From R&D to Commercialization : A System Dynamic Approach

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Abstract

This paper describes a comprehensive approach to examine how technological innovation contributes to the renewal of a firm's competences through its dynamic and reciprocal relationship with R&D and product commercialization. Three theories of technology and innovation (the R&D and technological knowledge concept, product-process concept, technological interdependence concept) are used to relate technology and innovation to strategic management.

Based on these theories, this paper attempts to identify the dynamic relationship between product innovation and process innovation using system dynamics by investigating that aspect of the dynamic changes in the closed feedback circulation structure in which R&D investments drive the accumulation of technological knowledge.

Further, such knowledge accumulation actualizes product innovation and process innovation, subsequently resulting in an increase in productivity, customer satisfaction, profit generation, and.

1. Introduction

Research and development (R&D) activities have revealed that technological innovation and the diffusion of new technology are influencing the productivity of firms and customer satisfaction; therefore, the measurement of the new technology has become a crucial decision for business activities. Different innovation characteristic for each industry and the correlation between innovation and the firm's performance is also considered to be a key business activity. In order for a company to manage its business mission and pursue the right policy,

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it has to recognize the characteristics of technological innovation, namely, the dynamic processes that impact each innovation and the economical and political factors that influence technological innovation.

Technological change and business management have a close and mutually reciprocal relationship. Resource allocation R&D over a period of time changes the technological level, stimulates the proliferation of new products, and influences all related industries. Further, business profits from the sale of new products or new services are reinvested in R&D activities.

According to Kline and Rosenberg (1986), pursuing the growth of a business entity through technological innovation is effectively an incentive for R&D activities, this motivates innovation in other new technologies. Accordingly, the starting point of technological change is the investment in R&D activities. The company that attained technological innovation through R&D activities will have a price advantage due to its improved technological productivity, and this in turn will increase its market share. Then, the profit gained by the dominant market power would be reinvested in furthering technological innovation, thus resulting in the same process being repeated again. Thus, technological innovation has a circular causal relations such as the following: "investment in R&D → accumulation of technological knowledge → product innovation → process innovation → new product and service production → profits maximization → reinvestment in R&D activities." It is impossible to explain the technological innovation process on the basis of the simple linear relationship shown above. Therefore, it becomes necessary to understand the complicated closed feedback loop circulation within variables in order to understand the technology innovation process. The existing papers that deal with technological innovation have conducted a data analysis of R&D investment; this analysis provides optimized coefficients or establishes major variables that influence the capital/labor productivities throughout the correlation analysis. However, the connectivity and dependency between variables in the technological innovation systems are explained to a limited extent in these papers because they have employed a static and partial approach and the explanation provided is from the short-term perspective.

Unlike the existing papers, which are characterized by discrete and linear thinking, this paper will introduce the system dynamics (SD) methodology; this methodology is based on dynamic and systematic thinking emphasized on an internal feedback loop process and deals with the causal relations between the dynamic behavioral analysis and multi-variables. Further, this paper indicates the decision support tools that can forecast the long-term perspective. These tools will be used from the overall point of view, which optimistically supports decision-making while integrating individual loops within each cognitive model of the technological innovation process.

The objective of this paper is to examine the dynamic circulation relationship within the entire process from R&D investment to technological innovation throughout the accumulated knowledge, particularly in regard to product and process innovation that generates the profits that would be reinvested in R&D. Further, this paper examines the correlation between the existing theories and a firm's performance by analyzing and re-evaluating the prevailing technology innovation process and subsequently complementing the limitations. For this purpose, it uses the SD simulation approach to empirically analyze the dynamic technological innovation theory and to review the dynamic process of technological innovation. This paper also proposes a suggestion to optimize profit generation by controlling the parameters of policy variables in the dynamic technological innovation model.

In this paper, the characteristics of the technological innovation that is required while each step of the innovation process moves to the next phase will be analyzed and reviewed. Since the technological innovation process is very dynamic and fluid, it requires a unique prescription and strategy due to the rapid changes in the business environment and time strategies. As technological innovation is presumed to be a dynamic and esoteric system, reviewing the technological innovation strategy is important for analyzing the interaction of the internal technology capacity of technological change. In other words, the effectiveness and efficiency of technological innovation will be analyzed and re-evaluated by considering the interactions of the R&D investment that reflect the technology capacity of technological change, new product development (NPD), and the manufacture of a product.

2. Literature Review of the Technological Innovation Process

2.1 R&D Investment and Knowledge Accumulation of Technological Innovation

R&D investment is one of the crucial factors in the production process; it includes human and material resources along with information and knowledge. This R&D investment process includes not only certain specific techniques utilized in the production process but also scientific knowledge such as a diverse range of experience and technical know-how that is achieved due to R&D activities (Utterback, 1994, Utterback and Abernathy, 1975). Kline and Rosenberg (1986) explained knowledge accumulation achieved through R&D investment and also defined knowledge accumulation as being derived from two aspects-R&D investment as the flow and technological knowledge as the stock. R&D investment is the key activity that creates technical know-how, and an organization can increase the amount of knowledge accumulation through this R&D activity (Klein and Rosenberg 1996). In other words, technical know-how is a very extensive concept that includes knowledge and skill needed for acquiring, assimilating, applying, modifying, altering, and creating technologies. From among all these activities, systematic R&D activity is a critical factor for knowledge production. In addition, the scale of innovative investment would therefore depend not only on the size of the investment in production resources and in the abilities and incentives of learners but also on the duration of the investment necessary to sustain this process for the duration of the period over which learning occurs.

Stamboulis, Adamides, and Malakis (2002) asserted that R&D investments increase the R&D intensity and the accumulated R&D capability that would be the driving factor to make technological innovation possible (Teece, Pisano and Shuen 1997). R&D activity is a conscious activity that is linked to innovation by knowledge accumulation through a preliminary learning; further, technical know-how includes not only engineering know-how but also knowledge of the organization structure, NPD process, and even the behavioral patterns of customers. Thus, technical know-how increases the product quality level, leads to the invention of a new product that could correspond to the consuming type, and specifies a new manufacturing process in order to strengthen the competitiveness. Griliches (1998) proved that the technical capability and potentiality of a company is not determined by temporary knowledge creation activity such as R&D but by how much knowledge has been accumulated by the company (Branch 1974, Griliches 1998). In other words, technical innovation is most likely to result from the knowledge accumulated based on a company's past technological experience. Incidentally, while formulating knowledge accumulation, a certain time delay has to be considered because a time gap exists between the R&D process and the actual commercialization process. As is the case with the capital stock, since R&D activity progresses with the passage of time, the value of the existing R&D knowledge and experience could be obsolescent.

2.2 Technological Innovation and Interrelation Between Product and Process Innovation

Technological innovation is the outcome of a dynamic, continuous process, which is composed of a sequence of actions that take place over a certain period of time. In other words, things do not occur statically over a specified duration of time, they occur dynamically with the lapse of time. Utterback and Abernathy (1975) insisted that technological innovation is the continuity of product innovation and process innovation. Further, R&D processes that give rise to technological innovation also follow a continuous process, namely, basic research → applied research → NPD → commercialization (Utterback and Abernathy, 1975).

Technological innovation is the combined result of two different forms: product innovation and process innovation. Product innovation pertains to a company's efforts in the development of new products or the improvement of the property, functionality, and quality of an existing product. In other words, technologically, new product innovation not only implies the creation of a new market based on related core technology through increasing quality and productivity but also includes the establishment of a company as a competitive power within the market (OECD, 1997).

Process innovation entails a company's efforts to enhance the process method for improving productivity and quality and reducing costs by understanding how to optimize the production process (Ashey and Schmutzler, 1995). In particular, the company could affect the economies of scale by cutting costs with the increase in the volume of products. Process innovation is particularly related to the production process; its objective is to increase the efficiency and quality level or to cut down on intermediate costs such as raw materials, energy, and maintenance.

Table 1. Literature review of dynamic technology innovation

Management of technology innovation	Industry Dynamics	Abernathy, William J. and Kim Clark (1985), Arthur, W. B. (1988), Carroll, G., and Hannan, M. (2000), Geroski, P. A. (2001), Hall(1994), Klepper, S. (1997), Pavitt, Keith. (1984), Tushman, Michael L. and Philip Anderson (1986), Walsh, Vivien (1984)
	Diffusion of Technologies	Bresnahan, T. and M. Trajtenberg (1995), David, Paul (1990), Griliches, Z. (1998), Kline and Rosenberg(1986), Nelson, R. R. and Phelps, E. S., (1966), Rogers, Everett M. (1983)
Organizational capacity or capability of technology innovation	R&D Intensity → Organizational Innovation -Knowledge Level	Armelle Godener and Klas Eric Soderquist (2004), Boer (1999), Jaffe, A. B., M. Trajtenberg, *et al*. (2000), Griliches, Z. (1998), Jonathan D. Moizer and Mike J. Towler(2001), Kogut, Bruce, and Udo Zander. (1992), Nonaka, I. (1994), Pisano, Gary. (1996), Tyre, M. J. and E. von Hippel (1997), Van de Ven, Andrew H., and Douglas Polley. (1992)
Innovation Process	Organizational Innovation -Knowledge Level → Product Innovation or Process Innovation	Alden S. Bean, Alexander, Christopher. (1964), Baldwin, Carliss, and Kim Clark. (2000), Clark, Kim B. (1985), Fariborz Damanpour and Shanthi Gopalakrishnan (1997), Keith Linard and Lubomir Dvorsky (2001), Meyer, Marc, and Arthur DeTore. (1999), Meyer, Marc (1996), Peter Tertzakian, and James Utterback. (1997), Nelson P. Repenning and John D. Sterman (1998), Pisano, Gary. (1996), Robert G. Cooper and Elko J. Kleinschmidt (1998), Rosenberg and Kline (1986), Simon, Herbert A. (1981), Ulrich, Karl. (1995), Utterback and Abernathy (1978), Wheelwright, S. C. and K. B. Clark (1992), Yeoryios A. Stamboulis, Emmanuel D. Adamides and Thomas E. Malakis (2000)
	Independency of Product and Process Innovation	John E. Ettlie and Ernesto M. Reza (1998), Peter M. Milling and Joachim Stumpfe(2000), Suresh Kotha and Daniel Orne (1988), Kim, Ritzman, Benton and Synder (1992), John E. Ettlie (1998), Stamboulis, Adamides and Malakis (2002), Steven D. Eppinger, Paul S. Adler (1999), Kotha and Orne (1989)
	Product or Process Innovation) → Commercialization	Marvin L. Patterson (1985), Andreas Glöβler (1996),Rafael Llorca Vivero (1997), Frank H. Maier (1998), Craig W. Kirkwood (1999), Andreas Glöβler and Peter M. Milling (2000), Peter M. Milling, Jőrn-Henrik Thun (2001), Nile W. Hatch and David C. Mowery(2002)

The key point of the technological innovation process is how to design the process within the knowledge system of each functional NPD project and information flow. Boer (1999) defined the R&D process to begin with basic research; this would then be linked to applied research, and finally, development, production, and sales activity would be followed by the achievement of this R&D process (Boer, 1999). Each functional division, such as R&D, production, and sales, would be specialized to optimize the effectiveness and efficiency of each division itself. This is one of the sequential phases within the whole process.

Kline and Rosenberg (1986) designed a very useful model of innovation called “the chain-linked model”; this model emphasizes continuous feedback and the influence of knowledge throughout the innovation process. This model explains the relation between basic research and the innovative firm, as it is a duplicated process that includes feedback from various directions. This indicates that the information flow between each division has an interactive relationship rather than a one-way direction. For example, technical know-how and knowledge, which are achieved through R&D activities, are transmitted to the production activities; however, problems arising in the production and sales activities also simultaneously contribute to the rapid increase in the R&D activities.

3. Research Model and Methodology

Since technological innovation is based on technology, understanding the attributes of technological changes becomes a critical domain of technological innovation. Thus far, research on technological innovation was conducted in the framework of defining its characteristics, appearance, and pattern. Recently, there was a remarkable increase in studies in which the “system approach” concept was introduced to technological change in order to create an understanding of this subject.

This study analyzes the changing pattern of technological innovation by using SD Simulation. SD is a framework that can substitute the existing manner of static and linear thinking with holistic and dynamic thinking. Dynamic thinking is believed to explain the behavioral pattern of problems as a lapse of time rather than to detect the cause of the problem for a specific time. Because technological changes occur continuously, from the long-term perspective, it is impossible to evaluate the technological change at a specified point. Thus, the analysis considers behavioral patterns as time strategies rather than focusing on a particular event at a certain point in time.

3.1 Research Model and Hypothesis

The model of dynamic technological innovation considered in this paper is based on Utterback and Abernathy's hypothesis of product and process innovation along with the chain-linked model of Kline and Rosenberg and OECD (Klein and Rosenberg, 1996, OECD, 1997, Utterback and Abernathy, 1975). This model is employed to evaluate the dynamic flow of technological innovation, which tends to be a complicated aspect. Technological innovation is achieved through the internal exchange of mutual feedback between each diverse division within the firm. Technological innovation also progresses because of the articulated relations with the R&D department and the manufacturing process organization.

3.2 Relationship Between R&D Investment and the Time of R&D

Examining the interrelation between the R&D organization that is subjected to knowledge creation and its business entity at this stage, a firm's internal innovative process and a fundamental knowledge of technology and R&D are interconnected in order to capitalize on the potential of new markets through the development of a knowledge base of science and technology (Branch, 1974, Rosanna and Calantone, 2002). If a company invests in R&D, the R&D knowledge stock would get accumulated, thereby leading to technological innovation or incremental improvements in productivity that would be linked to the firm's economic growth. Knowledge accumulation directly leads to the firm's economic growth with respect to capital/labor productivity and technological progress. On the other hand, the knowledge stock and technological innovation through human and material resources indirectly affect its efficiency (Grabowski and Mueller, 1978). Branch (1974) confirmed this interactive causal relationship by using the number of patents held by the firm as its success criteria and by ascertaining whether successful R&D investment would raise the sales and profits or whether increasing the sales and profits would result in additional reinvestment in R&D (Branch, 1974). His research concluded that successful investment in R&D would cause exponential growth of the sales and profits. Grabowski (1978) also concluded that successful investment in R&D would strengthen the market controllability by technological innovation that would increase the sales and profits, thereby resulting in a reinvestment in R&D. Assuming that R&D investment is one of the elements of market activities, an analysis of the structure-action-performance paradigm of Carlton and Perloff (1990) reveals that technological innovation leads to knowledge accumulation as well as new product and process renewal. This paper arrived at the conclusion that R&D investment is the means by which the productivities, sales, and profits of a firm can be increased. Lundvall (2002) explains the accumulated causal relationship between technology and the economic growth of a firm. He insisted that R&D and technological innovation lead to growth through the capital accumulation caused by raising the technological capability; further, the growth of capital also becomes a resource for the investment in R&D as incentives (Lundvall, 2002). The study of Moizer and Towler (2004) demonstrated that the accumulated knowledge would generate profits. For example, increasing the budget for R&D investment would lead to increased R&D activities, thereby affecting the accumulation of technological knowledge, which would finally influence the profit (Moizer and Towler, 2004).

Considering the existing studies that have examined the relationship between R&D investment and a firm's profitability, raising the investment in R&D or technological innovation generally has positive effects on the firm's economic growth and profitability (Ettlie 1995). However, it is still not clear how companies could optimize their investment policy on R&D and which investment process they should follow for maintaining optimal investment decision-making (Hansen, Malcolm and Kwak, 1999). Arguments on allocating investment resources continue to be raised. For example, how much of the investment resources should a company allocate between product innovation and process innovation for profit maximization? Therefore, this paper examines the profit structure of a firm that depends on the changes in the R&D investment portfolio under the following hypothesis.

There exists an inevitable time delay between the allocation of inputs toward R&D investment and the generation of profits. A new knowledge stock, which is the outcome of the R&D investment, is embodied in a new product or new facilities and equipment after a certain time lapse (Branch, 1974, Pakes, 1984). Branch (1974) examined the time gap between R&D investments, knowledge patents achievement, and profitability. His research analyzed how the number of patents held by a firm affects its profitability by using the theory that R&D investment and a firm's economic profit positively affect each other. This study concluded that there is a relationship between the number of patents, which is substituted for the R&D activities, and the firm's profitability within a time gap. Pakes and Schankerman (1984) investigated the time gap between the R&D investment and the number of patents over a period of five years. Pakes and Griliches (1984) presented the relationship between R&D investment and knowledge accumulation through the "knowledge production function." In their study, patents were used as a substitution variable for the increased knowledge, and by using the "time-lag distribute model" and assuming that R&D investment yields in the form of patents, the knowledge production function is generated. This research showed that for the time being, R&D investment is negatively affected with regard to the firm's net profits; however, by analyzing this using the time-lag analysis model, R&D investment is generally positively affected after 1 or 2 years. Further, it takes a certain amount of time before R&D investment influences the firm's economic growth and profitability. Therefore, in order to analyze this relationship clearly, a time lag should be considered.

To summarize the abovementioned researches, there is a time lag between the inputs toward R&D investment for creating innovative knowledge and a firm's economic performance (Hartmann, 2003). Although the time lag is generally approved, there is no common opinion about the optimal point of investment and the investment portfolio for optimizing the firm's economic profitability. Thus, this paper will quantify the time lag of R&D investment in terms of its effect on the profitability of a firm and will also ascertain the interrelation between the time lag of R&D investment and the firms' profitability in the following hypothesis.

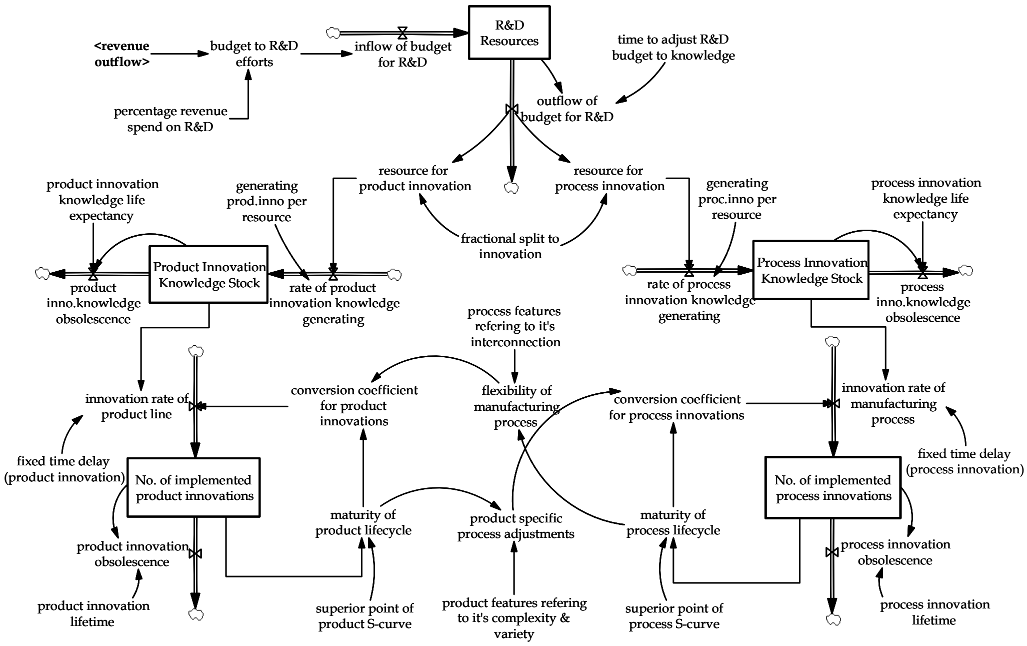

Figure 1. A SD model of Relationship between R&D investment and the time gap of R&D

3.3 Relationship Between Technology Innovation and the Product Development Period

In order to find out the dynamic pattern of technological innovation, the interrelationship between product innovation and process innovation in the innovative cycle has to be understood first. Utterback and Abernathy (1975) analyzed product innovation in terms of their production-process life cycle model. In a period called the "fluid phase," customer's needs, which always vary, and new features and functionalities of products lead technological innovation, such that a great deal of experimentation with product design and the operational characteristics for its product innovation take place among competitors (Utterback and Abernathy, 1975). Since the radical innovation means that fundamental changes which existent technology systems converting to another, most likely, radical innovation is driven by systematic R&D activities of its companies along with uncertainty and technological discontinuities, based on knowledge stock through increasing R&D investment. The differentiation and variety of new products achieved through knowledge accumulation for product innovation enhances the technological level of the firm. Further, this leads to an increase in the customers' needs for new products, which would serve to increase the possibility of actual sales in the commercializa-

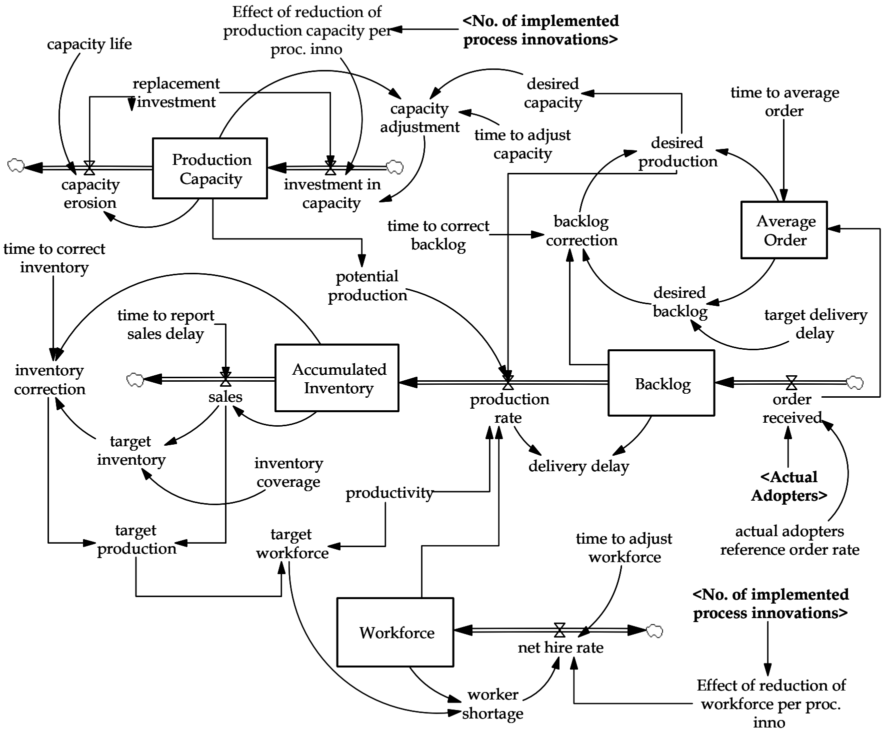

Figure 2. A SD model of Relationship between Process Innovation and the Productivity

tion stage. The profits gained by an increase in the sales would be reinvested in R&D activities. Moreover, increasing the investment in NPD projects along with knowledge accumulation for product innovation would also augment the initiatives of the NPD projects (Eppinger, 2002, Rothwell, 1992). Therefore, increasing the firm's investments in NPD projects and expanding the production capacity of new products would contribute to the firm's economic profits by accelerating the production of new products. As the life cycle of a new product is shortened in the market, the company is pressurized to develop new products in a short period of time in order to maximize profits (Ford and Sterman, 1998). Accordingly, time risk for the development of a new product increases, and delaying the NPD affects the firm's profits considerably. Therefore, in theoretical terms, the company should recognize the maximum point of the "product S-curve"; the S-curve begins from the inflection point of the logistics regression curve in technological innovation. In other words, the company should realize the current technological position of the firm in the S-curve of the product life cycle from time to time (Christensen, 1994). Further, the market always requests shortening the durations of the NPD regardless of the NPD cycle (Meyer and Utterback, 1995). The rapidity of NPD becomes a critical factor for the company's competitive power in the markets due to intensified competition; therefore, customers prefer to have new products. In order to develop more products within a short period, diverse resources for NPD should be increased. However, increasing resources would raise the complexity of the product design and hinder the standard of the NPD process, thereby resulting in poor productivity and profitability. Thus, manufacturing companies should devise ways of shortening the life cycle of product innovation along with profit maximization.

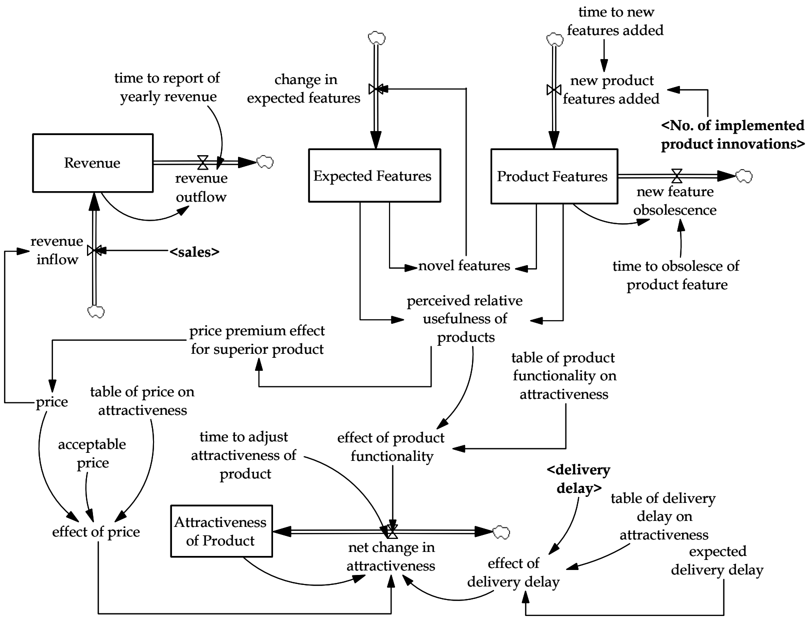

Figure 3. A SD model of Relationship between Product Innovation and the Attractiveness of Product

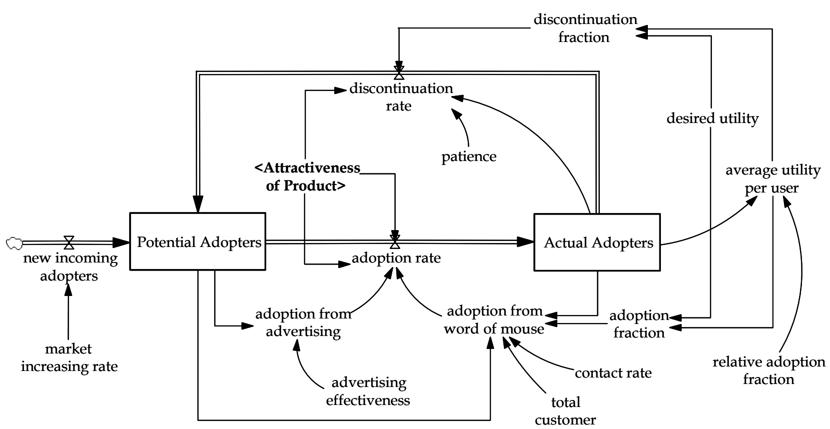

Figure 4. A SD model of Adoption process of Technological Product

3.4 Inter-adjusting the Relationship Between Product Innovation and Process Innovation

Increased technological levels through product innovation in the fluid phase increase the pressures for the standardization of services and products based on the emerging dominant design. This reduces the desire for new product innovation, thereby decreasing rapid innovation; however, the desire for partial and incremental innovation increases. There is a negative feedback relationship, which shifts the entire loop system of product innovation to a certain target level. With the passage of time, the negative feedback loop tends to stabilize at a certain level of objectives. At the fluid phase that is characterized by the rapidity of product innovation, innovation of the production process is not very important, and therefore, the process innovation tends to be low in this phase. Accordingly, at this stage, the firm maintains a flexible but low-efficiency manufacturing process that easily accepts substantial changes in the process by the general-purpose facilities and expertise (Utterback and Abernathy, 1975). The period of fluidity, according to the Utterback-Abernathy model, typically gives way to a “transitional phase” in which the rate of major product innovation slows down and the rate of major process innovations accelerates. At this point, product variety begins to give way to standard designs that have either proven themselves in the marketplace as the best form for satisfying customer needs or designs that have been dictated by accepted standards. When the product innovation reaches the maturity stage within the innovation cycle, there is disagreement with the existing production process as the new product is standardized such that there needs to be a change in the production process. Accordingly, product-specific process adjustment occurs continuously as the product innovation is in progress (Ettlie, 1995, Stumpfe, 2001). Process adjustment is one of the factors that induce process innovation. However, as a result of product innovation, the variety and complexity of new products hinder process standardization, thereby affecting the rate of process innovation negatively. In other words, the complexity of the product design induces an excessive investment in the initial process for mass production; further, the specializing production system that is not possible to be controlled by the existing facilities needs to be organized. Therefore, process innovation reduces as if the technical solution of the process could not be found with regard to new ideas that could be differentiated by the complexity specification (Kim, Ritzman, Benton and Synder, 1992).

On the other hand, investment in process innovation and accumulated knowledge on the production process is another factor that accelerates process innovation. With process innovation, the company that produces homogeneous products reduces its average production unit cost with enhancing labor and capital productivity. The average production unit cost is lowered by automating the process in the production division, thereby enabling the company to provide more products or services to customers at a lower marginal cost (Ettlie, 1995). Low prices strengthen the competitiveness of the manufacturing company, making it attractive to the customers and which, in turn, leads to increasing sales. The firm's profits from the increasing sales would then be reinvested in R&D.

The productivity that reached the maturity phase in the process life cycle during the adjustment of product innovation and accumulated knowledge on process innovation tends to impede new changes because of the specific-purpose facility and automation of the production process. It reduces the pressure for change in the manufacturing process and diminishes the rate of process innovation. The latter gradually decreases because the need for process rationalization, which is one of the factors that induce process innovation, is reduced (Teece, Pisano and shuen, 1997). This proves that as the related processes, namely, the relationship between the innovation process and the production process, reach a certain period in time, the negative feedback relationship between the two processes is maintained, which serves to reduce the rate of process innovation. Similar to the manner in which product innovation was negatively affected by process innovation, increasing process innovation reduces product innovation as per the constraint condition (Kim *et al.*, 1992). When process innovation reaches the maturity phase on the process S-curve, it affects product selection due to a lack of flexibility in the production process. In other words, in the maturity phase of the process life cycle, the production process will be fixed because process changes involve high costs; therefore, a specific-purpose facility and an automated production process are maintained. Accordingly, a company tends to produce within its existing capacity, such that the need for product change is reduced. With regard to the production process, the disagreement in the process interconnectivity increases, and the rate of product innovation decreases. As the attempts at process adjustment aimed at stabilizing the production process increase, the rate of product innovation reduces, and finally, this leads to a decrease in product innovation (Maier, 1999). On the whole, there is a negative feedback relationship between product innovation and process innovation such that the equilibrium of technological innovation is maintained.

There exist some fields of business that even reach the "specific phases", in which the rate of major innovation dwindles for both the product and the process. These companies become extremely focused on cost, volume, and capacity; therefore, product and process innovation occur in small, incremental steps. Since innovation in this period produces undifferentiated and stanproducts, these companies focus on continuous improvement in productivity and gradual quality improvement (Utterback and Abernathy, 1975).

4. Simulation Analysis

Innovations in the product system as well as the manufacturing processes are essential for industrial companies. Based on technological facts, there is a close relationship between technical products and the processes implemented to generate these products. Innovation management has to consider the dynamics of the underlying product and process interactions, and the resulting constraints in the coherent implementation of the different types of innovation. An SD-based approach that encompasses the essential underlying cause and effect relationships provides suitable support for understanding and managing the complexity and the inherent dynamics of the industrial innovation process. The SD model developed here links the cycle of product innovation to the innovation cycle of the related manufacturing process and enables the analysis of the dynamic consequences of different activities in innovation management. This paper uses the SD model to analyze the dynamics of technological innovation. In other words, it used the long-term and holistic decision-making to replace the existing studies, which are limited in that they explain only the partial and static aspect. Accordingly, system thinking based on system dynamic analysis substitutes for linear thinking. System thinking is based on the fact that the importance of the dominant feedback loop changes relatively depending on the time and conditions, thus, it does not solve the problem statically but tries to understand the problem with a dynamic relationship through continuous interaction continuously. Accordingly, the SD methodology focuses on dynamic behavior analysis, which supports decision-making for the resource allocation of technological innovation. Based on the resource allocating behavioral change for technological innovation, this paper discovers the changes and improvement in various aspects of the entire system over the time lag. Furthermore, throughout this dynamic SD analysis, this study provides meaningful information to technological policy operators by selecting an investment portfolio and controllable variables for optimizing the firm's profits.

The dynamic technological innovation model, which is based on a cause and effect relationship, needs a simulating test of the present and future decision-making performance. For this reason, the model can be simulated as shown in Figure 2, this is the conceptual dynamic technological innovation model, as modeled in Figure 3. In general, the firm appropriates the budgets for R&D investment according to the R&D intensity based on the accumulated profits. For example, one of the electronic companies in Korea earmarks a 6.8% average over the total sales for its R&D budget. The company increases the R&D resources, such as human and material resources, with the allotted budget, which could lead to technological innovation. R&D resources would be divided in a fractional split into product innovation and process innovation, thereby raising the innovative knowledge stock that would lead to product and process innovation. The current impact index of the patents, which is the number of patents for the quantitative index and the number of patents on a practical new device, can be used to substitute for the knowledge stock of R&D. To analogize the generated knowledge per resource, we analyze the data for the relevant company with figuring the number of the patents registered, and it is used as the substitution for the breakthrough probability of R&D knowledge toward patent. This paper focuses on the transition process from technological knowledge to product and process innovation without considering the possibility of the technology license sales. With the passage of time, knowledge obsolescence with respect to the knowledge stock that is accumulated through R&D in the past is no longer useful. This paper computes the knowledge life expectancy for the company under consideration based on the technology life cycle and the duration of the technology knowledge stock of related industries. In order to compute the knowledge life expectancy, the R&D knowledge stock needs to be calculated for the starting year in advance.

If the company arrives at the conclusion that it can recognize the demand of customers and if it possesses the technology to meet their needs, then it generates a specific innovation to produce new products for meeting the market requirements. Unlike the existing product, product innovation creates a new channel for a new potential market, thereby increasing the sales along with the profits by inventing differentiated new products with respect to features, quality, and function. In the case of one of the electronic companies in Korea, the NPD project was lead by the effect of the NPD project accelerator on the customers' needs and innovative knowledge in the market; further, they undertook the NPD project with an average budget of 37.2% depending on their sales. The NPD project was assumed to take place once every three months, covering a total simulation period of 60 months and following the pattern of the "PULSE TRAIN" function in the SD equation. Although it is preferable to calculate the budget rate of the accumulated profits for the multi-years between the time the product was released to the time it was discontinued for better accuracy, this paper computed the profit of the project for a new product for only one fiscal year due to difficulties in the follow up of multi-year profits. Typically, it takes approximately 5.6 months to complete the NPD project; therefore, this paper has set up the completed lead-time of the project by considering the effect of the diminished completed time of the NPD project following the product's life cycle. The new product, which was developed through the NPD project, reaches the production process stage for mass production and finally goes on to the market after the production stage. At the production stage, the average unit cost of production is reduced because of the effect of process innovation. The new products are sold in the market on the basis of the commercial product sales ratio, and the profits are calculated by multiplying the average sales price per new product. The design specification and the product prototype are accomplished with product innovation, after which the highest point of the product S-curve is reached. From this point, the process moves down to the production stage, and the existing manufacturing facilities would be modified because there are many technical limitations in the designs of the molds and jig used in the production process. Thus, adjustments are needed for the product-specific process to produce innovative new products throughout product innovation.

With regard to the transition period, the pilot production in the production process is considered to be complete when the standardization of the new product has progressed and the quality of the new product has settled. In the mass production process, process innovation aims at expanding the profits by lowering the average unit cost of production. Process innovation rationalizes the production process and produces a product in a short time by meeting the quality of the product design and saving the material and labor costs in a manner such that optimizing productivity increase the firm's profits. Accordingly, process innovation is generally conducted after the product standardization or the mass production phases. In order that the standardized products achieve popularity in the market, price competitiveness is an important factor, and therefore, process innovation plays a key role in achieving the price advantage. This is the specified phase, in which technological innovation mainly occurs in the process of lowering the production cost. If the company has a standardized mass production system with regard to process innovation, then the obstruction of product innovation by lowering the flexibility of the production process would be a constraint condition. Thus, there would be another adjustment in the interconnectivity between the characteristics of the process and the product. The products that pass through the entire production process would generate profits to the firm; these profits would then be reinvested in R&D as a complete cyclic process.

The objective of this paper is to suggest a policy by linking the various dynamic processes in the technological innovation of the manufacturing company. Thus, this paper verified its simulation based on several issues that were presented from the hypothesis. Basically, in the initial stages of the simulation, innovative investments tend to remain at the same rates in the case of both product and process innovation. The resources raised from R&D investment would increase the knowledge for inducing innovation considering a time lag, and technological innovation specifically occurs with regard to the product and process. The number of product innovations implemented decreases gradually in the early stages due to the R&D time lag; however, it rapidly increases in the next stage. After the maximum point of the product innovation S-curve, product innovation gradually decreases again, resulting in partial product improvements. Process innovation rapidly decreases in the early stages due to a relatively long R&D time lag between R&D investment and innovation knowledge accumulation; however, at the point where product innovation is decreasing, the number of process innovations implemented increases gradually. An increased process innovation again diminishes at a certain point, following which product and process innovation become stagnant. The NPD project considers product innovation to be a continuously repeating fluctuation, and it becomes a factor that continuously increases the release of new products after the NPD project. From the financial perspective, the cumulative profits for the early stages are reducing because the initial R&D investment is rather excessive as compared to the increased revenue; however, after the setoff point, the cumulative profit increases continuously against relevant investment.

5. Conclusion and Implication

In order to achieve competency in global competition, it is imperative that a firm have a portfolio of various products and time to market these products. A company should be as quick as possible in launching new products characterized by diverse functionality, high quality, and a low price; further, it should acquire the capability to produce a massive quantity of these products: this is the shortcut to success in business (Ford and Sterman, 1998, Lundvall, 2002). Therefore, a product portfolio with diverse product configuration and process flexibility in the production phases is the key factors that determine the success of a company. The existing researches on technological innovation have not paid sufficient attention to the interrelationship between the innovations that lie in the technological innovation process of firms, but these have merely emphasized the direct and unilateral relationship that exists between the R&D investment induced technological innovation and the technological innovation that affects a firm's economic performance. On the contrary, this research offers the best means of decision-making by understanding the implicit relationship of technological innovation and proposing alternatives based on technological innovation. The significance of this research is as follows. First, it presents the dynamic process of technological innovation by analyzing various dynamic relationships regarding the existing technological innovation and by modeling and quantifying it dynamically. In other words, this research embodies the structural elements of the interaction of technological innovation based on interaction theory and overcomes the implicit constraints of the linear model by presenting the feedback from the interaction relationship between the structural components. Second, it demonstrates the cyclic process with respect to R&D investment, technological innovation, profit generation, and reinvestment. The existing researches have only explained R&D investment in relation to a firm's growth or technological innovation and profit generation using the partial and static approach. However, with regard to technological innovation, this research has analyzed R&D, technological innovation, NPD, and profit generation within a comprehensive and dynamic approach. Third, with regard to the technological innovation policy in firms, this research has helped firms to make correct decisions by proposing investments on the basis of process innovation rather than product innovation. Thus far, firms have consistently made their best efforts with respect to product innovation in the short term. However, this research suggests that a firm's investment policy relies on product innovation in order to maximize the short-term profit. As regards technological innovation, both product and process innovation are critical policy parameters. Therefore, this research suggests a mechanism for making an investment decision in the mid- and long-term dynamic aspect according to the situation of the firms and the market structure. Fourth, this research attempted to quantify the R&D interval and product development lifespan, which were not analyzed empirically.

Nevertheless, this research has some limitations, which subsequent researches should attempt to eliminate. Since the SD model defined the time interval arbitrarily, an arbitrary time interval may make it difficult to measure each parameter precisely. Further, although it conducted a multivariate sensitivity analysis for each parameter, there might be errors in the sensitivity simulation setup. Therefore, a more objective and detailed data analysis is required in order to check the validity of the model for each firm. It should be noted that the model proposed in this research might present different results when applied to another industry or different innovative processes. Hence, future research must prepare an additional approach for other industries based on this technological innovation theory.

The research must incorporate more data on the behavior of consumers in the process, from the launch of a new product by technological innovation to the customers' purchase of this product to R&D reinvestment using the profits gained. Although technological innovation makes a product superior and cheaper than the existing products in terms of function and quality, the process of introducing a new product from a customer's viewpoint provides another research topic. Therefore, the next research should include the behavior of consumers with respect to new products in the market.

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