s_{\ell m} = \int_0^\infty \prod_{k \neq \ell, k \in \mathcal{M}} \left(1 - F^c_{1,km}(c)\right) dF^c_{1,\ell m}(c) = \frac{N_\ell \phi_{\ell m}}{\Phi_m}, \tag{10}$$

where $F^c_{1,\ell m}(c) = 1 - \exp\left(-N_\ell \phi_{\ell m} c^\theta\right)$ characterizes the distribution of the lowest-cost plant at ℓ across all firms. The probability represents location ℓ's competitive advantage. A market m sources more from locations with a higher plant count, better efficiency, lower input costs, or reduced trade costs.

2.2.2 Choice of plant locations

A firm chooses the set of plant locations from a finite discrete space $\mathcal{M}$ to maximize the expected total profit summing over its plants. The expected variable profit, whose details are presented in the online Appendix (Sections A.4 and A.5), is

$$E\left[\pi_f\right] = \kappa \sum_m A_m \left(\bar{R}_{fm} - \bar{C}_{fm}\right), \tag{11}$$

where the constant $\kappa = \Gamma\left(\frac{\theta+1-\eta}{\theta}\right)$, and

$$\bar{R}_{fm} = \left(\Phi_m - (1-\bar{\mu}^{-\theta})\Phi_{fm}\right)^{-\frac{1-\eta}{\theta}} - \left(\Phi_m - \Phi_{fm}\right)\Phi_m^{-\frac{\theta+1-\eta}{\theta}},$$

$$\bar{C}_{fm} = \Phi_{fm} \times \Bigg[(\theta+1-\eta)(\Phi_m - \Phi_{fm}) \int_1^{\bar{\mu}} \mu^{-\theta-2}\left(\Phi_m - (1-\mu^{-\theta})\Phi_{fm}\right)^{-\frac{2\theta+1-\eta}{\theta}} d\mu + \bar{\mu}^{-\theta-1}\left(\Phi_m - (1-\bar{\mu}^{-\theta})\Phi_{fm}\right)^{-\frac{\theta+1-\eta}{\theta}}\Bigg].$$

It depends on the capability of supplying the good from all of the firm's plants and its competitors' plants. More importantly, plants are not separately additive, rendering the multi-plant firms' location decision a combinatorial optimization problem. For a well-defined expected variable profit, I restrict $(\eta - 1)/\theta < 1$.[12]

[12]The same restriction can be found in Eaton and Kortum (2002), Eaton et al. (2011), and Bernard et al. (2003). The condition ensures that suppliers are competitive enough such that consumption is not concen-

Comparative statics of firm profit regarding θ and η elucidate optimal plant location strategy. Propositions 1–3 ensure that a firm obtains positive marginal variable profit from building one more plant. However, when plants are more homogeneous (high θ), additional plants will not reduce firm costs by much. Furthermore, when demand is less elastic (low η), the firm's variable profit reacts less to cost reductions, diminishing gains.

A multi-plant firm incurs plant-specific fixed costs, $\{FC_{f\ell}, \forall \ell \in \mathcal{L}_f\}$.[13] Fixing the same set of plant locations, firms would expect exactly the same variable profits because plants at the same location are symmetric. Thus, lower average fixed costs drive one firm to have more plants than another. Location choices hinge on a firm's idiosyncratic fixed costs at various locations and profitability considering competitors' fixed costs and location choices. A firm solves

$$\max_{\mathcal{L}_f \subseteq \mathcal{M}} E\big[\Pi_f(\mathcal{L}_f)\big] = E\big[\pi_f(\mathcal{L}_f)\big] - \sum_{\ell \in \mathcal{L}_f} FC_{f\ell}. \tag{12}$$

Finally, I close the model with the local price index, which is a composite of prices that all firms charge to consumers in m.

$$P_m = \sum_{f \in \mathcal{F}} E[P_{m|f}] \times s_{fm} = \Gamma\left(\frac{\theta+1}{\theta}\right) \Phi_m^{-1/\theta} \times \left[(1-N) + \sum_{f \in \mathcal{F}} \left(1 - (1-\bar{\mu}^{-\theta}) s_{fm}\right)^{-1/\theta}\right], \tag{13}$$

where $N = |\mathcal{F}|$ is the given number of firms. The equation explains how local price variations are channeled through plants' spatial distribution globally.

2.3 Equilibrium

There are three aspects of complexity in characterizing equilibrium production locations in this multi-plant, multi-firm, game-theoretic model: (i) discrete choices, since firms decide to enter or not, (ii) multidimensional, since each strategy is defined as a finite number of zeros and ones, and (iii) strategic substitutes, since firms face competition and canni-

trated on a few of them. It has little to do with submodularity of the profit function. This is different from the sub-/super-modularity condition in Antràs et al. (2017) which θ in their setting does not denote heterogeneity of final good suppliers, but rather of input producers.

[13] There are studies concerning greenfield entry versus merger and acquisition. Using my baseline model, one can think of the acquisition price as the fixed cost, except when it depends on the seller's past dependent residual value. If so, fixed costs are also endogenous and need to be solved using a dynamic model.

balization.[14] In a two-firm $|\mathcal{M}|$-location game, the first two features cause the domain of strategies being an enormous set of $2^{2|\mathcal{M}|}$ configurations. It is infeasible to calculate firms' profits for all combinations of locations and pick the set yielding the maximum profit by brute force. More importantly, previous literature has shown substantial imbalances in existence of equilibrium between games with strategic substitutes and strategic complements (i.e., Vives, 1999; Jackson and Zenou, 2015; Jensen, 2005). A PSNE exists in a game with strategic complements according to Tarski's fixed point theorem (Tarski et al., 1955) and Topkis's monotonicity theorem (Topkis, 1978), but the same does not generally apply in games with strategic substitutes. So what is the sufficient condition to ensure the existence of an optimal location configuration and how can it be found in a cost-efficient way?

Dubey et al. (2006) and Jensen (2010) used best-reply potential game properties to prove the existence of a PSNE in games of strategic substitutes by restricting attention to aggregative games in which the payoff of a player only depends on its own strategy and an aggregate of others' strategies. In my model, the firm's profit equation (12) is a function of its own location strategy $\mathcal{L}_f$ and a weighted additive aggregate of rivals' locations, Φ_m, making it a *quasi-aggregative game* by the definition in Jensen (2010).[15] This game satisfies important conditions such that it is also a best-response pseudo-potential game where a PSNE always exists.[16,17] In particular, the firm's profit is strictly submodular without any admissible parameter setting because the marginal return to any plant opening of a firm de-

[14] I adopt the definitions of strategic substitutes and strategic complements from Jackson and Zenou (2015) p.103, where a game has *strategic substitutes* when "an increase in other players' actions leads to relatively lower payoffs to higher actions of a given player". In contrast, games of *strategic complements* are where "an increase in the actions of other players leads a given player's higher actions to have relatively higher payoffs compared to that player's lower actions".

[15] According to Definition 1 in Jensen (2010), the game has an aggregator $g(\mathcal{L}) = \Phi_m = \sum_{f\in\mathcal{F}} \Phi_{fm}(\mathcal{L}_f)$. Take the interaction functions $x_{-f} \equiv \sigma_f(\mathcal{L}_{-f}) = \sum_{g\neq f, g\in\mathcal{F}} \Phi_{gm}(\mathcal{L}_g)$, and the shift-functions $F_f(x_{-f}, \mathcal{L}_f) = x_{-f} + \Phi_{fm}(\mathcal{L}_f)$. The firm's expected payoff function can be written as $E\big[\Pi_f(\mathcal{L})\big] = E\big[\Pi_f(g(\mathcal{L}), \mathcal{L}_f)\big]$, where $g(\mathcal{L}) = F_f(x_{-f}, \mathcal{L}_f)$ for all f.

[16] This quasi-aggregative game satisfies two properties. (i) In this game of strategic substitutes, each firm's expected profit exhibits decreasing differences in the firm's own strategy and opponents' strategies, $D^2_{x_{-f}\mathcal{L}_f} E\big[\Pi_{fm}(g(\mathcal{L}), \mathcal{L}_f)\big] \leq 0$. This is sufficient for the firm's best-reply correspondence function $r_f(x_{-f})$ to decrease in x_{-f}. (ii) There exists a monotone transformation, for example, $\tilde{F}_f = h \circ F_f = \exp(x_{-f} + \Phi_{fm}(\mathcal{L}_f))$, such that the shift functions $\tilde{F}_f$ exhibit strictly increasing differences in x_{-f} and $\mathcal{L}_f$, i.e., $D^2_{x_{-f}\mathcal{L}_f}\tilde{F}_f(x_{-f}, \mathcal{L}_f) > 0$. These two properties correspond to Assumption 1 and Assumption 2 of Jensen (2010). By Theorem 1 and Corollary 1 in Jensen (2010), for a quasi-aggregative game with compact strategy sets and upper semi-continuous payoff functions, if both assumptions are satisfied, the game is a best-reply pseudo-potential game and a PSNE exists. I refer readers to Jensen (2010) for proofs.

[17] Arkolakis and Eckert (2017) proved the existence of PSNE in a CDC game with single-crossing differences conditional on that the profit function needs to be *additively separated* to a firm f's specific part and a common part of all firms' actions. This is a stronger sufficient condition than what is needed here.

creases with plants of the firm itself and rival firms' plants. The model does not have forces that could make plants be strategic complements to each other. For example, no agglomeration forces, such as cost or knowledge sharing among nearby plants as in Jia (2008), is introduced in the model. If, however, a mixture of positive and negative spillovers coexist, the firm's optimal choice of production locations is almost impossible to characterize.

Proposition 4: *For the $|\mathcal{F}|$-player, $|\mathcal{M}|$-location quasi-aggregative multi-plant location game in this paper, the expected profit function exhibiting submodularity for all players, and the set of pure-strategy Nash equilibria is not empty.*

To find such PSNE, Arkolakis and Eckert (2017) provided a solution algorithm that can iteratively and repetitively refine the combinatorial discrete choice set without evaluating all configurations. The algorithm relies on the objective function exhibiting single crossing differences, for which submodularity of the firm's profit function in this paper is a sufficient condition.

Despite the existence of equilibrium, there are typically more than one equilibrium outcome in a simultaneous entry game with complete information, which raises the coherency problem in econometric inference (Heckman, 1978; Tamer, 2003). I will discuss how I tackle this issue and the detailed procedure in adapting the CDC solution algorithm to a multi-firm game in Section 4.3.

2.4 Welfare measures

To prepare the multi-plant firm model for policy evaluation in subsequent sections, I specify welfare terms and the cost of carbon emissions. Policy interventions that result in cost shocks to firms can lead to long-run adjustment in production locations after re-optimizing the profit function. Due to spatial interdependency among plants, a local change is likely to trigger a global reshuffling given a sufficiently large shock. Let's denote the change in plant locations from $\mathcal{L}_f^0$ to $\mathcal{L}_f^1$, the associated change in local capabilities of supply from $\boldsymbol{\phi}^0$ to $\boldsymbol{\phi}^1$, and the change in price index from P_m^0 to P_m^1. The effects on producer and consumer surpluses are summarized as

$$\Delta PS = \sum_{f \in \mathcal{F}} \left(\pi_f(\mathcal{L}_f^1; \mathcal{L}_{-f}^1, \boldsymbol{\phi}^1, \mathbf{A}, \theta, \eta) - \pi_f(\mathcal{L}_f^0; \mathcal{L}_{-f}^0, \boldsymbol{\phi}^0, \mathbf{A}, \theta, \eta) \right) \tag{14}$$

$$\Delta CS = \frac{1}{1-\eta} \sum_{m \in \mathcal{M}} A_m \left(\left(P_m^0\right)^{1-\eta} - \left(P_m^1\right)^{1-\eta} \right). \tag{15}$$

Plant relocation is accompanied with leakage of carbon emissions. For carbon dioxide, all locations endure the environmental consequences of aggregate emission changes, irrespective of their origins. To evaluate environmental policy taking into account these externalities, it is necessary to quantify the monetary impact of long-term damage caused by a tonne of CO_2 emissions in a given year, commonly referred to as the social cost of carbon (SCC). The change in total surplus to the taxing economy is therefore

$$\Delta CS + \Delta PS + \Delta GR + SCC \times (1 - \lambda) \times \Delta e, \tag{16}$$

where the change in government revenue is denoted by ΔGR. I define $\lambda = -\Delta e^*/\Delta e$ as the leakage rate, meaning the ratio of emission changes in unregulated locations to the changes in emissions of the regulated location.

3 The Cement Industry

In this section, I apply the model to the data and draw on key institutional details about the cement industry in the contiguous US and part of Canada in 2016.[18]

3.1 Data description

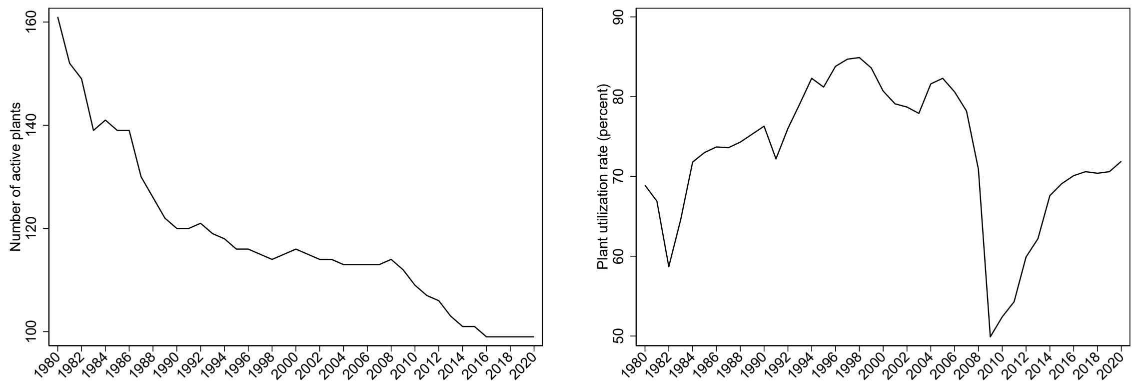
The data used in this study was obtained from four main sources. Firstly, cement plant locations were obtained from the 12th edition of the Global Cement Report, published by the International Cement Review. The report covers 2,108 operating cement plants globally in 2016, including 104 located in the US and 17 in Canada. Each plant is listed in the directory with its name, ownership, location, and capacity. Using the plant ownership data, all multi- and single-plant firms in the region were identified. However, it should be noted that this dataset is cross-sectional. To justify the use of 2016 data as the basis for partial equilibrium analysis, I present Figure 1a which shows that the US cement industry has remained stable without changes to the number of plants from 2016 to 2020.[19]

Secondly, the bilateral cement trade flow was constructed from three sources: the Freight Analysis Framework (FAF) released by the US Department of Transportation, the

[18] The Canadian provinces and territories of Newfoundland and Labrador, Prince Edward Island, Northwest Territories, Nunavut and Yukon are not included in my sample because these are tiny markets for cement and have zero production.

[19] Prior to 2016, the US cement industry experienced two waves of plant closures in its history: one in the 1980s due to outdated technology and the other in 2008 due to the housing crisis.

Figure 1: Active plants and plant utilization in the US cement industry over years



(a) Number of plants

(b) Plant utilization

Note: Data is for the US only, excluding Puerto Rico, obtained from the US Geological Survey.

Canadian Freight Analysis Framework provided by Statistics Canada, and the US Geological Survey database (USGS), from 2012 to 2016. The production locations and consumption markets are zones defined by the Freight Analysis Framework, which are the smallest geographical units available in these datasets. The 149 zones comprise census agglomerations, census metropolitan areas, and the remaining areas of provinces/states. Cross-checking with cement merger cases documented by the Federal Trade Commission, I found the FAF zones highly overlap with the market definition used by FTC to assess competition impacts as well. Furthermore, it is rare for cement firms to have more than one plant in a FAF zone.[20] This empirical definition of location is consistent with the multi-plant firm model, in which a firm decides whether or not to establish a plant, rather than determining the number of plants to have in a single location.

Thirdly, bilateral trade frictions were sourced from various datasets. Across FAF zones, distance was measured as the great-circle distance between zone centroids. Within a zone, internal distance was measured between the northeastern and southwestern boundaries. The FAF-zone-level analysis is complemented by country-level regressions, in which I use the CERDI-sea-distance database and shipping days measured in Feyrer (2019).[21] The

[20] Only four out of 149 locations have two plants belonged to the same firm, with one of them belonging to Cemex in a Florida FAF zone. In these cases, I combined plants into one.

[21] CERDI-sea-distance database computes sea distance as the shortest sea route between the two highest traffic ports in the respective countries, and landlocked countries are associated with the nearest foreign ports. Feyrer (2019) calculated round-trip shipping days between primary ports for each bilateral pair, assuming an average speed of 20 knots.

country-level regressions also use tariff data from the World Integrated Trade Solution by the World Bank and other gravity variables from the CEPII research center.

Lastly, to estimate demand, several input costs were collected to construct instrument variables for prices, including durable goods manufacturing wages, limestone prices, and natural gas and electricity prices. They were obtained from the US Energy Information Administration, US Quarterly Census of Employment and Wages, US Geological Survey, Statistics Canada, Natural Resources Canada, and Quebec Hydro. Additionally, population and units of building permit issued were also collected from the US Census and Statistics Canada. To ensure consistency among the trade, production and consumption data, all of these variables were collected for the same period between 2012 and 2016.

3.2 Industry background

Cement is a fine mineral dust that acts as the glue after mixture with water to bind the aggregates. It is used to form concrete, the most-used input in construction and transportation infrastructure. According to USGS, there are more than 5000 ready-mix concrete producers that purchased cement from 121 plants in the US and part of Canada in 2016. The large number of downstream producers form the continuous measure of consumers in the model.

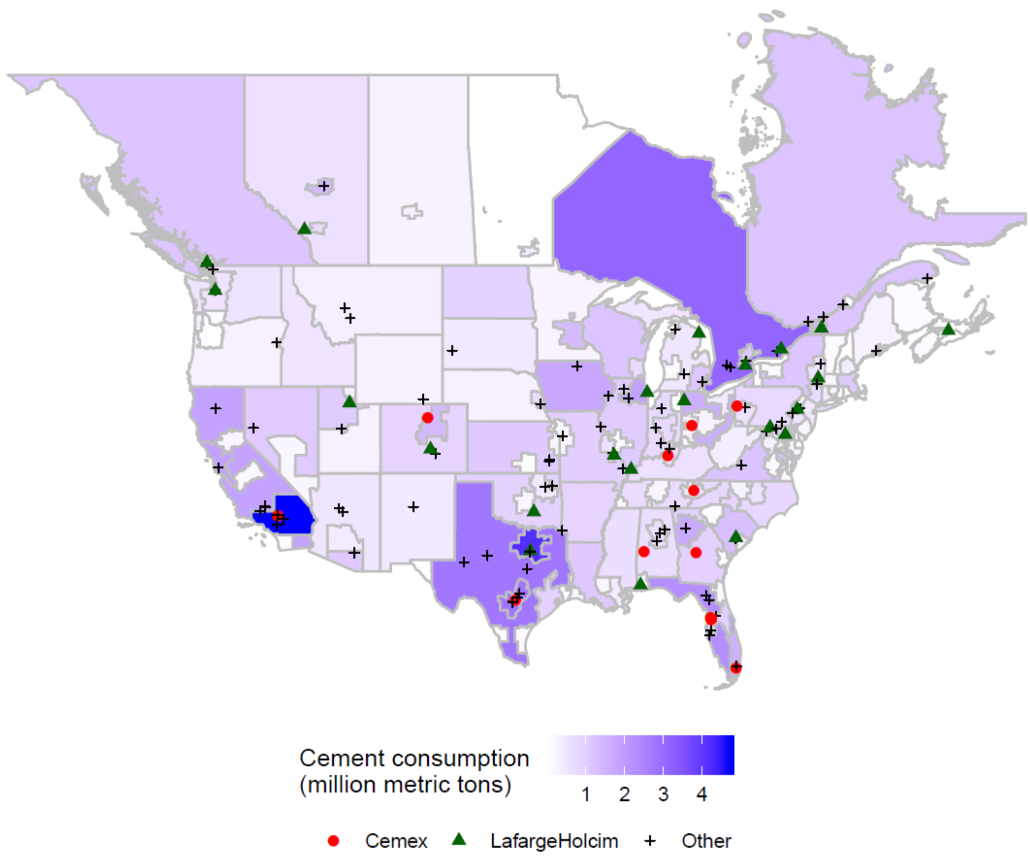
These concrete producers not only purchase cement locally, but also import cement from elsewhere. The active cement trade in this region is attributed to the fact that cement is not produced everywhere, as seen in Figure 2. The map shows that out of the 149 FAF zones, only 73 have cement plants, whereas the rest entirely rely on imports. Figure 3a shows the export intensity and import penetration across the 73 FAF zones.[22] On average, a zone exports 44 percent of its local production and imports 27 percent of its cement consumption. The positive correlation between export intensity and import penetration suggests intra-industry trade in cement, which is consistent with plants having buyer-seller idiosyncrasies in the multi-plant firm model.

Across the US and Canada, trade in cement is comparable to other manufacturing products. Figure 3b depicts how trade decreases with distance for cement and all manufacturing goods, and compares those with the benchmark case of frictionless trade where each origin is equally likely to export to a destination regardless of distance. Half of the cement in

[22]Note that Canada Freight Analysis Framework is a logistics file, and thus the origin and destination of cement flow within Canada may not be documented as places of production and final consumption. This leads to extremely high export intensity and import penetration ratio for some places due to re-export and re-import, such as Hamilton, Oshawa, and part of Alberta.

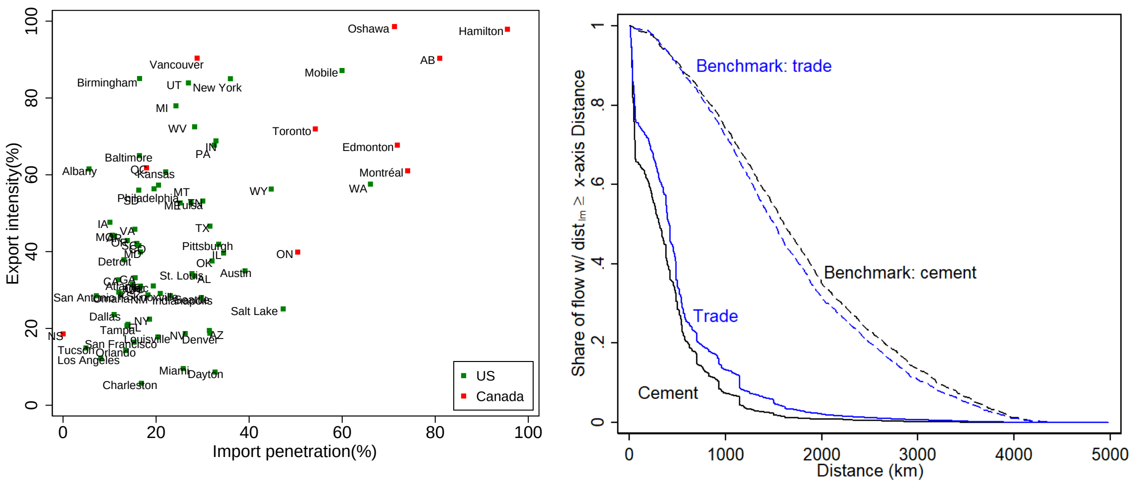
this region is traded within 300 kilometers, and it extends to 420 kilometers for manufacturing goods. Nevertheless, about 10 percent of cement is traded at distances beyond 900 kilometers.

Figure 2: Cement plants and consumption in 2016



Due to the existence of export platforms, all cement plants are potential competitors in every location. Furthermore, these 121 plants belong to 26 firms, out of which 17 are multi-plant owners that control 92.6 percent of the cement plants. The two largest firms, LafargeHolcim and Cemex, own 20 percent and 10 percent of the cement plants, respectively. Figure 2 plots a map of the plants owned by these two multi-plant firms, as well as a group of fringe plants owned by the other 24 firms. The online Appendix (Section F.2) provides more detailed distributions of the number of firms, plants, and market share measured by production capacity. The presence of a few large, multi-plant cement firms, facing cannibalization within their own plants, makes the multi-plant firm model an apt framework for studying their location decisions.

Figure 3: Cement trade across FAF zones in the US and Canada, 2016



(a) Trade intensity (b) Trade distribution by distance

What cost factors does a multi-plant cement firm consider in determining production and plant locations? Establishing a one million tonne cement plant incurs around \$200 million fixed cost (Ryan, 2012; Fowlie et al., 2016; Salvo, 2010), making the plant location problem a nontrivial decision for firms. As for the variable cost of production, it consists of costs equally contributed by materials, energy and labor.[23] The marginal cost is likely to follow constant returns to scale in recent years. Ryan (2012) used data from 1980 to 1999 to estimate that the marginal cost would be convex if a cement plant utilizes more than 87 percent of its capacity due to cost of equipment maintenance. However, since 2008, USGS reports no surveyed regions has had a plant utilization rate beyond this threshold, and the average has been between 50 percent and 70 percent, as shown in Figure 1b.

Of all the raw materials used to produce cement, limestone accounts for roughly 85 percent (Van Oss and Padovani, 2003). Due to the considerable weight of limestone and high transportation costs, one may presume that cement plant location is bound by the location of limestone quarries. However, in the online Appendix (Section F.1), I demonstrate that there are nearly 3,000 limestone quarries dispersed across the US and Canada. While cement firms generally transport limestone from nearby quarries using belt conveyors or trucks, the location of quarries is not the sole factor determining where to establish cement plants.

[23]The cost breakdown is documented in the Lafarge annual report for 2007. Source: bib.kuleuven.be/files/ebib/jaarverslagen/Lafarge_2007.pdf

The energy used in cement production mainly stems from heating raw materials in a kiln. The process requires combustion of significant amounts of fossil fuels to increase the temperature to a peak of 1400-1450° Celsius. Fuel combustion contributes to about half of the CO_2 emissions produced in cement manufacturing, with the rest arising from the chemical reaction. Overall, the production of one tonne of cement releases approximately 0.8 tonnes of carbon into the atmosphere (Van Oss and Padovani, 2003; Kapur et al., 2009).

The cement industry is responsible for about 8 percent of man-made CO_2 emissions worldwide, making it a major industrial contributor of greenhouse gases. Firms and governments are actively seeking ways to address the environmental concerns associated with cement production. The Portland Cement Association reports that as of 2016, around 96 percent of cement capacity used an energy-efficient dry process kiln.[24] The adoption of standardized industry practices and technology partially rationalizes the use of the multi-plant firm model without ex-ante differences in firm productivity.

Governments are primarily focused on shifting the industry away from fossil fuels by imposing carbon prices on dirty fuels like coal. Coal currently provides 90 percent of the energy consumed by cement plants globally.[25] In developed economies like the US and Canada, the share of coal in energy sources is lower at 42 percent, but fossil fuels in general still account for 81 percent.[26] The speed at which cement plants will adopt cleaner energies is a question beyond the scope of this paper. Nevertheless, I will examine other aspects of adjustment by cement plants facing environmental policies if they maintain the same fuel composition.

4 Multi-plant Firm Estimation

In this section, I describe an estimation procedure of the multi-plant firm model. The typical dataset that econometricians observe involves a combination of aggregated data at location level and limited firm level data. Other micro data, such as prices or shipping flows for individual plants, are not always available to researchers. I propose a procedure to estimate the full model with minimal data requirements.

[24]"Wet" or "dry" refers to the moisture content of raw materials. The wet process needs more energy because the moisture needs to evaporate.

[25]Source: globalcement.com/magazine/articles/974-coal-for-cement-present-and-future-trends

[26]For a complete breakdown of fossil fuel usage and energy efficiency, please refer to Table D.8.

I specify trade costs as a function of observed determinants, denoted $X_{\ell m}$,

$$\tau_{\ell m} = \exp\left(\mathbf{X}'_{\ell m}\beta^{\tau}\right), \tag{17}$$

where β^{τ} is a vector of the trade cost parameters. The vector $\mathbf{X_{\ell m}}$ includes the standard explanatory variables used in gravity equations: distance, contiguity, and whether the dyads are located in the same state, province, or country. These variables have been shown to matter for trade flows in the past literature. Demand shifters at each location are characterized as a function of population and the number of building permits for new privately-owned residential construction units, according to

$$A_m = \exp\left(\mathbf{X}'_{m}\beta^{A}\right), \tag{18}$$

where β^{A} is the vector of demand parameters. As for the fixed costs, instead of estimating all specific firm-location fixed costs, which are impossible to identify, I specify that they are realizations from a log-normal distribution,

$$\log\left(FC_{f\ell}\right) \sim N\left(\mathbf{X}'_{f\ell}\beta^{F}, \left(\sigma^{F}\right)^{2}\right). \tag{19}$$

The distributions of fixed costs are shifted by the distance between FAF zones and each firm's North American headquarters, as well as an interaction dummy of the firm and the country where FAF zones are located. Distance is a proxy for management and communication frictions faced by multi-plant firms, while the firm-country dummy captures a firm's local knowledge, such as regulatory requirement and administrative procedure to build a cement plant. After parametrization, what needs to be estimated to fully specify the model are $\{\theta, \eta, \mathbf{T}\mathbf{w}^{-\theta}, \beta^{\tau}, \beta^{A}, \beta^{F}, \sigma^{F}\}$.

The estimation is performed in three steps. First, I use a gravity-type regression to estimate the location production capability, trade costs, and the degree of plant productivity dispersion. The sourcing probability derived from the model provides a natural link between theoretical implication and the bilateral trade data. Next, I project local consumption on the model-consistent price index to estimate the demand elasticity using the generalized method of moments with instruments. What is obtained in the first two steps is crucial for constructing firms' expected profit as a function of plant location configurations and fixed costs. In the final step, I match the predicted optimal plant locations to the actual ones to pin down the fixed cost distribution via the method of simulated moments (MSM).

Separability in estimation allows me to reduce dimensionality of the problem and save computational cost. More importantly, I can verify that the profit function is well defined before implementing the combinatorial optimization algorithm in the last step.

4.1 Step 1: Estimation of local production capability, trade costs, and plant productivity dispersion

The first step is to estimate each location's production capability summarized by the term $T_\ell w_\ell^{-\theta}$, trade costs parameters β^τ, and the dispersion of plants' productivities θ. I take the plant locations as given and exploit differences in trade attributed to local endowments, such as productivity, input costs, and trade costs. Recall that equation (10) provides the probability of m sourcing from ℓ. Empirically, the model-predicted sourcing probability is associated with the trade share in volume, i.e. $s_{\ell m} = \frac{Q_{\ell m}}{Q_m}$. I transform equation (10) to its estimable version,

$$\frac{Q_{\ell m}}{Q_m} = \exp\left[\text{FE}_\ell + \text{FE}_m - \theta \mathbf{X}'_{\ell m}\beta^\tau + \epsilon_{\ell m}\right], \tag{20}$$

where the origin fixed effect $\text{FE}_\ell = \ln\left(N_\ell T_\ell w_\ell^{-\theta}\right)$, and the destination fixed effect $\text{FE}_m = -\ln \Phi_m$. The gravity regression is estimated via Poisson Pseudo Maximum Likelihood (PPML) due to the consistency it delivers under general conditions and its capability of incorporating zeros, as explained in Silva and Tenreyro (2006) and Head and Mayer (2014).

There are two caveats when estimating equation (20). One is that θ is not separately identified from β^τ. To deal with this issue, I supplement the FAF-zone level gravity regression with a country-level regression that exploits tariff variation to identify the trade elasticity. Tariff refers to the logarithm of one plus the bilateral tariff as an *ad valorem* cost shock, of which the coefficient is an estimate of $-\theta$. Distances between country pairs use measures of sea distance to reflect the fact that international trade in cement is mostly seaborne. When using the auxiliary country-level regression, I implicitly assume that the trade elasticity is the same for trade between FAF zones and trade between countries. This is justifiable because the model provides nice aggregation properties such that the trade elasticity continues to be $-\theta$ at higher levels.

The other caveat is that to obtain the component $T_\ell w_\ell^{-\theta}$ at each location, I need to separate the number of plants N_ℓ from the estimated origin fixed effects. With the multi-plant firm model that abstracts away from general equilibrium feedback of cement plants' spatial distribution on factor markets, I can substitute N_ℓ with the observed data on plant locations. However, for the subset of FAF zones without cement plants, the potential production capabilities remain unknown to econometricians. Based on the map of limestone quarries in Figure F.3, states and provinces with zero production are also places with almost no sources of raw materials, such as Saskatchewan, Manitoba, North Dakota, Nebraska, Wisconsin, Louisiana, and Mississippi. Hence, assuming those FAF zones have costs too high to build any cement firms in equilibrium, it is plausible to exclude them from firms' choice sets.

Table 1 summarizes the first-step results. Columns (1) to (3) report the results for the US and Canada FAF zones, and columns (4) and (5) are pertain to the auxiliary sample of 144 countries. The key parameter of interest is the elasticity of trade with respect to trade costs. It maps to the negative plant productivity dispersion parameter in the multi-plant firm model. Columns (4) and (5) obtain similar estimates of the trade elasticity, with an average of -11. Considering the homogeneous nature of cement and therefore the tougher competition among cement plants, it makes sense to have θ higher than what is typically found in the literature (around -5 in Head and Mayer, 2014).

As for the trade cost parameters, the distance elasticity estimated using the country sample is similar to that using FAF zones. At the FAF-zone level, the effects of internal distance and distance to other FAF zones are separately estimated. The elasticity of distance to other zones is estimated to be around -1.2, consistent with the -1 benchmark found in the past literature. The effect of internal distance is smaller, at around -0.45, suggesting that cement is more than proportionally consumed in home locations, a result in accordance with the positive and significant home coefficient in the country-level regression. All columns show more trade if locations are adjacent, sharing the same state/province/country, or having common trade agreements. OLS overestimates compared to PPML in the presence of heteroskedastic gravity errors, while the PPML estimates using trade flows and trade shares are close. For the following steps of estimation, I take $\theta = 11$ and the estimated trade costs computed from Table 1, column (3), as my benchmark.

4.2 Step 2: Estimation of demand

I now turn to estimating the price elasticity of demand $-\eta$ and demand parameters β^A. Using equation (13), the local price index is a function of the estimates from the first step, the observed plant locations, and only one unknown η. I combine it with equation (1) to

Table 1: Estimation of trade costs

	FAF zone sample			Country sample	
	(1)	(2)	(3)	(4)	(5)
	OLS, $\log Q_{\ell m}$	PPML, $Q_{\ell m}$	PPML, $Q_{\ell m}/Q_m$	PPML, $Q_{\ell m}/Q_m$	PPML, $Q_{\ell m}/Q_m$
log (1+ cement tariff$_{\ell m}$), $-\theta$				-10.567^a	-11.633^a
				(2.590)	(2.711)
log sea dist$_{\ell m}$				-1.359^a	
				(0.157)	
log shipping time$_{\ell m}$					-1.067^a
					(0.138)
log dist$_{\ell m, m \neq \ell}$	-2.297^a	-1.174^a	-1.198^a		
	(0.032)	(0.034)	(0.032)		
log dist$_{\ell \ell}$	-1.499^a	-0.462^a	-0.455^a		
	(0.042)	(0.037)	(0.039)		
intra-nation$_{\ell m}$	3.176^a	1.048^a	1.757^a		
	(0.134)	(0.123)	(0.239)		
intra-state$_{\ell m}$	0.393^a	0.546^a	0.414^a		
	(0.100)	(0.093)	(0.086)		
contiguity$_{\ell m}$	1.258^a	1.401^a	1.223^a	2.740^a	2.617^a
	(0.073)	(0.062)	(0.075)	(0.342)	(0.410)
language$_{\ell m}$				-0.449	-0.465
				(0.296)	(0.291)
RTA$_{\ell m}$				1.559^a	1.738^a
				(0.323)	(0.302)
home$_{\ell m}$				7.456^a	7.749^a
				(0.476)	(0.625)
Observations	25435	54385	54385	20736	20736
R^2	0.576	0.917	0.687	0.975	0.973

For the regressions using the FAF zone sample for 2012-2016, columns (1)-(3) include origin-year and destination-year fixed effects. The set of origins include 73 FAF zones across the US and Canada that have positive cement production. The set of destinations are 149 FAF zones. For the regressions using the country-level sample, columns (4)-(5) include origin and destination fixed effects. Regressions use 144 countries' squared sample for year 2016. R^2 is the correlation of fitted and true dependent variables. Robust standard errors are in parentheses. Significance levels: ^{c} p<0.1, ^{b} p<0.05, ^{a} p<0.01.

estimate

$$\ln Q_m = \mathbf{X}_m' \beta^A - \eta \ln P_m(\eta) + \nu_m. \tag{21}$$

Since η enters the demand function non-linearly, I apply GMM with instruments for price. I use the average of local and nearby locations' input costs as instruments, weighted by the inverse of trade costs. The input costs include durable goods manufacturing wages, limestone prices, natural gas and electricity prices. Table 2 presents the results. As expected, the estimated price elasticity in column (2) corrects the upward bias estimated using nonlinear least squares without instruments in column (1). The effects of two demand shifters, population and allocated building permits, are both estimated to be positive and significant.

Table 2: Estimation of demand

	Model consistent		Pure empirical
	(1) NLLS	(2) GMM	(3) 2SLS
log price$_m$, $-\eta$	-1.382^a	-2.683^a	-2.117^b
	(0.323)	(0.627)	(1.014)
log building permits$_m$	0.424^a	0.399^a	0.536^a
	(0.048)	(0.051)	(0.067)
log population$_m$	0.653^a	0.628^a	0.562^a
	(0.058)	(0.059)	(0.074)
Observations	744	744	739

All regressions include year fixed effects. The dependent variable is the log cement consumption in thousand tonnes. The last two columns use instruments, but not column (1). The set of markets includes 149 FAF zones during 2012-2016. Robust standard errors in parentheses. First-stage regression results for column (3) are in the online Appendix Table C.3. Significance levels: ^{c} p<0.1, ^{b} p<0.05, ^{a} p<0.01.

As a robustness check, I also estimate the demand using the USGS data on cement market prices. The classification of USGS price survey area is broader than FAF zones, consisting of 28 clusters of states and provinces. I leverage the instruments to address the issue of measurement error and price endogeneity. Column (3) in Table 2 presents this result.

The literature studying the cement industry has yet to reach a consensus about its demand elasticity. Jans and Rosenbaum (1997) estimated the US domestic demand elasticity as -0.81. Ryan (2012) estimated a range between -1.99 and -3.21, and later Fowlie et al. (2016) estimated -0.89 to -2.03. My estimate, -2.68, falls within the interval of these estimates and is close to the preferred estimate of -2.96 in Ryan (2012). Estimates of $\eta = 2.68$ and $\theta = 11$ also confirm $(\eta - 1)/\theta < 1$ such that the firm's profit function is well defined for solving the multi-plant location game.

4.3 Step 3: Estimation of fixed costs

Having the necessary elements for constructing firms' expected payoff, the last step is to estimate the fixed costs of establishing plants by solving a combinatorial discrete location game within a method of simulated moments estimation.

To make the problem more tractable, I restrain the location game to a duopoly, LafargeHolcim and Cemex, the two largest multi-plant cement producers in my sample. Since fringe firms are also important, I allow all the other firms to be incumbents competing in price, but keep their locations fixed, assuming small firms entered without anticipating LafargeHolcim and Cemex in the later period. The spatial distribution of small firms then defines covariates that LafargeHolcim and Cemex take as given when choosing locations. This timing assumption is consistent with the background of the cement industry in the US and Canada. The region had many small local firms before large multinationals entered. Any ex-post regret by the small firms is ruled out by the one-shot static game.

I apply the solution algorithm proposed in Arkolakis and Eckert (2017) to solve the submodular game with combinatorial discrete choices over a large set of potential locations. The intuition is that with plants being substitutes, a firm will always stay out of a location if adding it to the null set incurs negative marginal profit, because the location does not add value to the firm even when no other plants compete against it. Likewise, a firm will always enter a location if subtracting it from the full set incurs negative marginal profit, because the location still adds value to the firm even when all other plants could steal business from it. Following this idea, I can iteratively squeeze the set to the optimum if the marginal profit of adding a plant location decreases with the number of existing locations. Instead of evaluating every configuration, I leverage the submodularity of the profit function to discard non-optimal location sets without having to evaluate them.

When there is more than one firm, firms take turns to solve the best location response, given the other player's current plant locations and fringe firms' locations. Best responses are solved iteratively until strategies of both players converge. The speed of convergence in a game with best-response potential properties is exponential, proved in Swenson and Kar (2017).[27]

To tackle multiplicity of equilibria, I choose an equilibrium by imposing a certain entry sequence and allow for different ordering as robustness checks. Although the entry game is

[27]The online Appendix Table C.4 presents simulation results of the speed of convergence in a duopoly game with various number of locations. It takes a maximum of three rounds of iteration to find the best response CDC solution for two firms.

static, the assumption is convenient to avoid multiple equilibria. As baseline, I estimate the model by selecting the equilibrium that is most profitable for LafargeHolcim, the largest player and an early entrant in North America in the 1950s.[28] I start from the solution of LafargeHolcim for its best response using the algorithm by assuming Cemex does not enter anywhere. Then Cemex finds its best response given LafargeHolcim's initial strategy. Alternatively, I also estimate the equilibrium that is most profitable for Cemex, and another one that gives each firm regional advantage by moving first.

Knowing how to solve for the firms' optimal location strategy given a vector of fixed costs, I can estimate the parameters governing the fixed cost distribution via MSM. I simulate the entry probability for each firm in every location by drawing firm-location specific fixed costs from the log-normal distribution. For each draw, firms maximize total expected profits by choosing where to build plants. The simulated entry probabilities are used to construct moments to match the observed values of (a) the number of LafargeHolcim/Cemex plants in Canada and the US; (b) the average distance from headquarters of LafargeHolcim/Cemex to plants;[29] and (c) the difference between the average production capability for locations where LafargeHolcim/Cemex produces and those where it is absent. The first two sets of moments are informative about the mean fixed costs. The last set of moments helps to pin down the dispersion of the fixed cost distribution. The larger the dispersion is, the more entry decisions vary by fixed costs and less by local profitability. In other words, firms care more about fixed costs in deciding where to build plants and they could enter even if the local production capability is not as high.

Estimates of the fixed costs parameters for three different equilibria are displayed in Table 3, corresponding to the scenario that is most profitable for LafargeHolcim (LFH), most profitable for Cemex (CEX), and where LFH has a local advantage in Canada and CEX in Texas and Florida. They are not significantly different from one another, and thus ease the generality concern of the counterfactual results. The equilibrium selection rule does not have "bite" here because the two oligopolists are sufficiently asymmetric. Specifically, LafargeHolcim owns twice the number of plants as Cemex. Assuming Cemex moves first, the

[28]Lafarge (prior to the merged entity LafargeHolcim) built its first cement plant in Richmond, Canada in 1956. By the end of 1960s, Lafarge was the third largest cement producer in Canada. Its market in the US expanded after its acquisition of General Portland in 1983. Cemex has never produced in Canada and its operation in the US started until the anti-dumping duty on imports of gray Portland cement from Mexico went into effect in 1990.

[29]For LafargeHolcim, I use its North America headquarter, which is in Chicago, Illinois, because it is unlikely that plant operations are managed by its global headquarter in Switzerland given the firm size. For Cemex, I use its global headquarter in Mexico.

model must rationalize the fact that Cemex enters half the number of locations as LafargeHolcim. It does so by making Cemex acquiesce to LafargeHolcim's entry and choose to forgo some locations, expecting LafargeHolcim would enter. Estimates reflect that Cemex has disadvantages in those locations. Vice versa, assuming LafargeHolcim moves first, the estimates need to be consistent with the patterns in the data whereby LafargeHolcim is the dominant player.

Table 3: Estimation of fixed costs

	(1) Favor LafargeHolcim	(2) Favor Cemex	(3) Local advantage for two firms
β^F_{cons}	-6.631	-6.126	-5.617
	(1.616)	(1.688)	(1.559)
$\beta^F_{\text{CEX-USA}}$	-0.406	-0.363	-0.280
	(0.373)	(0.382)	(0.372)
$\beta^F_{\text{LFH-CAN}}$	-3.734	-3.475	-3.480
	(1.867)	(2.318)	(1.992)
β^F_{dist}	1.795	1.698	1.634
	(0.220)	(0.245)	(0.221)
σ^F	2.790	2.581	2.694
	(0.481)	(0.504)	(0.503)

Identity matrix are used to weight the moments equally. Cluster bootstrapped standard errors are in parentheses. Cemex does not have any Canadian plants in the actual data, which makes it impossible to identify the Cemex-Canada dummy. I drop the Cemex-Canada and LafargeHolcim-US dummies. Results are robust to using the optimal weighting matrix and asymptotic variance of the MSM estimator as shown in Table C.6.

I find a location that is 10% more distant from the firm's headquarter, the average fixed costs of establishing plants will be nearly 18% higher holding everything else constant. The effect seems to be large considering communication and management cost alone, but should be interpreted with caution. First, it could reflect increasing information friction at locations further away from the firm's headquarter. Second, there could be loss of productivity associated with transferring headquarter services to production locations. The model does not capture such cost of producing, and it could be picked up by fixed costs in estimation. With limited plant-level data, I cannot separately identify plants' ex-ante differences in variable costs from fixed costs.

The average fixed cost is significantly lower when LafargeHolcim builds a plant in

Canada, whereas Cemex does not share the country-specific advantage in fixed costs. Variance of the fixed cost distribution is rather high, suggesting that firms' entry decisions are predominantly determined by fixed costs rather than local profitability. The result is consistent with high fixed cost investment in the cement industry. One may argue that the reason local profitability appears to matter less could be that the variable profit modeled in the multi-plant firm framework fails to capture some important aspects. I perform external validity checks to show that the estimated fixed costs align with the industry facts.

To compare the costs estimated from the model to the cement industry standard, I transform the estimates to their corresponding monetary values.[30] A back-of-envelope calculation reveals that the average fixed cost across the cement plants owned by LafargeHolcim is estimated at around $181 million and that for the Cemex plants around $280 million. They fall within the industry norm of $200∼$300 million. LafargeHolcim's fixed cost advantage enables it to operate twice the number of plants compared to Cemex.

As for the costs of production, LafargeHolcim is estimated to incur an average cost of $57 per tonne of cement supplied using equation (4). At LafargHolcim's average price of $98 per tonne based on equation (7), this implies a gross margin of 41.8 percent for LafargeHolcim. For Cemex, the average cost is $65 per tonne of cement, implying a gross margin of 33 percent using Cemex's average price of $97. The lower cost and higher markup for LafargeHolcim compared to Cemex are consistent with the model's propositions that a firm having more plants will gain competitive advantages and market power. I compare the estimated profit margins with the 2016 financial statements of the two firms to assess the plausibility of these estimates. LafargeHolcim reported a profit margin of 41.9 percent, and Cemex reported 35.5 percent, both of which almost exactly match the estimates above.[31] The costs of production are also close to the engineering costs of $60 in 2016 documented by the US Environmental Protection Agency.[32] In sum, these cross-firm comparisons corroborate the cost estimates of the multi-plant firm model.

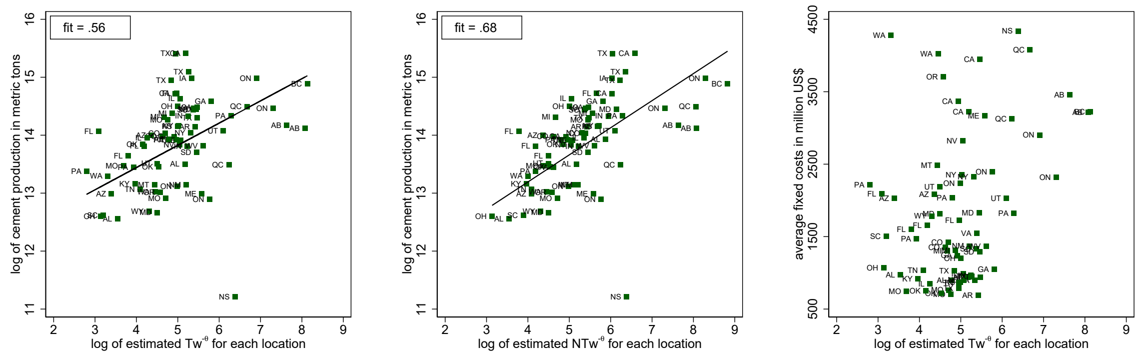
Across locations, I analyze the interaction between the estimated production capability, the estimated average fixed costs and the observed cement production volume by FAF zones. Figure 4 plots the estimated cement production capability against the actual production volume for each location in panel (a), and the combined effect with the number

[30] Please refer to the online Appendix (Section C.4) for more details of the transformation.

[31] The 2016 financial statement of LafargeHolcim lists a gross profit of $11,272 million on sales of $26,904 million. Cemex's 2016 statement reports a gross profit of $4,756 million on sales of $13,404 million.

[32] EPA reports engineering estimates of average production costs of $50.3 per tonne of cement in 2005 (RTI International, 2009). I convert this into 2016 dollars.

Figure 4: Cement production, estimated fixed costs and production capability by location



(a) Excluding number of firms (b) Including number of firms (c) Estimated fixed costs

of plants in panel (b). The positive correlation in both figures suggests a credible ranking of the estimated location production capability. The higher R-square in panel (b) indicates that the number of plants contributes to explaining cement production.[33] Comparing across the three panels, the variation in cement production is a result of differences in location-specific input costs and fixed costs of entry. For example, Nova Scotia, a province having moderate production capability, produces an exceptionally small amount of cement. The inconsistency is reconciled by Nova Scotia having the highest average fixed costs. In contrast, FAF zones in Texas are as capable of producing cement as Nova Scotia but are among the lowest fixed-cost locations, contributing to Texas being the largest cement producer in the sample. The cross-location analysis, complemented by the firm-level comparison, highlights the importance of heterogeneous fixed costs at the plant level for matching the model to the data.

4.4 Fit of the model

I further evaluate the model's goodness of fit across both targeted and untargeted dimensions. As shown by Table 4, the model fits the data generally well in the number of plants, despite a slight over-estimation in Canada. Figure 5a presents a close fit of trade share by

[33]The fit displayed in Figure 4 is the R-square by regressing log production on log location production capability and controlling for average trade costs weighted by destination market size. One can derive from equation (10) that $\ln \sum_m Q_{\ell m} = \ln N_\ell T_\ell (w_\ell)^{-\theta} + \ln \sum_m \left(\frac{\tau_{\ell m}^{-\theta} Q_m}{\Phi_m} \right)$, where the second term is the average trade costs controlled when plotting.

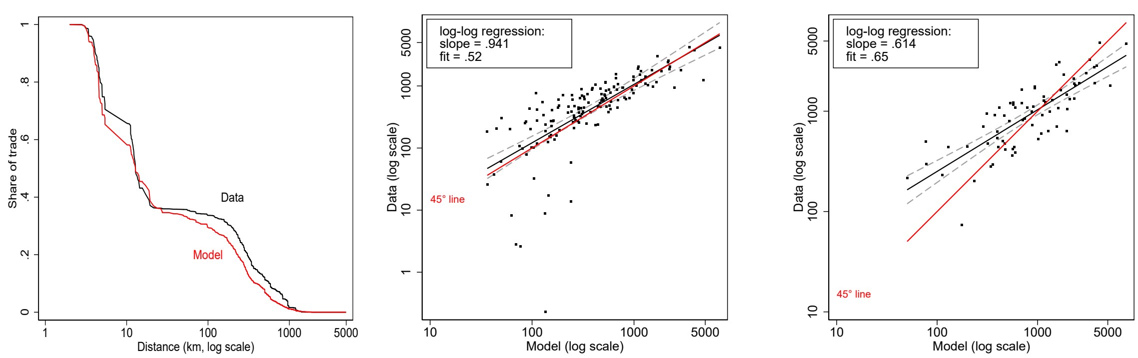
distance.[34] Additionally, the actual and predicted cement consumption across markets are distributed tightly along the 45-degree line in Figure 5b and 5c. The prediction on production, although deviating from the diagonal relationship, captures 65% of the data variation. Multiple test results establish confidence in the following counterfactual analysis.

Table 4: Model fit of plant number and distance to headquarters

	LafargeHolcim		Cemex	
	Data	Model	Data	Model
Number of plants	22	22.50	11	11.02
Number of plants, Canada	6	6.74	0	0.71
Number of plants, US	16	15.76	11	10.31
Average distance of HQ to plants (km)	369	330	271	283

The predicted numbers of plants are not integers because they are summations of the simulated entry probabilities.

Figure 5: Model fit of cement trade, consumption and production



(a) Trade flow over distance (b) Consumption ('000 tonnes) (c) Production ('000 tonnes)

5 Counterfactual: Greenhouse Gas Pollution Pricing Act

In 2018, Canada enacted the Greenhouse Gas Pollution Pricing Act, which established a federal backstop system to increase the carbon price to $50 per tonne by 2022. The framework includes two carbon pricing initiatives: a carbon tax on fossil fuels and an

[34] Additional comparisons of predicted and actual bilateral share of imports and trade volume are provided in the online Appendix (Section C.5).

output-based pricing system for industrial facilities.[35] My primary interest is to evaluate the welfare costs of these environmental regulations for both consumers and producers by examining the alternative spatial allocation of plants and market structure in the long run.

5.1 Carbon tax on fossil fuels

In this section, I examine the effect of a carbon tax levied on fossil fuels, which are essential for generating energy to produce cement. Assuming that there is no substitution of fuel to other carbon-saving sources, the average cost of fuel for producing one tonne of cement increases from \$12.44 to \$29.37 after the policy.[36] It implies a 33 percent increase in the input cost w_ℓ, or a 96 percent decrease in local production capability $T_\ell w_\ell^{-\theta}$ for all FAF zones in Canada, exacerbated by the relatively high θ.[37] When plants are not widely differentiated, an increase in production costs can lead to greater losses of market share, explaining why carbon policy could be a significant threat to the competitiveness of the local cement industry.

Facing cost increases, cement firms tend to relocate plants to "pollution havens". Figure 6a compares the spatial distribution of plants before and after the carbon tax, combining the top two cement firms. Red indicates the share of plants predicted to close, while green indicates the share of plants predicted to open. FAF zones other than the 73 are excluded from the potential location set and shaded in grey. The map shows plant closures are spread across FAF zones in Canada, with the most notable exit ratio in Quebec where over 20 percent of the plants will be shut down. Cement plants are relocated to zones along the US border, near the original Canadian locations, as they are close substitutes in distance to destination markets. Additionally, plants are also built in places where costs of production is low, such as Utah. On the west coast, Washington and Montana experience the highest increase in plants, around 16 percent more. On the east coast, plant openings are weaker because there is already a dense production network, as shown in Figure 2.

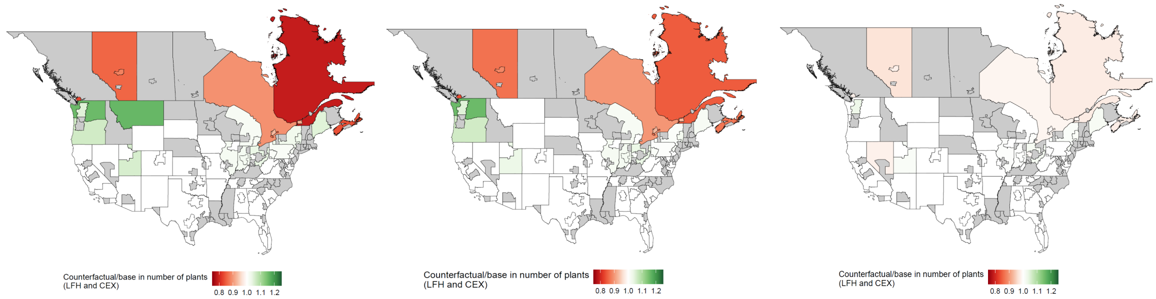
Table 5 presents the effects of carbon policies on firms and countries. When Canada charges a \$50 carbon tax on fossil fuels, the top two cement firms lost around 13 percent

[35]In practice, the federal benchmark allows provinces to implement their own carbon pollution pricing systems to account for their unique circumstances. For example, Alberta has its own Carbon Competitiveness Incentive Regulation. Nova Scotia and Quebec implement cap-and-trade systems. These provincial regulations meet the federal government's minimum stringency requirements for pricing carbon pollution. For simplification, counterfactual analysis in this paper assumes a uniform change in all Canadian provinces.

[36]Please refer to the online Appendix (Section D) for model details in calculating the cost of fuel.

[37]Based on Section 3.2, fuel accounts for one-third of the input costs, and therefore $\%\Delta w_\ell = (29.37/12.44)^{1/3} - 1 \approx 33\%$, and $\%\Delta T_\ell w_\ell^{-\theta} = ((29.37/12.44)^{1/3})^{-11} - 1 \approx -96\%$.

Figure 6: Change of plant locations



(a) \$50 carbon levy on fuel (b) \$50 levy & 33% BTA (c) OBPS at 95% allowance

of Canadian plants relative to the baseline, and these losses are not fully compensated by building plants in the US. Across firms, the carbon tax hurts LafargeHolcim, the dominant player in Canada, the most. It is worth noting that the model overestimates the presence of Cemex in Canada compared to the actual data, which suggests that Cemex could potentially benefit from the weakening of a competitor following the implementation of the carbon tax.

The average unit price in Canada increases by almost one-third of the baseline cement price, which is more than the amount of increase in fuel prices due to the rising market concentration. The result is in line with Ganapati et al. (2020) and Miller et al. (2017), who found that changes of fuel cost are more than fully passed to cement prices. However, in the US, the impact on price is modest driving by two opposing forces: the downward pressure from intensified market competition through new plant entries and the upward pressure from the loss of cheap cement imported from Canada, in which case the latter slightly dominates.

Production are more responsive to the policy changes than the extensive margin adjustment on plants entry and exit. The contraction of production in Canada is substantial, at approximately 66 percent. The difference in changes between production and the number of plants implies that the Canadian plants become underutilized, whereas US plants experience the opposite. As for the impacts on trade, the cement exports from Canada to the US almost vanish. Instead, the amount of imports from the US to Canada is more than tripled, implying an increase in import penetration from 6 percent to 30.5 percent.

Table 6 reports the welfare changes. Facing a \$50 carbon tax on fuel, Canadian consumers lose around \$310 million and producers lose around \$68 million annually.[38] The combined loss amounts to about 24 percent of the \$1.6 billion revenue generated by the

[38]Producer surplus is calculated by combining all firms including the small ones operating in the region.

Table 5: Aggregate effects of carbon policies in Canada on market outcomes

	Number of plants		Price	Consumption	Production	Trade	
	LFH	CEX				Canada	US
(a) Baseline:							
Canada	6.74	0.71	96.29	8.56	11.43	8.06	3.37
US	15.76	10.31	107.21	88.27	85.40	0.50	84.90
(b) $50 carbon levy on fuel:							
Canada	6.00	0.50	123.11	5.31	3.87	3.69	0.18
US	15.85	10.43	107.95	85.95	87.39	1.62	85.77
(c) $50 carbon levy on fuel and 33% BTA:							
Canada	6.07	0.51	128.53	3.97	3.92	3.74	0.18
US	15.81	10.41	107.96	85.92	85.97	0.23	85.74
(d) OBPS:							
Canada	6.64	0.69	99.44	7.91	9.79	7.35	2.44
US	15.79	10.33	107.41	87.6	85.72	0.56	85.16

There are 10 potential production locations in Canada and 63 in the US. Number of plants is calculated by summing the probability of entry to locations, and thus, can be fractional. Price is denoted in US dollars. Consumption, production and trade volume are denoted in millions of metric tonnes. The row countries are exporters, and the column countries are importers in the last two columns.

Table 6: Aggregate effects of carbon policies in Canada on welfare and emissions

	Δ CS	Δ PS	Δ TaxRev	Δ Emissions	Leakage rate
(a) $50 carbon levy on fuel:					
Canada	-310.50	-68.04	77.40	-6.05	26.32
US	-35.54	10.70	-	1.60	-
(b) $50 carbon levy on fuel and 33% BTA:					
Canada	-322.76	-66.27	89.09	-6.00	7.60
US	-36.30	10.93	-	0.46	-
(c) OBPS:					
Canada	-46.36	-9.57	19.58	-1.31	19.51
US	-9.57	2.67	-	0.26	-

Change is relative to baseline. Consumer surplus, producer surplus, and government revenue are denoted in millions of US dollars. Emissions are calculated based on an emission intensity of 0.8 tonne of CO_2 per tonne of cement produced in both the US and Canada. It is denoted in millions of tonnes. The leakage rate is represented as a percentage.

Canadian cement industry in 2016. Consumers bear about 82 percent of the tax burden, comparable to the 89 percent found by Miller et al. (2017) in their study of a US carbon tax. Using 0.4 tonne of CO_2 emitted from fuel combustion per tonne of cement produced, the government revenue is approximately $77 million. Producers can be fully compensated with 88 percent of the revenue obtained from the carbon tax. Although one may expect a negative cost shock in Canada to benefit the US, the welfare assessment indicates otherwise. The US also incurs a loss of around $25 million driven by higher prices faced by consumers. Just as the carbon pollution has a global impact, the effects of a carbon tax in one country also transmit to others through multi-plant production and trade.

In terms of environmental impacts, for every 100 tonnes of CO_2 abated in Canada, around 26 tonnes "leak" to the US, resulting in a net reduction of 4.45 million tonnes of carbon emissions.

5.2 Border tax adjustment

To mitigate carbon leakage, one approach is to issue a border tax adjustment (BTA), as exemplified by the European Union's adoption of this measure since 2023. This mechanism involves the levying of an *ad valorem* border tax on unregulated imports, which aims to equalize the competition between domestically produced cement and its foreign counterparts. In the case of Canada, a $50 carbon tax on fossil fuels is equivalent to raising the border tax by 33 percent.[39]

Augmenting the carbon tax on fuel with a BTA mitigates the loss of domestic market share to foreign producers, thus slowing the change of plant locations from Canada to the US as shown in Figure 6b compared to Figure 6a. Specifically, the plant exit ratio in Quebec drops from over 20 percent to 15 percent, and new plants no long enter Montana. Compared to the scenario with a carbon tax alone, Table 5 presents smaller changes in the number of plants and higher level of production in Canada.

The border tax adjustment is effective in reducing the carbon leakage from 26 percent to 7.6 percent, as shown in Table 6. It cuts down the total emissions by an additional 1.2 million tonnes. However, BTA cannot override the closure of cement plants or eliminate carbon leakage because Canadian exporters—a significant share of Canadian cement producers—would still relocate their production to the US.

5.3 Output-based pricing system

In the previous section, I demonstrated that a sufficient level of BTA alongside a carbon tax can partially address the issue of leakage. However, if the majority of Canadian plants are exporters that compete in foreign markets, the gain from this strategy is compromised. An

[39]Because w and τ both affect the sourcing probability by θ, leveling the playing field between Canadian the US producers implies equal amount of increase in US-to-Canada trade costs and Canadian input costs.

alternative is to impose an output-based pricing system (OBPS) as adopted by the Canadian Greenhouse Gas Pollution Pricing Act. OBPS prices carbon on the basis of emission intensity. For the cement industry, if a plant emits more than 0.76 tonne CO_2 per tonne of cement (95 percent of sectoral emission intensity 0.8tCO_2/tonne of cement), it faces a marginal tax rate of \$50/tCO_2 on the excess portion.[40]

The objectives of OBPS are twofold: firstly, to provide relief from fuel charges so that domestic firms retain some level of competitiveness compared to foreign rivals, and secondly, to incentivize firms financially to transit to cleaner technologies. However, this carbon pricing scheme comes with a notable side effect—smaller carbon reductions in targeted industries—as I will show in Table 6.

I model the OBPS as an output-based "rebate" following Canada Gazette (2019). Since data on firm- or plant-level carbon emissions intensity is unavailable, and the static model is unable to accommodate endogenous technological improvement, I take a heuristic approach and assume that all cement plants operate at the industry average. The assumption is not as unreasonable considering the industry has standardized production practices for almost all plants as mentioned in Section 3.2. Therefore, in this counterfactual exercise, the OBPS is effectively a lower carbon tax at the average rate of \$2 per tonne of cement, or *ad valorem* 2.76 percent increase in the production cost of Canadian plants.[41] One caveat is that predictions here are an upper bound of the effect of OBPS on plant locations and a lower bound on carbon reduction, as firms are treated as passive taxpayers without adaptation for cleaner production process.

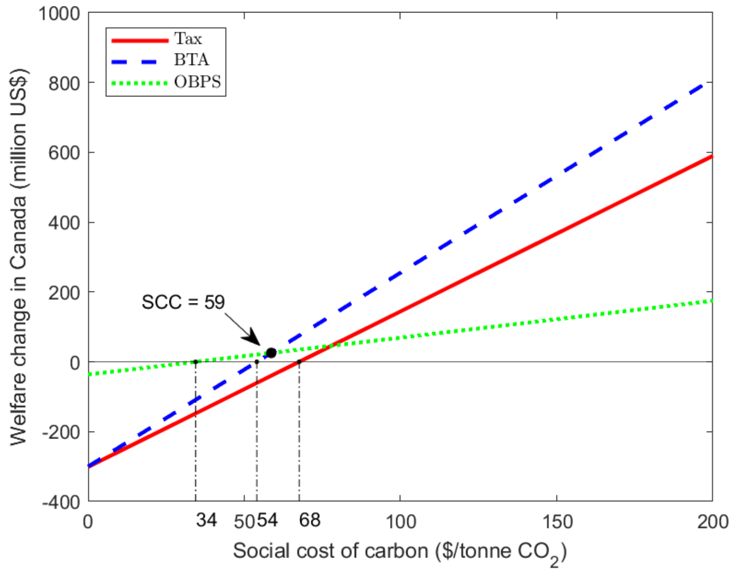
Figure 6c illustrates that OBPS triggers the least amount of change in plant locations among the three carbon pricing schemes. Very few locations in the US are observed with entry, and some locations, such as Nevada, even experience plants exiting due to expansion in the nearby area (Seattle). The changes in market outcomes are not qualitatively different from those facing a \$50 carbon tax, albeit with smaller magnitudes. Carbon leakage rate decreases from 26 to 19.5 percent. However, the net carbon emissions abatement is the least of the three policies and only around a quarter of the emissions reduction achieved with \$50 carbon tax on fuels.

Figure 7 presents a comparison of the welfare effects of three carbon pricing schemes using equation (16) across different levels of social costs of carbon. When SCC is below

[40]Firms that emit less than the limit will obtain surplus credits that can be sold to firms that need credits for compliance. This carbon trading aspect of OBPS is ignored due to limited firm-level data.

[41]The effective rate of OBPS is $50 \times 0.8 \times (1 - 95\%) = 2$ per tonne of cement. The estimated average Canadian plant production cost is \$72.56, calculated from equation (4). Therefore, $2/72.56 = 2.76\%$.

Figure 7: Welfare comparison of carbon policies



$34 per tonne of CO_2, none of the carbon policies generates a positive welfare change for Canada. The losses experienced by consumers and producers due to high production costs and prices cannot be compensated by the reduction of a less damaging pollutant. As carbon emissions become more harmful, OBPS first emerges as welfare-improving. By granting free allowances to cement producers, it incurs the least losses for consumers and producers per tonne of emissions abatement, which can be easily outweighed by the environmental benefits.

When SCC reaches $59, imposing border tax adjustment attains an equivalent level of welfare gain to that of OBPS. Beyond this threshold, BTA outperforms the other two schemes by effectively reducing a more damaging pollutant through charging taxes also on foreign-produced goods.

A carbon tax on fossil fuels alone is suboptimal in this analysis for two reasons. Firstly, it gives rise to carbon leakage, which entails global damages. Secondly, the market distortion is exacerbated in the presence of oligopolists. Conversely, a BTA addresses the first concern by internalizing the leakage. An OBPS tackles the second concern by mitigating the escalating production costs faced by an already under-produced industry.

6 Single-plant Approximation

With the multi-plant (MP) firm framework in place, a crucial question remains: how relevant is incorporating interdependent entry in the study of multi-plant firms? After all, assuming separate plant entries is empirically convenient and avoid the need to solve a combinatorial optimization problem. In reality, a multi-plant firm can operate with varying degrees of control over its plants, ranging from complete oversight to full delegation to local managers. Rather than debating which premise is correct, I present comparisons between the two.

Using the same model, I approximate the fixed cost assuming that each plant makes separate location decision instead of estimating them jointly. A plant enters if and only if its own expected variable profit is not less than its fixed cost. Keeping the same parametric assumption of fixed costs, the empirical form of entry probability under single-plant (SP) approximation is

$$\Pr\left[\ell \in \mathcal{L}_f\right] = \Phi\left(\frac{1}{\sigma^F}\ln E\left[\pi_{f\ell}\right] - \mathbf{X}'_{f\ell}\frac{\beta^F}{\sigma^F}\right), \tag{22}$$

where $E\left[\pi_{f\ell}\right] = \kappa\sum_m \left(\phi_{\ell m}/\Phi_{fm}\right) A_m \left(\bar{R}_{fm} - \bar{C}_{fm}\right)$ constructed using the first two-step estimates from Sections 4.1 and 4.2.[42] Parameters that govern the fixed cost distribution are estimated via binary Probit.[43]

With the SP approximated parameters in Table 7, constructing a LafargeHolcim plant costs an average of \$63.4 million, while for Cemex, it is \$61.9 million. These amounts are about one-third and one-fifth of the MP estimates, respectively. The SP approximated fixed costs are significantly biased downward due to omitted interdependencies. In the multi-plant firm model, firms benefit from more plants to compete against rivals, making entry profitable at the firm level but not necessarily at the plant level. Consequently, plant-level fixed costs are lower to match observed plant numbers. The bias is smaller for LafargeHolcim because the marginal benefit diminishes with the number of plants. However, having more plants does not guarantee smaller biases since MP is equivalent to SP when a firm has only one plant. The bias instead exhibits a hump shape.[44]

Differences in fixed costs lead to deviations in counterfactual policy evaluations. Figure 8 compares the change of plant locations using the two sets of estimates under a \$50 carbon

[42] See the online Appendix (Section E) for derivation and other details of the SP approximation.

[43] The Probit regression at plant level is no longer i.i.d, I use the spatial interdependent Probit models in Franzese and Hays (2008) to correct for the bias. Results are shown in Table E.9.

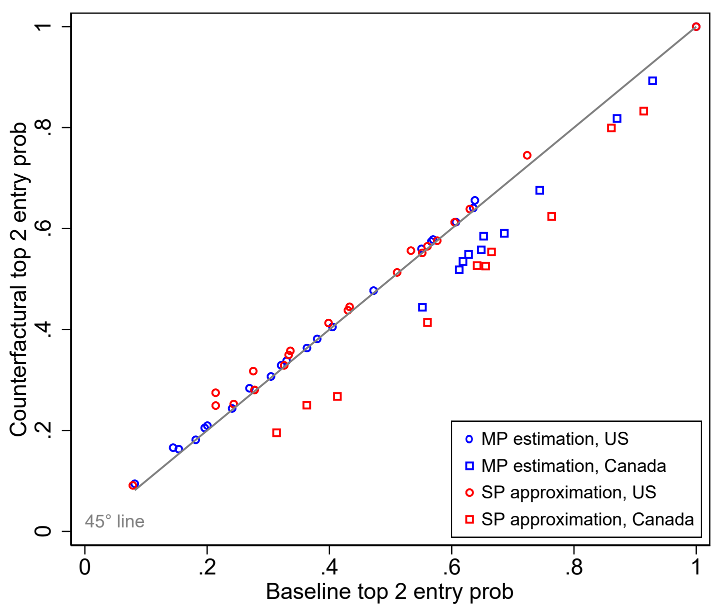
[44] I leave more investigation of the firm size that would suffer the largest estimation bias assuming separate entry to the future.

Table 7: Estimation of fixed costs: Multi-plant estimation vs. Single-plant approximation

	(1) MP estimation	(2) SP approximation
β^F_{cons}	-6.631	-0.219
	(1.616)	(2.668)
$\beta^F_{\text{CEX-USA}}$	-0.406	-0.294
	(0.373)	(0.495)
$\beta^F_{\text{LFH-CAN}}$	-3.734	-1.570
	(1.867)	(1.016)
β^F_{dist}	1.795	0.734
	(0.220)	(0.401)
σ^F	2.790	1.777
	(0.481)	(0.551)

Column (1) is taken from Table 3 column (1). Standard errors in column (2) are computed using Delta method.

Figure 8: Change of plant locations for $50 carbon levy on fuel: MP vs. SP



tax in Canada. Each dot represents the probability of a top-two firm entering a FAF zone. Smaller SP approximated fixed costs result in a larger dispersion from the 45-degree line, indicating greater relocation from Canada to the US. Further details are provided in the online Appendix Table E.10. Policymakers employing a naive separate-entry approach for estimating multi-plant firms' interdependent location decisions would overstate the amount of production and carbon leakage. These findings highlight the interdependencies underlying multi-plant production.

7 Conclusions

This paper provides a novel framework to study the spatial organization of production and export by multi-plant oligopolists. It highlights the importance of endogenous, interdependent plant locations and their impact on a firm's pricing and markups. Submodularity and aggregative property of the location game underpin the existence of a combinatorial discrete choice optimization solution and the method to find it effectively. Key model parameters are structurally estimated, demonstrating that overlooking spatial interdependencies in these estimations introduces substantial biases.

I apply the multi-plant firm model to the cement industry in the US and Canada, evaluating the carbon leakage issue prominent in environmental policy design and welfare impacts stemming from multi-plant production. A $50 carbon tax in Canada induces 13 percent of Canadian plants to either close or relocate, with 26 percent of carbon abatement "leaking" to the unregulated US, thereby undermining the environmental aims of the taxing economy. The resulting welfare loss to consumers and producers nearly amounts to a quarter of the Canadian cement industry's 2016 revenue due to the exacerbated market distortion led by two large multi-plant manufacturers. Two alternative carbon pricing mechanisms, border tax adjustment (BTA) and output-based pricing system (OBPS), are analyzed. The welfare comparison indicates that in emission-intensive, trade-exposed, and concentrated sectors like cement, policymakers should implement OBPS for pollutants that cause less environmental harm and BTA for more damaging pollutants.

Given the ubiquity of multi-plant or multinational oligopolists in many industries, this paper aims to broaden the scope of empirical research for policy evaluations and spatial organization issues, emphasizing the necessity for careful consideration of location interdependencies in entry and potentially other extensive margin decisions. Hence, natural next steps are to engage interdependencies across buyer and seller locations along the entire supply chain, to study interdependencies in entry and exit in a dynamic framework, or to account for general equilibrium effects.

References

Aghion, P., Bergeaud, A., Boppart, T., Klenow, P. J., and Li, H. (2019). A theory of falling growth and rising rents. Technical report, National Bureau of Economic Research.

Alfaro-Urena, A., Castro-Vincenzi, J., Fanelli, S., and Morales, E. (2022). Firm export dynamics in interdependent markets. Technical report.

Antràs, P., Fadeev, E., Fort, T. C., and Tintelnot, F. (2022). Global sourcing and multinational activity: A unified approach. Technical report, National Bureau of Economic Research.

Antràs, P., Fort, T. C., and Tintelnot, F. (2017). The margins of global sourcing: Theory and evidence from us firms. *American Economic Review*, 107(9):2514–64.

Arkolakis, C. and Eckert, F. (2017). Combinatorial discrete choice. *Available at SSRN 3455353*.

Arkolakis, C., Eckert, F., and Shi, R. (2021). Combinatorial discrete choice.

Arkolakis, C., Papageorgiou, T., and Timoshenko, O. A. (2018). Firm learning and growth. *Review of Economic Dynamics*, 27:146–168.

Atkeson, A. and Burstein, A. (2008). Pricing-to-market, trade costs, and international relative prices. *American Economic Review*, 98(5):1998–2031.

Bernard, A. B., Eaton, J., Jensen, J. B., and Kortum, S. (2003). Plants and productivity in international trade. *American economic review*, 93(4):1268–1290.

Canada Gazette (2019). Output-based pricing system regulations: Sor/2019-266. Canada Gazette, Part II, Volume 153, Number 14.

Cao, D., Hyatt, H. R., Mukoyama, T., and Sager, E. (2017). Firm growth through new establishments. *Available at SSRN 3361451*.

De Blas, B. and Russ, K. N. (2015). Understanding markups in the open economy. *American Economic Journal: Macroeconomics*, 7(2):157–80.

Dubey, P., Haimanko, O., and Zapechelnyuk, A. (2006). Strategic complements and substitutes, and potential games. *Games and Economic Behavior*, 54(1):77–94.

Eaton, J. and Kortum, S. (2002). Technology, geography, and trade. *Econometrica*, 70(5):1741–1779.

Eaton, J., Kortum, S., and Kramarz, F. (2011). An anatomy of international trade: Evidence from french firms. *Econometrica*, 79(5):1453–1498.

Europejska, K. (2009). Commission decision of 24 december 2009 determining, pursuant to directive 2003/87. *EC of the European Parliament and of the Council, a list of sectors and subsectors which are deemed to be exposed to a significant risk of carbon leakage*.

Feyrer, J. (2019). Trade and income—exploiting time series in geography. *American Economic Journal: Applied Economics*, 11(4):1–35.

Fowlie, M., Reguant, M., and Ryan, S. P. (2016). Market-based emissions regulation and industry dynamics. *Journal of Political Economy*, 124(1):249–302.

Franzese, R. J. and Hays, J. C. (2008). Empirical models of spatial interdependence.

Ganapati, S., Shapiro, J. S., and Walker, R. (2020). Energy cost pass-through in us manufacturing: Estimates and implications for carbon taxes. *American Economic Journal: Applied Economics*, 12(2):303–342.

Head, K. and Mayer, T. (2014). Gravity equations: Workhorse, toolkit, and cookbook. In *Handbook of international economics*, volume 4, pages 131–195. Elsevier.

Heckman, J. J. (1978). Dummy endogenous variables in a simultaneous equation system. *Econometrica*, 46(4):931–959.

Holmes, T. J. (2011). The diffusion of wal-mart and economies of density. *Econometrica*, 79(1):253–302.

Holmes, T. J., Hsu, W.-T., and Lee, S. (2011). Plants, productivity, and market size with head-to-head competition. *Manuscript University of Minnesota (23 June)*, page 14.

Holmes, T. J., Hsu, W.-T., and Lee, S. (2014). Allocative efficiency, mark-ups, and the welfare gains from trade. *Journal of International Economics*, 94(2):195–206.

Hsieh, C.-T. and Rossi-Hansberg, E. (2023). The industrial revolution in services. *Journal of Political Economy Macroeconomics*, 1(1):3–42.

Igami, M. and Yang, N. (2013). Cannibalization and preemptive entry of multi-product firms. *Rand Journal of Economics*, 36:908–929.

Jackson, M. O. and Zenou, Y. (2015). Games on networks. In *Handbook of game theory with economic applications*, volume 4, pages 95–163. Elsevier.

Jans, I. and Rosenbaum, D. I. (1997). Multimarket contact and pricing: Evidence from the us cement industry. *International Journal of Industrial Organization*, 15(3):391–412.

Jensen, M. K. (2005). Existence, comparative statics, and stability in games with strategic substitutes. *University of Birmingham*, page 31.

Jensen, M. K. (2010). Aggregative games and best-reply potentials. *Economic theory*, 43(1):45–66.

Jia, P. (2008). What happens when Wal-Mart comes to town: An empirical analysis of the discount retailing industry. *Econometrica*, 76(6):1263–1316.

Jiang, E. and Tyazhelnikov, V. (2020). Shadow o shoring and complementarity in inputs.

Kapur, A., Van Oss, H. G., Keoleian, G., Kesler, S. E., and Kendall, A. (2009). The contemporary cement cycle of the united states. *Journal of material cycles and waste management*, 11(2):155–165.

Miller, N. H., Osborne, M., and Sheu, G. (2017). Pass-through in a concentrated industry: empirical evidence and regulatory implications. *The RAND Journal of Economics*, 48(1):69–93.

Oberfield, E., Rossi-Hansberg, E., Sarte, P.-D., and Trachter, N. (2023). Plants in space. *Journal of Political Economy*, forthcoming.

Rossi-Hansberg, E., Sarte, P.-D., and Trachter, N. (2021). Diverging trends in national and local concentration. *NBER Macroeconomics Annual*, 35(1):115–150.

Ryan, S. P. (2012). The costs of environmental regulation in a concentrated industry. *Econometrica*, 80(3):1019–1061.

Salvo, A. (2010). Inferring market power under the threat of entry: The case of the brazilian cement industry. *The RAND Journal of Economics*, 41(2):326–350.

Silva, J. S. and Tenreyro, S. (2006). The log of gravity. *The Review of Economics and statistics*, 88(4):641–658.

Swenson, B. and Kar, S. (2017). On the exponential rate of convergence of fictitious play in potential games. In *2017 55th Annual Allerton Conference on Communication, Control, and Computing (Allerton)*, pages 275–279. IEEE.

Tamer, E. (2003). Incomplete simultaneous discrete response model with multiple equilibria. *The Review of Economic Studies*, 70(1):147–165.

Tarski, A. et al. (1955). A lattice-theoretical fixpoint theorem and its applications. *Pacific journal of Mathematics*, 5(2):285–309.

Tintelnot, F. (2017). Global production with export platforms. *The Quarterly Journal of Economics*, 132(1):157–209.

Topkis, D. M. (1978). Minimizing a submodular function on a lattice. *Operations research*, 26(2):305–321.

Van Oss, H. G. and Padovani, A. C. (2003). Cement manufacture and the environment part ii: environmental challenges and opportunities. *Journal of Industrial ecology*, 7(1):93–126.

Vives, X. (1999). *Oligopoly pricing: old ideas and new tools*. MIT press.

Zheng, F. (2016). Spatial competition and preemptive entry in the discount retail industry. *Columbia Business School Research Paper*, (16-37).