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On the multiplicity of open-loop equilibrium strategies in a non-renewable natural resource duopoly☆

Rémi Morin Chassé[a], Markus Herrmann[b,*]

[a] Department of Economics, University of Prince Edward Island, Canada
[b] Department of Economics and CREATE, Université Laval, Canada

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ABSTRACT

We identify two possible open-loop equilibrium configurations for a non-renewable resource duopoly in a discrete-time framework. For the purpose of illustration, we characterize initial endowments of firms that allow for a maximum of two extraction periods. In the first possible equilibrium, the duopoly exists for two periods, while in the second possible equilibrium, the duopoly lasts only for one period and the firm with the higher initial endowment becomes a monopolist in the second and last period. As neither equilibrium configuration dominates the other for both firms at the same time, it is unclear whether firms acting simultaneously can coordinate on one particular configuration.

1. Introduction

The analysis of extraction strategies in oligopolistic resource markets has been an ongoing endeavour for now over 30 years starting with the analysis of a cartel-fringe, open-loop market structure by Salant (1976). As Gaudet (2007) notes, such interest from the economic profession was motivated by the foundation in 1960 of the Organization of the Petroleum Exporting Countries (OPEC) and the following oil crisis in the 1970s. Trying to understand the extraction pattern (and related price) of natural resources, the economic literature has covered since then the analysis of the Cournot and Stackelberg market structure in a closed-loop setting, where each agent conditions its extraction decision on its own resource stock.[1]

Open-loop and closed-loop Nash equilibria have been characterized analytically for the case of particular demand and cost structures, while more general settings can so far only be dealt with numerically (Salo and Tahvonen, 2001). Whether open-loop or closed-loop strategies apply depends on the players' ability of commitment at the beginning of the game. However,

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* Corresponding author at: Département d'économique, Université Laval, Pavillon J.-A.-DeSève, 1025, avenue des Sciences-Humaines, Québec, Canada G1V 0A6.

E-mail address: markus.herrmann@ecn.ulaval.ca (M. Herrmann).

[1] A good review on how market structure in particular, as well as extraction costs, durability aspects and uncertainty affects the Hotelling rule of resource pricing can be found in Gaudet (2007).

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such commitment may seem particularly unrealistic when the environment of the players changes (*e.g.* a changing carbon tax penalizing fossil fuel extraction).

Following the terminology by Dockner et al. (1985), when a game is "state-separable," or in the terminology by Dockner et al. (2000) a "linear state game," open- and closed-loop strategies will coincide when the terminal time horizon is *exogenously* given. Although such an exogenous terminal time is not necessarily a realistic assumption in resource extracting oligopolies, it becomes an underlying implicit assumption when a particular market structure is assumed to prevail until the exhaustion of the resource. This observation applies to the discrete-time model of Hartwick and Brolley (2008) who assume initial resource stocks of players to be such that exhaustion of the resource occurs in the same period. They find that a player's closed-loop strategy is independent of its competitor's, or equivalently, that closed-loop and open-loop strategies coincide.

In this paper, we also adopt the discrete time modelling framework and characterize explicitly the initial stocks of two players such that exhaustion of each player's resource stock occurs in the same period. Our simple "state-linear" modelling framework guarantees that open-loop and closed-loop strategies coincide in this case. We then show that there exist combinations of asymmetric, initial resource stocks that could sustain two different open-loop equilibrium configurations: (i) a duopoly up to a common, finite time period and (ii) a duopoly followed by a monopoly exhausting its resource pool at a later point of time. We show that the player with a relatively low initial stock prefers the duopoly market structure, while the player with a relatively high initial stock prefers to turn into a monopolist before complete exhaustion of his resource pool occurs. Thus, no open-loop equilibrium dominates the other and it is unclear whether the players may coordinate on a particular market equilibrium.

The model and equilibria of equal and unequal periods of exhaustion are presented in Section 2. In Section 3, we verify which market equilibrium is preferred by each player and discuss whether transfer payments may make firms better off by maintaining the equilibrium characterized by unequal periods of resource exhaustion. We conclude in Section 4.

2. The model

We assume a discrete-time model with a linear inverse demand function $p(q_t) = a - bq_t$, where q_t is the total quantity on the market in period t. The presence of a choke price a makes the resource unessential, such that extraction will end in finite time. There are two firms (players), $i = 1, 2$, serving the market, each firm extracting from its own resource pool. Let q_t^i be the production of firm i, which is assumed to have a linear cost function $C(q_t^i) = cq_t^i$, where $c \geq 0$.[2] Parameters satisfy $a > c$, which implies the resource is valuable and reserves are completely extracted. Firm i's initial stock of the non-renewable resource is given exogenously by s_1^i and the law of motion is $s_{t+1}^i = s_t^i - q_t^i$. We do not allow for resource storage. Once a firm has completely extracted its resource pool, it exits the market.

Firm i has a per-period payoff given by $\pi^i(q_t^1, q_t^2) = p(q_t^1 + q_t^2)q_t^i - C(q_t^i)$. Let $\delta < 1$ be a firm's per-period discount factor. A firm's objective thus consists in maximizing its discounted, intertemporal profits $\sum_1^{T_i} \delta^t \pi^i(q_t^1, q_t^2)$ with respect to its quantity extracted, q_t^i, and subject to its own and competitor's law of motion and initially available stock. T_i is the last period at which extraction by firm i occurs and is determined endogenously in the game. In this paper, we restrict our analysis to Markovian strategies of the form $q_t^i(s_t^1, s_t^2)$.

2.1. Equal periods of exhaustion

We start by characterizing the conditions on the firms' initial resource stocks, s_1^i, $i = 1, 2$, such that both firms operate in the market for the same number of periods, $T_1 = T_2 = T$. This is the only case studied by Hartwick and Brolley (2008) who are however silent on the conditions on initial resource stocks allowing for this symmetric case of equal exhaustion time.[3]

In order to characterize firm i's strategy, we choose to write its intertemporal profit maximization problem recursively by defining the value function $V^i(s_t^1, s_t^2)$, which depends on stocks (s_t^1, s_t^2):

$$V^i(s_t^1, s_t^2) = \max_{0 \leq q_t^i \leq s_t^i} \{\pi^i(q_t^1, q_t^2) + \delta V^i(s_{t+1}^1, s_{t+1}^2)\}, \tag{1}$$

subject to the laws of motion and initially available resource stocks. We show in Appendix B that for any period in which firm i extracts a strictly positive amount of the resource, the properly discounted marginal profit must be equal. This result stems from the fact that open- and closed-loop strategies coincide in our modelling framework. Indeed, we could obtain this result immediately when looking for open-loop strategies for each firm. Hence, for firm $i = 1, 2$, $i \neq j$ at any period $t \leq T - 1$, we can write for two consecutive periods:

$$\frac{\partial \pi^i(q_t^i, q_t^j)}{\partial q_t^i} = \delta \frac{\partial \pi^i(q_{t+1}^i, q_{t+1}^j)}{\partial q_{t+1}^i}. \tag{2}$$

[2] Note that our results also hold with a quadratic cost function, as shown in Appendix A.

[3] Their model set-up is similar to ours but relies on a quadratic extraction cost function.