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Dynamic optimal control of process–product innovation with learning by doing

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ABSTRACT

In this paper, we present a dynamic optimal control model of process–product innovation with learning by doing, and extend the model of Chenavaz (2012) to an even more general model in which the firm's cost functions of product and process innovation depend on both the innovation investments and the knowledge accumulations of product and process innovation; furthermore, in our paper, the product price, the investments of product and process innovation are decision variables; the product quality, production cost, the change rates of knowledge accumulations of product and process innovation are state variables. The main objective of this paper is to analyze the relationships between these variables, and investigate the model's optimal conditions and characteristics. Further, we solve the model with some numerical examples, and sensitivity analysis is conducted to study the effect of changing the parameters and coefficients on the objective function value.

1. Introduction

In this paper, we develop a dynamic optimal control model of process–product innovation with learning by doing. Our study is the intersection between two streams of research: The first of these streams originates in the studies of product and process innovation (e.g., Chenavaz, 2012; Lambertini & Mantovani, 2009; Mantovani, 2006); the second of these streams originates in the studies of learning by doing (e.g., Argotte & Epple, 1990; Arrow, 1962; Thompson, 2010).

Over the past few decades, globalization and the rise of new technologies have challenged firms' abilities in developing innovation strategies to face increasing market competition. Innovation has become a fundamental source of firm survival and growth. The literatures on innovation distinguish between product innovation and process innovation. Product innovation is the implementation/commercialization of a product or service with improved performance characteristics that delivers objectively new or improved services to the user. Product and/or service innovation entails activities such as design, research and development, acquisition of patents, technology licenses, trademarks, and tooling-up and industrial engineering. Process innovation is the implementation of new or significantly improved production or delivery methods. It may involve investment in new technology embodied in machinery and equipment, new software for supply-chain management, new software for designing products and training of staff to offer new services to customers. Many firms, especially in technological fields, simultaneously improve product quality by product innovation, and reduce production cost by process innovation.

Many authors have discussed the problems of innovation such as Kamien (1992), Lambertini and Mantovani (2009), Pine, Victor, and Boyton (1993), Athey and Schmutzler (1995), Klepper (1996), Reinhard (1990), Saha (2007), Utterback (1975), etc. Utterback (1975) reported results from empirical tests of relationships between the pattern of innovation within a firm and certain of the firm's characteristics. Reinhard (1990) assessed the overall contribution of product innovation to competitive advantage, analyzed the conditions under which such a contribution is likely, and discussed how this likelihood can be increased through company action. Kamien (1992) analyzed licensing of a cost reducing innovation to an oligopolistic industry. Pine et al. (1993) stated that more and more firms structure their organization so as to be able to carry out both process and product innovation simultaneously. Athey and Schmutzler (1995) studied two dimensions of innovation: demand-enhancing (product) and cost-reducing (process). These two types of innovation are complementary in terms of increasing the firm's net revenue in the short run. Klepper (1996) presented a model emphasizing differences infirm innovative capabilities and the importance of firm size in appropriating the returns from innovation is developed to explain the regularities. The model also explained regularities regarding

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the relationship within industries between firm size and firm innovative effort, innovative productivity, cost, and profitability. It predicted that over time firms devote more effort to process innovation but the number of firms and the rate and diversity of product innovation eventually wither. Fouad and Tapiero (1998) determined the optimal path of products enhancement innovation, i.e., of adding new functions (increasing flexibility) or substracting existing functions (increasing specialization) to existing products. Huisman and Kort (2003) determined the optimal timing of technology investment of a single firm in a duopoly framework. Based on the agent-based model, Ma and Nakamori (2005) developed a platform by using object-oriented programming to simulate the technological innovation process under different situations. Mantovani (2006) studied complementarity between market-enhancing product innovation and cost-reducing process innovation in a monopoly setting. Saha (2007) considered product and process R&D from the perspective of consumer preferences. The author found that the value of a process innovation depends only on the quantity sold while that of a product innovation depends also on how much buyers are willing to pay for it and hence also on who buys the product. Lara and Divakaran (2009) developed a decision model of a firm's optimal strategy for investment in security process innovations when confronted with a sequence of malicious attacks. Avagyan, Esteban-Bravo, and Vidal-Sanz (2014) presented a differential game to study how companies can simultaneously license their innovations to other firms when launching a new product. The authors considered the role of licensing to speed up the product diffusion, and fund evidence that licensing can be a potentially profitable strategy. As to the dynamic product and process innovation research, in recent works, Lambertini and Mantovani (2009) modeled the optimal behavior of a multiproduct monopolist investing both in process and in product innovation in a dynamic setting. Chenavaz (2012) developed a product–process innovation model where the problem is to determine an optimal product price, the product and process innovation investment facing a time-varying but under endogeny demand conditions. Furthermore, the author extended Chenavaz's (2011) model to different classes of demand functions and to general innovation functions.

In this paper, taking advantage of the analytical framework which is offered by Chenavaz (2012), we present a dynamic optimal control model of process–product innovation with learning by doing. Since much of our analysis concerns firm's learning by doing, the next of this paper surveys the literature on "learning by doing". Learning by doing is the result of the accumulation of knowledge generated by experience in the production process. The success of this accumulation depends critically on five factors: firstly, the type of work organization employed in production, especially the capacity of management to motivate production workers to provide feedback; secondly, establishing communication between producers and users; thirdly, it depends on the willingness of management to act on this information; fourthly, the competitive strategy of the producing firm and specifically the extent to which it competes on quality, customization to client need, design and achieving cost reductions through innovation and capital investment; finally, it depends on a wide distribution of technical competence within the producing firm's workforce and across the users of its goods and services. Learning by doing has occupied a central place within economics ever since Arrow (1962) used the concept as a workhorse in his theory of endogenous growth. Arrow (1962) conceptualized learning by doing within the actual activity of production, with cumulative gross investment as the catalyst for experience. Nearly two decades later, the role of experience in shaping and driving productivity growth was central in Lucas' (1988) explanations of increasing returns to human capital. Indeed, Lucas (1988) argued "on-the-job-training or learning by doing appear to be at least as important as schooling in the formation of human capital". Yang and Borland (1991) furthered this line of thought by theoretically linking the division of labor and learning by doing, highlighting an important source of comparative advantage. Empirical studies have confirmed the importance of learning by doing in practice. Scholars have frequently observed that improvements in the efficiency with which outputs are produced from existing technologies and inputs are an important source of total factor productivity growth. Thompson (2010) reviewed the theoretical and empirical literature on learning by doing. The theoretical literature on innovation and technical change has also confirmed the role of learning derived from experience as a key driver in knowledge accumulation leading to innovation. Nelson and Winter (1982) stressed the importance of learning by doing and learning to learn effects in innovation. From the perspective of the dynamic capabilities approach, Teece, Pisano, and Shuen (1997), Zollo and Winter (2002) pointed out the accumulation of experience as one of the learning mechanisms and built the operating routines. Alvarez and Cerda (2003) presented the analytical solution for a class of discrete time T-period learning by doing problems. Linton and Walsh (2004) considered the learning curve literature and integrate it with the literature on technological trajectories and innovation to develop a theory for modeling the learning curve for emerging process technologies. Edward and Zabojnik (2005) showed that after an initial period of learning-by-doing, the new technology makes the goods more attractive to consumers. Anticipating a better product, consumers delay their current purchases which lowers today's profits, but increases future profits since the monopolist can charge a higher price for the high-quality good. For empirical purposes, Chryssolouris, Mavrikios, Fragos, Karabatsou, and Pistiolis (2002) investigated a novel virtual experimentation approach to planning and training for manufacturing processes. Pruett and Thomas (2008) used data on the innovation and production histories of 294 product platforms to explore experience-based learning. A noted feature of the authors' paper is to extend learning curve concepts from their traditional domain – the production process – into the product innovation process to build and test a richer, quantitative model of learning. It is clear that there is a very real and urgent need for training people for the factories of the future. There have been a number of European initiatives such as 'Manufuture' and the contrasting situation with the US and Japan has been nicely summarized by Mavrikios, Papakostas, Mourtzis, and Chryssolouris (2013). Furthermore, O'Sullivan, Rolstadås, and Filos (2011) provided a number of suggestions for strategic change to research and education in manufacturing in the future. Levitt, List, and Syverson (2012) used detailed data from an assembly plant of a major auto producer to investigate the learning by doing process. The authors focused on the acquisition, aggregation, transmission, and embodiment of the knowledge stock built through learning. They found that most of the substantial learning by doing knowledge at the plant was not retained by the plant's workers, even though they were an important conduit for knowledge acquisition. Hatch and Mowery (1998) analyzed the relationship between process innovation and learning by doing in the semiconductor industry where improvements in manufacturing yield are a catalyst for dynamic cost reductions.

The main contribution of this paper is twofold. First, we extend the model of Chenavaz (2012) to an even more general model in which learning by doing is taken into account. In Chenavaz's (2012) model, the firm's cost functions of product and process innovation only depend on the instantaneous investments. In this paper, the firm's cost functions of product and process innovation depend on both the instantaneous investments and the knowledge accumulations of the product and process innovation. This assumption relies on the simple analogy that patent protection generally applies to knowledge accumulations (R&D accumulations) outcomes rather than instantaneous efforts. A similar interpretation is found in Cellini and Lambertini's (2009) work, where a firm's R&D investments seek to accumulate cost reductions. Second, in our paper, the product price, product and process innovation investments are the decision