European Journal of Operational Research 256 (2017) 605–618

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Innovative Applications of O.R.

Modeling strategic investment decisions in spatial markets[☆]

Stefan Lorenczik[a,*], Raimund Malischek[a], Johannes Trüby[b]

[a] ewi Energy Research & Scenarios, Vogelsanger Straße 321a, Cologne 50827, Germany
[b] International Energy Agency (IEA), 9 rue de la Fédération, Paris Cedex 15 75739, France

ARTICLE INFO

Article history:
Received 18 December 2015
Accepted 22 June 2016
Available online 25 June 2016

Keywords:
Spatial natural resource markets
Capacity investment
Oligopoly
Equilibrium Problem with Equilibrium Constraints (EPEC)
Coal

ABSTRACT

Markets for natural resources and commodities are often oligopolistic. In these markets, production capacities are key for strategic interaction between the oligopolists. We analyze how different market structures influence oligopolistic capacity investments and thereby affect supply, prices and rents in spatial natural resource markets using mathematical programming models. The models comprise an investment stage and a supply stage in which players compete in quantities. We compare three models, a perfect competition and two Cournot models, in which the product is either traded through long-term contracts or on spot markets in the supply stage. Tractability and practicality of the approach are demonstrated in an application to the international metallurgical coal market. Results may vary substantially between the different models. The metallurgical coal market has recently made progress in moving away from long-term contracts and more towards spot market-based trade. Based on our results, we conclude that this regime switch is likely to raise consumer rents but lower producer rents, while the effect on total welfare is negligible.

1. Introduction

Markets for natural resources and commodities such as iron ore, copper ore, coal, oil or gas are often highly concentrated and do not appear to be competitively organized at first glance. In such markets, large companies run mines, rigs or gas wells and trade their product globally. In the short term, marginal production costs and capacities are given and determine the companies' competitive position in the oligopolistic market. However, in the longer term, companies can choose their capacity and consequently alter their competitive position.

Investing in production capacity is a key managerial challenge and determining the right amount of capacity is rarely trivial in oligopolistic markets. Suppliers have to take competitors' reactions into account not only when deciding on the best supply level but also when choosing the best amount of capacity.

In this paper, we introduce three different models to address this capacity expansion problem in oligopolistic natural resource markets under varying assumptions of market structure and conduct. Moreover, we pursue the question as to how different market structures influence capacity investments, supply, prices and rents. The models comprise two stages: an investment stage and a supply stage in which players compete in quantities. We explicitly account for the spatial structure of natural resource markets, i.e., demand and supply regions are geographically separated and market participants incur distance-dependent transportation costs.

The first model assumes markets to be contestable; hence investment follows competitive logic. Solving this model yields the same result as would be given by a perfectly competitive market. The second model assumes the product to be sold through long-term contracts under imperfect competition. Even though supply takes place in stage two, the supply and investment decisions are made simultaneously in stage one. The long-term contract that is fulfilled in stage two determines the level of capacity investment in stage one. Any production capacity that is different from the one needed to produce the quantity of the best-supply equilibrium in stage two reduces the respective players profits and is not a Nash equilibrium. The outcome is termed 'open-loop Cournot equilibrium' and corresponds to the result of a static one-stage Cournot game (accounting for investment costs). The third model assumes that investment and supply decisions are made consecutively: In

☆ We are grateful to the anonymous referee for the helpful comments and suggestions. All remaining shortcomings are our own. The contents of this paper reflect the opinions of its authors only and not those of ewi or the International Energy Agency. Although this paper was written when Johannes Trüby was employed by the IEA, the views expressed in this paper do not necessarily reflect the views or policy of the IEA Secretariat or of its individual member countries.

* Corresponding author. Tel.: +49 221 277 29 495.
E-mail address: stefan.lorenczik@ewi.research-scenarios.de (S. Lorenczik).

http://dx.doi.org/10.1016/j.ejor.2016.06.047
0377-2217/

stage one, when investment takes place, none of the oligopolists can commit to their future output decision in stage two (unlike in the open-loop case). In stage two, when the market clears, the investment cost spent in the first stage is sunk and the players base their output decision solely on production cost. The resulting equilibrium is termed 'closed-loop Cournot equilibrium' and may differ from the open-loop outcome.

Intuitively, the lack of commitment in the closed-loop game and therefore the repeated interaction of the oligopolists would suggest a higher degree of competition and thus lower prices and higher market volumes than in the open-loop equilibrium. However, the players anticipate this strategic effect and make their investment decisions accordingly. How prices and volumes rank compared to the open-loop game is parameter-dependent and requires a numerical analysis. As discussed for instance in Fudenberg and Tirole (1991) in a more general context, each player in the closed-loop model has a strategic incentive to deviate from his first stage open-loop action as he can thereby influence the other players' second stage action. Applying this general economic framework to the capacity expansion problem examined in this paper, indeed tends to lead to higher investment and supply levels in the closed-loop model and hence to lower prices.

Computing open-loop games is relatively well understood, and existence and uniqueness of the equilibrium can be guaranteed under certain conditions (see, e.g., Takayama & Judge, 1964, 1971; Harker, 1984, 1986). The open-loop Cournot model can be solved via the Karush–Kuhn–Tucker conditions as a mixed complementarity problem (MCP). Oligopolistic spatial equilibrium models have been widely deployed in analyzing resource markets, without taking investments decisions into account, e.g., for steam coal markets (Haftendorn & Holz, 2010; Kolstad & Abbey, 1984; Trüby & Paulus, 2012), metallurgical coal markets (Graham, Thorpe, & Hogan, 1999; Trüby, 2013), natural gas markets (Gabriel, Kiet, & Zhuang, 2005; Growitsch, Hecking & Panke, 2014; Holz, von Hirschhausen, & Kemfert, 2008; Zhuang & Gabriel, 2008), wheat markets (Kolstad & Burris, 1986), oil markets (Huppmann & Holz, 2012) or for iron ore markets (Hecking & Panke, 2015). Investments in additional production capacity have been analyzed for example in Huppmann (2013) with investment and production decisions being made simultaneously and therefore implicitly assuming a market structure with long-term contracts.

Closed-loop models are computationally challenging due to their non-linear nature. Depending on the problem this can be resolved. Gabriel and Leuthold (2010) for instance model an electricity market with a Stackelberg leader using linearization to guarantee a globally optimal solution. Closed-loop models in energy market analysis have primarily been used to study restructured electricity markets (e.g., Daxhelet & Smeers, 2007; Shanbhag, Infanger, & Glynn, 2011; Yao, Oren, & Adler, 2007; Yao, Adler, & Oren, 2008). Murphy and Smeers (2005) and Wogrin, Barquín, and Centeno (2013a); Wogrin, Hobbs, Ralph, Centeno, and Barquín (2013b) have analyzed the implications of closed- and open-loop modeling on market output and social welfare as well as characterized conditions under which closed- and open-loop model results coincide.

Our two-stage model consists of multiple players on both, the first and second stage (investment in stage one and supply in stage two), and therefore existence and uniqueness of (pure strategy) equilibria cannot be guaranteed. The closed-loop model, which is formulated as an Equilibrium Problem with Equilibrium Constraints (EPEC), is implemented using a diagonalization approach (see, e.g., Gabriel, Conejo, Fuller, Hobbs, & Ruiz, 2012). In doing so, we reduce the solution of the EPEC to the solution of a series of Mathematical Programs with Equilibrium Constraints (MPEC). Concerning the solution of the MPECs we implement two algorithms, grid search along the investment decisions of the individual players and a Mixed Integer Linear Program reformulation following Wogrin et al. (2013a).

We demonstrate the tractability and practicality of our investment models in an application to the international metallurgical (or coking) coal trade. Metallurgical coal is, due to its special chemical properties, a key input in the process of steel-making. The market for this rare coal variety is characterized by a spatial oligopoly with producers mainly located in Australia, the United States and Canada competing against each other and providing the bulk of the traded coal (Bowden, 2012; Trüby, 2013). The players hold existing mining capacity and can invest into new capacity. Investment and mining costs differ regionally. Key uncertainties in this market are demand evolution and price responsiveness of demand. We therefore compute sensitivities for these parameters to demonstrate the robustness of our results.

Our findings are generally in line with previous results found in the literature on two-stage games with players choosing capacity and output, i.e., we find that prices and supply levels in the closed-loop game fall between those in the perfect competition and the open-loop game (see, e.g., Murphy & Smeers, 2005). If investment costs are low compared to variable costs of supply, the strategic effect of the two-stage optimization in the closed-loop game diminishes. With investment costs approaching zero, the closed-loop result converges to the open-loop result. Hence, the closed-loop model is particularly useful for capital-intensive natural resource industries in which the product is traded on spot markets.

The numerical results for supply levels, prices and rents in the metallurgical coal market analysis differ markedly between the three models. Consistent with actual industry investment pipelines, our model suggests that the bulk of the future capacity investment comes from companies operating in Australia followed by Canadian and US firms. Starting in 2010, the metallurgical coal market has undergone a paradigm shift, moving away from long-term contracts and more towards a spot market-based trade – with similar tendencies being observed in other commodity markets such as the iron ore trade. In light of our findings, this effect is detrimental to the companies' profits but beneficial to consumer rents. The effect on welfare is negligible: Gains in consumer rents and losses in producers' profits are of almost equal magnitude.

The contribution of this paper is threefold: First, by extending the multi-stage investment approach to the case of spatial markets, we introduce a novel feature to the literature on Cournot capacity expansion games. Second, we outline how our modeling approach can be implemented and solved to analyze capacity investments in natural resource markets. We thereby extend previous research on natural resource markets, which has typically assumed capacities to be given. Finally, we illustrate and discuss the model properties on the basis of a real-world application to the international metallurgical coal trade and draw conclusions for this market. In doing so, we also take into account existing capacities of the players and hence incorporate a feature which to our knowledge has been ignored in previous work on multi-stage Cournot capacity expansion games. By comparing open- and closed-loop model results, we illustrate possible consequences of the ongoing regime switch from long-term contracts to a more spot market-based trade in the international metallurgical coal market. Our analysis in particular allows for the first quantification of the magnitude of the divergence between open- and closed-loop model results in a real-world application.

The remainder of the paper is structured as follows: Section 2 describes the models developed in this paper and Section 3 provides details about their implementation. The data is outlined in Section 4, results are presented in Section 5. Section 6 discusses computational issues and Section 7 concludes.