International Journal of Industrial Organization 42 (2015) 23–33

Contents lists available at ScienceDirect

International Journal of Industrial Organization

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

Innovation in a generalized timing game☆

Vladimir Smirnov, Andrew Wait *

School of Economics, University of Sydney, NSW 2006, Australia

ARTICLE INFO

Article history:
Received 9 October 2014
Received in revised form 5 June 2015
Accepted 10 June 2015
Available online 2 July 2015

JEL classification:
C72
L13
O31
O33

Keywords:
Timing games
Entry
Leader
Follower
Process innovation
Product innovation

ABSTRACT

We examine innovation as a market-entry timing game with complete information and observable actions. We characterize all pure-strategy subgame perfect equilibria for the two-player symmetric model allowing both the leader's and the follower's payoff functions to be multi-peaked, non-monotonic and discontinuous. We provide sufficient conditions for when the equilibria can be Pareto-ranked and when the equilibrium is unique. Economic applications discussed include process and product innovation and the timing of the sale of an asset.

1. Introduction

The availability of new products and processes underlies economic development and improvements in welfare (Romer, 1994). But new technology does not automatically equate to innovation in the marketplace. Rather, any innovation—be it market entry with a new product or adoption of a new production process—must be deliberately implemented as part of a firm's profit-maximizing strategy. Following Fudenberg and Tirole (1985), Dutta et al. (1995) and Hoppe and Lehmann-Grube (2005), we study an innovation-timing game in which two competing firms consider the optimal time to enter a market.

In this paper, we extend these existing market entry models in several dimensions. First, we generalize both the leader's and the follower's profit functions, solving for the pure-strategy subgame perfect equilibria when payoffs for both firms can be non-monotonic or multi-peaked. In this way, our framework allows us to solve a broader range of economic problems than was previously possible. For example, in Section 3.1 we show that a process-innovation or a product-innovation model, augmented with an experience good or some switching cost, can generate a non-monotonic payoff for both the leader and the follower. The same point can be made for the profit derived from an asset; the revenue generated can vary non-monotonically depending on the time of sale. Unlike existing methods, the solution algorithm developed here is able to allow for any possible continuous payoff structure.

Second, our model is sufficiently general to accommodate discontinuities in payoffs. Discontinuities arise in a variety of situations; for instance, at some point in time (in terms of the leader's entry time), the regulatory environment could change, creating a discontinuity in the leader's or the follower's payoff (or both).[1] As an example, consider the situation when the patent for a production process is due to expire at a known time. This change might cause a discrete decrease in a firm's entry costs, resulting in a discontinuous jump in its payoff. Alternatively, the provision of complementary technologies in related markets, such as new

☆ We would like to thank Murali Agastya, Yumiko Baba, Priyanka Dang, Mark Melatos, Nicolas de Roos, Jonathan Newton, Suraj Prasad, Guillaume Roger, John Romalis, John Rust, Philipp Schmidt-Dengler (co-editor), Abhijit Sengupta, Kunal Sengupta, Don Wright, the anonymous referees and participants at presentations at the Australian National University, Waseda University, the Econometrics Society Australasian Meeting 2013 and the International Industrial Organization Conference 2013 in Boston. The authors are responsible for any errors.

* Corresponding author.
E-mail addresses: vladimir.smirnov@sydney.edu.au (V. Smirnov), andrew.wait@sydney.edu.au (A. Wait).

[1] As noted by Bobtcheff and Mariotti (2012), many factors that affect an entrant's profitability are exogenous, outside of the control of the firms themselves. These events could see a discontinuous jump in the payoffs of the leader and/or the follower. Fudenberg and Tirole (1985, Section 5) also discuss how three (or more) firms can generate a discontinuity in payoffs for the remaining firms in a timing game similar to the one we study here.

http://dx.doi.org/10.1016/j.ijindorg.2015.06.003
0167-7187/

software applications for a particular type of phone handset, could create a discontinuity in the entrants' payoffs. Similarly, the product choices of firms selling substitute products, such as tablets, may disrupt the phone handset sellers, generating discontinuities.

Some of the key results in the paper are as follows. In characterizing all pure-strategy subgame perfect equilibria, we find that there can be multiple equilibria. First, there could be a set of equilibria that exhibit rent equalization. The leader's entry times in these equilibria occur at times when the leader and follower payoff curves intersect and the leader's payoff is at a historic maximum for the game up until that time; they are similar to the joint-adoption equilibria in Fudenberg and Tirole (1985). Second, equilibria can exist with the leader entering at points of discontinuity, for example, if the leader receives a higher payoff than the follower at this time, and that the expected payoff in equilibrium is higher than the payoff from entering as a leader at any earlier time. An example of this is immediate entry at the very start of the game when both firms prefer to be first into the market. Third, there can be equilibria with asymmetric payoffs, like the second-mover advantage equilibrium of Hoppe and Lehmann-Grube (2005) and the maturation equilibrium of Dutta et al. (1995). Finally, when there are multiple equilibria, we provide sufficient conditions to ensure that these equilibria can be Pareto ranked. We also outline sufficient conditions for when the subgame perfect equilibrium is unique.

This paper draws on an extensive literature on innovation timing games.[2] Our analysis of an irreversible investment decision with complete information and observable actions (closed-loop equilibria) follows Fudenberg and Tirole (1985), Dutta et al. (1995) and Hoppe and Lehmann-Grube (2005). This framework has been used to study a variety of applications. For example, Argenziano and Schmidt-Dengler (2012, 2013, 2014) adopt a variant of Fudenberg and Tirole (1985) to examine the order of market entry, clustering and delay. They show that with many firms the most efficient firm need not be the first to enter the market and that delays are non-monotonic with the number of firms. In addition, they suggest a new justification for clustering of entries.[3]

An alternative approach to study innovation is to assume players' actions are unobservable as in Reinganum (1981a, 1981b). In her models, unobservable actions are equivalent to each firm being able to pre-commit to its strategy at the start of the game. Reinganum shows that in the (open-loop) equilibria, there will be diffusion in the sense that firms adopt the technology at different dates, even though all firms are ex ante identical. Park and Smith (2008) develop an innovation game with unobservable actions that permits any firm (in terms of the order of entry) to receive the highest payoff. This allows for a war of attrition, with higher payoffs for late movers, a preemption game with higher payoffs for early movers and a combination of both. They solve for the (open-loop) mixed-strategy equilibria.[4] As a point of comparison, in our model, firms use feedback rules to determine their strategy at any particular point in time; this means that they are unable to commit to their strategy at the beginning of the game.

Finally, several other authors consider innovation when there is asymmetric information. For example, Bobtcheff and Mariotti (2012), Hendricks (1992) and Hopenhayn and Squintani (2011) assume that a firm's capability to innovate is private information. In these models, delay allows a firm to get better information about the potential innovation (its costs, value, and so on), but waiting runs the risk that a rival will innovate first, capturing the lion's share of the returns.

2. The model

Assume two firms ($i = 1, 2$) are in a continuous-time stopping game starting at $t = 0$ until some terminating time $T \in (0, \infty]$. Firm i's decision to stop (that is, 'enter' the market) at $t_i \geq 0$ can only be made once, and this decision is irreversible and observable immediately by the other firm. The game ends when both players have stopped. Firm i's payoff depends on the stopping times of both firms: $\pi_i(t_1, t_2)$. If the game ends with the two players stopping at different times, assume that the payoffs of the leader and the follower are $L(t_1, t_2) = \pi_i(t_1, t_2)$ and $F(t_1, t_2) = \pi_j(t_1, t_2)$, respectively, $t_i < t_j$ where $i, j = 1, 2$ and $i \neq j$.

We make the following standard assumptions.

Assumption 1. *Time is continuous in that it is 'discrete but with a grid that is infinitely fine'.*

Assumption 2. *Firms always choose to stop earlier rather than later in payoff-equivalent situations.*

Assumption 3. *If more than one firm chooses to stop (enter) at exactly the same time, one of these firms is selected to stop (each with probability $\frac{1}{2}$ ex ante); the other firm is then able to reconsider its decision to stop at this time.*

Equivalent assumptions are adopted in the literature. For example, Assumption 1 replicates A1 of Hoppe and Lehmann-Grube (2005). It invokes Simon and Stinchcombe (1989), who show that under certain conditions, a continuous-time strategy profile is the limit of a discrete-time game with increasingly fine time grids.[5] Assumption 2, which is very similar to A3 in Hoppe and Lehmann-Grube (2005), allows us to focus on just one (payoff-equivalent) equilibrium in the case of indifference between early and late entry.[6] This simplifies our analysis so as to focus on the timing of entry rather than on issues of equilibrium selection.

Assumption 3—part of A3 in Hoppe and Lehmann-Grube (2005) and Assumption 5 in Dutta et al. (1995)—avoids potential coordination failures involving simultaneous entry. Given its importance, further discussion of the intuition underlying this assumption is worthwhile. This assumption can be justified in several ways. In some situations, as a practical matter, if two firms try to enter the market at the same time, there might be some capacity constraint or institutional requirement that prevents joint entry—consequently, only one firm becomes the leader and the other firm is relegated to the role of second entrant. For example, in a particular market, there could be a bureaucratic rule which requires that the leadership role be allocated to the firm that has the first email registered in a designated inbox. Even if both firms simultaneously send their messages, only one email can arrive first. As a consequence, with simultaneous moves, each firm has some probability of being the leader. In our model, Assumption 3 gives either firm an equal chance of having its email received first.[7]

Following Fudenberg and Tirole (1985), we use subgame perfection as our equilibrium concept. A history h_t is defined as the knowledge of whether or not firm $i = 1, 2$ previously stopped at any time $\hat{t} < t$, and if so when. A strategy of firm i, denoted by $\sigma_i(h_t)$, indicates at each history h_t whether firm i stops at t ($\sigma_i(h_t) = 1$) or does not stop at t

[2] See Hoppe (2002) or Van Long (2010, Chapter 5) for a survey of the literature. Further, Fudenberg and Tirole (1991) consider innovation when the firms make one irreversible decision (to enter) in a simple timing-game framework (see Sections 4.5 and 4.12).

[3] Timing games have been studied in a number of other contexts. Katz and Shapiro (1987) analyze an innovation game with heterogenous firms when there is licencing (by the leader) and imitation (by the follower). Dutta and Rustichini (1993) consider a stochastic timing game with continuous payoffs. Gale (1995) shows that inefficient delays can occur when n players make a one-off investment decision in a dynamic coordination game.

[4] They also briefly consider observable actions and show that there are multiple equilibria.

[5] See Hoppe and Lehmann-Grube (2005), footnote 4 for a further discussion.

[6] Hoppe and Lehmann-Grube (2005) assume that if the follower is indifferent between two alternative entry times, it chooses the earliest time. For consistency, we extend this assumption to both firms.

[7] Dutta et al. (1995) present a similar rationale for this assumption, suggesting there could be small random delays between when a decision is made and when a new technology is adopted that provide some probability that either firm will be first in the event of joint adoption.