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A dynamic analysis of investment in process and product innovation with learning-by-doing

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HIGHLIGHTS

- Develop a dynamic control model of a monopolist's investments in process and product innovation under learning-by-doing.
- Derive the optimal investment levels in the saddle stable steady state under monopolist optimum and social optimum.
- Investigate the effects of learning-by-doing on the process and product innovation investments and their the complementarity (substitutability) relationship.
- Compare the social incentive towards both product and process innovation against the private incentive that characterizes the profit-seeking monopolist.

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ABSTRACT

This paper investigates the optimal control problem of a monopolist's investments in process and product innovation under learning-by-doing in a dynamic setting. We show that: (i) there exists the saddle stable steady state under monopolist optimum and social optimum; (ii) the learning rates of product and process innovation affect not only the monopolist's process or product innovation investments, but also the complementarity (substitutability) relationship between product and process innovation; (iii) the social incentive towards both product and process innovation is always larger than the private incentive characterizing the profit-seeking monopolist. These results are valuable complement and development to the results drawn from the standard product and process innovation model.

1. Introduction

Product and process innovation is considered to be one of the key criteria for evaluating sustainable development and competitiveness of firms. Typical early studies include Utterback and Abernathy (1975), Athey and Schmutzler (1995), and Klepper (1996). In recent years, Lin and Saggi (2002) showed that product innovation affects the degree of product differentiation by reducing product substitutability. Lambertini (2003) evaluated the multiproduct monopolist's incentives towards product and process innovations against the social optimum. Lin (2004) extended the model of Lambertini (2003) to show that whether or not process R&D incentive and the number of varieties are positively related depends on the degree of scope economies in process R&D. Lambertini (2004) further expanded the analysis of both Lambertini (2003) and Lin (2004) to conclude that the complementarity between process R&D and product proliferation will be restored under the full internalization of spillovers. Mantovani (2006) studied the complementarity between market-enhancing product innovation and cost-reducing process innovation. Jun and Vives (2004) considered a general symmetric differential game duopoly model and analysed the strategic substitutability or complementarity between state variables of firms. Lambertini and Mantovani (2006) then investigated the issue of strategic substitutability (complementarity) in differential games when the Hamiltonian functions are multiplicative or additively separable. Cucculelli and Ermini (2013) analysed the impact of individual risk attitude on the relationship between product innovation and firm performance. In recent works, Lambertini and Mantovani (2009) investigated the dynamic behaviour of a multiproduct monopolist investing both in process and product innovation, and Lambertini and Mantovani (2010) analysed the optimal behaviour of firms investing both in

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process and product innovation in a dynamic setting. Besides, the idea that product differentiation depends upon firms' investments has been investigated in dynamic models by Cellini and Lambertini (2009). Further, Lambertini and Orsini (2015) analysed the R&D portfolio of a monopolist investing in cost-reducing and quality enhancing R&D.

However, it appears that existing literature has seldom addressed the dynamic role of learning-by-doing that can affect process and product innovation. Learning-by-doing is the result of the accumulation of knowledge generated by experience in the production process (Arrow, 1962). Learning-by-doing and using are the principal drivers of incremental innovation. In almost all fields of production of goods and services, the repetition of production tasks leads to a gradual improvement in the efficiency of production processes and product/service design and performance. The importance of such 'learning-by-doing' processes has long been recognized, as has the central place of direct production workers in innovation as sources of work-based learning (Landes, 1972). Hatch and Mowery (1998) analysed the relationship between process innovation and learning by doing in the semiconductor industry. The authors showed that the improvement of manufacturing performance through learning is not an exogenous result of output expansion but is influenced primarily by the systematic allocation of engineering labour to problem-solving activities. Furthermore, the learning curve is the product of deliberate activities intended to improve product quality and reduce production cost, rather than the incidental byproduct of production volume (Hatch and Mowery, 1998). Since one important source of technological progress is learning-by-doing (Thompson, 2010), in recent years, many authors have addressed learning-by-doing in abatement investment (Li and Pan, 2014) and accumulation technology (Clarke, 2006).

In this paper, our goal is to investigate the optimal control problem of a monopolist's investments in process and product innovation under learning-by-doing in a dynamic setting. Our work has two main features: (i) in our model, monopolist's instantaneous cost function depends on both the investment and the knowledge accumulations of process and product innovation; (ii) the change rates of knowledge accumulations of product and process innovation are state variables. In fact, our paper can be viewed as an extension and continuation of Lambertini and Orsini's (2015) work. Specifically, we extend the work of Lambertini and Orsini (2015) by explicitly incorporate the knowledge accumulation (i.e., learning-by-doing) in both the product and process innovation. Further, we reveal some effects of the firm's knowledge accumulation on the product and process innovation investments. In particular, we show that the learning rates of product and process innovation affect not only the monopolist's process or product innovation investments, but also the complementarity (substitutability) relationship between product and process innovation.

The outline of the paper is as follows: Section 2 introduces the basics of the model. Section 3 discusses the monopolist's optimum. Section 4 investigates the social optimum. Section 5 concludes the paper. All proofs are given in the online appendix.

2. The basic model

In this paper, we consider an optimal control problem over continuous time $t \in [0, +\infty)$, where at any instant a monopolist chooses the investment levels of process and product innovation under learning-by-doing. Production takes place at marginal cost $c(t)$, which can be decreased via an instantaneous investment $h(t)$ at time t. The monopolist also invests in product innovation via the instantaneous investment $k(t)$ to increase product quality $q(t)$ at time t. The differential equations of $q(t)$ and $c(t)$ are given by the following form:

$$q(t) = k(t) - \delta q(t) \tag{1}$$

$$c(t) = -h(t) + \sigma c(t) \tag{2}$$

where parameter $\delta > 0$ is the decay rate of quality, while $\sigma > 0$ is the obsolescence rate affecting production technology.

The instantaneous cost functions of investing in product and process innovation are, respectively, given by $C(k(t)) = \alpha k^2(t)$ and $C(h(t)) = \beta h^2(t)$, where α and β are positive parameters.

According to Lambertini and Orsini (2015), the total cost function borne by the firm can been written by following form:

$$C(t) = c(t)x(t) + \alpha k^2(t) + \beta h^2(t) + \upsilon q^2(t) \tag{3}$$

where $x(t)$ is the form's production level at time t. The term $\upsilon q^2(t)$ measures the instantaneous cost of producing a quality level $q(t)$ using machinery and/or skilled labour operating at decreasing returns.

One important source of technological progress is learning-by-doing. According to Thompson (2010), we can measure the knowledge accumulations of product innovation $A_1(t)$ and process innovation $A_2(t)$ from time 0 to t by the following forms, respectively,

$$A_1(t) = A_{10} + \mu \int_0^t k(s)ds \tag{4}$$

$$A_2(t) = A_{20} + \xi \int_0^t h(s)ds \tag{5}$$

where A_{10} and A_{20} denote the initial level of knowledge accumulation of product and process innovation, μ and ξ characterize the growth rates of knowledge accumulation of product and process innovation, respectively.

Differentiating expressions (4) and (5) with respect to time t, respectively, gives

$$\dot{A}_1(t) = \mu k(t) \tag{6}$$

$$\dot{A}_2(t) = \xi h(t). \tag{7}$$

Further, following Thompson (2010) and Clarke et al. (1982), we assume that the instantaneous cost functions of product and process innovation are given by the following the forms:

$$C(k(t), A_1(t)) = \alpha k^2(t) - b_1(A_1(t) - A_{10}) \tag{8}$$

$$C(h(t), A_2(t)) = \beta h^2(t) - b_2(A_2(t) - A_{20}) \tag{9}$$

where $b_1 > 0$ and $b_2 > 0$ are the rates of learning of product and process innovation, respectively.

In this paper, we assume that monopolist produces a single item, there is no stock, and all the production is sold. Further, according to Hackner (2000), we assume that the monopolist's inverse demand function $D(t)$ is given by $D(t) = a - a_1 p(t)$, where a measures basic quality in a vertical sense. It is worth noting that since Hackner (2000), "quality" is approximated by the "reservation price" a in the standard demand function. In a recent work of Chenavaz (2012), the demand function is specified as an additively separable demand function. Following Chenavaz (2012) and Hackner (2000), we assume that monopolist inverse demand function can be written as

$$D(t) = x(t) = [a + a_1 q(t)] - a_2 p(t). \tag{10}$$

In expression (10), $[a + a_1 q(t)]$ represents the reservation price under product innovation, where a is analogous to Hackner (2000), while $a_1 q(t)$ denotes the improved quality arising from product innovation, with a_1 being a dynamic adjustment coefficient as in Chenavaz (2012).

From expressions (3), (8), (9) and (10), we can derive that firm's total cost function under learning-by-doing is given by the following form:

$$\begin{aligned} C(t) = {} & c(t)D(t) + [\alpha k^2(t) - b_1(A_1(t) - A_{10})] \\ & + [\beta h^2(t) - b_2(A_2(t) - A_{20})] + \upsilon q^2(t). \end{aligned} \tag{11}$$