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Decision Support

Opening the technological innovation black box: The case of the electronics industry in Korea

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ABSTRACT

In this system dynamics simulation study we analyze a series of feedback causal relationships wherein R&D investments create new knowledge stocks, increasing technological knowledge "triggers" and interactions among entities of technological innovation, leading to firm profits through the commercialization process.

Major aspects of this study are: First, we provide a holistic modeling approach to technological innovation in order to explicate the *hidden* causal relationships underlying innovation and the mechanisms which lead to innovative performance. Second, hypotheses pertaining to process and product innovation are tested utilizing the system dynamics model to open the black box of technological innovation incorporating *long-term* and *dynamic* perspectives.

This study addresses *strategic innovation policies* vis-a-vis product complexity and suggests that a new paradigm wherein product and process innovations are pursued concurrently instead of sequentially can ensure a firm's sustainable growth.

1. Introduction

In a knowledge-based economy, technological innovation is pursued by firms as a major strategy for continued business growth. With increasing competition among firms due to globalization of markets and shortening product lifecycles, innovative new product development (NPD) has emerged as an important and essential element of increasing a firm's competitiveness (Salomon, Weise, & Gemunden, 2007). If a firm is to have competitive advantage in a rapidly changing market environment, technological innovation is essential; a precise understanding of the dynamic feedback structure by which R&D investments are translated into financial performance through technological innovation is a prerequisite for pursuing such a strategy (Ettlie, 1998; Utterback & Abernathy, 1975).

However, most of current models in the literature do not adequately explain what is referred to as the '*black box of technological innovation*' in an environment of rapidly changing technological evolution (Coombs & Bierly, 2006; Koellinger, 2008). The standard methodologies for the analysis of technological innovation are based on the correlation between a set of independent variables or influences and the steady state of the system. This modeling approach may be valid in technological innovations where technology change exhibits a smooth pattern over long product lifecycles and a low coefficient of variation. There is, however, an increasingly important family of innovative products with shorter new product lifecycles and larger technology variability for which the traditional linear and static methodologies may lead to incorrect conclusions (Kline & Rosenberg, 1986; Samara, Georgiadis, & Bakouros, 2012). Unlike before, the multifarious pathways by which technological innovation affects firm performance have become more complicated and uncertain. This makes it difficult to comprehend the multidimensional and complex nature of the interaction between technological capability and firm performance.

There are a series of system dynamics (SD) papers in the literature that employ similar SD structures for technological innovation and derive either more specialized results or offer more generalizable views of Abernathy and Utterback's 'dynamic model of product and process innovation' hypotheses (Maier, 1999; Milling & Stumpfe, 2000). However, these studies are less applicable to the rapidly changing, current technological innovation strategies

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linking R&D investment, technological innovation, and financial performance.

This paper proposes and analyzes a different series of feedback relationships from technological innovation to financial value creation based on information from the digital IT division of a global electronics firm in Korea (Kim & Choi, 2009). Further, this study is an attempt to carry out this unexplored avenue of research on technological innovation by building a system dynamics (SD) model to explain the hidden '*black box of technological innovation*' under conditions of rapid technological evolution.

The research issues of interest in this study are: (1) How should a firm choose between product innovation that is innovativeness-focused and process innovation that is efficiency-focused? Can they be pursued simultaneously? (2) Given the importance of releasing innovative new products in response to customer demands and shortened product lifecycles, how does product complexity affect the performance of a firm that seeks to be the '*first mover*' through innovative products? And, (3) since technological innovation is achieved by means of feedback relationships between product and process innovations, in a situation where market demands for innovative products are steadily increasing, how do trade-off relationships between product and process innovation change over time?

Since technological innovation process is highly fluid and dynamic, technological innovation needs unique prescriptions and strategies that fit well with the rapidly changing business environment (Danneels, 2002; Kline & Rosenberg, 1986). Therefore, it is important to examine the dynamic feedback processes that underpin the effects of technological innovation strategies on firm performance. This research offers four main contributions:

- We extend previous studies by modeling the system dynamics to uncover the hidden *black box* relating technological innovation to performance.
- We demonstrate that investments in product innovation rather than process innovation maximize a firm's profits in the long run.
- We demonstrate that product portfolio complexity is a constraint on new product introduction; however, manufacturing process innovation is a facilitating factor for achieving time to market objective.
- Our results suggest that in an environment of short product and process life cycles, product and process innovation should be pursued simultaneously, *not sequentially*.

In the next section, we review the literature on dynamics of technological innovation and develop the causal loop diagram (CLD) for the innovation process. Section 3 describes the SD methodology. Section 4 presents the analyses and results of simulation runs, and Section 5 discusses the implications of the results and offers suggestions for future research.

2. Theoretical model

Our model is based on the chain-link hypothesis of Garcia, Calantone, and Levine (2003), Kline and Rosenberg (1986); the dynamic model of product and process innovation due to Taylor and Taylor (2012), Utterback and Abernathy (1975); system thinking on innovation process of Galanakis (2006), and the national innovation system dynamics model of Samara et al. (2012). The model of the dynamics of technological innovation presented in this study is designed to assess the complicated dynamic process of interactions between technological innovation and firm performance.

2.1. Technological innovation and firm performance

A review of the relationships between R&D as a means of knowledge creation and financial performance indicates that scientific technological knowledge and interdepartmental or intradepartmental innovations are utilized by firms to create existing and new markets. As R&D investments increase, R&D knowledge related to new products is accumulated, resulting in enhanced market performance through innovative new products (Ford & Sterman, 1998; Garcia et al., 2003; Murmann & Frenken, 2006; Yeh, Chu, Sher, & Chiu, 2010). This can be viewed as a *direct effect* of R&D investment on performance.

In contrast, accumulated knowledge of manufacturing process and technological advancement resulting from it causes *indirect effects* by reducing production costs by enhancing efficiency of labor and capital. While explaining accumulative relationships of cause and effect between technology and corporate growth, Mozier and Towler (2004) argue that increased R&D budgets raise R&D resources, through which technological knowledge is accumulated, and accumulated knowledge, in turn, increases a firm's profits. A review of the literature elucidating the relationships between R&D and profit leads to the conclusion that, in general, increased R&D investments or technological innovation leads to increased level of R&D concentration, which, in turn, positively affects revenue and growth. The review also suggests that it can negatively affect business profit and growth in the short term since there is a considerable time lag before technological knowledge and innovation is incorporated into innovative products or manufacturing processes (Coad & Rao, 2008; Hagspiel, Huisman, & Nunes, 2015). Therefore, R&D or technological innovation has a dual effect.

Utterback and Abernathy (1975) and Taylor and Taylor (2012) show that firms are spurred to introduce innovative products to be responsive to customer needs. During what the authors refer to as the *fluid* phase, a period for introduction of new technological paradigms, product innovation occurs extremely rapidly, largely by relying on new product traits. Radical innovation which is a fundamental change, representing a shift in existing technological systems, is made largely by discontinuous technological initiatives based on knowledge stocks accumulated through R&D investments. Differentiation and diversity of accumulated knowledge pertaining to product innovation through R&D investments and the variety of new products created through specific product innovations enhance the technological standing of new products in the market; the level of consumer attraction to the product, thus, increases product purchases during the commercialization phase. Expansion of investments in new product development (NPD) along with accumulation of product innovation leads to increases in the number of NPD projects (Godener & Söderquist, 2004; Sheng, Zhou, & Lessassy, 2013), and the increase in NPD projects accelerates introduction of new products, thereby increasing the firm's profit. Increased total profits arising from increased sales are linked back to reinvestments in R&D (see feedback relationships depicted in *R1 and R3 Loops* in Fig. 1).

A firm in a competitive situation seeks to enhance its competitiveness in two ways. First, firms seek to enhance competitiveness by upgrading quality and functionality of products, which is a form of product innovation arising from R&D (Sterman, 2000; Yeh et al., 2010). Second, firms seek to minimize costs through process innovation aimed at maximizing efficiency of resources employed in production. R&D investments in process innovation and the ensuing accumulation of knowledge about manufacturing process serve as a factor accelerating process innovation (Repenning & Sterman, 2001). As process innovation increases, average unit production costs are reduced and increased profits lead to R&D investments for process innovation (see *R2 Loop* in Fig. 1 that captures these relationships).

A firm's R&D investment *portfolio* can be viewed in terms of product and process innovation investments (Huisman & Kort, 2003). Based on the arguments presented, this study analyzes changes in the investment portfolio comprised of product innovation and process innovations and how these changes affect the firm's total profit through the causal relationships depicted in Fig. 1. As discussed previously, product innovations can have a direct effect on performance by enhancing the competitiveness of the firm and through positive

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