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Production with learning and forgetting in a competitive environment

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ABSTRACT

It has been shown that learning-by-doing enables firms to reduce marginal production costs, but that this effect weakens due to organizational forgetting. In order to assess the impact of both learning and forgetting on long-term competitiveness and a firm's profitability, we model an experience accumulation process with depreciation and consider two competing firms that produce fully substitutable products. In this model, unit production costs decrease with the firm's experience due to the proprietary learning process as well as the spillover of experience from the competing firm. Firms can either share or hide from each other their information about the state of their respective experience throughout the game. We found that in an equilibrium steady state, if the organizational forgetting is sufficiently large (larger than the spillover rate value), then information sharing, compared to information hiding, results both in less competitiveness and increased profits for firms. Conversely, if the organizational forgetting is small and the spillover opportunities are relatively large, then information sharing promotes both long term competitiveness and firm profits. Accordingly, firms are better off in the long term by deliberately limiting (expanding) their experience accumulation process whenever organizational forgetting is relatively large (small). A high ability of proprietary learning, however, can interfere in this relationship so that limiting the firms' experience process will always be compatible with higher profitability.

1. Introduction

Comprehensive data on all solar photovoltaic industry installations in California from 2002 to 2012 points out that 1000 additional installations by a contractor in a county reduces non-hardware marginal costs by $0.36 per watt on average; in addition to this learning by doing, 1000 installations by competitors spills over and reduces the contractor's non-hardware costs by $0.005 per watt (Bollinger and Gillingham, 2014). Similarly, the production of the L-1011 and L-1011-500 commercial aircraft in the Eighties by Lockheed Aeronautics (California) was characterized by high learning rates of approximately 35% in terms of production experience. Since commercial aircraft production is highly labor-intensive and production rates are very low, learning results primarily from a more experienced workforce. The marginal costs of producing aircraft do not, however, always decrease over time, as would be expected if production were subject to pure learning. Indeed, labor requirements were observed to increase after the strike in 1977 thereby explicitly illuminating the "forgetting effect". By that time, the competing model, the L-1011-500 was introduced. The decision to bring out a new model significantly set back the learning process. Due to partial experience spillover, the first L-1011–500 produced required approximately 25% more labor than the previous model. The labor requirements for the two competing models, however, then converged over time inducing similar reduced marginal production costs (Benkard, 2000).

In general, the economic and strategic implications of learning-by-doing-alone have been extensively documented (see the reviews in Arrow, 1962; Yelle, 1979; Dutton and Thomas, 1984; Cabral and Riordan, 1994; McDonald and Schrattenholzer, 2001; Fogliatto and Anzanello, 2011, Argote, 2011). However, the consequences of organizational forgetting on the competitive dynamics of industries where learning with spillovers is present remain under-investigated (Bailey, 2000; Argote et al., 1990; Benkard, 2000; Martin De Holan and Phillips, 2004). This paper seeks to fill this gap by analyzing how a firm's competitive behavior is affected by the extent to which it accumulates experience under spillovers and organizational forgetting.

To investigate this issue, we consider a duopolistic industry involving fully substitutable products, in which two firms compete on production (Cournot competition). As usual in a Cournot setup, the production decisions determine the market price and thereby the firms' profits (Chung et al., 2012; Hu et al., 2014). Each firm's production activity leads to accumulate experience over time through learning-by-doing. Because of its cumulative nature, experience is interpreted as a stock variable that allows for spillovers between firms (Chen et al.,

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2015). We also assume that the stock of experience can be reduced by organizational forgetting over time.

Due to the cumulative nature of experience, we use a dynamic game to determine how competitive production decisions are made under experience accumulation with forgetting in the presence of both proprietary and spillover learning.

In dynamic games (e.g., Dockner et al., 2000; Jørgensen and Zaccour, 2004; Long, 2010), the mutual observability of each firm's stock of experience over time plays an essential role in each firm's respective strategy (Dockner et al., 2000). When each firm's current stock of experience is observable by both parties at each period of time, a firm can update its production decisions with the current values of its own stock of experience and that of its competitor. In such instances, which are referred to as closed-loop equilibria, each firm's production strategy is *contingent* upon information regarding the rival's reaction to a change in the current stocks of experience. Conversely, if the firms' current stock of experience cannot be observed (or can only be seen after a certain time lag) it is appropriate for each firm to optimize its production decisions throughout the game based on its sole knowledge of the initial stocks of experience given at the beginning of the game. In this case, which is referred to as open-loop equilibrium, a firm's strategy is based on *precommitment* to execute a plan of production throughout the game.

In reality the state of production experience is frequently and intentionally concealed by the competing firms. This extends to keeping secret main features of new products until their release. A firm may, however, discover the state of the production experience of its rivals by learning from the suppliers or customers they have in common, sending employees to trade shows and professional conferences, reverse-engineering of rival's products and so on (von Hippel, 1988). Consequently, we consider in this paper both observable and unobservable stocks of experience as possible scenarios to determine how the observability of the rival's current experience stocks affects competitive production decisions under experience accumulation with forgetting in the presence of both proprietary and spillover learning. To this end, we evaluate and compare production levels of both firms under open-loop and closed loop equilibria.

The contribution of the present paper is manifold. In particular, the results account for learning-by-doing along with organizational forgetting over an infinite time horizon with discounting. We determine important properties of the steady-state equilibria (which do not exist under a finite planning horizon). Further, unlike previous studies, we derive a pivotal condition that compares analytically open-loop and closed-loop steady-state equilibria thereby predicting the effect of information observability on competing firms. This condition emphasizes in particular the role of organizational forgetting, experience spillovers and discounting rate. In contrast to the results obtained in two-period models, our results suggest that the difference between production quantities of the two types of equilibrium is not cancelled out when the discounting rate is negligible.

In the next section, we review the relevant literature. Section 3 develops the differential game model. Section 4 analyzes the commitment strategy, and Section 5 focuses on the contingent strategy. Section 6 compares our results. Section 7 concludes.

2. Literature review

Our research lies at the intersection of three literatures, those concerning empirical models on determinants of learning by doing, production decisions under learning and forgetting, and game models analysis of decision rules in production problems of horizontal competition.

Jarmin (1993) develops and estimates an empirical model to study the intertemporal nature of learning by doing and spillovers. He finds evidence of both proprietary and spillover learning and shows that a firm's ability to learn from its own experience differs from its ability to learn from its rival's experience. Benkard (2000), in addition to learning with spillovers, incorporates organizational forgetting that depreciates experience at a constant rate. Using data from the commercial aircraft industry, he suggests that the strategic effects of organizational forgetting must be taken into account when the products are labor-intensive; learning is thought to be important at the individual worker level; and the turnover is relatively high. In this paper, we integrate the influence of both spillovers and forgetting on experience accumulation.

Most recent studies about the implications of forgetting in industries where learning takes place have been limited to operations management considerations. Teyarachakul et al. (2008) analyze the long-run characteristics of batch production time for a constant demand problem with learning and forgetting in production time. Teyarachakul et al. (2014) extend this result to a large class of learning and forgetting functions with some differentiability conditions. Teyarachakul et al. (2011) investigate the effect of learning and forgetting on production decisions based on the assumptions that i) the amount forgotten increases with longer interruptions in production and ii) the forgetting could be initially slow and become fast afterward. They show that these assumptions lead firms to produce smaller rather than larger quantities in the presence of learning and forgetting. Our approach differs from these studies in that we analyze how learning and forgetting affect a firm's competitive behavior (see Table 1 for the basic features of the competition related research in learning-by-doing).

Earlier analytical game-based models accounting for the effect of experience typically consider quantity-based competition over two

Table 1
Basic features of research on dynamic games with learning-by-doing.

Research	Learning	Spillover	Forgetting	Time Horizon	Equilibrium type	Analytical comparison of FNE and OLNE
Spence (1981)	+	–	–	Finite horizon with discounting	FNE and OLNE for two periods	+
Fudenberg and Tirole (1983)	+	–	–	Infinite horizon with discounting	OLNE	–
Jørgensen and Zaccour (2000)	+	+	–	Finite, discrete-time with discounting	FNE and OLNE for two periods	+
Stokey (1986)	+	Complete spillover	–	Infinite horizon with discounting	FNE	–
Miravete (2003)	Fixed cost learning	–	–	Infinite horizon with discounting	FNE and OLNE	+
Besanko et al. (2010)	Finite stock of knowledge	–	+	Discrete-time, infinite horizon with discounting	FNE	–
Kogan et al. (2016)	+	+	–	Finite horizon without discounting	FNE and OLNE	–
This paper	+	+	+	Infinite horizon with discounting	FNE and OLNE	+