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# Strategic response to pollution taxes in supply chain networks: Dynamic, spatial, and organizational dimensions

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ABSTRACT

This paper presents a model of the strategic behavior of firms operating in a spatial supply chain network. The manufacturing and retailing firms engage in an oligopolistic, noncooperative game by sharing customer demand such that a firm's decisions impact the product prices, which in turn result in changes in all other firms' decisions. Each firm's payoff is to maximize its own profit and we show that, in response to such changes in prices and to exogenous environmental taxes, the manufacturing firms may strategically alter a variety of choices such as 'make-buy' decisions with respect to intermediate inputs, spatial distribution of production, product shipment patterns and inventory management, environmental tax payment vs recycling decisions, and timing of all such choices to sustainably manage the profit and the environmental regulations. An important implication is that effects of a tax depends on the oligopolistic game structure. With respect to methods, we show that this dynamic game can be represented as a set of differential variational inequalities (DVIs) that motivate a computationally efficient nonlinear complementarity (NCP) approach that enables the full exploitation of above-mentioned salient features. We also provide a numerical example that confirms the utility of our proposed framework and shows substantial strategic reaction can be expected to a tax on pollution stocks.


## 1. Introduction

Environmental pollution constitutes a persistent problem that challenges the social welfare performance of decentralized economic systems. As pollution is emitted from particular enterprises, studies of policy approaches to its management have reconsidered Pigou's (1932) prescription to focus on incentives or standards and their effects on the behavior of the polluting firm (Baumol and Oates, 1975, 1988; David and Sinclair-Desgagné, 2005). Both voluntary and regulatory approaches have been considered to incorporate particular salient features of the economic systems or particular facets of the problem, see reviews in Heyes (2000), and Bovenberg and Goulder (2002). In this paper, we consider a set of key salient features that often characterize the policy setting: dynamics, spatial dimensions of multi-plant production, vertical organization of firms within supply chains, and strategic gaming among firms over demand. Together, these features characterize the complexity of economic systems within which firms operate. Within this context, we show that while analytic methods become intractable, computational methods provide a fruitful approach to analysis of pollution policy despite substantial levels of complexity.

In response to environmental policy, we show that firms have a variety of possibilities to control their environmental effects that go beyond simple firm-level production responses. In particular, we show firms may alter organizational strategies such as outsourcing (make-buy), change the spatial shipment patterns, or change the spatial distribution of production intensity (location of processes or stocks). We also show that each decision leads to different levels and distributions of contributions of pollution, which are valued differently by each manufacturing firm as firms may face costs that differ over time and over the spatial locations of production processes and stocks. We assume that manufacturing firms' payoffs are net profits that depend not only on its own decisions but also on those of all other firms. Such dependency has cascading effects as well. For example, if a firm's revenue at some spatial location changes due to other firms' decisions (e.g., sales) in the same spatial region, the firm may alter its production distribution so that production at some other region may increase. Furthermore, the change in revenue will also result in the difference of revenue-tax ratio so that the firm may reconsider pollution related activities such as recycling and altering make-buy intensity.

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We consider a continuous sequence of one-shot games in which all firms such as suppliers, manufacturers, and retailers are involved such that at each time a Nash equilibrium is achieved. Thus, we implicitly assume our firms have equal bargaining power and no timing advantage over rivals. Furthermore, we assume they operate in a perfect information setting implying that all firms' past decisions are known to all other firms. Within this setting, we show that each manufacturing firm may adjust its strategy continuously over time in a noncooperative manner. When firms are engaged in an oligopoly game across product markets, we show how rivalry will condition environmental outcomes, as well as the economic performance of the firms and the supply chain in which they are operating. We show that firms may also control the timing and spatial location of their actions to impact their environmental footprint, however, the efficacy of such controls will be conditioned by rival actions. We note that oligopoly structures within supply chains characterize many industries where firms game over limited, yet shared retail demand and its implied, derived demands that are transmitted upstream. Contemporary examples include automobiles, energy, electronics, pharmaceuticals, food processing, and metals.

We view pollution as arising from emissions of production processes and as negatively impacting the environment. Consistent with the relevance of dynamics in our problem, we allow the pollutant to be stored, recycled, or emitted as pollution by the manufacturers. Here, we limit our consideration to emissions that occur and remain at each spatial node. Thus, our concern is with local emissions and stocks of pollution, rather than a transboundary problem. If stored, we allow for physical deterioration. Spatially, we view the existence of multiple, spatially differentiated plants as well as transport path management as providing important opportunities for firms to manage their environmental footprints and to affect those of their supply chain. Given our consideration of space, we are able to incorporate features of transportation networks that reflect infrastructure and operating costs and their utilization through management of flows on origin - destination paths that differ in environmental effects. Within the context of spatial supply chain organization, we explicitly consider the role of the make-buy decision as a determinant of environmental impacts consistent with the observation that emissions intensity of market-procured inputs often differ from those of internally produced inputs. In addition to the obvious difference in transportation and shipping-related emissions that might differentiate the environmental impacts of these input types, process bases for differentiation often exist due to scale, timing, and technology differences across internal and external sources, (see, e.g. Jung et al., 1996; Milliman and Prince, 1989; Weaver and Chung, 2009). Further, we explicitly consider the associated rivalry that results when the capacity for emissions at spatial nodes is constrained as could occur in the presence of sustainability constraints.

This paper offers several contributions to the literature. Consistent with the observed feasibility of the strategic use of timing of firm actions as a control of environmental impacts and with the continuous time nature of environmental degradation, our specification extends past work by incorporating dynamics and continuous time (for studies employing discrete time, see, e.g., Inderfurth et al., 2001; Kiesmüller and Scherer, 2003; Richter and Weber, 2001). By employing continuous time environmental dynamics, we eliminate the need to make assumptions on boundary conditions of natural degradation of pollution stocks. Our framework also allows us to consider three types of firm responses to pollution taxes: (1) outsourcing of input supply, (2) timing of production, and (3) spatial aspects such as shipment patterns and spatial location of production and stocks of products and pollution. While considerable literature exists that examines implications of oligopoly behavior (Barrett, 1994; Canton et al., 2008; Chung et al., 2012, 2013; Damania, 1996; Innes and Bial, 2002; Moledina et al., 2003; Requate, 2006; Shaffer, 1995) or of supply chains (Hammond and Beullens, 2007; Nagurney, 2010; Savaskan et al., 2004) for environmental impacts, to our knowledge, our paper is the first to consider firm-level management response to environmental policy in a continuous time, dynamic, spatial, and oligopolistic supply chain. We extend the Friesz et al. (2011) three-level supply chain problem with make-buy dynamics motivated by pollutant generation that is differentiated by the internal and external (market) sources inputs. Further, our specification considers both the dynamics of emissions and pollution stocks that are controllable through recycling and input choice at the location of production. In addition, by interpretation of nodes as spatially distinct, our specification explicitly allows control of emissions and pollution stocks at spatial locations through choice of production location. Finally, we explicitly consider rivalry across firms as a Nash noncooperative game, consistent with contemporary industry examples.

We note that past literature has considered a variety of specific strategies for reducing environmental impacts. Examples include recycling processes (Florida, 1996; Pati et al., 2008), green product design and product life extension (Finster et al., 2001; Sarkis and Cordeiro, 2001), network design and reverse logistics (Dowlatshahi, 2000; Srivastava, 2008), infrastructure management (Friesz et al., 2010; Walz, 2007), and specific firm-level environmental management practices (Chung et al., 2012; Zhu et al., 2008). Within this context, our paper adds to this literature by examining strategic responses of firms to manage both product and pollutant timing, spatial placement and shipping, as well as make-buy decisions that affect the organization of the spatial supply chain.

With respect to methods, we present our specification within the context of the formalism of differential variational inequalities (DVIs). This powerful modeling paradigm supports continuous dynamics and has been shown to be an equivalent representation of a dynamic Nash game and suitable for tackling large and complex problems such as the disruption management in dynamic supply chains (Friesz et al., 2011; Lee, 2011). We prove the equivalence of our DVI representation and the oligopoly Nash game in our integrated environmental-economic supply chain. Recent reviews of the DVI and its use are available (Friesz, 2010; Pang and Stewart, 2008). To solve our model, we first re-formulate its DVI representation as a nonlinear complementarity problem that supports numerical solution through a successive linearization algorithm proposed by Pang and Chan (1982).

The organization of this paper is as follows. In Section 2, we introduce the model. We present the typical manufacturer's and retailer's extremal problem in Section 3. We formulate the spatial supply chain problem and its equivalent DVI representation in Section 4. In Section 5, we discuss numerical methods and solution algorithms. A numerical example is presented in Section 6. In Section 7, we draw conclusions.

## 2. Model framework

We consider multiple manufacturing firms and retailing firms embedded in a spatial supply chain network in which each node (region) may be populated by manufacturers or retailers. The spatial supply chain network is depicted in Fig. 1. Each manufacturing firm may have its production facilities and/or warehouses in multiple locations (spatial nodes), manages its production and inventory, and considers demands from retailers that are spatially distributed. If there is a demand from a retailer in a specific location, the manufacturing firm may want to produce a final good at the facility located in the spatial node close to the retailer (it may even be the same spatial node where the retailer is located)