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Managing Innovation Probabilities:

Core-driven vs. Bottleneck-removing Innovations

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Abstract

This paper provides a simplified framework of focusing devices that generate different patterns of innovation, i.e., core-driven and bottleneck-removing innovations, and discusses the managerial implications. We show that core-driven innovation should be undertaken when technology components are independent (independent technology system), while bottleneck-removing innovation should be pursued when they are interdependent (interdependent technology system). Different types of focusing device should therefore be adopted based primarily on the degree of interdependence among technology components, which in turn maximizes underlying innovation probabilities. One of the implications of the results is that the effective management of innovation is made possible when innovative activities and corresponding focusing devices are appropriately arranged and coordinated to maximize innovation probability. We discuss these managerial challenges in terms of incentives, governance, and competitive strategies.

Keywords: focusing device, independent technology system, interdependent technology system, core-driven innovation, bottleneck-removing innovation, innovation probability maximization

JEL Classification: O31; O33; L2

1. Introduction

Today, it is widely accepted that the growth of technological knowledge is fundamental to the improvement of economic performance. According to Rosenberg (1994, 9), to further investigate the role of innovation in economic growth, two relevant questions must be answered: "What can be said about the manner in which the stock of technological knowledge grows over time?" And "To what factors is it responsive, and in what ways?" Satisfactory answers to these questions still have not been developed, at least through formal analysis.

In industrial organization literature, the relationship between competition and innovation has been extensively studied both theoretically and empirically, stimulated by the famous Schumpeter hypotheses that emphasize a tradeoff between innovation and static efficiency[1]. However, since innovation has generally been modeled as an improvement of a single technology, rather than of multiple technologies, the direction of innovation has been relatively disregarded. Instead, the rate of innovation has been formalized and analyzed as the incentive problem of R&D investment. Thus, institutional factors that enhance this incentive, such as market power, patents, and regulation, were shown to increase the rate of innovation (see, for example, Aghion and Howitt 2008).

This paper departs from these studies in that technology is regarded as a system of multiple component technologies and the direction of technological change among them is explicitly examined[2]. Rosenberg (1976) argued that the innovative efforts of entrepreneurs are directed to ease "the most restrictive constraint on their operation". The restrictive constraints or technical bottlenecks force entrepreneurs to focus their attention on these areas because that is

[1] The Schumpeter hypotheses state that (1) innovation increases more than proportionately with firm size, and (2) innovation increases with market concentration. See Cohen and Levin (1989), Reinganum (1989), and Griliches (1984) for a survey and theoretical and empirical studies on the hypotheses.

[2] Acemoglu (1998, 2002) also succeeded in providing a microfoundation for the theory of induced innovation under a general equilibrium framework. However, his model did not incorporate supply side constraints so that technological change proceeds in response to market forces alone. By contrast, this paper focuses more on the supply side constraints.

the compelling and obvious need. This allocation mechanism of innovative efforts was referred to as the "focusing device" by Rosenberg (1976), and it generates specific signals indicating precise directions in which technological efforts can be usefully focused.

Hughes (1983) also proposed a similar concept of the "reverse salient" in studying the evolution of technology systems. Reverse salients are components that have fallen behind or are out of phase with other system components. Such components represent bottlenecks or backward elements that prevent the further advance of the system. The nature of these reverse salients can be technical, economic, organizational or political (Hughes 1987, 73). Reverse salients that cannot be overcome within the context of the existing system may bring about radical innovations and a shift in prevailing technological regimes. They therefore play the role of focusing device in the process of innovation, though the underlying economic mechanism has not yet been fully analyzed.

In contrast, Harada (2014a) developed a model of focusing device in which the final good firm that purchases technology components adopts a pricing scheme, which in turn provides specialized suppliers with the incentive for R&D. It was shown that equilibrium factor prices are based on productivity, and that this reward scheme generates core-driven innovation. However, core-driven innovation stands in sharp contrast to the type of innovation pointed out by Rosenberg (1976) and Hughes (1983). Harada (2014b) therefore constructed an alternative model that results in bottleneck-removing innovation.

The purpose of this paper is to provide a much more simplified framework of focusing devices that generate different patterns of innovation, i.e., core-driven and bottleneck-removing innovations, and discuss the managerial implications. Focusing devices are the mechanisms that determine the direction of innovation, which in turn consists of underlying technology systems, incentives, governance, and strategies. We show that core-driven innovation should be undertaken under an independent technology system, when the technology components are independent. Bottleneck-removing innovation should be pursued when the components are interdependent, under an interdependent technology system. Thus, different types of focusing device should be adopted primarily based on the degree of interdependence among technology components. This management of innovation activities maximizes underlying innovation probabilities. One of the implications of the results is that the effective management of innovation is made possible when innovative activities and corresponding focusing devices are appropriately arranged and coordinated to maximize innovation probability (the innovation probability maximization principle), instead of relying on elusive concepts such as enactments (Weick, 1979), resources (Wernerfelt, 1984), routines (Nelson and Winter, 1982), and capabilities (Teece et al., 1997). Thus, managing innovation probabilities is a key to dynamic efficiency of the firm.

The rest of the paper is organized as follows. Section 2 presents a basic model of focusing devices, examines their effects on the rate and direction of innovation, compares the relative dynamic efficiencies, and discusses the implications. Section 3 generalizes management of focusing devices as innovation probability maximization and discusses several managerial challenges. Finally, Section 4 presents our conclusions.

2. Core-driven vs. Bottleneck-removing Innovation

2.1 Technology System

In this section, we will present a simple conceptual model of a technology system and show how interdependence of technology components affects the direction of innovation. We suppose a technology system consists of several technology components. For example, the railway vehicle technology system includes safety, drive control, power system, braking, vehicle motion, vehicle vibration, vehicle strength, energy control, communication and transmission. Each technology component is in turn divided into more detailed subcomponents.

Suppose the value of innovation is V, and the probability of success of innovation for the i th technology component is denoted by

$$p\left(r_i; a_i\right) = q\left(r_i\right) - a_i, \tag{1}$$

where r_i measures the amount of R&D investment and a_i is the intrinsic difficulty of R&D in this technology component. $q\left(r\right)$ increases with R&D investment and is strictly concave to ensure interior solutions. If $p\left(r_i\right) \le 0$, we assume $p\left(r_i\right) = 0$ to rule out negative probabilities.

Suppose a technology system consists of k technology components. The heterogeneity across technology components is incorporated by assuming different values of a_j for $j = 1, \ldots, k.$ For ease of exposition, we assume $a_1 < \cdots < a_k$. The 1st and the k th technology components are referred to as core and bottleneck technologies, respectively. This is because core technology usually implies a higher innovation probability while a bottleneck technology suffers from a lower innovation probability.

To keep the model as simple as possible without loss of generality, we assume the function form of $q\left(r\right)$ is the same for all technology components. Now, we introduce two types of interaction among technology components, (1) independent technology components (modular type) and (2) interdependent technology components (complex products and systems (CoPS) type), and examine how the intensity of R&D investment is affected by these different interaction patterns.

2.2 Independent Technology Components

First, consider the case of independent multiple technology components. Suppose there are k kinds of technology components. If each technology component is independent, the probability that at least one technology component succeeds in innovation is given by

$$p(r_1,\dots,r_k)=1-\prod_{j=1}^{k}\left(1-p\left(n_j;q_j\right)\right)=1-\prod_{j=1}^{k}\left(1-q(r_i)+a_i\right). \quad (2)$$

The expected profits from innovation are

$$p(r_1,\dots,r_k)V-\sum_{j=1}^{k}r_j. \quad (3)$$

When a_i is low (core technology), the expected gains from its innovation are higher than other technology components with higher values of a_j (bottleneck technology) because its marginal impact on the total innovation probability (2) is higher[3]. Therefore, it is more efficient to invest in core technology more intensively than bottleneck technology. As a result, core technologies are more likely to discover a new technology in this case.

Proposition 1: In the case of independent technology components, core-driven innovation should prevail such that $r_1^* > \cdots > r_K^*$ and $p\left(r_1^*;a_1\right) > \cdots > p\left(r_K^*;a_k\right)$.

In other words, if each technology component has an independent effect on the total innovation probability, technology components with higher innovation probabilities should be intensively explored. Consequently, core-driven innovation prevails and technology divergence is more likely to expand over time. This result is consistent with innovation processes of general purpose technologies (GPT) such as machine tools and information technologies (see Helpman 1998, for a systematic analysis).

2.3 Interdependent Technology Components

As a number of case studies of innovation suggest, innovation proceeds within larger sociotechnological systems consisting of interdependent technology components (Rosenberg, 1976; Hughes, 1983). Miller et al. (1995) and Hobday (1998) argued that while most innovation studies have examined mass-manufactured goods, a large number of industries supply high-cost, technology-intensive, customized, capital goods, such as flight simulation systems, bridges, chemical plants, robotics equipment, and submarines. They are systemic in the sense that they work through the interplay of many interacting components. They defined these technology systems as CoPS. In these CoPS, bottlenecks, rather than core technologies, play a more critical role.

In this case, it is therefore reasonable to introduce interdependence across heterogeneous technology components. The innovation function can be specified as

$$p(r_1,\dots,r_k)=\prod_{j=1}^{k}p\left(n_j;q_j\right)=\prod_{j=1}^{k}\left(q\left(r_j\right)-a_j\right). \quad (4)$$

This multiplicative form implies that the total innovation probability is severely damaged if the innovation probability of any one technology component decreases. For example, if $p\left(n_j;q_j\right)=0$, the total innovation probability also becomes zero. In the additive specification of (2), this will not happen. In this case, R&D investment in other technology components with positive innovation probabilities does not make sense because the total innovation probability does not change as long as $p\left(n_j;q_j\right)=0$ is maintained. Thus, increasing $p\left(n_j;q_j\right)$ becomes the top priority[4]. As a result, bottleneck technologies should receive more R&D investment than core technologies in the interdependent case.

Proposition 2: In the case of interdependent technology components, bottleneck-removing innovation should prevail such that $r_1^* < \cdots < r_k^*$.

Note that in this proposition, we cannot establish $p\left(r_1^*;a_1\right) < \cdots < p\left(r_K^*;a_k\right)$ even if $n_1^* < \cdots < n_k^*$ holds. This is because more diversity does not necessarily lead to a higher innovation probability of the corresponding technology

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[3] More formally, the marginal productivity is calculated as $\prod_{j\neq i}^{k}\left(1-q\left(r_j\right)+a_j\right)q'\left(r_i\right)V$. If a_i is minimized, this is maximized.

[4] More formally, the marginal productivity is calculated as $\prod_{j\neq i}^{k}p\left(r_j;a_j\right)q'\left(r_i\right)V$. If a_i is maximized, so is this.

component owing to the intrinsic difficulty a_j. But the firm attempts to increase the innovation probability of bottleneck technologies as much as possible to increase the total innovation probability. Consequently, bottleneck-removing innovation prevails and technology convergence is more likely over time. This pattern of innovation is consistent with historical evidence provided by Rosenberg (1976) and Hughes (1983) in which bottlenecks or reverse salients play a critical role in determining the direction of innovation.

2.4 Application to Capability Management in Two-tier Technology Systems

These results can also be applied to capability management in more complex technology systems. To illustrate this, let us define core capability as technology components with the highest innovation probability, and peripheral capability as those with the lowest innovation probability. Standard capability management emphasizes core capabilities to be invested and improved, rather than peripheral ones. However, proposition 1 suggests that this management is effective if and only if the underlying technology system is independent. If technology components are interdependent, it is peripheral capabilities that must be highlighted in managing innovation processes. Thus, even in capability management, to derive effective managerial implications, innovation probability should be the basic unit of analysis in the face of uncertainty.

In more complicated cases, suppose a technology system consists of two tiers of subsystems. The first and second tiers are either independent or interdependent. Then, we have four types of technology system, as shown in Table 1. Core capabilities should be highlighted only in the case that a technology system consists only of independent technology components. When an interdependent tier is included, peripheral capabilities should be prioritized in R&D investment at that tier. For example, suppose the first and second tiers consist of independent and interdependent technology components, respectively. While the first tier is managed primarily to increase core capabilities, peripheral capabilities should be improved in the second tier. Without introducing innovation probability as a measure for capability management, these subtle differences could not be derived.

Table 1. Capability management in two-tier technology systems

Types of technology systems		Management focus	
Upper tier	Lower tier	Upper tier	Lower tier
Independent	Independent	Core	Core
Independent	Interdependent	Core	Peripheral
Interdependent	Independent	Peripheral	Core
Interdependent	Interdependent	Peripheral	Peripheral

3. Management of Innovation Probability

3.1 Innovation Probability Maximization

If the direction of innovation follows the optimal trajectory, as specified in propositions 1 and 2, this implies that the total innovation probability is also maximized. Thus, the optimality of innovation trajectory depends on whether the underlying innovation probability is maximized or not. We will refer to this as the innovation probability maximization principle. According to this principle, effective management of innovation is conceived as management of innovation probabilities. The previous section suggests that the patterns of interaction across technology components matter in this management.

By contrast, the literature on R&D management typically focuses on knowledge (Kogt and Zanger, 1992; Henderson and Cockburn, 1994; Fleming, 2001), capabilities (Teece et al., 1997; Nerkar and Paruchuri, 2005), communications (Allen, 1977; Harada, 2003) or structures (Clark, 1985; von Hippel, 1990; von Zedtwitz and Gassmann, 2002; Argyres and Silverman, 2004; Zhang et al., 2007) without much reference to innovation probabilities. But those factors are primarily conducive to the management of operational issues in which significant uncertainty does not exist. When stochastic processes must be effectively controlled, management of innovation should be directly concerned with the underlying innovation probabilities to be increased by corresponding innovative moves.

Thus, innovation probability should be the unit of analysis in the face of uncertainty, and other factors such as knowledge and capabilities are instruments in the management of innovation probabilities. In other words, knowledge and capabilities should be efficiently utilized to increase innovation probabilities.

However, in reality, the innovation probability maximization principle is sometimes difficult to implement owing to organizational practices, different pricing schemes, and a lack of attention to innovation probabilities. If these obstacles are significant, the management of innovation probabilities consistent with propositions 1 and 2 inevitably necessitates the management of focusing devices. Focusing devices can be defined as mechanisms of innovation that indicate the direction of innovation, such as technical signals, pricing schemes, and feedback loops. Harada (2014a) formalized focusing devices in terms of factor prices of technology components in which core technologies are priced highest, generating core-driven innovation, as suggested in proposition 1. If technology components are supplied through markets with equilibrium factor prices, this implies that innovation probability maximization is discouraged under the interdependent technology system.

Even if technology components are internally procured, divergence from innovation probability maximization can still take place. To overcome or transgress a reverse salient, it is crucial that firms are capable of defining them as a set of critical problems (Hughes 1983). However, this capacity to identify reverse salients under CoPSs is not always available. Rather, it must be developed and improved over time. For example, Dedehayir and Mäkinen (2008) discussed in their empirical study of the personal computer (PC) gaming industry that game developers, to guarantee success, tend to launch products with a focus on factors other than technological bottlenecks. They pointed out that the ability to gauge the magnitude of bottleneck severity in technological subsystems is likely to increase innovation performance. This argument suggests that conventional incentive schemes do not provide correct information that is conducive to innovation probability maximization.

Similarly, Geyer and Davies (2000) suggested in their analysis of railway projects in the United Kingdom and Germany that successful innovation in market-based railway operations increasingly depends on dynamic systems integration and effective coordination between railway projects and the operational railway network. However, a fragmented market structure in the operational railway system makes it extremely difficult to build and maintain these links. Systematic efforts are required to establish some feedback loops between the two.

These arguments clearly suggest that management of innovation probabilities should entail the management of focusing devices. The innovation mechanism that determines the direction of innovation should be corrected as soon as it diverges from the innovation probability maximization principle. More specifically, it is one of the most important challenges in the management of innovation to identify core and bottleneck technologies and direct innovative efforts so as to maximize innovation probability.

Table 2 summarizes the management challenges of technology systems discussed in the previous section. This table indicates that incentives, governance, and strategies must be congruent with the underlying technology system to maximize innovation probability. Complementary sets of incentives, governance, and strategies constitute an efficient focusing device that achieves dynamic efficiency of the firm. In what follows, we will consider these management challenges.

Table 2. Management of technology systems

	Independent system	Interdependent system
Innovation	Core-driven	Bottleneck-removing
Incentive	Performance-based	Marginal productivity-based
Governance	Internal development	Relational outsourcing
Strategy	Cost-reducing, quality-improving	Hybrid
Advantage	Core strength	Flexibility
Disadvantage	Rigidity	Core weakness

3.2 Incentives

First, management of focusing device requires appropriate incentive schemes that facilitate desirable innovation. In market transactions, core technology is usually characterized by high quality, relative to other technology components. Bottleneck technology is usually rewarded less than other technology components as otherwise, suppliers of technology components, including both employees and outside suppliers, are not motivated to improve quality. On the contrary, they have more incentive to reduce quality because the corresponding payment increases as a result. Bottleneck technology should therefore be rewarded less than other technology components. This is the equilibrium price schedule in the model of focusing device in Harada (2014a).

In the case of independent technology components, since core technology must be primarily developed, higher rewards should be provided to suppliers of core technology to facilitate innovation. A decrease in the innovation reward obviously reduces the incentive to make R&D investments in core technology, and hence, discourages innovation.

In the case of interdependent technology components, however, the difficulty arises in incentive schemes. According to proposition 2, the optimal incentive scheme should be a reversed version of core-driven innovation, i.e., a marginal productivity-based reward. Consequently, suppliers of bottleneck technology are less motivated to invest in R&D. The management challenge here is to introduce a marginal productivity-based reward scheme in the firm without discouraging innovation and providing an incentive to downgrade quality. However, this is sometimes very difficult to implement via selective intervention (Williamson, 1985) because employees and suppliers of high quality technology components face high reservation utility. If they are rewarded less, they will leave the firm.

To respond to this challenge, the firm often introduces a different reward scheme for bottleneck technologies. For example, if core technology is internally procured, bottleneck technology is outsourced so that the negative effect on employees' incentive to make R&D investment is mitigated by separating the reward schemes.

Alternatively, the firm can adopt a fixed reward scheme so that all technology components are equally motivated for innovation. But this cannot resolve the potential problem of incentive incompatibility because employees in charge of bottleneck technology could have more bargaining power than other employees, demanding more nonpecuniary incentives such as promotion and budget. Once again, this might discourage innovative activities of other employees to some extent. Ideally, if the incentive scheme can feasibly reward lower quality, this facilitates bottleneck-removing innovation. Otherwise, the firm must introduce either different governance for bottleneck technology or a fixed reward scheme as second best alternatives.

3.3 Governance

We must now examine the governance required for core and other technologies to fix the appropriate reward scheme for bottleneck technology. Core technology reflects the core capability of the firm, and the resource-based view of management recommends that core technology should be internally procured. If it is outsourced, this implies competitors can also get access to core technology, leading to a decline in competitive advantage. To outperform competitors, the firm must own valuable, rare, inimitable, and well-organized resources and capabilities (Barney, 1991). Obviously, core technology satisfies this criterion.

From the perspective of transaction cost economics (Williamson, 1985), internalization of core technology implies relation-specific investment in core technology is also facilitated. As a result, innovation in core technology is facilitated. In this case, if the firm pursues core-driven innovation, it should adopt a performance-based (average productivity) reward scheme. In other words, innovation in high quality technology components will be rewarded more. Employees in charge of core technology will become highly motivated to innovate.

However, from the perspective of innovation probability maximization, it is not always desirable to internalize core technology. Although transaction cost minimization is efficient from a static perspective, another aspect needs to be considered from a more dynamic perspective, namely, to maximize the total innovation probability. To clarify this, suppose the i th technology component is currently outsourced and the firm is now considering whether it internalizes this technology component or not. When a technology component is outsourced, outside suppliers make the corresponding R&D investment.

If this technology component requires relation-specific investment to the firm, outside suppliers have less incentive to make the R&D investment, which could be reflected in a lower value of V in (3). For example, the firm uses packaged software from the outside supplier, but its productivity increases if the software is more customized. The firm must internally develop the customized software because outside suppliers have no incentive to do so. If the firm succeeds in the customization, it increases the value of its technology system (V) so that $V_I > V_O$ holds where subscripts I and O denote internal procurement and outsourcing, respectively. From a static perspective, this decision is optimal as $V_I > V_O$, from the relation-specific investment.

Now, assume that the innovation probability of the i th technology component is exogenously given when it is outsourced. If many outside suppliers investing in R&D in this technology component exist in the market, the corresponding innovation probability is expected to be higher than the innovation probability of the firm. Assume also that innovation increases V over time and the growth rates under outsourcing and internal procurement are μ_O and μ_I, respectively, with $\mu_O > \mu_I$. The expected sum of the future gains from innovation is higher under outsourcing than under internal procurement if the gap between the innovation probabilities (μ_O and μ_I) is sufficiently large[5].

In particular, GPT components are most likely to be outsourced since outside GPT suppliers provide them with lower prices through economies of specialization (Rosenberg, 1976). The emergence of GPT sectors provides the firm with the option of outsourcing with higher level and growth effects (Harada, 2010). While internal procurement could be efficient from the static perspective, it could be inefficient from the dynamic perspective. Under certain conditions, the firm faces a tradeoff between commitment (relation-specific investment) and innovation probability. In other words, the tradeoff emerges between static and dynamic efficiencies. For the latter, the innovation probability maximization principle should be more pronounced.

If core technology has to be outsourced owing to more rapid pace of innovation outside the firm, the reward scheme simply becomes market prices. As we mentioned above, core technology is rewarded more than other technology components in markets. Thus, if the firm intends to implement core-driven innovation, a market pricing scheme is complementary. However, outsourcing also involves the risk of losing competitive advantage because competitors can also get access to the same core technology. This is indeed what is observed in the PC industry in which core

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[5] More formally, this condition is given by $V_O/r-\mu_O > V_I/r-\mu_I$ where r denotes a discount factor.

technologies such as operating systems and MPU are outsourced respectively to Microsoft and Intel so that product differentiation in this industry remains harder to achieve. In this case, a technology component with the second highest quality might become the source of competitive advantage. But if this technology component is also subject to a rapid pace of innovation in the market, it must be outsourced once again to maximize innovation probability. This technology component cannot be the source of competitive advantage, as long as outside suppliers are available to competitors. Eventually, if the firm pursues core-driven innovation and gains sustainable competitive advantage, technology components as the source of competitive advantage must be internalized to block imitation by competitors.

By contrast, if the firm pursues bottleneck-removing innovation with the interdependent technology components, bottleneck technology becomes the source of competitive advantage. Once again, the optimal governance should be determined based on the innovation probability maximization principle. If outside suppliers provide the bottleneck technology with a rapid pace of innovation, the firm should obtain it from outside suppliers. If competitors regard the same technology component as a bottleneck and pursue bottleneck-removing innovation, outsourcing implies the loss of competitive advantage. In this case, the second lowest quality technology component becomes the source of competitive advantage. Eventually, bottleneck technology as the source of competitive advantage must be either internalized or outsourced to suppliers establishing a specific relation to the firm.

Regarding outsourcing to a relation-specific supplier, note that bottleneck technology is priced lowest in the markets. In contrast to core technology, outside suppliers also face less incentive to invest in R&D. On the other hand, the firm pursuing bottleneck-removing innovation has the incentive to invest heavily in R&D in the bottleneck technology. Consequently, the firm can provide sufficient incentives and governance mechanisms such as relational contracts. In this case, competitors cannot get access to the same bottleneck technology. This relational contract is likely to be unfeasible in the case of core technology because the opportunity costs of core technology in the market are high, so that the firm cannot provide sufficient incentive to these suppliers.

Suppose the marginal productivity-based reward scheme cannot be implemented in the firm. When a bottleneck technology is either internally procured or outsourced to relation-specific contractors, higher quality technology components should be outsourced and rewarded according to market prices. The remaining lower quality technology components are rewarded based on a fixed reward scheme in the firm. When the bottleneck technology is outsourced to relation-specific contractors, more incentives should be provided to those contractors to facilitate R&D investment.

3.4 Competitive Strategies

Innovation probability maximization leads to sustainable competitive advantage or dynamic efficiency over time. To fully exploit dynamic efficiency, the corresponding competitive strategy must be congruent with the underlying focusing device.

In contrast to competitive strategies proposed by Porter (1996)[6], Harada (2014b) introduced the concept of dynamic strategies that refer to innovation trajectories of given competitive strategies. For example, the competitive space represented in Figure 1 is specified by two axes: quality and cost advantage. A consumer chooses a bundle of these two properties of the product from the set of available alternatives. Its utility is assumed to be well-behaved and the profits of the firm are in proportion to the utility level achieved by its product.

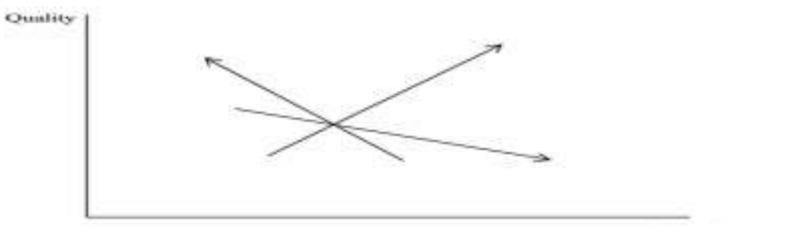

Figure 1. Innovation trajectories

If the firm is positioned on A in this competitive space (see Figure 2), this position is equivalent to Porter's competitive strategy. However, innovation enables the firm to shift its own position to somewhere that increases the consumer's utility. In Figure 2, three types of innovation trajectories are identified: (1) quality-improving; (2) cost-reducing; and (3) hybrid strategies. Harada (2014b) argued that while the hybrid strategy is associated with Porter's stuck-in-the-middle strategy, which pursues both differentiation and cost leadership simultaneously, this dynamic strategy alone generates

[6] Porter (1996) defined competitive strategy as "the creation of a unique and valuable position, involving a different set of activities".

dynamic efficiency.

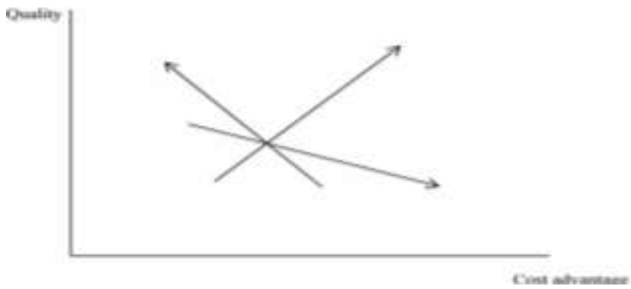

Figure 2. Three types of dynamic strategies

Figure 3 shows that the quality-improving strategy of AB is inferior to the hybrid strategy of AA' because U'>U holds. Indeed, this figure indicates that both positions of A and B provide the same utility to the customer. Paradoxically, if quality-improving innovation continues from A to B, its competitiveness remains the same, whereas if it stops somewhere before reaching B, the firm improves its competitive advantage. However, as long as the firm stays in the trajectory of AB, it cannot gain competitive advantage over competitors in AA'. Therefore, the firm should eventually shift to the hybrid strategy at some point in time even if it currently pursues either cost-reducing or quality-improving strategies.

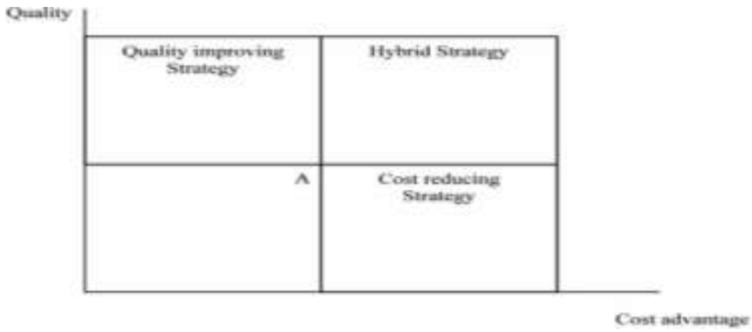

Figure 3. Shifts in competitive advantages and innovation trajectories

Now, suppose the firm adopts a hybrid strategy. Then, the corresponding technology system should be interdependent because a balanced innovation trajectory must be realized under this strategy. If the firm is currently advancing in cost performance, its next target of innovation should be quality-improving because the hybrid strategy pursues cost reduction and quality improvement simultaneously. This simultaneous pursuit is only possible by bottleneck-removing innovation.

On the other hand, if the firm pursues either cost-reducing or quality-improving strategies, it should focus on innovation in cost reduction or quality improvement, respectively. Obviously, an independent technology system is complementary to these dynamic strategies because it generates core-driven innovation.

Thus, our results in propositions 1 and 2 clearly suggest that structure (technology system) follows strategy (dynamic strategy) consistently. If the firm shifts its dynamic strategy between a hybrid and single strategy, the underlying technology system must also be altered to one that is complementary to the new dynamic strategy.

3.5 Endogenous Technological Interdependence

So far, we have simply assumed that technology systems can be classified as either independent or interdependent technology components. This interdependence among technology components is primarily determined by the technological properties of the underlying architecture of the product (Henderson and Clark, 1990). Although the effect of architecture is significant on the degree of interdependence among technology components, the firm could affect this interdependence to some extent by changing incentive schemes and dynamic strategies.

For example, automobile firms are usually equipped with an interdependent technology system because an automobile is composed of many interdependent parts and materials. According to Table 2, automobile firms must pursue a hybrid strategy with bottleneck-removing innovation. Toyota seems to follow this innovation path with relation-specific keiretsu suppliers. However, Honda, BMW, and Mercedes put more emphasis on distinguishing features of their own cars such as design, engine performance, quality, and usage. Thus, their dynamic strategies are quality-improving, rather than hybrid. This clearly implies that these automobile firms succeed in generating unique focusing devices that are not implied by the underlying (pure) technology system. Although their technology systems are also subject to high degrees of interdependence among technology components, they put more emphasis on the independent nature of product properties that appeal to customers, a type of focusing device can be endogenously determined in the competitive strategy space, even if the firm and competitors share the same technology system. Hence, we should distinguish the strategic technology system from the pure one. The former is the endogenously-designed innovation mechanism, while the latter is the exogenously-predetermined technical relationships across technology components. Obviously, the former alone matters in managing innovation probabilities.

4. Concluding Remarks

In response to the two questions raised by Rosenberg (1994), we have developed a simple framework of focusing devices. We have shown that core-driven innovation should be undertaken with independent technologies, while bottleneck-removing innovation should be pursued under the interdependent technology system. These results provide an answer to the first question of Rosenberg (1994) about the manner in which the stock of technological knowledge increases.

In the process of innovation, we inevitably face the tradeoff between static and dynamic efficiency implied in the Schumpeter hypotheses. Thus, institutional designs such as the boundary of the firm must be evaluated in terms of the innovation probability maximization principle, in addition to the transaction cost minimization principle. A standard economic institutional analysis such as transaction cost economics is primarily concerned with static efficiency, represented by underinvestment in relation-specific assets (Williamson 1985). However, dynamic consideration modifies this preoccupation with static efficiency in favor of dynamic efficiency.

Thus, Rosenberg's (1994) second question, about the factors to which technological knowledge is responsive, can now be answered by pointing out not only economic factors such as factor prices but also institutional factors that reflect either the transaction cost minimization principle or the innovation probability maximization principle. This paper illustrates the need to shift our attention towards the latter in the evaluation and design of institutions.

The results obtained in this paper have several implications. They suggest that R&D management literature that emphasizes knowledge and capabilities should be evaluated in terms of the effects on innovation probabilities, and used to increase innovation probabilities, based on these evaluations. This is because the existing studies on R&D management lack appropriate measures. As illustrated in Table 1, even in capability management, to derive effective managerial implications, innovation probability should be the basic unit of analysis in the face of uncertainty.

In terms of the literature on focusing devices, this paper has formalized the informal arguments in Rosenberg (1976) and Hughes (1983), and integrated their concepts of bottlenecks and reverse salients with the core-driven innovation suggested by Harada (2014a) in a very simple framework of focusing devices. A number of case studies on innovation processes have been built upon the framework of reverse salients (Geyer and Davies, 2000; Prencipe, 2000; Fransman, 2001; Mulder and Knot, 2001; Christiansen and Buen, 2002; Markard and Truffer, 2006; Dedehayir and Mäkinen, 2008). However, these arguments seem valid only in interdependent technology systems such as CoPS. Thus, the model in this paper provides a more balanced view on the innovation processes.

Finally, let us make a few remarks on dynamic capabilities. Dynamic capabilities are the ability to build, integrate, or reconfigure other resources and capabilities (Teece et al., 1997), which consists of routines (Zollo and Winter, 2002). Innovation probability is also concerned with building, integrating, and reconfiguring other resources and capabilities as long as they are related to innovation.

However, innovation probability should be clearly distinguished from dynamic capabilities because innovation probability is not a routine. It is one aspect of controlled stochastic processes and changes over time. Innovation probability is the outcome of stochastic events and actions, which in turn might reflect dynamic capabilities. This paper was not interested in linking innovation probability and dynamic capabilities. As Williamson suggested, the related work has not yet succeeded in operationalizing dynamic capabilities. Dynamic capabilities, as the framework of management of innovation, are too elusive to provide specific prescriptions regarding innovation activities. Instead of relying on dynamic capabilities, we therefore believe that it is more instructive to make innovation probabilities the basic unit of analysis for innovation strategy and management.

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