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Modeling Strategic Investment Decisions in Spatial Markets☆

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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 programing models. The models comprise an investment period and a supply period in which players compete in quantities. We compare three models, one perfect competition and two Cournot models, in which the product is either traded through long-term contracts or on spot markets in the supply period. 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. The total welfare differs only negligibly.

Keywords: Investment, Coal, Oligopoly, Natural resources, Mathematical programming, Capacity Expansion, Spatial Markets, Equilibrium Problem with Equilibrium Constraints (EPEC)

JEL classification: L13, L72, C61, C70

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. In these markets, large companies run

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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 periods: an investment period and a supply period 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 period two, the supply and investment decisions are made simultaneously in period one. The outcome is termed 'open-loop Cournot equilibrium' and corresponds to the result of a static one-period Cournot game (accounting for investment costs). The third model assumes that investment and supply decisions are made consecutively: In the first period, oligopolists choose their capacity investment, anticipating the best-supply response of their rivals on a spot market in the second period. The resulting equilibrium is termed 'closed-loop Cournot equilibrium' and may differ from the open-loop outcome.

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 period open-loop action as he can thereby influence the other players' second period action. Applying this general economic framework to the capacity expansion problem examined in this paper, 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. The open-loop Cournot model can be solved via the Karush-Kuhn-Tucker conditions as a mixed complementarity problem. This approach has been widely deployed in analyzing spatial market equilibria without investments, e.g., for steam coal markets (Kolstad and

Abbey, 1984; Haftendorn and Holz, 2010; Trüby and Paulus, 2012), metallurgical coal markets (Graham et al., 1999; Trüby, 2013), natural gas markets (Gabriel et al., 2005; Holz et al., 2008; Growitsch et al., 2013), wheat markets (Kolstad and Burris, 1986), oil markets (Huppmann and Holz, 2012) or for iron ore markets (Hecking and Panke, 2014).

The closed-loop model is computationally challenging and due to its highly non-linear nature, existence and uniqueness of (pure strategy) equilibria cannot be guaranteed. Previous closed-loop models in energy market analysis have primarily been used to study restructured (single node) electricity markets, e.g., by Murphy and Smeers (2005) and Wogrin et al. (2013a,b). Among others, this research stream has 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 closed-loop model, which is formulated as an Equilibrium Problem with Equilibrium Constraints (EPEC), is implemented using a diagonalization approach (see, e.g., Gabriel et al., 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, 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 and Smeers, 2005). If investment costs are low compared to variable costs of supply, the strategic effect of the bilevel 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. 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.

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.

2. The Model

We introduce three different approaches to the capacity expansion problem – two open-loop models and a closed-loop model. In the open-loop models, players decide *simultaneously* on their investment and production levels, whereas in the closed-loop model players first decide on their investment levels and then, based on *observed* investment levels, decide on their production levels. The two open-loop models vary in their underlying market structure: one model assumes perfect competition, the other model assumes Cournot competition with a competitive fringe. The closed-loop model also assumes Cournot competition with a competitive fringe.

2.1. *General Setting and Notations*

We assume a spatial, homogeneous good market consisting of producers $i \in I$, production facilities $m \in M$ and demand regions $j \in J$. Each producer i owns production facilities $m \in M_i \subset M$. Furthermore, we assume that $M_i \cap M_j = \emptyset$ for $i \neq j$, i.e., production facilities are exclusively owned by one producer. Producers decide on both their investment in production facilities as well as on their supply levels, with supply taking place at time points $t \in T$.[1]

The supply from production facility m to market j at time t is given by $x^t_{m,j}$. Total production of production facility m at time t is hence given by $\sum_j x^t_{m,j}$. It is limited by the facilities' capacity $cap^0_m + y_m$, where cap^0_m is the initial production capacity and y_m denotes the capacity investment. Capacity investments y_m are non-negative and limited by y^{max}_m. Capacity investments in an existing production facility (i.e., $cap^0_m \neq 0$) can be interpreted as capacity expansions, and investments in the case of $cap^0_m = 0$ as newly built production facilities.

Investment expenditures for facility m are given by C^{inv}_m. We assume that C^{inv}_m is a linear function in the investment level y_m, with k_m denoting marginal investment costs, i.e.,

$$C^{inv}_m(y_m) = k_m \cdot y_m.$$

Variable costs $C^{var,t}_m$ at time t are specific to the production facility m. They are composed of transportation costs $\tau^t_{m,j}$ per unit delivered from m to market j as well as the variable production costs v^t_m. We assume that v^t_m is a linear function in the total production of the facility. Total variable costs of facility m at time t therefore amount to

$$C^{var,t}_m(\mathbf{x}^t_m) = \sum_j (x^t_{m,j} \cdot \tau^t_{m,j}) + v^t_m(\sum_j x^t_{m,j}),$$

with $\mathbf{x}^t_m = (x^t_{m,j})_j$ denoting the production vector of facility m at time t.

Market prices P^t_j in market j at time t are given by a linear inverse demand function, i.e.,

$$P^t_j = a^t_j - b^t_j \cdot \sum_m x^t_{m,j}.$$

[1] In our application to the metallurgical coal market, we consider only one time point; in this section, however, we present the model in a more general form.

Table 1: Model sets, parameters and variables

Abbreviation	Description
Model sets	
$m \in M$	Production facilities
$j \in J$	Markets
$i \in I$	Players
$t \in T$	Time
Model parameters	
k_m	Marginal investment costs [US$ per unit per year]
v_m^t	Variable production costs [US$ per unit]
$\tau_{m,j}^t$	Transportation costs [US$ per unit]
a_j^t	Reservation price [US$ per unit]
b_j^t	Linear slope of demand function
cap_m^0	Initial production capacity [units per year]
y_m^{max}	Maximum capacity expansion [units per year]
Model variables	
$C_m^{var,t}$	Total variable production costs [US$]
C_m^{inv}	Investment expenditures [US$]
$x_{m,j}^t$	Supply [units]
P_j^t	Market price [US$ per unit]
y_m	Capacity investments [units per year]

2.2. Model 1: The Open-Loop Perfect Competition Model

In the open-loop perfect competition model (in the following simply termed 'perfect competition model'), each producer $i \in I$ solves the optimization problem

$$\max_{\mathbf{x}_m^t, y_m : m \in M_i} \sum_{t \in T} \sum_{m \in M_i} \big(\sum_{j \in J} P_j^t \cdot x_{m,j}^t - C_m^{var,t}(\mathbf{x}_m^t) \big) - \sum_{m \in M_i} C_m^{inv}(y_m)$$

subject to

$$P_j^t = a_j^t - b_j^t \cdot (X_{i,j}^t + X_{-i,j}^t), \ \forall j, t$$

$$cap_m^0 + y_m - \sum_j x_{m,j}^t \geq 0, \ \forall m \in M_i, t \ (\lambda_m^t)$$

$$y_m^{max} - y_m \geq 0, \ \forall m \in M_i \ (\theta_m)$$

$$x_{m,j}^t \geq 0, \ \forall m \in M_i, j, t$$

$$y_m \geq 0, \ \forall m \in M_i$$

while taking the supplies $X_{-i,j}^t$ of the other producers $(-i)$ as given. Here and in the following, we use the abbreviation $X_{I_1,j}^t = \sum_{i \in I_1} \sum_{m \in M_i} x_{m,j}^t$ for some $I_1 \subset I$.

Hence, in the perfect competition model, each producer *simultaneously* makes his ("long-term") investment and ("short-term") production decisions in order to maximize profits. In doing so, each producer takes capacity restrictions into account. However, players do not take into account their influence on price.

Any solution to the above optimization problem has to satisfy the short-term Karush-Kuhn-Tucker (KKT) conditions

$$0 \leq \frac{\partial C_m^{var,t}(\mathbf{x}_m^t)}{\partial x_{m,j}^t} - [a_j^t - b_j^t \cdot (X_{i,j}^t + X_{-i,j}^t)] + \lambda_m^t \perp x_{m,j}^t \geq 0, \ \forall i, m \in M_i, j, t$$
$$0 \leq cap_m^0 + y_m - \sum_j x_{m,j}^t \perp \lambda_m^t \geq 0, \ \forall i, m \in M_i, t$$

as well as the long-term KKT conditions

$$0 \leq k_m - \sum_{t \in T} \lambda_m^t + \theta_m \perp y_m \geq 0, \ \forall i, m \in M_i$$
$$0 \leq y_m^{max} - y_m \perp \theta_m \geq 0, \ \forall i, m \in M_i.$$

In equilibrium, all KKT conditions have to hold simultaneously. Uniqueness of the solution is guaranteed due to the quasi-concave objective function and the convexity of the restrictions. The derived KKT conditions are thus necessary and sufficient for obtaining the solution.

2.3. Model 2: The Open-Loop Cournot Model with Competitive Fringe

As in the perfect competition model, in the open-loop Cournot model with competitive fringe (in the following simply termed 'open-loop model'), each producer $i \in I$ solves the optimization problem

$$\max_{\mathbf{x}_m^t, y_m : m \in M_i} \sum_{t \in T} \sum_{m \in M_i} \Big(\sum_{j \in J} P_j^t \cdot x_{m,j}^t - C_m^{var,t}(\mathbf{x}_m^t) \Big) - \sum_{m \in M_i} C_m^{inv}(y_m)$$

subject to

$$P_j^t = a_j^t - b_j^t \cdot (X_{i,j}^t + X_{-i,j}^t), \ \forall j, t$$
$$cap_m^0 + y_m - \sum_j x_{m,j}^t \geq 0, \ \forall m \in M_i, t \ (\lambda_m^t)$$
$$y_m^{max} - y_m \geq 0, \ \forall m \in M_i \ (\theta_m)$$
$$x_{m,j}^t \geq 0, \ \forall m \in M_i, j, t$$
$$y_m \geq 0, \ \forall m \in M_i$$

while taking the supplies $X_{-i,j}^t$ of the other producers $(-i)$ as given.

Each producer *simultaneously* makes his investment and production decisions with the objective to maximize profits. In doing so, each producer takes into account his capacity restrictions and his influence on price. We assume this price influence to be represented by a conjectural variation parameter ψ_i, where $\frac{\partial P_j^t}{\partial x_{m,j}^t} = \psi_i \cdot b_j^t$ for all $m \in M_i$. This allows us to model Cournot behavior with a competitive fringe ($\psi_i = 1$ for the Cournot players and $\psi_i = 0$ for the competitive fringe).

Any solution to the above optimization problem satisfies the short-term Karush-Kuhn-Tucker (KKT) conditions

$$
\begin{aligned}
&0 \leq \frac{\partial C_m^{var,t}(\mathbf{x}_m^t)}{\partial x_{m,j}^t} - [a_j^t - b_j^t \cdot (X_{i,j}^t + X_{-i,j}^t)] + \psi_i \cdot b_j^t \cdot X_{i,j}^t + \lambda_m^t \perp x_{m,j}^t \geq 0,\ \forall i, m \in M_i, j, t \\
&0 \leq cap_m^0 + y_m - \sum_j x_{m,j}^t \perp \lambda_m^t \geq 0,\ \forall i, m \in M_i, t
\end{aligned}
$$

as well as the long-term KKT conditions

$$
\begin{aligned}
&0 \leq k_m - \sum_{t \in T} \lambda_m^t + \theta_m \perp y_m \geq 0,\ \forall i, m \in M_i \\
&0 \leq y_m^{max} - y_m \perp \theta_m \geq 0,\ \forall i, m \in M_i.
\end{aligned}
$$

In equilibrium, all KKT conditions have to hold simultaneously. As in the perfect competition case, uniqueness of the solution is guaranteed due to the quasi-concave objective function and the convexity of the restrictions. The derived KKT conditions are thus necessary and sufficient for obtaining the solution.

2.4. Model 3: The Closed-Loop Model

In the closed-loop model, producers play a two-stage game: In the first stage, lead (oligopolistic) producers l ($l \in L \subset I$) decide on their investment levels. In the second stage, they choose, based on *observed* investment decisions of the other lead producers, their production and supply levels. In addition, in the second stage, a further player, the fringe player (F), makes his investment and supply decisions simultaneously.

2.4.1. The Short-Run Problem

For a given investment vector (y_l, y_{-l}) of the lead producers, let the short-run (Cournot) problem of lead producer l be given by

$$
\max_{x_{m,j}^t : m \in M_l} \sum_{t \in T} \sum_{m \in M_l} \Big(\sum_{j \in J} P_j^t \cdot x_{m,j}^t - C_m^{var,t}(\mathbf{x}_m^t) \Big)
$$

subject to

$$
\begin{aligned}
&P_j^t = a_j^t - b_j^t \cdot (X_{l,j}^t + X_{-l,j}^t + X_{F,j}^t),\ \forall j, t \\
&cap_m^0 + y_m - \sum_j x_{m,j}^t \geq 0,\ \forall m \in M_l, t\ (\lambda_m^t) \\
&x_{m,j}^t \geq 0,\ \forall m \in M_l, j, t.
\end{aligned}
$$

As in the open-loop model, lead producer l decides on his supplies while taking the supplies of the other lead producers ($-l$) and of the fringe player (F) as given. We further assume Cournot behavior, i.e., we assume $\psi_l = 1$. The corresponding KKT conditions to this problem are then given by

$$
\begin{aligned}
&0 \leq \frac{\partial C_m^{var,t}(\mathbf{x}_m^t)}{\partial x_{m,j}^t} - [a_j^t - b_j^t \cdot (X_{l,j}^t + X_{-l,j}^t + X_{F,j}^t)] + b_j^t \cdot X_{l,j}^t + \lambda_m^t \perp x_{m,j}^t \geq 0, \ \forall m \in M_l, j, t \\
&0 \leq cap_m^0 + y_m - \sum_j x_{m,j}^t \perp \lambda_m^t \geq 0, \ \forall m \in M_l, t.
\end{aligned}
$$

In addition, for a given investment vector (y_l, y_{-l}), the (competitive) fringe player faces the decision problem

$$
\max_{x_{m,j}^t, y_m : m \in M_F} \sum_{t \in T} \sum_{m \in M_F} \big(\sum_{j \in J} P_j^t \cdot x_{m,j}^t - C_m^{var,t}(\mathbf{x}_m^t) \big) - \sum_{m \in M_F} C_m^{inv}(y_m)
$$

subject to

$$
\begin{aligned}
&P_j^t = a_j^t - b_j^t \cdot (X_{F,j}^t + X_{-F,j}^t), \ \forall j, t \\
&cap_m^0 + y_m - \sum_j x_{m,j}^t \geq 0, \ \forall m \in M_F, t \ (\lambda_m^t) \\
&y_m^{max} - y_m \geq 0, \ \forall m \in M_F \ (\theta_m^{max,F}) \\
&x_{m,j}^t \geq 0, \ \forall m \in M_F, j, t \\
&y_m \geq 0, \ \forall m \in M_F,
\end{aligned}
$$

i.e., the fringe producer F makes his investment *and* supply decisions while taking the supply decisions of the other producers $(-F)$ as given. We assume that the fringe player does not take into account his influence on price, i.e., we assume $\psi_F = 0$. The corresponding KKT conditions to this problem are then given by

$$
\begin{aligned}
&0 \leq \frac{\partial C_m^{var,t}(\mathbf{x}_m^t)}{\partial x_{m,j}^t} - [a_j^t - b_j^t \cdot (X_{F,j}^t + X_{-F,j}^t)] + \lambda_m^t \perp x_{m,j}^t \geq 0, \ \forall m \in M_F, j, t \\
&0 \leq k_m - \sum_{t \in T} \lambda_m^t + \theta_m^{max,F} \perp y_m \geq 0, \ \forall m \in M_F \\
&0 \leq cap_m^0 + y_m - \sum_j x_{m,j}^t \perp \lambda_m^t \geq 0, \ \forall m \in M_F, t \\
&0 \leq y_m^{max} - y_m \perp \theta_m^{max,F} \geq 0, \ \forall m \in M_F.
\end{aligned}
$$

In the short-run equilibrium, the KKT conditions of fringe and lead producers have to hold simultaneously. In the following, let $\tilde{x}_{m,j}^t(y_l, y_{-l})$ denote the short-run production equilibrium for a given investment vector (y_l, y_{-l}).

2.4.2. The Long-Run Problem

The long-run problem for lead producer $l \in L$ is given by

$$\max_{y_m : m \in M_l} \sum_{t \in T} \sum_{m \in M_l} \big(\sum_{j \in J} \tilde{P}_j^t \cdot \tilde{x}_{m,j}^t(y_l, y_{-l}) - C_m^{var,t}(\tilde{\mathbf{x}}_m^t(y_l, y_{-l})\big) - \sum_{m \in M_l} C_m^{inv}(y_m)$$

subject to

$$\begin{aligned}
&\tilde{P}_j^t = a_j^t - b_j^t \cdot (\tilde{X}_{l,j}^t(y_l, y_{-l}) + \tilde{X}_{-l,j}^t(y_l, y_{-l}) + \tilde{X}_{F,j}^t(y_l, y_{-l})), \ \forall j, t \\
&y_m^{max} - y_m \geq 0, \ \forall m \in M_l \\
&y_m \geq 0, \ \forall m \in M_l,
\end{aligned}$$

i.e., lead producer l chooses his investment levels in order to maximize profits for a given investment strategy of the other lead producers (y_{-l}) under consideration of the resulting short-run equilibrium outcome.

Combining the short-run and the long-run problem, we obtain the following MPEC for producer l, hereafter referred to as MPEC$_l$:

$$\max_{\Omega_l} \sum_{t \in T} \sum_{m \in M_l} \big(\sum_{j \in J} (a_j^t - b_j^t \cdot (X_{l,j}^t + X_{-l,j}^t + X_{F,j}^t)) \cdot x_{m,j}^t - C_m^{var,t}(\mathbf{x}_m^t)\big) - \sum_{m \in M_l} C_m^{inv}(y_m)$$

subject to

$$\begin{aligned}
&y_m^{max} - y_m \geq 0, \ \forall m \in M_l \\
&y_m \geq 0, \ \forall m \in M_l \\
&0 \leq \frac{\partial C_m^{var,t}(\mathbf{x}_m^t)}{\partial x_{m,j}^t} - [a_j^t - b_j^t \cdot (X_{i,j}^t + X_{-i,j}^t)] + [b_j^t \cdot X_{i,j}^t]_{i \in L} + \lambda_m^t \perp x_{m,j}^t \geq 0, \ \forall m \in M_i, j, t \\
&0 \leq cap_m^0 + y_m - \sum_j x_{m,j}^t \perp \lambda_m^t \geq 0, \ \forall m \in M_i, t \\
&0 \leq k_m - \sum_{t \in T} \lambda_m^t + \theta_m^{max,F} \perp y_m \geq 0, \ \forall m \in M_F \\
&0 \leq y_m^{max} - y_m \perp \theta_m^{max,F} \geq 0, \ \forall m \in M_F
\end{aligned}$$

given the investment vector (y_{-l}) of the other lead producers. Here, Ω_l is given by
$\Omega_l = \{(y_m)_{m \in M_l}; \quad (x_{m,j}^t, \lambda_m^t)_{m \in M, j \in J, t \in T}, (y_m, \theta_m^{max,F})_{m \in M_F}\}$.[2]

An investment strategy $(\tilde{y}_l, \tilde{y}_{-l})$ is a closed-loop equilibrium if for all $l \in L$, $\tilde{y}_l$ solves l's MPEC problem MPEC$_l$ given $\tilde{y}_{-l}$. The problem of finding a closed-loop equilibrium is hence of EPEC type (Gabriel et al., 2012), and therefore existence and uniqueness of equilibria typically is non-trivial and parameter dependent.

[2]Note that the leader's decision variable is separated from the followers' decision variables by a semicolon. The latter are indirectly determined by the leader's choice.

2.5. Discussion of the Models and Equilibrium Concepts

Closed-loop strategies allow players to condition their actions on actions taken in previous time periods; in open-loop strategies, this is not possible. Thus, equilibria in the closed-loop model are by definition subgame perfect, whereas open-loop equilibria are typically merely dynamically (time) consistent. The latter is a weaker equilibrium concept than subgame perfection. It requires only that no player has an incentive at any time to deviate from the strategy he announced at the beginning of the game, "given that no player has deviated in the past and no agent expects a future deviation" (see Karp and Newbery, 1992). Therefore, with subgame perfect equilibria requiring actions to be optimal in every subgame of the game, i.e., requiring that no player has an incentive to deviate from his strategy regardless of any deviation in the past, an equilibrium of the open-loop model may fail to be an equilibrium in the closed-loop game.[3]

Fudenberg and Tirole (1991) and the literature cited therein generally address the issue of diverging results of open-loop models in comparison to closed-loop models and provide intuition for the divergence: In the closed-loop model, in contrast to the open-loop model, a player's influence via its own actions in the first stage on the other players' actions in the second stage is taken into account. Applying this intuition to the special case of the capacity expansion problem, Murphy and Smeers (2005) show that in the closed-loop equilibrium, marginal investment costs may be higher than the sum of the short-term marginal value implied by the KKT conditions. In particular, they note that "the difference between the two characterizes the value for the player of being able to manipulate the short-term market by its first stage investments." This may lead to higher investments and supplies and hence lower prices in the closed-loop model compared to the open-loop model.

The existing literature on the subject, in particular the above mentioned Murphy and Smeers (2005) as well as Wogrin et al. (2013b), provides general properties of closed-loop and open-loop models and conditions for diverging and non-diverging results between the two models, assuming simplified settings (e.g., ignoring existing capacities). We conjecture that in a spatial application with non-generic data and existing capacities available to the players, equilibria are likely to deviate between the two modeling approaches, which is confirmed by our application to the metallurgical coal market (see Sections 4 and 5). Analytical analysis is no longer available in this setting due to increased complexity and thus makes a numerical analysis necessary. The numerical approach is also suitable to address an issue which to our knowledge has not yet been comprehensively touched upon in previous literature: a quantification of the magnitude of the divergence between closed-loop and open-loop model results.

[3]See Selten (1965) for the first formalization of the concept of subgame perfect equilibria and, e.g., Karp and Newbery (1989) for a general account on dynamic consistency.

3. Implementation

3.1. Model 1: The Open-Loop Model

Both open-loop models introduced in Section 2, i.e., the open-loop perfect competition model and the open-loop Cournot competition model with competitive fringe, are implemented as mixed complementarity problems.

3.2. Model 2: The Closed-Loop Model

We solve the closed-loop model using diagonalization (see for instance Gabriel et al., 2012):

1. Set starting values for the investment decisions y_l^0 of all lead producers $l \in L$, a convergence criterion ϵ, a maximum number of iterations N and a learning rate R
2. $n = 1$
3. Set $y_l^n = y_l^{n-1}$
4. Do for all $l \in L$
   (a) Fix the investment decisions y_{-l}^n of $-l$
   (b) Solve player l's MPEC problem MPEC_l to obtain an optimal investment level y_l
   (c) Set y_l^n equal to $R \cdot y_l + (1 - R) \cdot y_l^n$
5. If $|y_l^n - y_l^{n-1}| < \epsilon$ for all producers $l \in L$: quit
6. If $n = N$: quit
7. $n = n + 1$ and go back to step 3

Diagonalization thus reduces the closed-loop problem to a series of MPEC problems. Concerning the solution of the MPECs, we implement two procedures: grid search along the investment decision y_l and a reformulation of the MPEC as a Mixed Integer Linear Program (MILP).

Implementing both the grid search and MILP reformulation allows for the comparison of the computer run-times of the two models, with grid search typically being faster for reasonable grid sizes (see Section 6 for details on this issue).

3.2.1. Grid Search

When applying grid search along the investment decision y_l, MPEC_l simplifies to a sequence of complementarity problems. In our implementation, the grid width in the grid search is the same for all producers; the number of steps for a producer is thus dependent on his capacity expansion limit.

3.2.2. MILP Reformulation

In addition to grid search, we implement a MILP reformulation of the MPEC. Non-linearities arise in the MPEC due to the complementarity constraints and the non-linear term in the objective function. The former are replaced by their corresponding disjunctive constraints (see Fortuny-Amat and McCarl, 1981), e.g., we replace

$$0 \leq cap_m^0 + y_m - \sum_j x_{m,j}^t \perp \lambda_m^t \geq 0$$

by

$$\begin{aligned} &M^\lambda b_{m,t}^\lambda \geq \lambda_m^t \\ &M^\lambda (1 - b_{m,t}^\lambda) \geq cap_m^0 + y_m - \sum_j x_{m,j}^t \end{aligned}$$

for some suitably large constant M^λ and binary variables $b_{m,t}^\lambda$.

For the discretization of the non-linear term in the objective function, we proceed following Wogrin et al. (2013a) using a binary expansion of the supply variable. The binary expansion of $x_{m,j}^t$ is given by

$$x_{m,j}^t = \underline{x} + \Delta_x \sum_k 2^k b_{k,m,j,t}^x,$$

where $\underline{x}$ is the lower bound, Δ_x the stepsize, k the number of discretization intervals and $b_{k,m,j,t}^x$ binary variables. Substituting $P_j^t \cdot \underline{x} + \Delta_x \sum_k 2^k z_{k,m,j,t}^x$ for $P_j^t \cdot x_{m,j}^t$, we have to impose the additional constraints

$$\begin{aligned} &0 \leq z_{k,m,j,t}^x \leq M^x b_{k,m,j,t}^x \\ &0 \leq P_j^t - z_{k,m,j,t}^x \leq M^x (1 - b_{k,m,j,t}^x) \end{aligned}$$

for some suitably large constant M^x.

4. Data Set

The models are parametrized with data for the international metallurgical coal market (see Table 1 and the Appendix). Yet, as the structure of the international metallurgical coal trade is (from a modeling perspective) similar to that of other commodities, the model could easily be calibrated with data for other markets.

Metallurgical coal is used in steel-making to produce the coke needed for steel production in blast furnaces and as a source of energy in the process of steel-making. Metallurgical coal is distinct from thermal coal, which is typically used to generate electricity or heat. Currently around 70% of the global steel production crucially relies on metallurgical coal as an input.[4]

International trade of metallurgical coal amounted to 250 million tonnes (Mt) in 2012.[5] International trade is predominantly seaborne, using dry bulk vessels. Up until 2010, metallurgical coal was almost exclusively traded through long-term contracts. Since then, the market has begun to move away from this system towards more spot market-based trading. While the share of spot market activity has increased rapidly, a substantial amount of metallurgical coal is still traded through long-term contracts.

Key players in this market are large mining companies such as BHP-Billiton, Anglo-American, Glencore and Rio Tinto. These companies produce mainly in Australia and, together with Peabody Energy's Australian operations, control more than 50% of the global export capacity. In addition, adding to this the market share of the Canadian Teck consortium and the two key metallurgical coal exporters from the United States, Walter Energy and Xcoal, results in almost three quarters of the global export capacity, marketed by an oligopoly of eight companies. For the sake of simplicity and computational tractability, we aggregate these players' existing mines into one mining operation per player. Smaller exporters from Australia, the United States, Russia, New Zealand, Indonesia and South Africa are aggregated into three players: one Cournot player from Australia (AUS6), one Cournot player from the United States (USA1) and one competitive fringe player that comprises all other regions (Fringe). This results in eleven asymmetric players who differ with respect to their existing production capacity and the associated production and transport costs (see Table 2).[6]

Table 2: Existing Capacity, Variable and Investment Costs

Players	Existing Capacity [Mtpa]	Variable Costs [US$/t]	Investment Costs [US$/tpa]	Max. Investment [Mtpa]
USA1	38	122.0	-	-
USA2	9	122.1	98.2	50
USA3	11	141.0	98.0	50
AUS1	54	118.3	218.1	50
AUS2	11	118.4	218.0	50
AUS3	17	118.5	217.9	50
AUS4	10	118.6	217.8	50
AUS5	12	118.0	218.2	50
AUS6	18	118.1	-	-
CAN	26	105.0	161.0	20
Fringe	26	78.0	-	-

We assume that the three players representing the smaller exporters, i.e., USA1, AUS6 and Fringe,

[4]See WCA (2011).
[5]See IEA (2013).
[6]Data on capacities and costs are taken from Trüby (2013).

cannot invest in additional capacity. Hence, only the largest eight companies can endogenously expand their supply capacity. The investment decision, made in period one, is based on the players' capacities and costs in 2011. We consider one investment cycle with capacities becoming available after six years (i.e., in 2017) serving one demand period. Investment costs per tonne of annual production capacity (tpa) are broken down into equal annual payments based on an annuity calculation using an interest rate of 10% and a depreciation time of 10 years. Note that production cost of new mines correspond to the production cost of the respective player's existing mine.

The two largest importers of metallurgical coal are Europe and Japan, followed by India, China and Korea. These key importers account for more than 80% of the trade. We aggregate these and the remaining smaller countries into two demand regions: Europe-Atlantic and Asia-Pacific.[7] The former also includes the Mediterranean's neighboring countries and importers from the Atlantic shores of the Americas. The latter includes importers with coastlines on the Pacific or the Indian Ocean. Exporters from the United States have a transport cost advantage in the Europe-Atlantic region, while Canadian and Australian exporters are located closer to the consumers in the Asia-Pacific region (see Table 5 in the Appendix).

We assume the inverse import demand function for metallurgical coal to be linear. The function can be specified using a reference price and a corresponding reference quantity in combination with a point-elasticity *eta*. Investors in production capacity face demand evolution as a key uncertainty. We therefore run sensitivities in which we vary the point-elasticity parameter *eta* across the range -0.2 to -0.5 (see Figure 1).[8] This bandwidth is generally considered reasonable in the metallurgical coal market (see Trüby (2013) and the literature cited therein). Furthermore, we vary the reference demand quantity (see Table 6 in the Appendix) from 60% to 140% to account for different demand evolution trajectories.

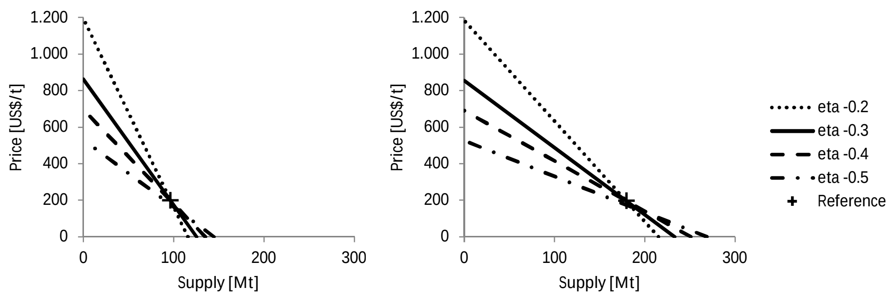

Figure 1: Demand functions for Europe-Atlantic and Asia-Pacific regions with varying elasticity

[7]Our approach covers 100% of the global seaborne metallurgical coal imports and exports (based on data from 2011).

[8]For *eta* smaller than -0.4, closed-loop model runs did not converge. Therefore, the results presented in Section 5 only comprise the range -0.2 to -0.4. For a discussion on computational issues, see Section 6.

5. Results

5.1. Variation of Demand Elasticity

Production is highest in all model runs in the perfect competition model followed by the closed-loop and the Cournot open-loop model (see Figure 2). Accordingly, prices are highest in the open-loop model and lowest in the perfect competition model. With decreasing *eta* (i.e., consumers are more price responsive), which results in a flatter gradient of the demand function (see Figure 1), total production increases. Average prices decrease in the Cournot models and increase in the perfect competition model. Note that in the perfect competition case, the aggregate supply and aggregate demand curves intersect below the reference point (explaining the increase in production), whereas for the open-loop and closed-loop model the inverse elasticity rule applies.

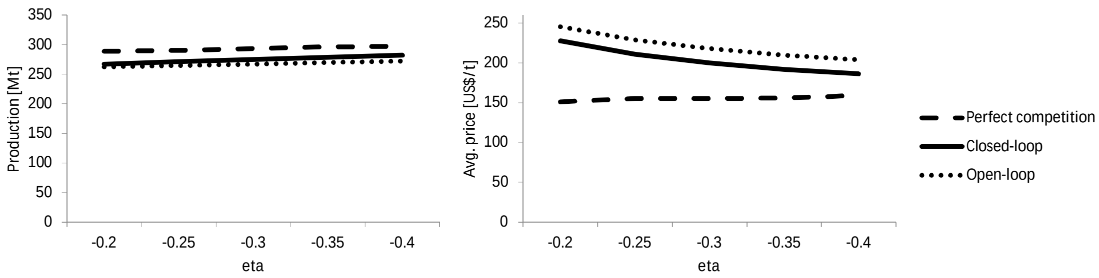

Figure 2: Total production (left) and average market price (right) for varying demand elasticity

Closed-loop investments are higher than open-loop investments in all model runs (see Figure 3 on the left). Model results (assuming *eta* to be -0.3) indicate a combined increase in production capacity in Australia and Canada of about 38 Mtpa and 64 Mtpa for the Cournot open-loop and the closed-loop models, respectively (see Figure 4). As for a comparison of model results to actual industry data, the total sum of additional production capacities in Australia and Canada is projected for 2017 to lie between 39 Mtpa (only completed and committed projects in Australia) and 63 Mtpa (with projects in feasibility stage).[9]

Closed-loop model investments are higher than open-loop investments, reflecting the value of influencing other players' production decisions by one's own investments. In the open-loop model, players invest until long-term marginal costs equal marginal revenue, whereas in the perfect competition model investments take place until long-term marginal costs equal market price. In our setting, perfect competition investments lie between closed-loop and open-loop investments. In the model setup used in Murphy and Smeers (2005),

[9]Based on Australian Government - Bureau of Resources and Energy Economics (2012) and McCloskey Coal Report (2013).

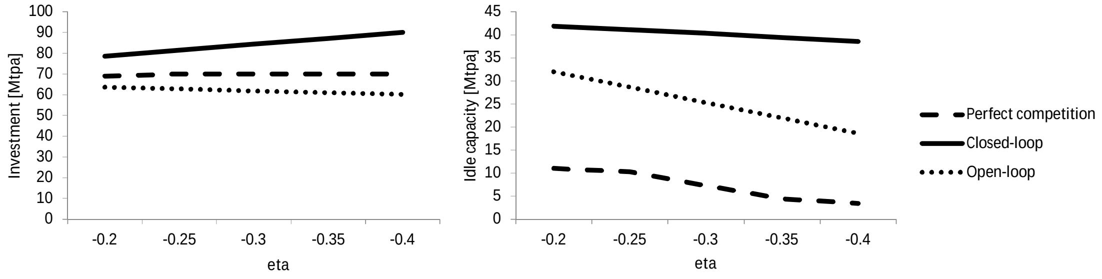

Figure 3: Capacity investments (left) and idle capacity (right) for varying demand elasticity

investments in the perfect competition case generally exceed those in the closed-loop model. Our results are due to *existing* capacities, that are withheld in the closed-loop model (and thus enable profitable investments into new capacities) but are mostly utilized in the competitive case (see Figure 3 on the right). Note that withholding (or idle capacity) refers, here and in the following, only to existing capacities. Each player fully exhausts existing capacities before investing in new capacities. Newly built capacities are always fully utilized in equilibrium as otherwise players could increase their profit by reducing investments.

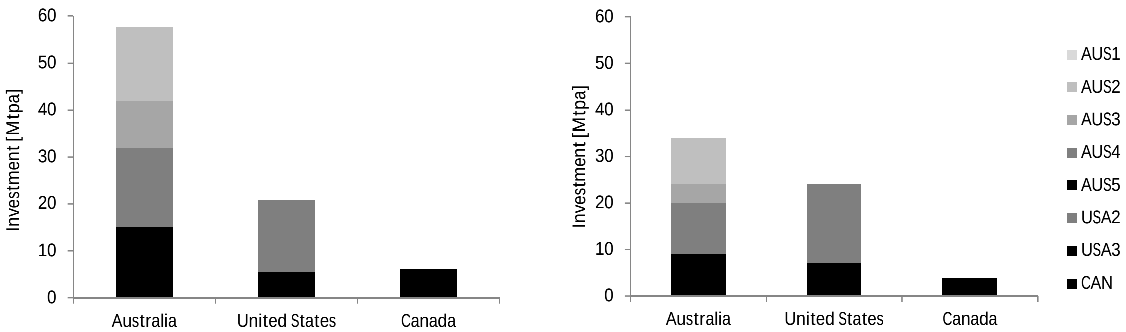

Figure 4: Capacity investments for the closed-loop (left) and open-loop model (right) ($eta = -0.3$)

Interestingly, the increase in production with decreasing *eta* is not accompanied by an increase in investments in capacities in all models (see Figure 3 on the left). In the perfect competition and the closed-loop models available production capacities are constant and increase, respectively, with decreasing demand elasticity in accordance with increasing supply. In the open-loop model, investments in new capacities decrease despite increasing production. This is due to a deviation in capacity withholding: In the closed-loop and perfect competition models, the amount of idle capacity decreases only slightly, whereas in the open-loop model withheld capacity rapidly declines and overcompensates for decreasing capacity additions. In the perfect competition case, idle capacity is due to excess existing capacities: Players produce until (short-term) marginal costs equal market price. Here, some high-cost capacity is not utilized in the United States. In the Cournot models, players withhold when (short-term) marginal costs exceed marginal revenue. In both Cournot models, capacity is exclusively withheld by the two largest players in Australia and in the United States, for each country respectively.

Consumer rent and profits for different levels of demand elasticity are depicted in Figure 5: Profits are lowest in the perfect competition case and highest in the open-loop model. The existence of profits in the perfect competition model is due to capacity restrictions of existing mines and limited expansion potential for new mines.

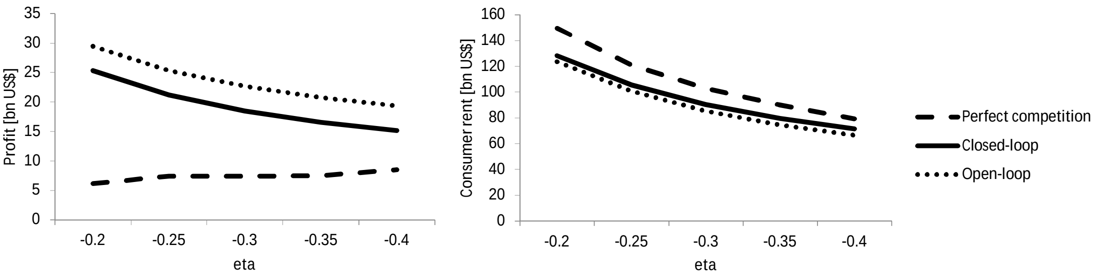

Figure 5: Accumulated profits (left) and consumer rent (right) with varying demand elasticity

Total welfare is similar in all models: in a perfectly competitive market welfare is slightly higher than in the Cournot models. Welfare is lowest in the open-loop model (see Figure 6).

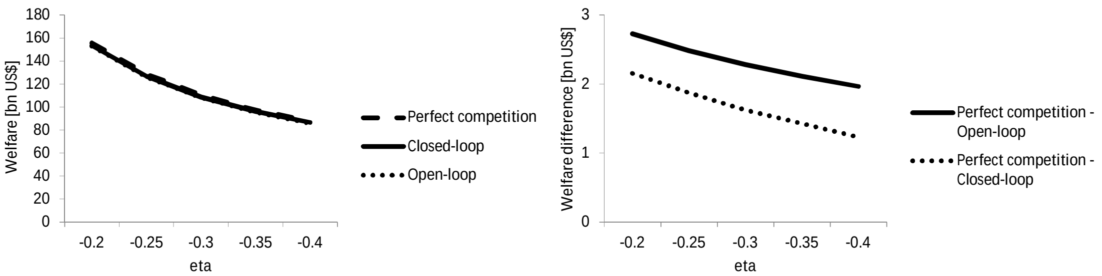

Figure 6: Overall welfare (left) and welfare differences (right)

Thus, the different underlying assumptions concerning the prevailing market structure (long-term contracts versus spot market) primarily influence the surplus distribution rather than its sum: In the open-loop case, in which the product is traded through long-term contracts, companies can earn significantly higher profits, while consumer surplus is higher in markets with spot market-based trade. The corresponding implications are especially interesting, when taking into account that, in commodity markets such as the metallurgical coal, copper or iron ore markets, consumers and producers are located in different countries and hence consumer and producer rents arise in different legislations.

5.2. Variation of Reference Demand

For the variation of reference demand, consumers' demand elasticity *eta* has been fixed to a value of -0.3; thus the case of 100% reference demand corresponds to the depicted results of the previous subsection with the same demand elasticity.

Production quantities under perfect competition are highest in all model runs, and the open-loop model yields the lowest production. Accordingly, prices are highest in the open-loop case followed by closed-loop and perfect competition (see Figure 7). In addition, production and average prices increase with increasing reference demand.

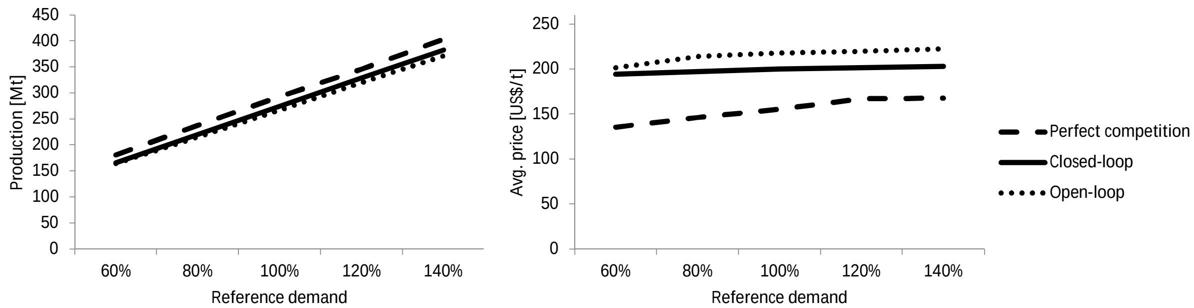

Figure 7: Total production (left) and average market price (right) for varying reference demand

The results in the open- and closed-loop Cournot model almost coincide for very low reference demand as only few investments are carried out. Investments in new production capacities are monotonously increasing for growing reference demand (see Figure 8). As in the case of varying demand elasticity, investments are constantly lower in the open-loop than in the closed-loop model. For low demand, investments in the competitive model are below those in the strategic models as existing capacities suffice to serve demand and thus render new investments unprofitable. In the Cournot models, investments are profitable for small players due to withholding by larger players.

For higher levels of demand, investments in the competitive model exceed those in the closed-loop model. with investments being lowest in the open-loop model. The order of idle capacity is similar to the case of varying demand elasticity: Idle capacity is highest in the closed-loop model followed by the open-loop case (both due to strategic considerations) and the perfect competition model (due to market prices below marginal costs).

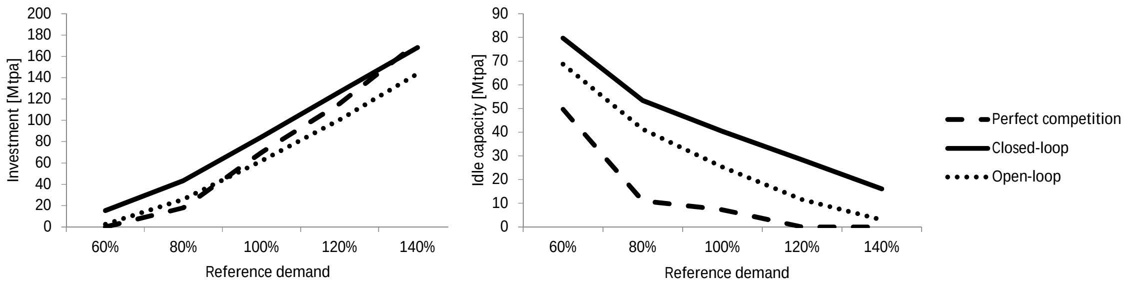

Figure 8: Capacity investments (left) and idle capacity (right) for varying reference demand

With increasing demand, profits as well as consumer rents increase (see Figure 9). Again, results for the open-loop and closed-loop model almost coincide in the case of very low demand as investments are of minor relevance. In the case of higher reference demand, profits in the open-loop model exceed those in the closed-loop model. Results for consumer rent are vice versa.

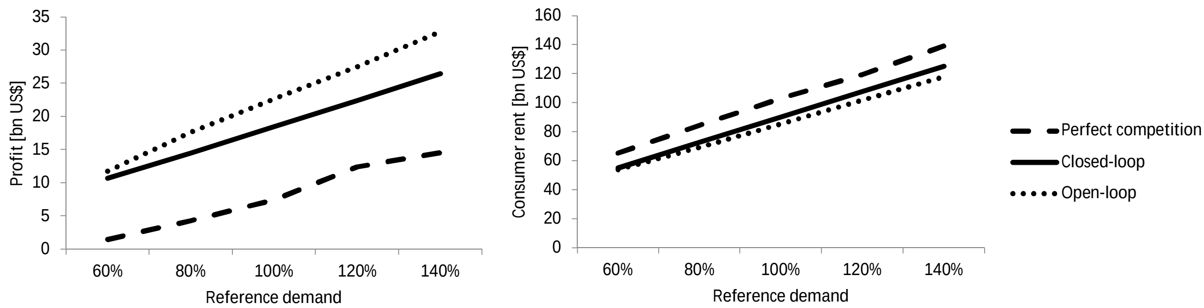

Figure 9: Accumulated profits (left) and consumer rent (right) with varying reference demand

Overall welfare turns out to be quite similar for all models, with the highest welfare occuring in the competitive model followed by the closed-loop and open-loop models (see Figure 10).

5.3. Summary

The results concerning production, price, consumer rent and profits for the three models are in line with the expectations based on previous work (see, e.g., Murphy and Smeers, 2005). Total production as well as consumer rent are highest in the case of a perfectly competitive market followed by the closed-loop and

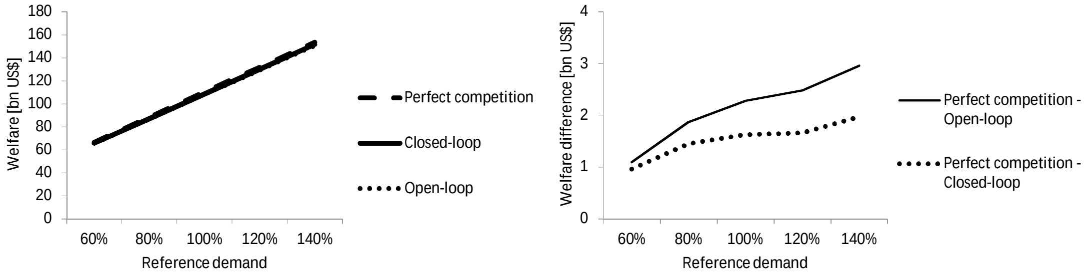

Figure 10: Overall welfare (left) and welfare difference (right, open-loop minus closed-loop)

open-loop models. Profits, on the other hand, increase from the perfect competition to the closed- and open-loop models. Interestingly, capacity expansions in the closed-loop model typically exceed those in the perfect competition case but are accompanied by the withholding of existing production capacities. Those who invest are different from those who withhold: Investment comes mostly from smaller players while withholding is done by the players who already have large existing capacities. This result is driven by the asymmetric endowment with existing production capacity of the players. Players that are already big in terms of capacity have a lower incentive to grow while smaller players expand their capacity.

The magnitude of result deviations between the different models, and thus the implications for market participants, are quite significant. The models of imperfect competition differ, for instance, in capacity expansions between 19% and up to 33% (low and high demand elasticity, respectively).

Even though social welfare only deviates slightly between the open-loop and closed-loop models in the applied dataset, the difference may be higher for different markets and different model parameters. In addition, the welfare distribution between consumer rent and profits differ significantly and thus may raise covetousness, especially considering regional differences between consumption and production.

6. Computational Issues

Equilibria in a closed-loop model, if any exist, do not necessarily have to be unique. Therefore, we perform a robustness check for our closed-loop results by using different starting values for capacity investments. Starting values are randomly drawn from a reasonable range of possible investments, with the maximum investment of each player as given in Table 2. Limiting the range of possible investments drastically reduces computer run-times and increases the probability of finding equilibria. In addition, calculations are made with starting values set to zero and to the open-loop results. The algorithm terminates if overall adjustments of investments δ are less than $\epsilon = 0.1$ Mtpa compared to the previous iteration. We use a learning rate parameter R for the adoption rate of new investments in order to avoid cycling behavior. The learning rate parameter is randomly set between 0.6 and 1.0 (see Gabriel et al., 2012). Calculations have been done on a 16 core server with 96 GB RAM and 2,67 GHz using CPLEX 12.2.

Table 3 shows calculation statistics when using the MILP version of our model (see Subsection 3.2.2). We perform six runs per parameter setting using random start values. Most runs converged to an equilibrium before the maximum number of iterations was reached. With increasing demand elasticity, the algorithm had difficulties to converge. In the case of $eta = -0.4$, only every third run converged to an equilibrium; for $eta < -0.4$, no equilibrium could be found at all. Using either zero investments or open-loop results as starting values, a closed-loop equilibrium was found, except for $eta < -0.4$.

Table 3: Computation time and convergence to equilibrium - MILP version (random, zero, open-loop starting values)

Scenario	Convergence (max. 10 iterations)	Iterations until convergence (only converged runs, max. 10)	Calculation time (only converged runs) [h]
reference case (eta -0.3, dem 1.0)	6/6, yes, yes	6-7 (avg. 6.8), 7, 6	10.7-13.7 (avg. 12.4), 7.1, 5.2
eta -0.2	6/6, yes, yes	7-8 (avg. 7.3), 6, 6	9.2-14.1 (avg. 11.0), 5.7, 4.1
eta -0.25	6/6, yes, yes	7-10 (avg. 8.2), 7, 6	11.4-14.9 (avg. 12.8), 6.9, 5.5
eta -0.35	6/6, yes, yes	6-8 (avg. 7.2), 6, 6	11.3-15.8 (avg. 12.7), 5.1, 5.6
eta -0.4	2/6, yes, yes	7-8 (avg. 7.5), 9, 7	12.2-12.7 (avg. 12.4), 5.6, 7.8
eta -0.45	0/6, no, no	-, -, -	-, -, -.
eta -0.5	0/6, no, no	-, -, -	-, -, -
dem 0.6	5/6, yes, yes	7-9 (avg. 7.4), 7, 7	1.9-3.5 (avg. 2.2), 0.1, 0.2
dem 0.8	6/6, yes, yes	7-8 (avg. 7.5), 6, 5	3.6-8.8 (avg. 7.1), 2.0, 2.3
dem 1.2	6/6, yes, yes	6-9 (avg. 7.8), 7, 6	9.8-13.9 (avg. 11.9), 8.3, 6.0
dem 1.4	6/6, yes, yes	6-10 (avg. 8.3), 7, 6	7.7-11.2 (avg. 8.7), 9.7, 5.7

Figure 11 illustrates the iterative solution process for a single model run for $eta = -0.5$ using random starting values. The model run did not converge to an equilibrium.[10] After initial adjustments of investments in the first iterations, investments start to cycle in a rather small range. Total investments from iteration 5 to 10 vary between 89 Mtpa and 97 Mtpa. This range is typical for all runs regardless of the starting values. The maximum range for a single player's investment deviations is 3 Mtpa. Thus, even if no equilibrium is reached, analyzing the solution process may hint to possible market developments.

Using zero investments or open-loop equilibrium results as starting values led to a significant reduction of computer run-times compared to random starting values. This is probably due to the rather large range of random starting values and the (comparably) rather small equilibrium investments. Thus, starting from zero investments in most cases is closer to the equilibrium values than starting with random values. In

[10] In our iterative approach, convergence depends on the choice of (an arbitrarily small) ϵ.

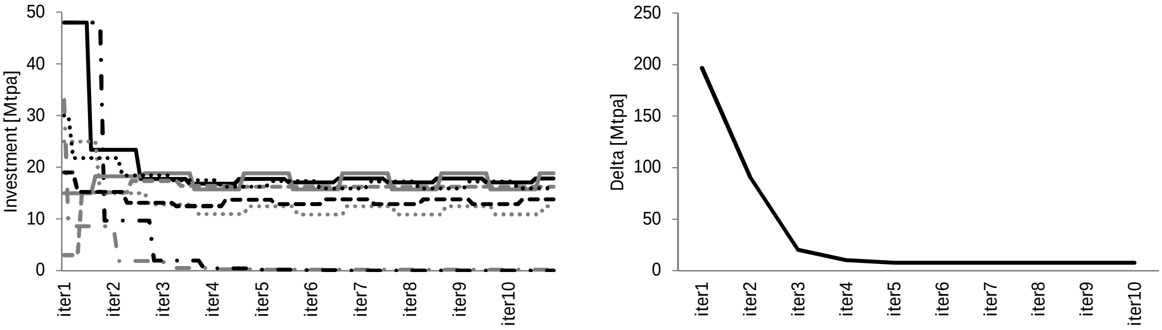

Figure 11: Course of investments of single players during solution process ($eta = -0.5$)

summary, using reasonable starting values can support the solution process significantly.

If the algorithm converged, model results were identical for all runs with the same parameters concerning demand level and demand elasticity. Thus, even if the existence of multiple equilibria cannot be excluded, equilibria appear to be stable.

Calculations using the MILP version of our model usually took several hours to converge to an equilibrium. Applying the grid search approach (see Subsection 3.2.1) and thus discretizing the search space reduced computer run-times significantly. The same calculations as in the MILP version have been done using grid search with investment steps of 0.1 Mtpa and the same convergence criterion as in the MILP version ($\epsilon = 0.1$ Mtpa). The model was implemented in GAMS using GUSS (see Bussieck et al., 2012).

Table 4: Computation time and convergence to equilibrium - Grid Search (random, zero, open-loop starting values)

Scenario	Convergence (max. 10 iterations)	Iterations until convergence (only converged runs, max. 10)	Calculation time (only converged runs) [min]	Accumulated absolute difference between investments in MILP and grid version [%]
reference case (eta -0.3, dem 1.0)	6/6, yes, yes	6-7 (avg. 6.3), 7, 6	2.8-15.7 (avg. 9.3), 2.2, 2.4	0.7-0.9, 0.8, 0.8
eta -0.2	6/6, yes, yes	5-7 (avg. 6.3), 7, 5	3.5-16.7 (avg. 10.2), 2.3, 2.0	1.0, 1.0, 1.0
eta -0.25	6/6, yes, yes	6-7 (avg. 6.7), 7, 6	2.4-16.5 (avg. 9.4), 2.2, 2.4	0.8, 0.7, 0.8
eta -0.35	6/6, yes, yes	6-8 (avg. 7.0), 7, 6	2.8-17.5 (avg. 10.4), 2.2, 2.4	0.8-1.2, 1.2, 0.8
eta -0.4	6/6, yes, yes	6-7 (avg. 6.5), 7, 6	2.5-16.2 (avg. 9.3), 2.2, 2.4	1.2-1.5, 1.5, 1.5
eta -0.45	0/6, no, no	-, -, -	-, -, -.	-, -, -
eta -0.5	0/6, no, no	-, -, -	-, -, -	-, -, -
dem 0.6	6/6, yes, yes	6-8 (avg. 7.0), 5, 5	3.2-16.9 (avg. 9.7), 2.0, 2.0	2.5-3.7, 3.1, 3.3
dem 0.8	6/6, yes, yes	6-7 (avg. 6.7), 6, 6	2.8-16.2 (avg. 9.6), 2.6, 2.4	0.9, 1.0, 0.9
dem 1.2	6/6, yes, yes	5-7 (avg. 6.8), 7, 6	2.9-17.2 (avg. 10.1), 2.3, 2.5	0.3, 0.3, 0.3
dem 1.4	6/6, yes, yes	5-6 (avg. 6.3), 7, 6	2.9-16.1 (avg. 9.7), 2.3, 2.5	0.3-0.4, 0.4, 0.4

Applying grid search, the solution process took only several minutes to converge. Thus, reducing the optimization process from a series of computationally challenging MPECs to comparably easy-to-solve complementarity problems reduced overall computer run-time significantly. As for the MILP version, all model runs converged to the same equilibrium (for $eta \geq -0.4$) or did not converge at all (for $eta < -0.4$). Aggregated absolute deviations of investments between the MILP and the grid search version of our model vary between 0.3% and 3.7%. Thus, in our parameter setting, only minor differences in the results occurred.

7. Conclusions

We presented three investment models for oligopolistic spatial markets. Our approach accounts for different degrees of competition and as to whether the product is sold through long-term contracts or on spot markets. The models are particularly suited for the analysis of investments in markets for natural resources and minerals. We applied the models to the international metallurgical coal trade, which features characteristics similar to those of other commodity markets.

Results may differ substantially between the different models. The closed-loop model, which is computationally challenging, is particularly well suited for when the product is traded on a spot market and the investment expenditure is large compared to production costs. The open-loop model is appropriate for markets with perfect competition or imperfectly competitive markets on which the product is traded through long-term contracts. Moreover, the open-loop model approximates the closed-loop outcome when investment costs are minor.

Over the last several years, progress has been made in the metallurgical coal and iron ore markets to move away from long-term contracts and introduce spot markets in commodity trade. Similarly, efforts are being made to introduce spot market-based pricing between European natural gas importers and the Russian gas exporting giant Gazprom. Such developments can have a multitude of effects – positive or negative. However, with respect to investments, our results suggest that moving away from long-term contracts in oligopolistic markets is likely to stimulate additional investment and consequently reduce profits and increase consumer rents. The overall effect on welfare is negligible. However, in natural resource markets, export revenues and consumer rents from imports are typically accrued in different legislations. Hence, policy makers from exporting and importing countries are likely to have differing views on how commodity trade should be organized.

Further research is needed to improve methods for solving complex bilevel problems. In addition, further research could apply the models presented here to other oligopolistic mining industries such as the copper or iron ore trade. Given that static pricing models tend to give unsatisfactory results for the oil market, in which variable costs are low but capital expenditure is very high, the closed-loop approach may provide interesting insights into the oligopolistic pricing when accounting for investments in capacity.

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Appendix

Table 5: Distance

from	to	distance [Nautical miles]
United States	Europe-Atlantic	3,387
	Asia-Pacific	10,978
Australia	Europe-Atlantic	11,626
	Asia-Pacific	3,731
Canada	Europe-Atlantic	8,840
	Asia-Pacific	4,227
Fringe	Europe-Atlantic	5,018
	Asia-Pacific	3,037

Table 6: Reference Demand and Reference Price

Market	Reference Demand [Mt]	Reference Price [US$/t]
Europe-Atlantic	96	180
Asia-Pacific	179	180