The Asymmetric Game Strategies Utilizing R&D Incentives under Uncertain Patent Race and Non-infringing Imitation

by

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Abstract

The primary objective of this research is to provide the optimal strategies for firms and decision makers to take advantage of competitive situations in which they obtain the greatest benefits. We analyze the various scenarios that can occur during the process of determining R&D investment with the probabilities of patent protection, patent acquisition and non-infringing imitation in a duopoly competition. In particular, through the R&D investment game model that determines the payoff from competition, we investigate how R&D decisions can be strategically made in various scenarios.

First, we consider the game situation of two competing firms where both firms decide simultaneously whether to invest in R&D or not in the first stage and then in the second stage compete with each other for payoffs along with patent acquisition. We compare the asymmetrical competitive model and the symmetrical competitive model to analyze which competitive structure offers more incentive for R&D. In particular, the analysis is done separately for markets with and without patent protection to shed light on whether R&D cooperation and technology licensing can be used strategically. The scenario analysis suggests a need for changing the strategy in accordance with the level of asymmetry in competition and the likelihood of non-infringing imitation.

Secondly, we assume a situation where competition for a certain product market reaches a saturation point and therefore the profit structure of the two firms becomes that of a zero-sum game. Under this assumption, the symmetric R&D game model is expanded and then analyzed.

In particular, by comparing situations where non-infringing imitation is likely with situations where such a case is not possible, we analyze the strategic R&D incentive in accordance with the other party's R&D investment decision.

Thirdly, we build a duopoly R&D competitive game model where winning and losing a patent competition is statistically applied then observe the changes in R&D incentives in accordance with the changes in the probability of acquiring a patent. Through a two-way sensitivity analysis on the changes in probability of a patent acquisition and the probability of a non-infringing imitation between the two firms, we compare R&D investment strategies in a nonzero-sum and a zero-sum game environment. By comparing a symmetric R&D investment game model and an asymmetric R&D game model, we are able to identify a strategy that increases the incentive for R&D.

Lastly, we conduct sensitivity analysis to understand how patent protection and the likelihood of imitation affect the decision on R&D investment and to identify the most notable variables that the decision-maker should take into account. In particular, we offer a strategic selection range for R&D cooperation and technology licensing in a bilateral R&D investment situation.

To my wife, Jiin

and

my daughters: GyuRee, Hannah, and Sarah

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Chapter 1

Introduction

1.1 Research Background

Sony of Japan used to lead the TV market with the cathode ray tube (CRT) technology in early 1980s. If Samsung had not taken the risk to invest on the large-scale R&D to develop the flat-screen, it would not have acquired the fame and status it enjoys now. At this time, many companies are investing money in developing new technology to be competitive in the market place. We cannot deny that successful investment in R&D has been the important basis which guarantees the future of firms including Samsung. Even though investment in R&D is a core element in firm management, it is difficult for a firm to decide on proper investment because of uncertainties such as irreversibility of invested money, damages from overheated investment competitions with other companies and patent application for the technology by a competitor, etc.[1] Especially, in the high-tech industry where competition is intense and uncertainty is great, it is one of the most important matters to decide when and how much it will invest in R&D project. Poor decision to invest in an R&D project of a firm on big monetary investment can reduce investment profits, and, ultimately, endanger other investment opportunities of the firm. Thus, the more competitive companies in an industry, the more strategic a firm should be in the analysis of the situation[2].

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[1] According to World Intellectual Property Organization Statistics Database, October 2011, R&D productivities have followed a continuous downward trend.

[2] For example, firm's performance relies on the existence of patent protection, and investment plans are dependent on competitors' plans for R&D investment.

As new technology acquired from R&D investment is the source of profit for the firm, firms are engaged in competitions to acquire patents hoping that those patents will protect their newly developed technologies and profits coming from those technologies. Patent competition frequently occurs in the process of R&D investment and competition. Since winning patent by a firm crucially affects R&D investment of its competitor, it is an important strategic element of a firm. Even though securing patent is not necessarily decided by invested amount of money and time, companies are involved in patent competitions based on aggressive investment (in terms of monetary aspect). However, the problem is that patent does not always protect the technology and related interests of the firm who owns the patent. In reality, even in the markets where patents are well protected, patented technologies are leaked through industrial spies and hiring of core technicians related with patented technology from competitors. Thus, in some cases, it can be better as strategy to wait until its competitor invests in R&D and acquires a patent, and either to produce a non-infringing-imitation product similar to the patented one of its competitor, or use the patented technology by paying its royalty, rather than to take risks in patent competition.

Consequently, by making game models of R&D investment and patent competition, in this research we develop R&D investment strategies maximizing interests. Especially, this research use a two-stage game model: The first stage where companies decide on R&D investment based on competition scenarios either in the market where patents are protected or in the other market where they are not protected; the second stage where patent acquisition and interests of competing companies are determined.

1.2 Research Objectives and Goals

In this dissertation a strategic R&D investment model will be developed to demonstrate that best R&D decisions can assist the duopoly competing firms in making more profits. In particular, investigating markets with zero-sum and nonzero-sum profit models will make it possible to devise optimal competition scenarios that predict promising anticipated profits and R&D incentive. Thus this research will:

- Investigate on a two-stage game model to see how various conditions such as asymmetric and symmetric R&D investment competitions, zero-sum and nonzero-sum game environments, different cost (profit) function ranges, tournament effect, and etc. affect the game.

- Devise strategies for competing firms and show how firms can optimize their benefits depending on the changes of competing conditions and scenarios.

- Find the best timing and amount of R&D investment for competing firms.

The asymmetric R&D investment game model will:

- Find the best strategies based on the rivalry firm's R&D decision.
- Result in higher R&D incentives for each firm to achieve.
- Suggest best strategic decisions regarding R&D incentive from cooperative R&D and technology licensing when the firms are in a bilateral R&D competition.
- Provide a thorough understanding of the R&D investment game model in various scenarios as well as an evaluation of the cost-effectiveness of efforts to acquire such information by comparing the investment plan prior to and after obtaining the competing firm's decision.

1.3 Research Plan

Chapter 2 examines asymmetric R&D investment decision strategies with patent protection for two competing firms. By applying game theory, we present an asymmetric R&D investment competition model for firms in a duopoly market and identify the scenarios under which strategically anticipated profits can be increased with the other party's decision. Through the models that include various competitive factors such as patent protection, patent competition and the options of R&D cooperation or technology licensing, we investigate how R&D decisions can be strategically made depending on the various scenarios.

Chapter 3 investigates duopoly competition in two firms' symmetric R&D investment strategies under a zero-sum game. Our main focus is to identify the benefits of R&D investment strategies as they at some point reach the saturated competition of a certain product. In particular, with the goal of illustrating the variance in expected benefits using strategic gaming models, two different situations are compared and analyzed, one where patent protection is available, and another where it is not. With the assumption of zero-sum under a saturated market competition, we also draw a series of possible competition scenarios focusing on expected payoffs and better R&D incentives to achieve.

Chapter 4 constructs an asymmetric R&D competition game model and reconstructs the two variables - patent acquisition probability and non-infringing imitation probability - as probabilistic model, and conducts sensitivity analysis considering the changes of two variables. To seek an investment strategy generating the highest R&D incentives among various competition scenarios, we do the sensitivity analysis depending on the changes of patent acquisition probabilities and non-infringing imitation possibilities of the duopoly firms. In particular, we deal with bilateral R&D investment case where R&D competition can inevitably lead to patent competition to find the better choice between R&D cooperation and licensing options.

Chapter 5 analyzes factors influencing decisions on R&D investment of two competing firms. Matching expected profits and R&D incentives with decision-making paths, we analyze the best and second-best strategies of the two firms in an asymmetric competition situation. In particular, through DT analysis using not only payoff but strategic and non-strategic R&D incentives, we structure various variables included in the asymmetric R&D investment game model, and compared decision-making process based on expected values of decision-making nodes and changes of R&D incentives.

Chapter 6 presents a brief conclusion along with some suggestions for future research.

Chapter 2

The Asymmetric Game Strategy Utilizing R&D incentives with Patent

ABSTRACT

This paper examines asymmetric R&D investment decision strategies with patent for two competing firms. Our focus is placed on establishing cost functions with varying investment costs for competing firms. In particular, we consider a strategic decision making process for these firms where one is with a relatively higher brand image or cost functions and the other with low investment cost through non-infringing imitation. Our purpose is to develop a strategic competition model through game theory. Our findings are as follows: (1) If non-infringing imitation is less likely, bilateral R&D competition under patent protection tends to create higher strategic R&D incentives for R&D cooperation than independent R&D investment. (2) Under patent protection, technology licensing creates higher R&D incentives for both firms when compared with the without-licensing situations. In particular, we find that firms in asymmetric competition can expect higher non-strategic (strategic) R&D incentives through technology licensing (R&D cooperation) than through R&D cooperation (licensing) with patent protection.

2.1 Introduction

Anyone can win in a competitive situation. But winning is heavily dependent on circumstantial factors. That is to say, asymmetrical competition (e.g. superiority – inferiority) can generate different timings of profit due to different corporate situations and scenarios. Firms participating in a competition for a particular product in a market cannot have identical situations. Because of their brand names or firms' size, one firm has a head start whereas the other one begins the competition with disadvantages. Interestingly, the situational difference does not guarantee outcomes. If that difference were directly related to the quality of outcome, competition would be less likely to occur. Therefore, optimally utilizing a wide variety of variables and situations in a strategic manner, competing firms can perform to their maximum capacity, and thus produce quality results.

Research in R&D investment is very active, ranging from quantitative analysis on the performance of R&D (Li, 2001) to theoretical examination of firms' competition behavior through strategic and dynamic models (Fershtman and Markovich, 2006; Lim, 1998; Li, 2011; Reinganum, 1982). In particular, stating the lack of study about irreversibility, uncertainty, and choice of timing for investment, Dixit and Pindyck (1994) explain various characteristics of firm investment through strategic models of game theories and real options (Martzoukos and Zacharias, 2013; Pawlina and Kort 2006; Schwartz, 2004; Weeds 2002) and has given the basis of this field of research on which various models to explain competition could be developed. Especially, many researchers have upgraded the conditions (Huisnan and Kort, 2003; Mukherjee 2006; Pawlina and Thijssen 2004) assumed in existing researches for simplifying the model, and have also made efforts to strategically use patent along with R&D (Judd, Schmedders and

Yeltekin, 2012; Weeds 2000) and empirically analyze the effect of patenting on R&D[3] (Arora, Ceccagnoli and Cohen 2007).

As part of efforts finding more realistic models through duopoly investment competition, we assume a strategic situation in product development competition with a focus on patent competition to identify strategic ways of producing benefits for competing firms. By nature of patent policy, most patent competitions occur in the initial phase of developing ideas or products. That is, participant firms' investment performance will differ depending on the existence of a patent. In particular, the current trend in strategic competition among firms that develop products by copying competitors' products to decrease R&D costs makes perfect competition difficult to achieve.

Hence, this research centers on addressing the optimal competition scenario for market participants using a game model with a range of scenarios. While we restrained from utilizing a symmetry model in order to enhance simplicity, the appropriateness of an asymmetry investment model is addressed. Also, we intend to argue that the model can be more realistically applied to various cases through performance analysis of competitive scenarios. Therefore, this research is intended to develop an asymmetric R&D investment game model applying to a range of scenarios. Recognizing the importance of R&D and patent competition in recent years, we also identify the situations that demand R&D investment based on competitors' strategic scenarios[4]. This could help firms make informed investment decisions in response to competing firm's

3 Zhang (2012) designed an experiment to verify the findings of asymmetric R&D investment model and empirically showed how decision-makers decide R&D investment.

4 A variety of competitive strategies are available, as a firm's performance relies on the existence of patent protection, and investment plans are dependent on competitors' plans for R&D investment. Therefore, strategic utilization of R&D investment and patent in order to maximize both firms' profits will be addressed.

strategies. In other words, it is to establish investment plans that maximize profit dependent on given situations.

The remainder of this paper is organized as follows. The next section provides an important summary of prior work on firms' symmetric and asymmetric R&D investment. Also included in the literature review is a comparison of the presence and absence of patent protection in competition. Sections 3 presents the model and methodology that will be followed to develop a reasonable solution to the research question: "What strategy enhances R&D incentives in duopoly competition?". In Section 4 mutually exclusive options such as R&D cooperation and technology licensing are presented along with the independent R&D investment. We report conclusion in Section 5.

2.2 Background and Literature Review

2.2.1 Background

Reckless R&D competition decreases productivity and competitiveness, which impacts firms' financial status and eventually places pressures on customers while R&D investment plays an important role in firms' competition, because new product development depends on R&D, and new products can affect firms' profits. Competition among firms includes a variety of forms, ranging from new product development to cost competition to patent competition. In fact, firms in competition with each other may suffer significant financial losses. The extreme case is a phenomenon called 'competition without winner'[5]. Some companies even give up investing in

[5] The productivity of R&D investment, including patents, has followed a continuous downward trend for three decades. (Source: WIPO Statistics Database, October 2011.)

new product development, which requires huge sums of money, and instead strategically imitate competing firms' products.

2.2.2 R&D investment and return

Conventional R&D investment research has mainly focused on R&D investment's positive effect on a firm's profitability. Roberts (2001), for example, explains that a firm can secure profits through innovation and restricting competitors' imitation activities.

R&D investment is one of the most important drivers for long-term economic growth. Without an understanding of its importance, R&D investment has been treated as less important than capital expenditures, and it is assumed[6] that a firm can always raise enough funds for future or ongoing R&D projects in capital markets. With the more plausible assumption that R&D firms face financial constraints which affect new or ongoing projects, Li (2011) studies the relationship between financial constraints and R&D investment on expected returns. He used a sample of R&D-reporting firms with Fama-MacBeth (1973) cross-sectional regressions and shows that financially constrained firms had a high R&D-return relation.

2.2.3 R&D Investment Competition with Patent

R&D investment and patent competition have not been examined under realistic conditions in much research. Patent protection systems have long existed to protect intellectual property, including newly invented products. However, our expectations seem to have been challenged recently. Some industries, such as computer and software, have been very innovative, even

[6] Berk, Green, and Naik (2004).

though there has been weak patent protection (Bessen and Maskin, 2002; Bessen and Hunt, 2004). In such industries, although imitation reduces some firms' current profits, imitation may spur innovation and may lead to more efficient R&D processes (Fershtman and Markovich, 2006).

2.2.3.1 Symmetric Conditions for R&D and Patent Achievement

Recently, firms face difficult situations in which they are forced to pay to compete with each other not only with products, but also with patents and R&D investment. In a patent system, a patent holder receives the exclusive rights for the patented product and takes all benefits for a certain period of time (Weeds, 2002). So firms necessarily invest in R&D and file patents to secure stable benefits. In a situation where several firms make a claim to the same invention, R&D competition is effectively brought into a tournament[7]. Assuming that competing firms' have an equal probability of patent achievement and symmetric investment, and focusing on the rivalry of firms, Chowdhury (2005) studies how the tournament effect, which is the difference between the equilibrium payoffs of the firms in the presence and absence of patent protection when all firms engage in R&D, can affect incentives to engage in R&D[8]. Given the fact that the ultimate purpose of a firm is to make a profit, there could be many firms that try to imitate or invent around a patented product, which requires less money than developing a new product. Interestingly, IT firms and semi-conductor firms have historically had weak patent protection, which has allowed rapid imitation of products (Bessen and Maskin, 2006). Firms are often

[7] When there is patent protection, only one firm can control the technology, whereas all firms can use the technology under the absence of patent protection (Chowdhury, 2005).

[8] In a duopoly market and conditions of symmetric R&D investment, Chowdhury (2005) analyzed competing firms' payoffs based on whether there was patent protection and showed that patent protection has a positive effect on R&D incentives but may also have negative effects, such as reducing R&D investment and licensing.

confronted with a situation in which their competitors strategically imitate their products or develop superior products around their patents (Tirole, 1988).

2.2.3.2 Relaxed Condition for R&D Competition

2.2.3.2.1 Invention around a Patent

There is research that includes an assumption to account for invention around a patent in order to reflect a more realistic portrayal of competition among firms. Relaxing a model that does not allow for imitation under patent protection[9], Mukherjee (2006) assumes that R&D provides critical knowledge about innovative technology,[10] and even non-patent holders[11] can invent around patented technology through investment. No matter how patent protection is secured in the market, there may be non-infringing imitation through personnel movement across firms or intentional technology licensing. Making the more realistic assumption that invention around a patent is possible, he shows that the effects of imitation or technology licensing may dominate the tournament effect and create higher R&D investment under patent protection.

2.2.3.2.2 Cooperation

Unlike studies that describe firms' strategic competition in R&D investment stages, Che and Yang (2012) incorporate a cooperative R&D option into the first stage of competition with patent protection to encourage R&D incentives. In a two-stage game model in which firms

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[9] Chowdhury (2005).
[10] He assumed that the non-innovating firm cannot take the full benefit of the innovative technology through imitation.
[11] Under bilateral R&D where both firms engage in R&D, each firm has a fifty percent probability of getting the patent, and the non-patent holder can imitate the technology by investing money and reducing marginal costs.

simultaneously decide whether to invest in R&D or not in stage 1, and engage in Cournot competition in stage 2, they added the assumption of choice of cooperative R&D[12] in stage 1. In the sense that cooperative R&D between competing firms would be plausible in reality, firms can strategically decide to cooperate instead of independently investing in R&D. They show that when there is a cooperative R&D investment option, patent protection always increases the R&D incentive, irrespective of the tournament effect.

2.2.3.3 Asymmetric Conditions for R&D

Though the study above[13] had interesting results regarding the relationship between R&D investment and patent protection, one of the assumptions—symmetric R&D investment in the first stage of the game—might not be realistic when it is applied to industry. There have been many studies that assume asymmetric condition in firms' R&D capabilities, because firms experience different situations in reality[14]. Imperfect competition spurred Pawlina and Kort (2002) to study an asymmetric duopoly where the costs of exercising options differ among firms[15] and analyze a situation in which two firms have an opportunity to invest in a profit enhancing investment project and face different (effective) investment costs. Considering the first-mover advantage as well as the impact of uncertainty on optimal investment thresholds, they show how firms act strategically depending on the level of asymmetry and market conditions, and derive the relationship between the type of equilibrium and the level of consumer surplus.

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[12] In the case of cooperation, firms share the investment cost equally, reducing each firm's marginal cost from c to c′ ($c > c'$).
[13] Che & Yang (2012).
[14] Competing firms are different in size and capacity including many different characteristics, such as brand awareness and broad supply chain power. In particular, there might be a case in which small or medium-sized businesses compete with large companies for a specific product.
[15] Two firms' investment costs are asymmetric and one has a cost advantage over another.

Fershtman and Markovich (2010) consider dynamic processes of R&D investment in which firms can change their R&D investments over several intermediate stages based on their relative success in the R&D "race." Arguing that firms are not necessarily symmetric in their R&D abilities, they capture the asymmetry by allowing for different cost profiles and fin that a weak patent protection regime in the form of complete technology imitation may provide higher consumer surplus and higher value for firms than a strong patent regime.

In short, while research in R&D investment is active, ranging from quantitative analysis on the performance of R&D to theoretical examination of firms' competition behavior through strategic and dynamic models, research dealing with in-depth investigation that explains complex competition with a realistic perspective is relatively scant. Moreover, the current models of competition are unable to predict extremely strategic and intelligent firm competition or provide a theoretical explanation for patent competition, indicating the lack of cost-effective ways for firms to competition. Synthesizing the above, this research implements asymmetric game competition in an effort to fill a gap left by research studies that use symmetric models.

2.3 Model

2.3.1 Asymmetric R&D Investment Game Model with Patent

To accommodate the more realistic industry cases, we compare two game models whose assumptions are symmetric[16] and asymmetric R&D investment, respectively. Specifically, we compare the payoffs that the firms receive based on their game strategy. To set up the model, we suppose a duopoly market consisting of two competing firms and producing a homogeneous

[16] Chowdhury (2005), Mukherjee (2006) and Che and Yang (2012).

product. Following Chowdhury (2005), we let q_i be the output of firm i and $f(q)$ be the inverse market demand function, where $q = q1 + q2$ and satisfies $f' < 0$ and $f'(q) + q_i f''(q) < 0, \forall q, q_i$.

We denote the cost function and the profit function of each firm i as cq and $\pi i(.,.)$, where the first (second) argument shows Firm 1 (Firm 2)'s marginal cost. The cost function of each firm can be improved by investing F (F>0) in R&D. For example, when Firm 1 (Firm 2) invests F in R&D, the initial cost function of Firm 1(Firm2), the cq, becomes $c'q$, where $0 \le c' \le c$. Now, we define the terms that play an important role in the following models. The (non)strategic incentive for R&D is firm's payoff difference between conducting R&D and not conducting R&D cases when the other firm is (not) conducting R&D[17].

It is hard to make a strong assumption that equal levels of investment can be made without sharing information. Also, the cost function reflecting the two firms' competing conditions differ, which requires the model to assume that the firms will have cost functions and additional cost in the development of asymmetric model for R&D investment. When patent protection around invention is feasible due to investment, and when the level of brand reputation and the distribution network are different (asymmetric), the cost function incorporates that fact, thereby enabling the modeling of more varied competition situations. Thus, we assume in our model the asymmetric R&D investment game situation where each firm decides whether to invest in R&D or not in the first stage of the game and one firm invests in R&D more than the other firm so that the company investing more receives a cost benefit[18].

To describe the asymmetric investment in R&D, we assume that Firm 1 has a better cost function than Firm 2. That can be either changes of conditions including the brand reputation or

[17] Chowdhury (2005).
[18] We add c'' to the cost function to describe the effect of asymmetry in R&D investment, where $c'' < c' < \hat{c} \le c$.

distribution and supply chain or firms' efforts to make profit through asymmetric R&D investments. For a more realistic approach[19], we assume that the lower the cost, the better the profit (payoff), and that there is a cost-benefit for more R&D investment, so that we have the following ranking:

$$\pi_1(c'',c) = \pi_2(c,c'') > \pi_1(c',c) > \pi_1(\hat{c},c) > \pi_1(c,c)$$

and $$\pi_1(c'',c'') = \pi_2(c'',c'') \geq \pi_1(c',c') \geq \pi_1(\hat{c},\hat{c}) \geq \pi_1(c,c)$$

By adding the cost-benefit to asymmetric investment, the assumptions made in Mukherjee (2006) have been updated to reflect this change. Such assumptions include that each firm improves its marginal cost to $c''q$ without patent protection in a bilateral R&D situation where two firms invest in R&D. And, the firm reduces its cost to; $c''q$ (Firm 1) or $c'q$ (Firm 2), and knowledge spillover reduces the non-innovating firm's cost to $\hat{c}q$ when there is no patent protection and a unilateral R&D situation in which only one firm invests in R&D. Furthermore, when allowing for the concept of non-infringing imitation, the non-patent holder can have the patented technology without infringement with probability z. Each firm achieves patent with a probability of 0.5 in a bilateral R&D situation under patent protection. On the other hand, investing I causes the non-patent holder to imitate the patented technology with probability z and reduce the marginal cost up to the patent holder's cost. If Firm 1 is a patent holder, Firm 2 can produce with marginal cost c'' by investing I, and if Firm 2 is a patent holder, Firm 1 produces with marginal cost c'. Also, the marginal costs of the innovating firms are denoted as c'' (Firm 1) and c' (Firm 2) and non-innovating firms are c with no imitation under patent

[19] It is natural that a firm investing more on R&D can have a cost benefit over the other firm in duopoly competition.

protection and in a unilateral R&D situation. In contrast, the non-innovating firm decreases its marginal cost to $\hat{c}$ with probability z, through imitation.

The possible forms of competition between the two firms are considered in the game model, and the payoffs each firm would receive are described in the tables below. Tables 2.1 and 2.2 illustrate the game performance for two competing firms under no patent protection in both symmetric and asymmetric assumptions.

Table 2.1: Payoffs under no patent protection with symmetric R&D investment[20].

Firm 1/2	Symmetric R&D	No R&D
Symmetric R&D	$\pi_1(c',c')-F, \pi_2(c',c')-F$	$\pi_1(c',\hat{c})-F, \pi_2(c',\hat{c})$
No R&D	$\pi_1(\hat{c},c'), \pi_2(\hat{c},c')-F$	$\pi_1(c,c), \pi_2(c,c)$

Table 2.2: Payoffs under no patent protection with asymmetric R&D investment.

Firm 1/2	Asymmetric R&D	No R&D
Asymmetric R&D	$\pi_1(c'',c'')-kF, \pi_2(c'',c'')-F$	$\pi_1(c'',\hat{c})-kF, \pi_2(c'',\hat{c})$
No R&D	$\pi_1(\hat{c},c'), \pi_2(\hat{c},c')-F$	$\pi_1(c,c), \pi_2(c,c)$

We also assume that both firms can take benefits by investing simultaneously in R&D so that the followings are natural : $\pi(c',c')-\pi(c,c)\geq F$ and $\pi(c'',c'')-\pi(c,c)\geq kF$.

With the tables above, we solve the asymmetric game by backward induction to get the payoffs in the absence and presence of patent protection. The non-strategic and strategic incentives for R&D described in Chowdhury (2005) were applied. Knowing that the firms strive to maximize

[20] Chowdhury (2005).

profits and make strategic choices, we compare R&D investment incentive in the firms' choices with a focus on addressing unveiled motives and possible forms of strategic competition. The results are addressed in Table 2.2. Strategic or non-strategic R&D incentives come from the different decisions as to whether the firm invests in R&D or not, including the situations where a competing firm invests in R&D or does not invest in R&D. Tables 2.3 and 2.4 show the non-strategic and strategic incentives for R&D for the two competing firms; 1 and 2 with the categories of symmetric and asymmetric models.

Table 2.3: Firm 1's non-strategic and strategic incentives for R&D under no patent protection.

Firm 1	Non-strategic incentive	Strategic incentive
Symmetric	$\pi_1(c',\hat{c}) - \pi_1(c,c) - F$	$\pi_1(c',c') - \pi_1(\hat{c},c') - F$
Asymmetric	$\pi_1(c'',\hat{c}) - \pi_1(c,c) - kF$	$\pi_1(c'',c'') - \pi_1(\hat{c},c') - kF$

Table 2.4: Firm2's non-strategic and strategic incentives for R&D under no patent protection.

Firm 2	Non-strategic incentive	Strategic incentive
Symmetric	$\pi_2(\hat{c},c') - \pi_2(c,c) - F$	$\pi_2(c',c') - \pi_2(c',\hat{c}) - F$
Asymmetric	$\pi_2(\hat{c},c') - \pi_2(c,c) - F$	$\pi_2(c'',c'') - \pi_2(c'',\hat{c}) - F$

Given $\pi_1(c'',c'') - \pi_1(c,c) \geq kF$ and the ranks in profit function, we have $N(NP)_i, S(NP)_i \geq 0$, where $i = 1,2$ [21]. So, the asymmetric R&D investment game model has equilibrium when both firms invest in R&D.

[21] Following Chowdhury (2005), N, S, (NP), and (P) represent non-strategic incentive, strategic incentive, no patent, and patent, respectively.

We shall take a look at the non-strategic and strategic incentives for R&D described in Tables 2.3 and 2.4 from the perspectives of Firms 1 and 2. First, Firm 1's non-strategic incentive makes more benefits, as much as $\pi_1(c'',\hat{c}) - \pi_1(c',\hat{c}) - F(k-1)$, and its strategic incentive makes benefits $\pi_1(c'',c'') - \pi_1(c',c') - F(k-1)$, which are greater than the ones from the symmetric R&D investment[22] situation, respectively. The difference is noted as $\pi_1(c'',c'') - \pi_1(c',c') \geq F(k-1)$[23].

In the asymmetric case in which one firm has a superior position in brand image or distribution network or has a better enhancement of additional stock price due to R&D investment, the profits from modification of the cost function are greater than the amount of the original investment. Therefore, Firm 1 prefers an asymmetric R&D investment game strategy regardless of the competing firm's R&D investment under no patent protection.

In contrast, Firm 2 shows no difference in payoff between asymmetric and symmetric competitions with the non-strategic incentive. And strategic R&D inventive is higher in the asymmetric R&D investment game model[24]:

$$S(NP)_{A2} - S(NP)_{S2} = [\pi_2(c'',c'') - \pi_2(c',c')] + [\pi_2(c',\hat{c}) - \pi_2(c'',\hat{c})] \qquad (2.1)$$

It is easy to see that Eq.(2.1) > 0; the first and second brackets have positive values so that $S(NP)_{A2} > S(NP)_{S2}$; indicating that firm 2 is more advantageous when the competing firm invests in R&D when having no patent protection. When both firms prefer asymmetric competition, we

[22] Mukherjee (2006).
[23] It depends on how we define a cost function of a firm. That is to say, modifying cost function is larger than asymmetric investment when one expects enhancement of brand image or additional stock price due to R&D investment.
[24] Subscripted A2 and S2 represent asymmetric and symmetric R&D game model for firm 2, respectively.

envision that asymmetric game model is better able to explain strategic corporate choices and performance in the market where no patent protection is available.

Let us now take a look at the tables below to see if the payoffs from the game competition under patent protection make any difference in the above results. Table 2.5 and Table 2.6 illustrate the payoffs from symmetric and asymmetric R&D investment models respectively.

Table 2.5: Payoffs under patent protection with symmetric R&D investment[25].

Firm 1 / 2	Symmetric R&D	No R&D
Symmetric R&D	$z\pi_1(c',c') + \frac{(1-z)(\pi_1(c',c)+\pi_1(c,c'))}{2} - F - \frac{I}{2}$, $z\pi_2(c',c') + \frac{(1-z)(\pi_2(c,c')+\pi_2(c',c))}{2} - F - \frac{I}{2}$	$z\pi_1(c',\hat{c}) + (1-z)\pi_1(c',c) - F$, $z\pi_2(c',\hat{c}) + (1-z)\pi_2(c',c) - I$
No R&D	$z\pi_1(\hat{c},c') + (1-z)\pi_1(c,c') - I$, $z\pi_2(\hat{c},c') + (1-z)\pi_2(c,c') - F$	$\pi_1(c,c), \pi_2(c,c)$

Table 2.6: Payoffs under patent protection with asymmetric R&D investment.

Firm 1/2	Asymmetric R&D	No R&D
Asymmetric R&D	$\frac{z(\pi_1(c'',c'')+\pi_1(c',c'))}{2} + \frac{(1-z)(\pi_1(c'',c)+\pi_1(c,c'))}{2} - kF - \frac{I}{2}$, $\frac{z(\pi_2(c'',c'')+\pi_2(c',c'))}{2} + \frac{(1-z)(\pi_2(c,c')+\pi_2(c'',c))}{2} - F - \frac{I}{2}$	$z\pi_1(c'',\hat{c}) + (1-z)\pi_1(c'',c) - kF$, $z\pi_2(c'',\hat{c}) + (1-z)\pi_2(c'',c) - I$
No R&D	$z\pi_1(\hat{c},c') + (1-z)\pi_1(c,c') - I$, $z\pi_2(\hat{c},c') + (1-z)\pi_2(c,c') - F$	$\pi_1(c,c), \pi_2(c,c)$

In the same sense, the following categorizes anticipated results of the firms' competition under patent protection. A non-strategic incentive and strategic incentive are described.

Tables 2.7 and 2.8 show non-strategic and strategic incentives for R&D of the Firms 1 and 2 under patent protection.

[25] Following Mukherjee (2006), we also use the concept of non-infringing imitation.

Table 2.7: Firm 1's non-strategic and strategic incentives for R&D under patent protection.

	Non-strategic incentive	Strategic incentive
Symmetric	$z\pi_1(c',\hat{c})+(1-z)\pi_1(c',c)-\pi_1(c,c)-F$	$\frac{2z(\pi_1(c',c')-\pi_2(\hat{c},c'))+(1-z)(\pi_1(c',c)-\pi_1(c,c'))}{2}-F+\frac{I}{2}$
Asymmetric	$z\pi_1(c'',\hat{c})+(1-z)\pi_1(c'',c)-kF-\pi_1(c,c)$	$\frac{z(\pi_1(c'',c'')+\pi_1(c',c'))}{2}+\frac{(1-z)(\pi_1(c'',c)+\pi_1(c,c'))}{2}$ $-kF-\frac{I}{2}-[z\pi_1(\hat{c},c')+(1-z)\pi_1(c,c')-I]$

Table 2.8: Firm 2's non-strategic and strategic incentives for R&D under patent protection.

	Non-strategic incentive	Strategic incentive
Symmetric	$z\pi_2(\hat{c},c')+(1-z)\pi_2(c,c')-F-\pi_2(c,c)$	$\frac{2z(\pi_2(c',c')-\pi_2(c',\hat{c}))+(1-z)(\pi_2(c,c')-\pi_2(c',c))}{2}-F+\frac{I}{2}$
Asymmetric	$z\pi_2(\hat{c},c')+(1-z)\pi_2(c,c')-F-\pi_2(c,c)$	$\frac{z(\pi_2(c'',c'')+\pi_2(c',c'))}{2}+\frac{(1-z)(\pi_2(c,c')+\pi_2(c'',c))}{2}$ $-F-\frac{I}{2}-[z\pi_2(c'',\hat{c})+(1-z)\pi_2(c'',c)-I]$

Firm 1's non-strategic and strategic incentives for R&D investment differ from the asymmetric R&D game models as:

$$N(P)_{A1}-N(P)_{S1}=z(\pi_1(c'',\hat{c})-\pi_1(c',\hat{c}))+(1-z)(\pi_1(c'',c)-\pi_1(c',c))-F(k-1) \tag{2.2}$$

and

$$S(P)_{A1}-S(P)_{S1}=\frac{z(\pi_1(c'',c'')-\pi_1(c',c'))}{2}+\frac{(1-z)(\pi_1(c'',c)-\pi_1(c',c))}{2}-F(k-1). \tag{2.3}$$

From the equations above, we see that Eq.(2.2) > 0 because $\pi_1(c'',\hat{c})-\pi_1(c',\hat{c})>0$ and $\pi_1(c'',c)-\pi_1(c',c)>0$. It is also easy to see that Eq.(2.3) > 0 because $\pi_1(c'',c'')-\pi_1(c',c')>0$. Firm 1 is shown to take advantage by utilizing an asymmetric strategy when the profit modification effect through cost function is larger than the asymmetric investment. This leads to the conclusion that Firm 1 would choose asymmetric competition regardless of the competing firm's R&D investment.

As shown in Tables 2.7 and 2.8, given hierarchical condition such as $\pi_1(c'',c'') - \pi_1(c,c) \ge kF$ and the rankings in profit function make $N(P)_i, S(P)_i \ge 0$, where $i = 1,2$. So, the asymmetric R&D game model under patent protection also shows an equilibrium when both firms invest in R&D.

The non-strategic incentive for Firm 2 is shown no difference between asymmetric and symmetric models, whereas the strategic R&D incentive is described as

$$S(P)_{A2} - S(P)_{S2} = z(\pi_2(c',\hat{c}) - \pi_2(c'',\hat{c})) + \frac{z(\pi_2(c'',c'') - \pi_2(c',c'))}{2} - \frac{(1-z)(\pi_2(c'',c) + \pi_2(c',c))}{2} \ge 0 \qquad (2.4)$$

; Eq.(2.4) ≥ 0, showing larger strategic R&D incentives in the asymmetric R&D investment game model. This causes firm 2 to prefer the asymmetric investment when Firm 1 conducts R&D. The results are shown in Table 2.9.

Table 2.9: Preferred investment type for each firm.

	No patent protection		Patent protection	
	Firm 1	Firm 2	Firm 1	Firm 2
Non-strategic	Asymmetric	Indifferent	Asymmetric	Indifferent
Strategic	Asymmetric	Asymmetric	Asymmetric	Asymmetric

As shown in Table 2.9, the asymmetric model generally demonstrates better R&D incentives whether or not there is patent protection. In comparison to the symmetric R&D game situation, explaining firms' strategic competition with the asymmetric R&D investment game model is more realistic[26] due to the competition's profit in response to the firms' choices. Therefore, the next section will address a wide range of cases and situations using asymmetric models.

2.4 Which Option to Choose; R&D Cooperation or Technology Licensing?

2.4.1 R&D Cooperation Option

There will be diversity in competition scenarios for two firms in asymmetric investment situations. One of the scenarios is cooperation[27] in R&D for mutual benefits. For example, two unequal-sized firms consider investing in the same product, but they are both hesitant to decide on the investment because of the investment risk. The investment is not guaranteed to achieve the intended goals, and the other firm can emulate the results of R&D. This leads to another possibility, a cooperative R&D investment.

Cooperation in R&D refers to a situation in which two firms make a cooperative investment in R&D for the same product and split the profit from technology as a result of R&D. With this in mind, we analyze asymmetric investment game models in addressing a range of situations regarding the benefit from cooperative R&D and from asymmetric R&D in which cost and risk are involved as well as in those situations in which firms should choose cooperative R&D. We also analyze an asymmetric model with the degree of benefits involved.

In our asymmetric R&D investment game model, two firms decide on whether to invest in R&D cooperatively or not in the first stage and compete for payoff in the second stage. In the case of the former, the two firms invest in a cooperative manner and share the profits from the

[26] Assuming the two firms' cost functions are the same in the asymmetric R&D game model, $k = 0$ refers to the symmetric R&D game condition.
[27] Che and Yang (2012).

R&D investment. We assume that this cooperative relationship does not cause patent competition, suggesting the presence or absence of patent protection would have no effect. However, in the case of unilateral R&D investment, we believe there would be competition for patents and that the existence of patent protection would affect the results of the competition. The result of game competition for the two firms, including cooperative R&D, is illustrated in Table 2.10 (no patent protection) and Table 2.11 (patent protection). With these two tables, Table 2.12 shows each firm's strategic incentive depending on whether the firms have patent protection or not.

Table 2.10: Payoffs under no patent protection with R&D cooperation.

Firm 1/2	R&D cooperation	No R&D
R&D cooperation	$\frac{\pi_1(c'',c'')+\pi_1(c',c')}{2}-\frac{(k+1)}{2}F, \frac{\pi_2(c'',c'')+\pi_2(c',c')}{2}-\frac{(k+1)}{2}F$	$\pi_1(c'',\hat{c})-kF, \pi_2(c'',\hat{c})$
No R&D	$\pi_1(\hat{c},c'), \pi_2(\hat{c},c')-F$	$\pi_1(c,c), \pi_2(c,c)$

Table 2.11: Payoffs under patent protection with R&D cooperation.

Firm 1/2	R&D cooperation	No R&D
R&D cooperation	$\frac{\pi_1(c'',c'')+\pi_1(c',c')}{2}-\frac{(k+1)}{2}F, \frac{\pi_2(c'',c'')+\pi_2(c',c')}{2}-\frac{(k+1)}{2}F$	$z\pi_1(c'',\hat{c})+(1-z)\pi_1(c'',c)-kF,$ $z\pi_2(c'',\hat{c})+(1-z)\pi_2(c'',c)-I$
No R&D	$z\pi_1(\hat{c},c')+(1-z)\pi_1(c,c')-I,$ $z\pi_2(\hat{c},c')+(1-z)\pi_2(c,c')-F$	$\pi_1(c,c), \pi_2(c,c)$

Table 2.12: Strategic incentives for R&D cooperation with or without patent protection.

	Without patent protection	With patent protection
Firm 1	$\frac{\pi_1(c'',c'')+\pi_1(c',c')}{2}-\pi_1(\hat{c},c')-\frac{(k+1)}{2}F$	$\frac{\pi_1(c'',c'')+\pi_1(c',c')}{2}-\frac{(k+1)}{2}F-[z\pi_1(\hat{c},c')+(1-z)\pi_1(c,c')-I]$
Firm 2	$\frac{\pi_2(c'',c'')+\pi_2(c',c')}{2}-\pi_2(c'',\hat{c})-\frac{(k+1)}{2}F$	$\frac{\pi_2(c'',c'')+\pi_2(c',c')}{2}-\frac{(k+1)}{2}F-[z\pi_2(c'',\hat{c})+(1-z)\pi_2(c'',c)-I]$

As shown in Table 2.10 and Table 2.11, if firms choose R&D cooperation, we can expect cooperative R&D investment as $\frac{(k+1)}{2}F$, and also anticipate benefits as $\frac{\pi_1(c'',c'')+\pi_1(c',c')}{2}$, which is the average of expected performances with unilateral R&D.

If firms invest in R&D bilaterally, or do not invest at all in R&D, an identical payoff described in asymmetric model (Table 2.1) is expected with no changes in non-strategic incentives. Without patent protection, the following formulas show a comparison between strategic incentives from bilateral investment and strategic incentives from R&D cooperation[28]:

$$S(NPC)_1-S(NP)_1=\frac{\pi_1(c',c')-\pi_1(c'',c'')+(k-1)F}{2} \quad (2.5)$$

and

$$S(NPC)_2-S(NP)_2=\frac{\pi_2(c',c')-\pi_2(c'',c'')-(k-1)F}{2} \quad . \quad (2.6)$$

Proposition 1. *There is an incentive for the superior firm to take R&D cooperation if there is R&D investment from the opposite firm and no patent protection expected.*

[28] N refers to non-strategic whereas S means strategic incentive, and NPC in parentheses indicates no patent protection with cooperative R&D, and PC refers to patent protection with cooperative R&D.

Proof. Given $\pi(c',c') - \pi(c,c) \geq F$ and $\pi(c'',c'') - \pi(c,c) \geq kF$, we identified Eq.(2.5) ≥ 0 and Eq.(2.6) < 0. Therefore, without patent protection bilateral competition for Firm 1 (2) shows a larger (less) strategic incentive than R&D cooperation. In other words, R&D cooperation is more likely to happen while anticipating inferior firms' R&D investment in the case of no patent protection.

The next set of formulas describes situations where patent protection is available. From the Table 2.12 showing non-strategic and strategic incentives for R&D, we compare the strategic incentives depending on the existence of R&D cooperation:

$$S(PC)_1 - S(P)_1 = \frac{\pi_1(c'',c'') + \pi_1(c',c')}{2} - \frac{z(\pi_1(c'',c'') + \pi_1(c',c'))}{2} - \frac{(1-z)(\pi_1(c'',c) + \pi_1(c,c'))}{2} + \frac{(k-1)}{2}F + \frac{I}{2} \qquad (2.7)$$

and

$$S(PC)_2 - S(P)_2 = \frac{\pi_2(c'',c'') + \pi_2(c',c')}{2} - \frac{z(\pi_2(c'',c'') + \pi_2(c',c'))}{2} - \frac{(1-z)(\pi_2(c,c') + \pi_2(c'',c))}{2} + \frac{(k-1)}{2}F + \frac{I}{2}. \qquad (2.8)$$

Proposition 2. *If non-infringing imitation is more likely, bilateral R&D competition under patent protection creates higher strategic R&D incentive for R&D cooperation than independent R&D investment.*

Proof. The results indicate that R&D cooperation leads to more strategic incentive than non-cooperative R&D investment. Specifically, it is evident that the z closer to 1 establishes Equations (2.7) > 0 and (2.8) > 0, meaning the larger probability of invention around technology increases strategic incentive for R&D cooperation.

Synthesizing the above, we believe that cooperation in R&D can be beneficial when patent protection is available, because R&D cooperation decreases the risk and pressure of patent competition, although lower profits are expected to be produced compared to bilateral R&D with no R&D cooperation available.

2.4.2 Licensing Option

Firms can achieve considerable benefits through R&D investment and acquisition of patents. When they release new products or technology onto the market, they can gain the sole selling rights via patent, which is central to firms' revenue. Hence, another strand of revenue from R&D investment centers on licensing. Firms use new technology and products through patent rights, which generate profits. This chapter addresses the effects of licensing on asymmetric competing situations, and suggests the contexts in which the firms with licensing contracts can have an advantage in comparison to R&D cooperation as well as to independent R&D investment.

2.4.2.1 Licensing with chance of non-infringing imitation around technology

Unlike Rockett (1990)'s assumption[29], we assume that a non-innovating firm is able to produce a non-infringing imitation. However, except for the opportunity for a perfect imitation of technology (z = 1) through investment (I), licensing loyalty is expected to be as great as the difference between the innovating firm (patent holder for bilateral R&D case) and the non-innovating firm (non-patent holder for bilateral R&D case) ($c'' - \hat{c}$ or $c' - \hat{c}$). Hence, we assume[30] that a licensing contract between the innovating firm and the non-innovating firm is per

[29] In order for firms to imitate without violating infringement, significant amount of cost is required and thus unable to justify imitation investment. This imitation is considered unprofitable.
[30] Mukherjee (2006) also assumed impossible imitation.

unit output royalty rather than up-front fixed fee. Tables 2.13 and 2.14 illustrate possible payoffs depending on whether or not patent protection is available.

Table 2.13: Payoffs under no patent protection with technology licensing.

Firm 1 / 2	R&D	No R&D
R&D	$\pi_1(c'',c'')-kF,\pi_2(c'',c'')-F$	$\pi_1(c'',\hat{c})+R(c'',\hat{c})-kF,\pi_2(c'',\hat{c})$
No R&D	$\pi_1(\hat{c},c'),\pi_2(\hat{c},c')+R(\hat{c},c')-F$	$\pi_1(c,c),\pi_2(c,c)$

Table 2.14: Payoffs under patent protection with technology licensing.

Firm 1 / 2	Payoffs
R&D / R&D	$\frac{z(\pi_1(c'',c'')+\pi_1(c',c'))}{2}+\frac{(1-z)(\pi_1(c'',c)+\pi_1(c,c')+R(c'',c))}{2}-kF-\frac{I}{2},$ $\frac{z(\pi_2(c'',c'')+\pi_2(c',c'))}{2}+\frac{(1-z)(\pi_2(c,c')+\pi_2(c'',c)+R(c,c'))}{2}-F-\frac{I}{2}$
R&D / No R&D	$z(\pi_1(c'',\hat{c})+R(c'',\hat{c}))+(1-z)(\pi_1(c'',c)+R(c'',c))-kF,$ $z\pi_2(c'',\hat{c})+(1-z)\pi_2(c'',c)-I$
No R&D / R&D	$z\pi_1(\hat{c},c')+(1-z)\pi_1(c,c')-I,$ $z(\pi_2(\hat{c},c')+R(\hat{c},c'))+(1-z)(\pi_2(c,c')+R(c,c'))-F$
No R&D / No R&D	$\pi_1(c,c),\pi_2(c,c)$

As seen in Table 2.13, a licensing contract is not likely to materialize because of unlimited technology imitation without patent protection. However, if one firm invests in R&D and has the licensing right, then more revenues are generated $R(c'',\hat{c})$ when Firm 1 is the patent holder and $R(\hat{c}, c')$ when Firm 2 is the patent holder, and this increases the two firms' non-strategic incentive. That is, they can expect a higher non-strategic R&D incentive compared to those without licensing. Under the patent protection and with both firms involved in R&D, the non-patent holder contracts for the technology with the chance of non-infringing imitation by investing I, the profits for firms 1 and 2 are

$\frac{z(\pi_1(c'',c'')+\pi_1(c',c'))}{2}+\frac{(1-z)(\pi_1(c'',c)+\pi_1(c,c')+R(c'',c))}{2}-kF-\frac{I}{2}$ and

$\frac{z(\pi_2(c'',c'')+\pi_2(c',c'))}{2}+\frac{(1-z)(\pi_2(c,c')+\pi_2(c'',c)+R(c,c'))}{2}-F-\frac{I}{2}$, respectively.

From the Tables 2.3 and 2.4 showing non-strategic and strategic incentives for R&D, we compare the non-strategic and strategic incentives depending on the existence of technology licensing option:

$$N(PL)_1 - N(P)_1 = zR(c'',\hat{c}) + (1-z)R(c'',c) \quad (2.9)$$

$$N(PL)_2 - N(P)_2 = zR(\hat{c},c') + (1-z)R(c,c') \quad (2.10)$$

$$S(PL)_1 - S(P)_1 = \frac{(1-z)R(c'',c)}{2} \quad (2.11)$$

$$S(PL)_2 - S(P)_2 = \frac{(1-z)R(c,c')}{2} \quad (2.12)$$

In the case of unilateral R&D, the competing firm does not invest in R&D, leading the innovating firm to create more profits through a license contract than the non-innovating firm.

Proposition 3. *Under patent protection, technology licensing creates higher strategic and non-strategic R&D incentives than without licensing for the both firms.*

Unlike the situation without patent protection, in the case of bilateral R&D and unilateral R&D with patent protection, the non-patent holder (bilateral R&D case) or non-innovating firm (unilateral R&D case) can transfer technology via licensing. The extent of the difference in the level of technology is decided by comparing technology around invention achieved from I investment and patent holder's perfect level of technology. Therefore, firms with license rights make more profits by letting firms without licenses utilize the technology. As a proof, the Equations[31] (2.9), (2.10), (2.11) and (2.12) ≥ 0; $N(PL)_i > N(P)_i$ and $S(PL)_i \geq S(P)_i$, where $i = 1,2$ indicate larger strategic and non-strategic R&D incentives with licensing than without licensing[32].

2.4.2.2 The Comparison of Licensing with R&D Cooperation

Based on our discussion above, two situations in which licensing that increases R&D incentive and R&D cooperation are compared. In the case of a bilateral R&D scenario, selection of licensing and R&D cooperation is mutually exclusive in nature, limited to only one possible selection. Therefore, it is worth comparing how two firms make a strategic decision based on whether they have patent protection or not.

First, let's examine two competing firms' strategies for the selection of technology licensing and R&D cooperation without patent protection. The differences between two firms' strategic and non-strategic R&D incentives are addressed as follows:

[31] N refers to non-strategic whereas S means strategic incentive, and PL in parentheses indicates patent protection with technology licensing.

[32] To focus better on the comparison between the R&D cooperation and technology licensing options, I only showed the results of the patent protection case. The non-strategic incentives when there is no patent protection provided are the same as $N(NPL)_i > N(NP)_i$ where $i = 1,2$.

$$N(NPL)_1 - N(NPC)_1 = R(c'',\hat{c}), \tag{2.13}$$

$$N(NPL)_2 - N(NPC)_2 = R(\hat{c},c'), \tag{2.14}$$

$$S(NPL)_1 - S(NPC)_1 = \frac{\pi_1(c'',c'') - \pi_1(c',c') + (1-k)F}{2}, \tag{2.15}$$

and

$$S(NPL)_2 - S(NPC)_2 = \frac{\pi_2(c'',c'') - \pi_2(c',c') + (k-1)F}{2}. \tag{2.16}$$

Obviously, Equations (2.13), (2.14) and (2.15) > 0 but (2.16) ≥ or ≤ 0 (ambiguous); inferior firms can expect higher non-strategic incentive and strategic incentive with technology licensing rather than with cooperative R&D[33], whereas superior firms can have higher strategic R&D incentive with R&D cooperation rather than with licensing.

Below is an illustration of strategies for the selection of technology licensing and R&D cooperation with patent protection. The difference between two firms' strategic and non-strategic incentive is addressed as follows:

$$N(PL)_1 - N(PC)_1 = zR(c'',\hat{c}) + (1-z)R(c'',c) \tag{2.17}$$

$$N(PL)_2 - N(PC)_2 = zR(\hat{c},c') + (1-z)R(c,c'), \tag{2.18}$$

$$S(PL)_1 - S(PC)_1 = \frac{(1-z)[\pi_1(c'',c) - \pi_1(c'',c'') + \pi_1(c,c') - \pi_1(c',c') + R(c'',c)]}{2} + \frac{(1-k)F - I}{2}, \tag{2.19}$$

and

$$S(PL)_2 - S(PC)_2 = \frac{(1-z)[\pi_2(c,c') - \pi_2(c'',c'') + \pi_2(c'',c) - \pi_2(c',c') + R(c,c')]}{2} + \frac{(k-1)F - I}{2}. \tag{2.20}$$

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33 For Firm 1, when asymmetric investment cost is relatively too much ($\pi_1(c'',c'') - \pi_1(c',c') < (1-k)F$), it is also possible that R&D cooperation can generate higher strategic incentive than licensing. That is because inefficient increase of investment offsets benefits developed from bilateral competitions.

Proposition 4. *Firms in asymmetric competition can expect higher non-strategic R&D incentives through technology licensing than R&D cooperation with patent protection.*

Proposition 5. *Firms can expect higher strategic R&D incentives through R&D cooperation than technology licensing with patent protection.*

As a proof, Equations (2.17) and (2.18) > 0; $N(PL)_i > N(PC)_i$, where $i = 1,2$ corroborates that licensing yields more non-strategic incentive than R&D cooperation. However, for strategic incentive, results can vary based on imitation opportunity (z) and investment cost (k). Specifically, this leads Firm 1 to have greater strategic incentive with R&D cooperation, and for Firm 2, with licensing. Even in the case of a low possibility of imitation, Firm 2 can still generate a greater strategic incentive, and Firm 1 can have various strategic incentives from licensing and R&D cooperation through royalty income $R(c", c)$ and k value of licensing. In sum, with the existence of patent protection, Firm 2 with an inferior cost function achieves a greater strategic and non-strategic R&D incentive through licensing than R&D cooperation in bilateral competition. In addition, Firm 1 with superior cost function is expected to have a greater R&D incentive through licensing except for the situation in which strategic incentive becomes ambiguous.[34]

[34] While Che and Yang(2012) states that royalty licensing can achieve higher non-strategic R&D incentive than R&D cooperation, strategic incentive for R&D becomes ambiguous strategic incentive.

2.5 Scenario Analysis

Since the asymmetric R&D game seems ineffective in identifying an analytical solution, as it indicates a non-deterministic variable relationship, all potentially realizable scenarios in which values are sampled within the range of the given conditions[35] are employed to develop and analyze two firms' incentives generated by R&D competition. Through analyses of the initial asymmetrical situation—brand names or firm size (k=1), additional asymmetric investment competition[36] (k>1), and non-infringing imitation based on respective scenarios—we can anticipate profit level and identify advantageous factors that are changed depending on various situations. If one could predict a competing firm's decisions in advance, firms with that information would able to make the optimal decisions for maximizing profit (assuming the profit gaps happen based on whether or not that information is available), indicating the value of investigating methods for obtaining rivalry firms' information.

Table 2.15[37]: R&D incentives based on the degree of asymmetry and non-infringing imitation.

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[35] Pre-assumed $\pi_1(c'',c) = \pi_2(c,c'') > \pi_1(c',c) > \pi_1(\hat{c},c) > \pi_1(c,c)$ and $\pi_1(c'',c'') = \pi_2(c'',c'') \geq \pi_1(c',c') \geq \pi_1(\hat{c},\hat{c}) \geq \pi_1(c,c)$ are given as the condition for rank, and over 1000 iteration, R&D incentives are compared depending on patent protection and other firms' strategies.

[36] As potential profits through additional asymmetry investment is limited (c''), this study compares k=2 as the maximum level.

[37] R&D incentive values generated by simulations require contextual interpretation as simulation incorporates the limitation of $1,000 in the case of the maximum profitable variables ($\pi_1(c'',c) = \pi_2(c,c'')$).

z	k	Independent R&D								R&D Cooperation								Licensing							
		1, N(NP)	2, N(NP)	1, S(NP)	2, S(NP)	1, N(P)	2, N(P)	1, S(P)	2, S(P)	1, N(NP)	2, N(NP)	1, S(NP)	2, S(NP)	1, N(P)	2, N(P)	1, S(P)	2, S(P)	1, N(NP)	2, N(NP)	1, S(NP)	2, S(NP)	1, N(P)	2, N(P)	1, S(P)	2, S(P)
0	1	426.13	253.14	248.30	421.85	481.56	372.47	331.32	330.88	426.13	253.14	248.30	421.85	481.56	372.47	370.56	478.78	514.95	324.66	248.30	421.85	575.92	455.92	378.50	372.61
0.2	1	421.37	248.14	243.50	416.04	468.71	345.62	315.40	348.17	421.37	248.14	243.50	416.04	468.71	345.62	347.70	467.16	510.01	319.45	243.50	416.04	562.09	426.69	353.23	381.57
0.4	1	423.33	245.60	247.72	422.90	457.13	318.32	293.52	364.54	423.33	245.60	247.72	422.90	457.13	318.32	324.13	463.82	512.43	316.93	247.72	422.90	549.61	396.91	321.94	389.58
0.6	1	416.18	251.42	247.87	418.50	438.89	296.24	272.22	374.52	416.18	251.42	247.87	418.50	438.89	296.24	298.42	444.46	504.38	323.15	247.87	418.50	529.38	372.45	290.99	391.11
0.8	1	419.17	252.08	248.87	419.57	431.73	273.74	256.90	393.43	419.17	252.08	248.87	419.57	431.73	273.74	279.17	440.00	507.82	324.02	248.87	419.57	521.63	347.85	266.39	401.71
1	1	431.87	249.56	246.56	411.42	431.87	249.56	234.74	399.60	431.87	249.56	246.56	411.42	431.87	249.56	253.52	418.38	521.16	320.61	246.56	411.42	521.16	320.61	234.74	399.60
0	2	338.55	245.87	176.35	420.32	398.86	357.81	255.12	329.61	338.55	245.87	213.85	382.82	398.86	282.81	337.57	452.61	426.42	241.96	176.35	345.32	492.76	440.10	302.07	370.76
0.2	2	348.62	240.92	165.10	405.08	389.40	337.44	233.00	341.20	348.62	240.92	202.60	367.58	389.40	262.44	298.42	422.26	437.47	236.49	165.10	330.08	482.33	417.67	270.58	374.26
0.4	2	341.64	248.68	174.78	416.49	378.76	312.66	218.76	355.80	341.64	248.68	212.28	378.99	378.76	237.66	287.27	418.59	429.75	245.00	174.78	341.49	470.59	390.38	247.05	380.40
0.6	2	339.28	241.57	165.94	405.74	363.10	288.48	196.76	369.82	339.28	241.57	203.44	368.24	363.10	213.48	259.24	402.47	427.41	237.43	165.94	330.74	453.61	364.02	215.58	386.33
0.8	2	363.30	262.93	182.35	426.72	373.22	286.68	188.20	398.52	363.30	262.93	219.85	389.22	373.22	211.68	247.36	403.76	453.30	260.39	182.35	351.72	464.21	361.52	197.70	406.96
1	2	341.08	249.20	175.18	419.90	341.08	249.20	168.32	413.03	341.08	249.20	212.68	382.40	341.08	174.20	225.03	394.74	429.60	246.03	175.18	344.90	429.60	321.03	168.32	413.03
0	3	274.85	254.36	106.82	417.43	326.52	366.81	182.82	335.79	274.85	254.36	181.82	342.43	326.52	216.81	301.15	416.80	364.31	176.76	106.82	267.43	421.15	450.46	230.13	377.61
0.2	3	260.00	243.49	93.63	416.40	307.16	332.85	160.19	342.99	260.00	243.49	168.63	341.40	307.16	182.85	272.30	394.37	348.49	165.34	93.63	266.40	400.37	413.63	197.95	376.20
0.4	3	263.38	251.70	100.61	429.98	296.43	318.09	142.71	370.21	263.38	251.70	175.61	354.98	296.43	168.09	253.19	400.09	352.17	174.32	100.61	279.98	388.52	397.35	171.00	395.31
0.6	3	268.98	250.01	89.40	414.35	292.50	294.71	117.18	373.03	268.98	250.01	164.40	339.35	292.50	144.71	214.97	368.12	357.56	171.69	89.40	264.35	383.44	370.86	136.07	389.60
0.8	3	264.84	245.97	102.09	420.10	276.89	267.65	110.42	393.51	264.84	245.97	177.09	345.10	276.89	117.65	208.67	364.59	352.93	167.17	102.09	270.10	366.18	341.02	119.83	401.71
1	3	271.12	236.94	102.16	422.55	271.12	236.94	91.34	411.74	271.12	236.94	177.16	347.55	271.12	86.94	184.42	354.82	360.59	157.98	102.16	272.55	360.59	307.98	91.34	411.74
0	4	208.50	253.40	25.81	414.02	261.55	370.24	111.15	330.77	208.50	253.40	138.31	301.52	261.55	145.24	262.44	368.00	297.72	99.61	25.81	189.02	356.07	453.13	158.41	372.22
0.2	4	204.25	263.26	37.88	422.21	248.94	350.96	91.88	348.27	204.25	263.26	150.38	309.71	248.94	125.96	242.69	363.38	293.40	110.82	37.88	197.21	342.57	432.29	129.78	381.67
0.4	4	207.87	260.25	19.90	403.11	244.92	327.07	72.01	354.63	207.87	260.25	132.40	290.61	244.92	102.07	207.70	333.45	296.53	106.65	19.90	178.11	337.29	405.15	100.46	379.39
0.6	4	204.16	253.99	22.16	412.98	225.17	301.96	49.66	376.82	204.16	253.99	134.66	300.48	225.17	76.96	186.77	334.70	293.96	101.27	22.16	187.98	317.08	379.04	68.68	393.68
0.8	4	202.85	251.15	16.78	405.39	215.58	273.76	29.36	383.74	202.85	251.15	129.28	292.89	215.58	48.76	161.96	315.29	291.03	96.66	16.78	180.39	305.04	346.54	38.81	391.92
1	4	192.82	248.76	26.90	419.40	192.82	248.76	16.92	409.42	192.82	248.76	139.40	306.90	192.82	23.76	148.99	316.49	281.60	95.63	26.90	194.40	281.60	320.63	16.92	409.42
0	5	153.84	271.22	-52.89	401.64	216.51	390.11	42.79	331.30	153.84	271.22	97.11	251.64	216.51	90.11	207.12	310.54	242.61	41.73	-52.89	101.64	311.55	472.51	90.31	372.50
0.2	5	142.85	270.30	-39.15	416.70	192.52	361.73	25.72	348.26	142.85	270.30	110.85	266.70	192.52	61.73	203.83	314.03	231.91	42.11	-39.15	116.70	286.55	442.68	63.83	381.56
0.4	5	143.47	270.34	-43.39	425.11	181.02	339.13	4.43	368.60	143.47	270.34	106.61	275.11	181.02	39.13	181.75	315.32	232.73	42.28	-43.39	125.11	274.04	417.96	33.09	393.62
0.6	5	141.89	262.85	-54.45	400.46	165.47	310.59	-24.59	365.67	141.89	262.85	95.56	250.46	165.47	10.59	146.49	281.53	230.60	33.66	-54.45	100.46	256.54	386.17	-5.67	382.22
0.8	5	145.21	266.68	-62.40	391.53	156.71	289.64	-50.42	371.69	145.21	266.68	87.60	241.53	156.71	-10.36	118.29	263.61	234.09	37.70	-62.40	91.53	246.75	362.96	-40.95	379.94
1	5	143.80	270.63	-30.30	421.60	143.80	270.63	-42.38	409.51	143.80	270.63	119.71	271.60	143.80	-29.38	125.59	277.48	232.64	42.15	-30.30	121.60	232.64	342.15	-42.38	409.51

2.5.1 Strategic and Non-strategic R&D Incentives

In order for firms to make a strategic decision, considering that the two factors' (k and z) influence on expected profit[38] is essential. Thus, illustrating the numerical data from the impact of the degree of asymmetry as well as non-infringing imitation probability on R&D incentives based on the simulation results will be helpful in supporting the propositions discussed in the model (Chapter 3).

2.5.1.1 Changes in Incentives for Competing Firms Depending on the Degree of Asymmetry

2.5.1.1.1 Independent R&D Investment[39] Case

Looking at the payoffs gained from the numerical simulation, R&D incentives (Table 2.16) and changes of R&D incentives in association with the degree of firms' asymmetry are addressed (Figure 2.1).

Table 2.16[40]: Changes in incentives depending on the degree of asymmetry (k).

k	1, N(NP)	2, N(NP)	1, S(NP)	2, S(NP)	1, N(P)	2, N(P)	1, S(P)	2, S(P)
1	423.01	249.99	247.13	418.38	451.65	309.32	284.02	368.52
2	345.41	248.19	173.28	415.71	374.07	305.38	210.03	368.00
3	267.19	247.08	99.12	420.13	295.10	302.84	134.11	371.21
4	203.41	255.13	24.90	412.85	231.50	312.12	61.83	367.28
5	145.17	268.67	-47.10	409.50	176.01	326.97	-7.41	365.84

[38] Two firms' expected profits in a duopoly competition can be analyzed through R&D incentives.
[39] Situations without mutually exclusive two options; R&D cooperation and technology licensing
[40] The shade indicates that the value is decreasing based on the variables (k or z).

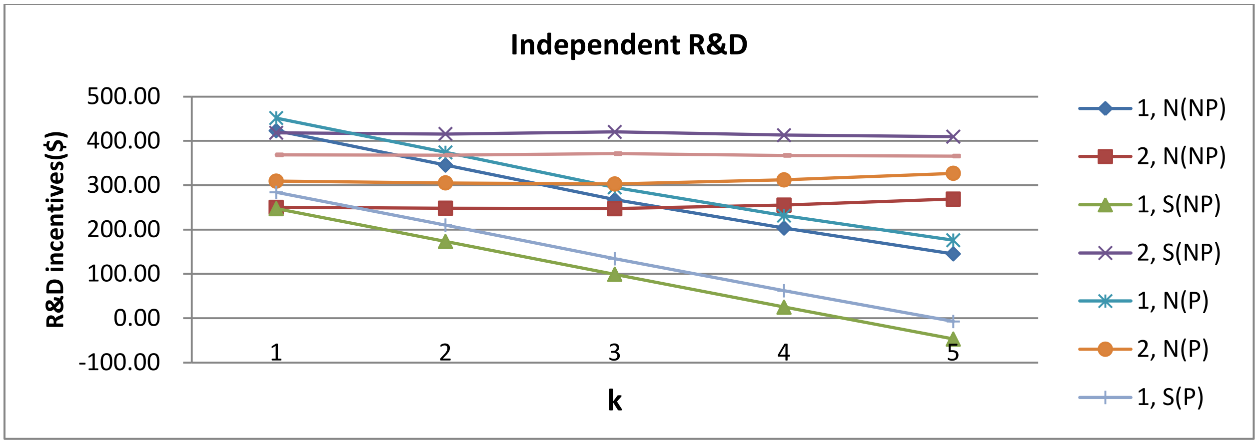

Figure 2.1: Changes in incentives depending on the degree of asymmetry (k).

As shown in Figure 2.1, Firm 1, which takes a superior position in the competition, has decreasing[41] incentives, regardless of the competing firm's R&D investment situation because of increasing asymmetry. In contrast, Firm 2 forms steady R&D incentives no matter the degree of asymmetry that Firm 1 has.

Comparing R&D incentives when consideration whether or not there is patent protection, both firms could have higher R&D incentives ($N(NP)_i < N(P)_i$, where $i = 1, 2$), and an even higher strategic R&D incentive without R&D cooperation. As to strategy, Firm 1 has a higher non-strategic than strategic R&D incentive regardless of patent protection ($N(NP)_1 > S(NP)_1$ and $N(P)_1 > S(P)_1$), whereas Firm 2 has a higher strategic incentive than non-strategic incentive. Therefore, firms that are in advantageous positions in competitions accomplish strategic benefits regardless of patent protection, but firms with disadvantages in competition can be strategically profitable with R&D investment.

[41] Since it is realistically impossible to predict the direct proportion between the degree of asymmetrical investments and profit enhancement, an assumption is made that the profit function increases a certain level rather than in linear fashion.

2.5.1.1.2 R&D Cooperation Case

As described in Tables 2.10, 2.11, and 2.12, expected profits differ with R&D cooperation and bilateral R&D investments. Results are addressed in Table 2.17, and Figure 2.2 illustrates incentive changes depending on the extent of asymmetry.

Table 2.17: Changes in incentives depending on the degree of asymmetry (k_R&D cooperation).

k	1, N(NP)	2, N(NP)	1, S(NP)	2, S(NP)	1, N(P)	2, N(P)	1, S(P)	2, S(P)
1	423.01	249.99	247.13	418.38	451.65	309.32	312.25	452.10
2	345.41	248.19	210.78	378.21	374.07	230.38	275.81	415.74
3	267.19	247.08	174.12	345.13	295.10	152.84	239.12	383.13
4	203.41	255.13	137.40	300.35	231.50	87.12	201.76	338.55
5	145.17	268.67	102.91	259.50	176.01	26.97	163.85	293.75

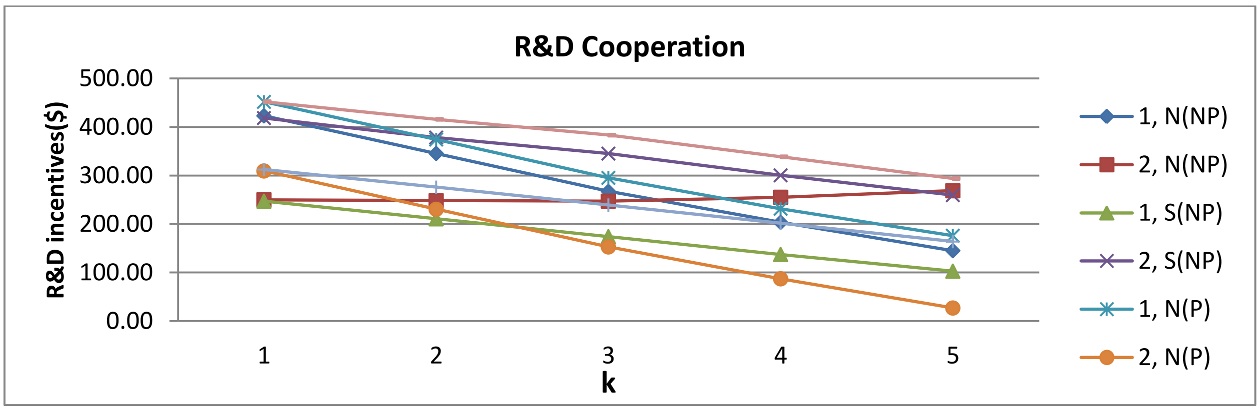

Figure 2.2: Changes in incentives depending on the degree of asymmetry (k_R&D cooperation).

Both firms have higher strategic incentives than the independent R&D case. In particular, both firms show higher strategic and non-strategic incentives under the patent protection($S(PC)_i > S(P)_i$, where $i = 1,2$). In the case of Firm 1, the decrease of strategic and non-strategic incentive regardless of patent protection indicates no need for asymmetrical investment when cooperation is available.

2.5.1.1.3 Licensing Case

As shown in Table 2.13, changes in R&D incentive with technology licensing are minimal without patent protection. However, with patent protection (Table 2.14), the two firms have expected profit through licensing, indicating a potential difference in the level of profits. Table 2.18 and Figure 2.3 include R&D incentives when technology licensing is possible.

Table 2.18: Changes in incentives depending on the degree of asymmetry (k_Licensing).

k	1, N(NP)	2, N(NP)	1, S(NP)	2, S(NP)	1, N(P)	2, N(P)	1, S(P)	2, S(P)
1	511.79	321.47	247.13	418.38	543.30	386.74	307.63	389.36
2	433.99	244.55	173.28	340.71	465.52	382.45	233.55	388.62
3	356.01	168.88	99.12	270.13	386.71	380.22	157.72	392.03
4	292.37	101.77	24.90	187.85	323.27	389.46	85.51	388.05
5	234.10	39.94	-47.10	109.50	268.01	404.07	16.37	386.56

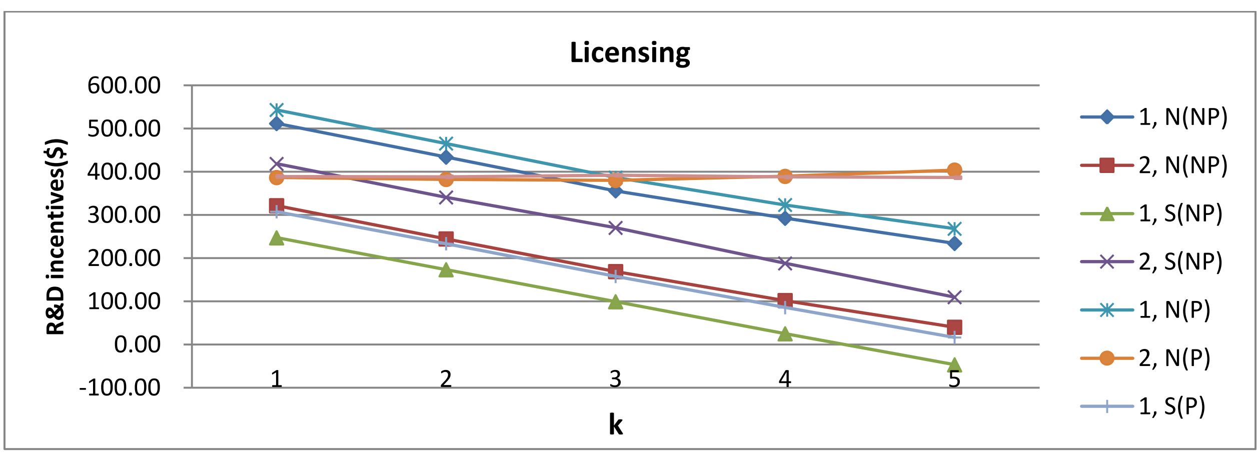

Figure 2.3: Changes in incentives depending on the degree of asymmetry (k_Licensing).

Firm 1 shows decreased strategic and non-strategic incentives whether patent protection exists or not, but firm 2 has decreasing strategic and non-strategic incentives with the increase in asymmetry with patent protection being available. Thus, Firm 1 would perform an asymmetrical investment which outweighs the rivalry firm's profit function, since more investment above the profit line will decrease investment inducement. Furthermore, technology licensing enables firm 1 to have higher strategic and non-strategic incentives even regardless of patent protection ($N(NPL)_1 > N(NP)_1$, $N(PL)_1 > N(P)_1$, $S(NPL)_1 \geq S(NP)_1$, and $S(PL)_1 > S(P)_1$), whereas Firm 2 can only expect higher R&D incentives from licensing only coupled with patent protection ($N(PL)_2 > N(P)_2$ and $S(PL)_2 > S(P)_2$).

2.5.1.2 Changes in Incentives for Competing Firms Depending on the *z*

2.5.1.2.1 Independent R&D Investment Case

Our model is a competition scenario in the patent protection situation, which possibly shows non-infringing imitation of firms without patent. Thus it is critical to analyze the anticipated probability (z) for R&D incentives. Table 2.19 illustrates two firms' changed incentives based on 'z'. Figure 2.4 provides graphs.

Table 2.19: Changes in incentives depending on the probability of non-infringing imitation (z).

z	1, N(NP)	2, N(NP)	1, S(NP)	2, S(NP)	1, N(P)	2, N(P)	1, S(P)	2, S(P)
0	280.373	255.594	100.875	415.05	336.999	371.484	184.6384	331.6684
0.2	275.415	253.22	100.189	415.282	321.3462	345.72	165.2384	345.7786
0.4	275.935	255.313	99.923	419.517	311.653	323.053	146.2875	362.7544
0.6	274.095	251.966	94.183	410.403	297.0294	298.3948	122.2462	371.9728
0.8	279.073	255.76	97.535	412.661	290.827	278.2946	106.8915	388.1798
1	276.137	251.014	104.1	418.973	276.137	251.014	93.7879	408.6609

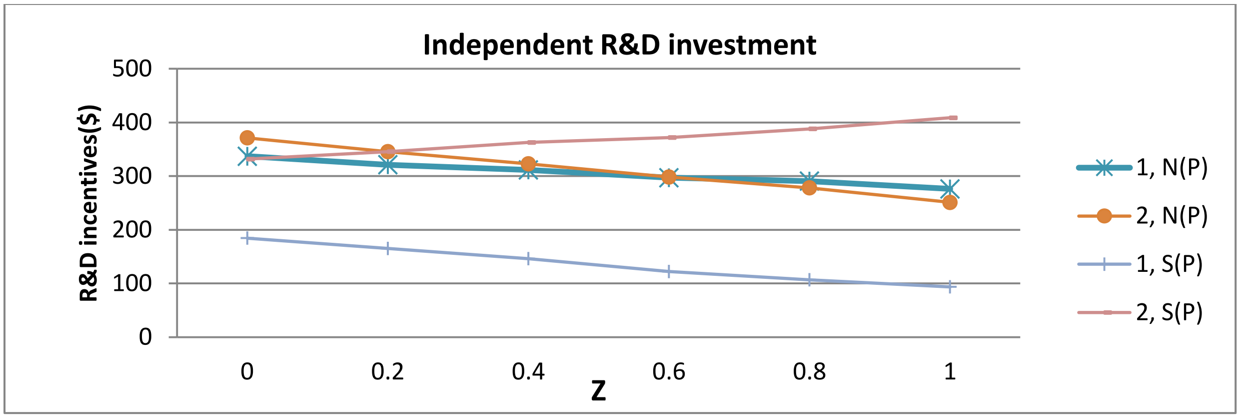

Figure 2.4: Changes in incentives depending on the probability of non-infringing imitation (z).

Table 2.19 shows that advantageous Firm 1 has a higher non-strategic than strategic R&D incentive, preferring that the competing firm not invest in R&D, whereas Firm 2 has a higher strategic R&D incentive than non-strategic incentive, indicating the preference for the competing firm's investment in R&D. In Figure 2.4, as 'z' increases, Firm 1's non-strategic and strategic R&D incentives are both decreasing, and Firm 2 shows a decrease in non-strategic incentive but an increase in strategic incentives. In other words, in the case of Firm 1, asymmetric investment increases the probability of obtaining patents, but it also increases the possibility of other firms imitating the technology, which ultimately decreases R&D incentives. In this sense, Firm 2 is likely to imitate the technology with the goal of enhancing expected profits, indicating a positive correlation between z and strategic R&D.

2.5.1.2.2 R&D Cooperation Case

With R&D cooperation (Table 2.20 and Figure 2.5), both firms have negative correlation between R&D incentives and strategic and non-strategic incentives. Moreover, both firms have a higher strategic R&D incentive when they do not cooperate. That is, when both firms expect each other to make R&D investments, R&D cooperation can increase expected profits for both firms.

Table 2.20: Changes in incentives depending on the probability of non-infringing imitation (z_R&D cooperation).

z	1, N(NP)	2, N(NP)	1, S(NP)	2, S(NP)	1, N(P)	2, N(P)	1, S(P)	2, S(P)
0	280.373	255.594	175.875	340.05	336.999	221.484	295.7693	405.3443
0.2	275.415	253.22	175.189	340.282	321.3462	195.72	272.9895	392.2385
0.4	275.935	255.313	174.923	344.517	311.653	173.053	250.808	386.2554
0.6	274.095	251.966	169.183	335.403	297.0294	148.3948	221.1782	366.2566
0.8	279.073	255.76	172.535	337.661	290.827	128.2946	203.0927	357.4505
1	276.137	251.014	179.1	343.973	276.137	101.014	187.5108	352.3838

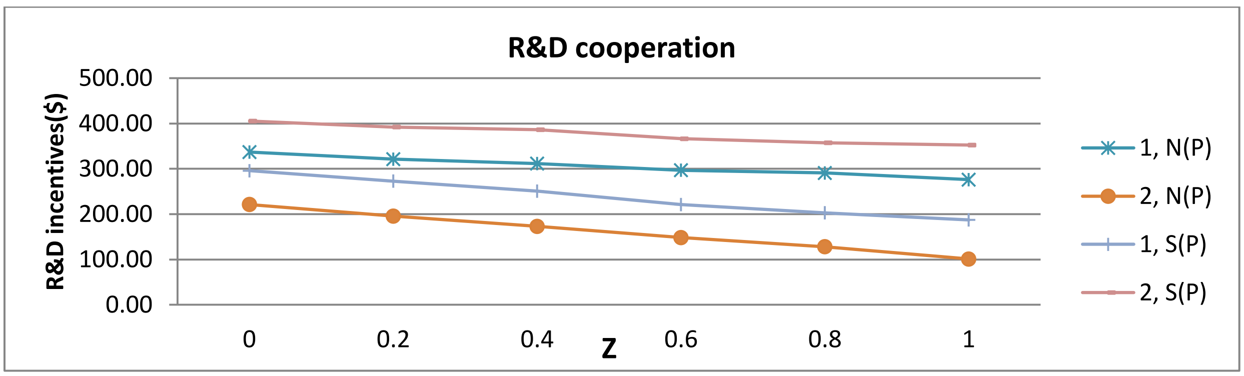

Figure 2.5: Changes in incentives depending on the probability of non-infringing imitation (z_R&D cooperation).

2.5.1.2.3 Licensing Case

Table 2.21 and Figure 2.6 show changes in R&D incentives based on non-infringing imitation probability with technology licensing.

Table 2.21: Changes in incentives depending on the probability of non-infringing imitation (z_Licensing).

z	1, N(NP)	2, N(NP)	1, S(NP)	2, S(NP)	1, N(P)	2, N(P)	1, S(P)	2, S(P)
0	369.2012	176.9443	100.875	265.05	431.4898	454.4233	231.8838	373.138
0.2	364.2569	174.8424	100.189	265.282	414.7812	426.5924	203.0718	379.0526
0.4	364.7206	177.0364	99.923	269.517	404.0104	401.5504	174.7091	387.6585
0.6	362.7815	173.4396	94.183	260.403	388.0093	374.5113	141.1302	388.5889
0.8	367.8338	177.1895	97.535	262.661	380.7632	351.9776	116.3553	396.4495
1	365.1172	172.4819	104.1	268.973	365.1172	322.4819	93.7879	408.6609

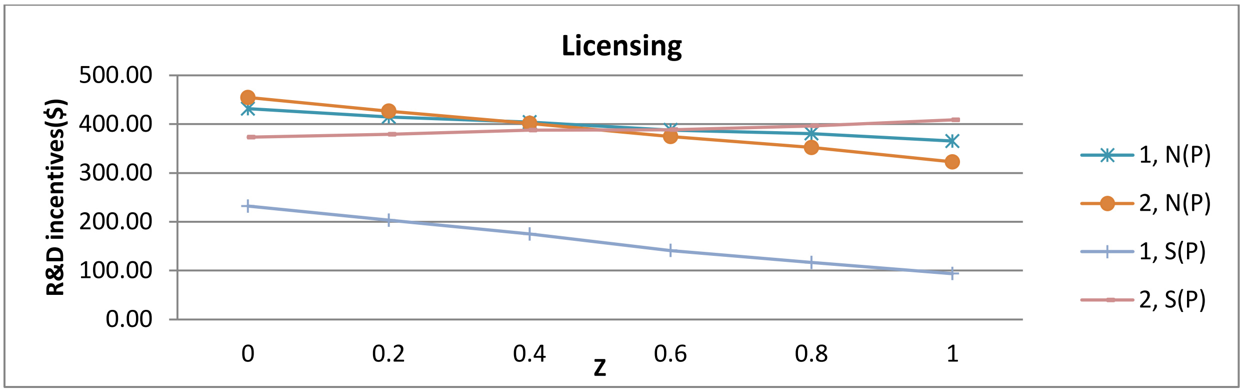

Figure 2.6: Changes in incentives depending on the probability of non-infringing imitation (z_Licensing).

Through technology licensing, both firms can expect additional profits, which suggests higher strategic and non-strategic incentives for both firms than does no licensing (Table 2.21). In addition, Firm 1 has a higher non-strategic than strategic R&D incentive regardless of z probability, implying a better situation when the other firm does not invest in R&D. Firm 2, however, has a higher strategic R&D incentive and a lower non-strategic incentive. This implies that the strategies of Firm 2 are dependent on the probability of performing imitation.

2.5.2 Which Option is Better (R&D Cooperation VS Licensing)?

As a result of the simulation, Tables 2.22 and 2.23 show which R&D incentive is more profitable for licensing and R&D cooperation for respective firms.

Table 2.22: R&D incentives between licensing and R&D cooperation (k-criterion).

k	1, N(NP)	2, N(NP)	1, S(NP)	2, S(NP)	1, N(P)	2, N(P)	1, S(P)	2, S(P)
1	88.78	71.48	0.00	0.00	91.65	77.42	-4.62	-62.74
2	88.58	-3.64	-37.50	-37.50	91.45	152.08	-42.27	-27.12
3	88.81	-78.20	-75.00	-75.00	91.60	227.38	-81.40	8.90
4	88.97	-153.36	-112.50	-112.50	91.78	302.34	-116.25	49.50
5	88.92	-228.73	-150.00	-150.00	92.01	377.10	-147.48	92.80

Table 2.23: The R&D incentives between licensing and R&D cooperation (z-criterion).

z	1, N(NP)	2, N(NP)	1, S(NP)	2, S(NP)	1, N(P)	2, N(P)	1, S(P)	2, S(P)
0.00	88.83	-78.65	-75.00	-75.00	94.49	232.94	-63.89	-32.21
0.20	88.84	-78.38	-75.00	-75.00	93.44	230.87	-69.92	-13.19
0.40	88.79	-78.28	-75.00	-75.00	92.36	228.50	-76.10	1.40
0.60	88.69	-78.53	-75.00	-75.00	90.98	226.12	-80.05	22.33
0.80	88.76	-78.57	-75.00	-75.00	89.94	223.68	-86.74	39.00
1.00	88.98	-78.53	-75.00	-75.00	88.98	221.47	-93.72	56.28

R&D incentives vary depending on k and z, so we can infer which decision is better for both firms when technology licensing and R&D cooperation are available. Hence, regardless of patent protection, firms with a higher position in the asymmetric R&D investment game can expect a higher non-strategic incentive through licensing than ones generated by R&D cooperation, and anticipate higher strategic incentive through R&D cooperation rather than through technology licensing. Firms with disadvantages in competition should go with R&D cooperation (Licensing) in order to yield a higher strategic and non-strategic R&D incentive; but in the case of a strategic

R&D incentive, small z and k are required. Based on these terms, possible options for two firms to have better outcomes are summarized in Table 2.24.

Table 2.24: Preferred options and firm situations (summary).

Preference	No patent protection		Patent protection	
	Non-strategic	Strategic	Non-strategic	Strategic
Firm 1	Licensing	R&D cooperation	Licensing	R&D cooperation
Firm 2	R&D cooperation	R&D cooperation	Licensing	Depends on z and k

2.6 Conclusion

This research examines strategic R&D investment decisions for two competing firms using game theory. In doing so, we generate a series of possible competition scenarios describing anticipated payoffs and higher R&D incentives. It is shown that bilateral R&D competition under patent protection can create higher strategic R&D incentive for R&D cooperation than independent R&D investment. Also we find that if non-infringing imitation is less likely, R&D cooperation with patent protection achieve higher strategic R&D incentives. With patent protection, technology licensing creates higher R&D incentives regardless of the rivalry firm's R&D decision, when compared with the situations without licensing for the two competing firms. Furthermore, firms in asymmetric competition expect higher strategic R&D incentives through the R&D cooperation.

All considered, future work should focus on simulating and analyzing asymmetric firms' possible competition scenarios, given the fact that strategic and non-strategic incentives differ, depending on non-infringing imitation opportunity and the degree of asymmetry. It would be possible to devise optimal competition scenarios that predict promising anticipated profits and R&D incentive by investigating markets with a zero-sum profit model.

Chapter 3

R&D Investment Strategies under a Duopoly Zero-Sum Game Environment

ABSTRACT

This paper investigates duopoly competition in two firms' symmetric R&D investment strategies under a zero-sum game. Our primary focus is to identify the benefits of R&D investment strategies as they at some point reach the saturated competition of a certain product. In particular, with the goal of illustrating the variance in expected benefits using strategic gaming models, two different situations are compared and analyzed, one where patent protection is available, and another where it is not. In brief, we present the following findings: (1) Patent protection increases non-strategic R&D incentive, but strategic R&D incentive decreases regardless of the tournament effect; (2) in the R&D cooperation circumstance, patent protection increases non-strategic R&D incentive while decreasing strategic R&D incentive; (3) in a strategic context, cooperative R&D(independent R&D) achieves higher R&D incentive with (without) patent protection; (4) with the licensing of technology, patent protection enhances non-strategic R&D incentive, and licensing technology always yields a higher R&D incentive than the situations without licensing; (5) in a non-strategic context, technology licensing generates higher R&D incentive than R&D cooperation can generate whether or not patent protection is available.

3.1 Introduction

With the variety of market structure and policies that is now available, firms can facilitate high-level strategy competition that considers not only product quality or technology as in the past, but also focuses on obtaining patents, emulating technology, or licensing it. Firms usually choose to maximize their benefits, but sometimes they try to bring about financial losses for competing firms. More specifically, firms entering a saturated market compete with each other to gain more benefits within the limited market. It is indeed a zero-sum game in that a rivalry firm can earn as much in profit as a competing firm loses in profit[42]. The present research seeks to address optimal strategic solutions with an emphasis on R&D incentive[43] for firms competing in a limited market—also called a limited pie—under the circumstances of a duopoly zero-sum R&D investment game. One of the primary variables covered in this research is patents. A patent[44] is known to be a significant factor in the profit structure of competing firms, as it leads both firms into a tournament process (Chowdhury, 2005). In addition, in an analysis of research related to the possibility and impacts of R&D cooperation between competing firms (Che and Yang, 2012; Kamien et al., 1992; Suzumura, 1992), we compare non-zero sum game simulations in order to determine which strategic choice can produce an optimal increase in R&D incentive when two exclusive options are possible; technology licensing with patents, and R&D cooperation.

3.2 The Model Setup

[42] For example, similar to futures trading, this is a phenomenon that leads to a zero-sum game because a competing firm's investment causes a decrease in the rivalry firm's profit, as a saturated market has limited resources.
[43] Profit that firms gain more when investing in R&D than when it is not.
[44] Without patent protection, firms without patents can nevertheless possess a copyright of the technology, but with patent protection, only firms with patents can own the full copyright and earn a profit from it.

We assume a market producing a single homogeneous product in a situation of symmetric duopoly and a zero-sum game. Following Chowdhury (2005), we let q_i be the output of the firm and $f(q)$ be the inverse market demand function, where $q = q1 + q2$ and satisfies $f' < 0$ and $f'(q) + q_i f''(q) < 0, \forall q, q_i$. As to the denotations, cq and $\pi_i(.,.)$, they represent the cost function and the profit function of each firm i, where the first (second) argument shows firm1 (firm 2)'s marginal cost. Each firm is able to improve the cost function with the investment F (F>0) in R&D. Thus, when Firm 1 (Firm 2) invests F in R&D, the initial cost function of Firm 1 (Firm 2), the cq, will be $c'q$, where $0 \le c' \le c$. Without patent protection, in a bilateral R&D situation, the cost function is denoted as $c'q$. Further, knowledge spillover can reduce the cost of the firm making no R&D investment as $\hat{c}q$ when there is no patent protection and a unilateral R&D situation in which only one firm invests in R&D. With the definition of the terms that play an important role in the following models, the strategic and non-strategic incentives for R&D derive from the firm's payoff differences between instances of conducting and not conducting R&D.

The competition consists of two main phases: the first phase makes a decision as to whether or not a firm invests in R&D, while the second phase is composed of a Cournot competition determining respective benefits. Payoff is dependent on whether or not patent protection exists; as Chowdhury (2005) suggests, firms without patents under the no-patent-protection situations can expect an improved cost function from the knowledge spillover or partial emulation of a product. In contrast, with patent protection, firms with patents are only able to yield profits, assuming the following cost function hierarchy:

$$\pi_1(c',c) = \pi_2(c,c') > \pi_1(c',c') > \pi_1(\hat{c},c) > \pi_1(c,c) > \pi_1(c,c') = \pi_2(c',c)$$

3.3 R&D Incentives in Zero-Sum Game

3.3.1 Basic Model

In a symmetry game model, Cournot equilibrium can only be achieved when both firms invest in R&D. Therefore, the total sum of benefits is calculated from both firms' expected benefits at a parallel point under the zero-sum game market. This means that with unilateral R&D investment, the expected benefit for firms investing in R&D is first determined, and the expected benefits from the firms not investing in R&D is calculated by subtracting their expected benefits from the total benefits. Tables 3.1 and 3.2 show the firms' expected benefits when assuming a zero-sum situation with and without patent protection.

Table 3.1: Payoffs under no patent protection with symmetric R&D investment.

Firm 1/2	R&D	No R&D
R&D	$\pi_1(c',c') - F, \pi_2(c',c') - F$	$\pi_1(c',\hat{c}) - F, 2\pi(c',c') - \pi_2(\hat{c},c')$
No R&D	$2\pi(c',c') - \pi_1(c',\hat{c}), \pi_2(\hat{c},c') - F$	$\pi_1(c,c), \pi_2(c,c)$

Table 3.2: Payoffs under patent protection with symmetric R&D investment.

Firm 1/2	R&D	No R&D
R&D	$\frac{\pi_1(c',c) + \pi_1(c,c')}{2} - F, \frac{\pi_2(c,c') + \pi_2(c',c)}{2} - F$	$\pi_1(c',c) - F, \pi_2(c',c)$
No R&D	$\pi_1(c,c'), \pi_2(c,c') - F$	$\pi_1(c,c), \pi_2(c,c)$

We also assume that both firms can take benefits by investing simultaneously in R&D so that the followings are natural : $\pi(c',c') - \pi(c,c) \geq F$

The following equations show both firms' non-strategic incentive with and without patent protection. $N(NP) = \pi_1(c'', \hat{c}) - \pi_1(c,c) - kF = \pi_2(\hat{c}, c') - \pi_2(c,c) - F$ and

$N(P) = \pi_1(c', c) - \pi_1(c,c) - F = \pi_2(c, c') - \pi_2(c,c) - F$.

Given hierarchical condition ($\pi_1(c', c) > \pi_1(c', \hat{c})$) tells $N(NP) < N(P)$, indicating an increase in strategic R&D incentive. With the same method, also considering whether or not patent protection is available, strategic incentive is as follows.

$S(NP) = \pi_2(c', c') - \pi_2(c', \hat{c}) - F = \pi_1(c', c') - \pi_1(\hat{c}, c') - F$, and

$$S(P) = \frac{\pi_1(c, c') - \pi_1(c', c)}{2} - F = \frac{\pi_2(c', c) - \pi_2(c, c')}{2} - F \ .$$

The differences between two incentives are $S(P) - S(NP) = [\frac{\pi_1(c, c') - \pi_1(c', c)}{2}] + [\pi_1(c', c') - \pi_1(c', \hat{c})]$, and values in the first and second parentheses both become negative ($\pi_1(c, c') - \pi_1(c', c) < 0$ and $\pi_1(c', c') - \pi_1(c', \hat{c}) < 0$), appearing as $S(NP) > S(P)$. Thus, when the model incorporates a zero-sum situation, patent protection decreases strategic R&D incentive regardless of the Tournament Effect(TE)[45].

3.3.2 The Model with R&D Cooperation Option

With the possibility of R&D cooperation between two competing firms, they can choose either independent R&D competition or R&D cooperation, whichever produces the optimal benefit.

[45] Tournament effect(TE) is defined as the difference between the equilibrium payoffs of the firms in the presence and absence of patent protection when all firms engage in R&D (Chowdhury, 2005).

When R&D cooperation is selected, two firms can avoid risk of failure by investing in independent R&D and patents, and they can also make an initial investment in a collaborative manner. Che and Yang (2012) state that two firms decide whether or not to invest in cooperative R&D and participate in the payoff competition. Bilateral R&D investment can produce a situation of R&D cooperation, which does not influence the benefit level based on the existence of patent protection. However, unilateral R&D investment significantly affects the payoff level with the availability of patent protection. Given this outcome, the results of the two firms' R&D investment game when considering the availability of the R&D cooperation option are summarized in Tables 3.3 and 3.4. Table 3.5 illustrates non-strategic and strategic incentives based on patent protection.

Table 3.3: Payoffs under no patent protection with R&D cooperation.

Firm 1/2	R&D cooperation	No R&D
R&D cooperation	$\pi_1(c',c')-\frac{F}{2},\pi_2(c',c')-\frac{F}{2}$	$\pi_1(c',\hat{c})-F,2\pi(c',c')-\pi_2(\hat{c},c')$
No R&D	$2\pi(c',c')-\pi_1(c',\hat{c}),\pi_2(\hat{c},c')-F$	$\pi_1(c,c),\pi_2(c,c)$

Table 3.4: Payoffs under patent protection with R&D cooperation.

Firm 1/2	R&D cooperation	No R&D
R&D cooperation	$\pi_1(c',c')-\frac{F}{2},\pi_2(c',c')-\frac{F}{2}$	$\pi_1(c',c)-F,2\pi(c',c')-\pi_2(c',c)$
No R&D	$2\pi(c',c')-\pi_1(c,c'),\pi_2(c,c')-F$	$\pi_1(c,c),\pi_2(c,c)$

Table 3.5: Non-strategic and strategic incentives for R&D with R&D cooperation.

R&D incentive	Without patent protection	With patent protection
Non-strategic	$\pi_2(\hat{c},c') - \pi_2(c,c) - F = \pi_1(c',\hat{c}) - \pi_1(c,c) - F$	$\pi_2(c,c') - \pi_2(c,c) - F = \pi_1(c',c) - \pi_1(c,c) - F$
Strategic	$\pi_2(\hat{c},c') - \pi_2(c',c') - \frac{F}{2} = \pi_1(c',\hat{c}) - \pi_1(c',c') - \frac{F}{2}$	$\pi_2(c',c) - \pi_2(c',c') - \frac{F}{2} = \pi_1(c,c') - \pi_1(c',c') - \frac{F}{2}$

As shown in Table 3.5, when R&D cooperation is available, patent protection increases non-strategic R&D incentive ($N(PC) - N(NPC) = \pi_1(c',c) - \pi_1(c',\hat{c}) > 0$), whereas it decreases strategic R&D incentive ($S(PC) - S(NPC) = \pi_1(c,c') - \pi_1(c',\hat{c}) < 0$) at the same time[46].

Thus, it is worthwhile to identify competitive situations with better R&D incentives comparing R&D cooperation and independent R&D investment. R&D cooperation is only possible when both firms invest in R&D, when there would be no difference in the non-strategic context regardless of the existence of R&D cooperation. However, in the strategic context, a higher R&D incentive can be generated through R&D cooperation without patent protection ($S(NPC) - S(NP) = \frac{F}{2} > 0$), and independent R&D investment ($S(PC) - S(P) = \pi_1(c',c') - \frac{\pi_1(c,c') + \pi_1(c',c)}{2} - \frac{F}{2} \leq 0$) when patent protection is available along with a positive Tournament Effect[47].

[46] N refers to non-strategic whereas S means strategic incentive, and NPC in parentheses indicates no patent protection with cooperative R&D, and PC refers to patent protection with cooperative R&D.

[47] $Tournament\_Effect(TE) = \left[\frac{\pi_1(c',c) + \pi_1(c,c')}{2} - \pi_1(c',c')\right]$ is positive when $\pi_1(c',c) + \pi_1(c,c') > 2\pi_1(c',c')$ and negative when $\pi_1(c',c) + \pi_1(c,c') < 2\pi_1(c',c')$.

3.3.3 The Model with Technology Licensing Option

Firms that obtain patents can expect additional benefits through licensing. The following Tables 3.6 and 3.7 show expected profits when a licensing option is added along with independent R&D investment, and Table 3.8 illustrates non-strategic and strategic incentives when patent protection is both available and not available.

Table 3.6: Payoffs under no patent protection with technology licensing.

Firm 1/2	R&D	No R&D
R&D	$\pi_1(c',c')-F, \pi_2(c',c')-F$	$\pi_1(c',\hat{c})+R(c',\hat{c})-F$, $2\pi_2(c',c')-\pi_2(\hat{c},c')-R(\hat{c},c')$
No R&D	$2\pi_1(c',c')-\pi_1(c',\hat{c})-R(c',\hat{c})$, $\pi_2(\hat{c},c')+R(\hat{c},c')-F$	$\pi_1(c,c), \pi_2(c,c)$

Table 3.7: Payoffs under patent protection with technology licensing.

Firm 1/2	R&D	No R&D
R&D	$\frac{\pi_1(c',c)+\pi_1(c,c')+R(c',c)}{2}-F$, $\frac{\pi_2(c,c')+\pi_2(c',c)+R(c,c')}{2}-F$	$\pi_1(c',c)+R(c',c)-F$, $\pi_2(c',c)+\frac{R(c,c')}{2}$
No R&D	$\pi_1(c,c')+\frac{R(c',c)}{2}$, $\pi_2(c,c')+R(c,c')-F$	$\pi_1(c,c), \pi_2(c,c)$

Table 3.8: Non-strategic and strategic incentives for R&D with technology licensing.

R&D incentive	Without patent protection
Non-strategic	$\pi_2(\hat{c},c') - \pi_2(c,c) + R(\hat{c},c') - F = \pi_1(c',\hat{c}) - \pi_1(c,c) + R(c',\hat{c}) - F$
Strategic	$\pi_2(\hat{c},c') - \pi_2(c',c') + R(\hat{c},c') - F = \pi_1(c',\hat{c}) - \pi_1(c',c') + R(c',\hat{c}) - F$
	With patent protection
Non-strategic	$\pi_2(c,c') + R(c,c') - \pi_2(c,c) - F = \pi_1(c',c) + R(c',c) - \pi_1(c,c) - F$
Strategic	$\frac{\pi_2(c,c') - \pi_2(c',c)}{2} - F = \frac{\pi_1(c',c) - \pi_1(c,c')}{2} - F$

As described in Table 3.6, without patent protection firms that hold patents expect decreased profits as firms not investing in R&D can obtain rivalry firms' technology through personnel or knowledge spillover. This indicates that profits from licensing can be lower than profits from patent protection ($R(c',\hat{c}) < R(c',c)$). Furthermore, Table 3.8 indicates that securing additional profit through licensing can yield a higher R&D incentive than without licensing [48] ($N(NPL) > N(NP)$, $N(PL) > S(P)$, and $S(PL) > S(P)$).

Table 3.8 summarizes the degree to which patent protection can enhance R&D incentive, and the difference in profit between with patent protection and without patent protection is denoted as

$$N(PL) - N(NPL) = [\pi_1(c',c) - \pi_1(c',\hat{c})] + [R(c',c) - R(c',\hat{c})] \geq 0$$ and

[48] In a strategic context, $S(NPL) > S(NP)$ is defined without patent protection under the condition of $\pi_1(\hat{c},c') + \pi_1(c',\hat{c}) + R(c',\hat{c}) > 2\pi_1(c',c')$.

$S(PL) - S(NPL) = \frac{[\pi_1(c',c) - \pi_1(c,c')]}{2} + [\pi_1(c',c') - \pi_1(c',\hat{c})] - R(c',\hat{c})$ [49]. In other words, when technology licensing is possible, patent protection increases non-strategic R&D incentive, which is the identical result when R&D cooperation is available or licensing or R&D cooperation are not available[50].

3.3.4 Which Option is Better under Zero-sum Game; R&D Cooperation or Licensing?

The basic model of independent R&D investment tells us that R&D cooperation and technology licensing options are mutually exclusive choices. Thus, this section compares R&D incentive, as described in Tables 3.5 and 3.8, to suggest more profitable options.

First, the non-strategic R&D incentive is denoted as $N(NPL) - N(NPC) = R(c',\hat{c})$ and $N(PL) - N(PC) = R(c',c)$, indicating that technology licensing improves R&D incentive more than R&D cooperation, whether patent protection is available or not. However, in the case of a strategic context, we denote $S(NPL) - S(NPC) = R(c',\hat{c}) - \frac{F}{2}$,

$S(PL) - S(PC) = \frac{\pi_1(c',c) - \pi_1(c,c')}{2} + [\pi_1(c',c') - \pi_1(c,c')] - \frac{F}{2} > 0$ and this shows that without patent protection, the investment amounts can make a difference in result. Competition through licensing seems to yield better R&D incentive than R&D cooperation when patents are protected.

[49] N refers to non-strategic whereas S means strategic incentive, and NPL in parentheses indicates no patent protection with technology licensing, and PL refers to patent protection with technology licensing.

[50] With licensing available, the impact of patent protection on strategic R&D incentive is a bit vague.

3.4 Revised Model with Non-infringing Imitation Available

So far we have identified symmetric R&D investment game strategy with R&D cooperation and technology licensing options in a zero-sum game situation. It is worth noting that the simulated model assumed that it was impossible for firms not investing into R&D to imitate a rivalry firm's patented technology under the unilateral R&D investment situation with patent protection, but this is realistically impossible due to industrial spying, scouting for core human resources, or the utilization of patent information, leading us see a need for further study with a modified model taking into consideration such variables. Therefore, this section attempts to generate a situation in which firms without patents can achieve non-infringing imitation by making additional investments, as suggested by Mukherjee (2006).

3.4.1 R&D Incentives in Basic Model

When there is non-infringing imitation possible, the non-patent holder can have the patented technology without infringement with probability z. Each firm achieves patent protection with a probability of 0.5 in a bilateral R&D situation with patent protection. By investing I, the non-patent holder can imitate the patented technology with probability z and produce with marginal cost c' in a bilateral R&D situation. In unilateral R&D situation where one firm invests in R&D, non-innovating firm decreases its marginal cost to $\hat{c}$ with probability z, through imitation with investing I. Tables 3.9 and 3.10 show the R&D-competing firms' expected payoffs when applying the assumption of non-infringing imitation with and without patent protection.

Table 3.9: Payoffs under no patent protection with symmetric R&D investment and non-infringing imitation.

Firm 1//2	R&D	No R&D
R&D	$\pi_1(c',c')-F,\pi_2(c',c')-F$	$\pi_1(c',\hat{c})-F, 2\pi_1(c',c')-\pi_2(\hat{c},c')$
No R&D	$2\pi_1(c',c')-\pi_1(c',\hat{c}),\pi_2(\hat{c},c')-F$	$\pi_1(c,c),\pi_2(c,c)$

Table 3.10: Payoffs under patent protection with symmetric R&D investment and non-infringing imitation.

Firm 1/2	R&D	No R&D
R&D	$z\pi_1(c',c')+\frac{(1-z)[\pi_1(c',c)+\pi_1(c,c')]}{2}-F-\frac{I}{2},$ $z\pi_2(c',c')+\frac{(1-z)[\pi_2(c,c')+\pi_2(c',c)]}{2}-F-\frac{I}{2}$	$z\pi_1(c',\hat{c})+(1-z)\pi_1(c',c)-F,$ $2z[\pi_2(c',c')-\frac{\pi_2(\hat{c},c')}{2}]+(1-z)\pi_2(c',c)-I$
No R&D	$2z[\pi_1(c',c')-\frac{\pi_1(c',\hat{c})}{2}]+(1-z)\pi_1(c,c')-I$ $z\pi_2(\hat{c},c')+(1-z)\pi_2(c,c')-F$	$\pi_1(c,c),\pi_2(c,c)$

The following equations[51] show both firms' non-strategic incentive with and without patent protection.

$$N(NPI)=\pi_2(\hat{c},c')-\pi_2(c,c)-F=\pi_1(c',\hat{c})-\pi_1(c,c)-F \text{ and}$$

$$N(PI)=z[\pi_1(c',\hat{c})-\pi_1(c,c)]+(1-z)[\pi_1(c',c)-\pi_1(c,c)]-F=z[\pi_2(\hat{c},c')-\pi_2(c,c)]+(1-z)[\pi_2(c,c')-\pi_2(c,c)]-F .$$

Given the conditions ($\pi_1(c',c)>\pi_1(c',\hat{c})$) it is easy to see $N(NPI)\le N(PI)$, showing that patent protection increases non-strategic R&D incentive, and this indicates that there is no difference

[51] N refers to non-strategic whereas S means strategic incentive, and NPI in parentheses indicates no patent protection with non-infringing imitation available, and PI refers to patent protection with non-infringing imitation available.

between the models with and without the assumption of non-infringing imitation. With the same method, also considering whether or not patent protection is available, strategic incentive is as follows.

$S(NPI) = \pi_2(c',c') - \pi_2(c',\hat{c}) - F = \pi_1(c',c') - \pi_1(\hat{c},c') - F$, and

$S(PI) = z(\pi_2(c',\hat{c}) - \pi_2(c',c') + \frac{(1-z)(\pi_2(c,c') - \pi_2(c',c))}{2} - F + \frac{I}{2} = z(\pi_1(c',\hat{c}) - \pi_1(c',c') + \frac{(1-z)(\pi_1(c',c) - \pi_1(c,c'))}{2} - F + \frac{I}{2}$.

The difference between two incentives is

$S(PI) - S(NPI) = (z-1)[\pi_1(c',\hat{c}) - \pi_1(c',c')] + \frac{(1-z)(\pi_1(c',c) - \pi_1(c,c'))}{2} + \frac{I}{2}$. Thus, when the non-infringing imitation is more likely, patent protection increases strategic R&D incentive[52].

3.4.2 The Model with R&D Cooperation Option

With the possibility of non-infringing imitation and R&D cooperation between two competing firms, the expected payoffs from the R&D investment game are summarized in Tables 3.11 and 3.12. Table 3.13 shows non-strategic and strategic incentives based on patent protection.

Table 3.11: Payoffs under no patent protection with R&D cooperation and non-infringing imitation.

Firm 1/2	R&D cooperation	No R&D
R&D cooperation	$\pi_1(c',c') - \frac{F}{2}, \pi_2(c',c') - \frac{F}{2}$	$\pi_1(c',\hat{c}) - F, 2\pi(c',c') - \pi_2(\hat{c},c')$
No R&D	$2\pi(c',c') - \pi_1(c',\hat{c}), \pi_2(\hat{c},c') - F$	$\pi_1(c,c), \pi_2(c,c)$

[52] When non-infringing imitation is available, patent protection decreases strategic R&D incentive.

Table 3.12: Payoffs under patent protection with R&D cooperation and non-infringing imitation.

Firm 1/2	R&D cooperation	No R&D
R&D cooperation	$\pi_1(c',c')-\frac{F}{2},\pi_2(c',c')-\frac{F}{2}$	$z\pi_1(c',\hat{c})+(1-z)\pi_1(c',c)-F,$ $2z[\pi_2(c',c')-\frac{\pi_2(\hat{c},c')}{2}]+(1-z)\pi_2(c',c)-I$
No R&D	$2z[\pi_1(c',c')-\frac{\pi_1(c',\hat{c})}{2}]+(1-z)\pi_1(c,c')-I$ $z\pi_2(\hat{c},c')+(1-z)\pi_2(c,c')-F$	$\pi_1(c,c),\pi_2(c,c)$

Table 3.13: Non-strategic and strategic incentives for R&D with R&D cooperation and non-infringing imitation.

R&D incentive	Without patent protection	With patent protection
Non-strategic	$\pi_2(\hat{c},c')-\pi_2(c,c)-F=\pi_1(c',\hat{c})-\pi_1(c,c)-F$	$z\pi_1(c',\hat{c})+(1-z)\pi_1(c',c)-\pi_1(c,c)-F$
Strategic	$\pi_2(\hat{c},c')-\pi_2(c',c')-\frac{F}{2}=\pi_1(c',\hat{c})-\pi_1(c',c')-\frac{F}{2}$	$\pi_1(c',c')-2z[\pi_1(c',c')-\frac{\pi_1(c',\hat{c})}{2}]-(1-z)\pi_1(c,c')+I-\frac{F}{2}$

As shown in Table 3.12, when non-infringing imitation is available, the expected payoffs in unilateral R&D situation for both firms are changed under patent protection. In addition, when there is R&D cooperation between competing firms, patent protection increases non-strategic R&D incentive[53] ($N(PCI)-N(NPCI)=(z-1)\pi_1(c',\hat{c})+(1-z)\pi_1(c',c)>0$) regardless of the probability of non-infringing imitation. However, the result for strategic R&D incentive depends on the probability of non-infringing imitation

[53] NPCI in parentheses indicates no patent protection with R&D cooperation and non-infringing imitation available, and PCI refers to patent protection with R&D cooperation and non-infringing imitation available.

$(S(PCI) - S(NPCI) = 2\pi_1(c',c') - \pi_1(c',\hat{c}) - 2z[\pi_1(c',c') - \frac{\pi_1(c',\hat{c})}{2}] - (1-z)\pi_1(c,c') + I)$.

Thus, it is worthwhile to verify competitive situations with better R&D incentives comparing R&D cooperation and independent R&D investment. R&D cooperation is only possible when both firms invest in R&D, when there would be no difference in the non-strategic context regardless of the existence of R&D cooperation.

Unlike the previous model which shows no difference depending on the availability of R&D cooperation, in the model with non-infringing imitation, independent R&D investment can expect higher non-strategic R&D incentive than R&D cooperation ($N(PCI) - N(PI) = z[\pi_1(c',\hat{c}) - \pi_1(c',c)] < 0$) when there is patent protection with non-infringing imitation. In the strategic context, a higher R&D incentive can be expected through R&D cooperation than independent R&D investment regardless of non-infringing imitation and the existence of patent protection[54]($S(NPCI) - S(NPI) = \frac{F}{2} > 0$ and

$$S(PCI) - S(PI) = \pi_1(c',c') - \frac{\pi_1(c,c') - \pi_1(c',c)}{2} - 2z[\pi_1(c',c') - \frac{\pi_1(c',\hat{c})}{2}] - (1-z)\pi_1(c,c') + I + \frac{F}{2} > 0$$).

3.4.3 The Model with Technology Licensing Option

The following Tables 3.14 and 3.15 show expected profits when a licensing option is added along with independent R&D investment, and Table 16 illustrates non-strategic and strategic incentives when patent protection is both available and not available.

[54] The model with non-infringing imitation indicates that cooperative(independent) R&D increases strategic R&D incentive when there is (no)patent protection.

Table 3.14: Payoffs under no patent protection with technology licensing and non-infringing imitation.

Firm 1/2	R&D	No R&D
R&D	$\pi_1(c',c')-F, \pi_2(c',c')-F$	$\pi_1(c',\hat{c})+R(c',\hat{c})-F,$ $2\pi_2(c',c')-\pi_2(\hat{c},c')-R(\hat{c},c')$
No R&D	$2\pi_1(c',c')-\pi_1(c',\hat{c})-R(c',\hat{c}),$ $\pi_2(\hat{c},c')+R(\hat{c},c')-F$	$\pi_1(c,c), \pi_2(c,c)$

Table 3.15: Payoffs under patent protection with technology licensing and non-infringing imitation.

Firm 1/2	R&D	No R&D
R&D	$z\pi_1(c',c')+\frac{(1-z)[\pi_1(c',c)+\pi_1(c,c')+R(c',c)]}{2}-F,$ $z\pi_2(c',c')+\frac{(1-z)[\pi_2(c,c')+\pi_2(c',c)+R(c,c')]}{2}-F$	$z[\pi_1(c',\hat{c})+R(c',\hat{c})]+(1-z)[\pi_1(c',c)+R(c',c)]-F,$ $2z[\pi_2(c',c')-\frac{(\pi_2(\hat{c},c')+R(\hat{c},c'))}{2}]+(1-z)\pi_2(c',c)-I$
No R&D	$2z[\pi_1(c',c')-\frac{(\pi_1(c',\hat{c})+R(c',\hat{c}))}{2}]+(1-z)\pi_1(c,c')-I,$ $z[\pi_2(\hat{c},c')+R(c',\hat{c})]+(1-z)[\pi_2(c,c')+R(c,c')]-F$	$\pi_1(c,c), \pi_2(c,c)$

Table 3.16: Non-strategic and strategic incentives for R&D with technology licensing and non-infringing imitation.

R&D incentive	Without patent protection
Non-strategic	$\pi_2(\hat{c},c')-\pi_2(c,c)+R(\hat{c},c')-F=\pi_1(c',\hat{c})-\pi_1(c,c)+R(c',\hat{c})-F$
Strategic	$\pi_2(\hat{c},c')-\pi_2(c',c')+R(\hat{c},c')-F=\pi_1(c',\hat{c})-\pi_1(c',c')+R(c',\hat{c})-F$
	With patent protection
Non-strategic	$z[\pi_1(c',\hat{c})+R(c',\hat{c})]+(1-z)[\pi_1(c',c)+R(c',c)]-\pi_1(c,c)-F$
Strategic	$z[\pi_1(c',\hat{c})-\pi_1(c',c')+R(c',\hat{c})]+\frac{(1-z)[\pi_1(c',c)-\pi_1(c,c')+R(c',c)]}{2}-F+I$

As described in Tables 3.7(with no imitation) and 3.15(with non-infringing imitation), when there is technology licensing available, a higher R&D incentive is expected regardless of the probability of non-infringing imitation and the existence of patent protection[55]

($N(NPLI) - N(NPI) = R(c', \hat{c}) > 0$, $N(PLI) - N(PI) = zR(c', \hat{c}) + (1-z)R(c', c) > 0$,

$S(NPLI) - S(NPI) = R(c', \hat{c}) > 0$, and $S(PLI) - S(PI) = zR(c', \hat{c}) + \frac{(1-z)R(c',c)}{2} + \frac{I}{2} > 0$).

Table 3.15 summarizes the degree to which patent protection can enhance R&D incentive, and the difference in profit between with patent protection and without patent protection is denoted as

$$N(PLI) - N(NPLI) = (z-1)[\pi_1(c', \hat{c}) + R(c', \hat{c})] + (1-z)[\pi_1(c', c) + R(c', c)]$$ and

$$S(PLI) - S(NPLI) = (z-1)[\pi_1(c', \hat{c}) - \pi_1(c', c') + R(c', \hat{c})] + \frac{(1-z)[\pi_1(c', c) - \pi_1(c, c') + R(c', c)]}{2} + I > 0 .$$

In other words, when technology licensing is possible, patent protection increases non-strategic R&D incentive (when non-infringing imitation is less likely) and strategic R&D incentive regardless of probability of non-infringing imitation[56].

3.4.4 Which Option is Better in Zero-sum Game; R&D Cooperation or Licensing?

[55] NPLI in parentheses indicates no patent protection with technology licensing and non-infringing imitation available, and PLI refers to patent protection with technology licensing and non-infringing imitation available.

[56] When non-infringing imitation is not available, it is shown that patent protection only increases non-strategic R&D incentive.

This section compares R&D incentive for cooperative R&D option and technology licensing option, as described in Tables 3.13 and 3.16 to suggest more profitable option with various scenarios.

First, the non-strategic R&D incentive is denoted as $N(NPLI)-N(NPCI)=R(c',\hat{c})$ and $N(PLI)-N(PCI)=z[\pi_1(c',\hat{c})+R(c',\hat{c})]+(1-z)[\pi_1(c',c)+R(c',c)]-\pi_1(c',c)$, indicating that technology licensing improves R&D incentive more than R&D cooperation, whether patent protection is available or not[57]. However, in the case of a strategic context, we denote

$$S(NPLI)-S(NPCI)=R(c',\hat{c})-\frac{F}{2},$$

$$S(PLI)-S(PCI)=z[\pi_1(c',\hat{c})-\pi_1(c',c')+R(c',\hat{c})]+\frac{(1-z)[\pi_1(c',c)-\pi_1(c,c')+R(c',c)]}{2}+[\pi_1(c',c')-\pi_1(c,c')-\frac{F}{2}+I]$$ and this

shows that without patent protection, the results can differ in investment amounts. Competition through licensing seems to yield better R&D incentive than R&D cooperation when patents are protected and non-infringing imitation is less likely.

3.5 Conclusion

This research examines R&D investment game strategies for competing firms to increase R&D incentive. In particular, with the assumption of zero-sum under a saturated market competition, we generate a series of possible competition scenarios focusing on expected payoffs and better R&D incentives to achieve. Comparing the two models with and without non-infringing imitation, it is shown that patent protection always increases non-strategic R&D incentive, but

[57] It is true only if non-infringing is less likely with patent protection.

strategic R&D incentive increases (decreases) when there is (not) non-infringing imitation available. In the R&D cooperation circumstance, patent protection increases non-strategic R&D incentive while decreasing strategic R&D incentive. Also we find that cooperative R&D can always expect higher strategic R&D incentive than independent R&D investment regardless of the existence of patent protection when there is non-infringing imitation available, whereas cooperative R&D (independent R&D) achieves higher R&D incentive with (without) patent protection when there is no imitation available. With the licensing of technology, patent protection enhances non-strategic R&D incentive in the mode, but increases strategic R&D incentive as well when there is non-infringing imitation considered and licensing technology always yields a higher R&D incentive than the situations without licensing regardless of non-infringing imitation. Furthermore, technology licensing generates higher non-strategic R&D incentive than R&D cooperation can generate whether or not patent protection is available.

All considered, future work should focus on asymmetric firms' zero-sum based model with value of information. Thus a variety of scenarios focused on calculating the profits derived from predicting a rivalry firm's R&D decision and its investment costs will be addressed. Consistent strategic game research will then provide a thorough understanding of the profit model as well as an evaluation of the cost-effectiveness of efforts to acquire such information by comparing the investment plan prior to and after obtaining the competing firm's decision.

Chapter 4

R&D Investment Strategies under Uncertain Patent Acquisition and Non-infringing Imitation

ABSTRACT

We construct R&D competition between two firms as a game, and reconstruct it as a probabilistic model. Then, we conduct the sensitivity analysis considering the changes of patent acquisition probabilities and imitation possibilities of the two firms. By differentiating changes of expected profits and R&D incentives by scenario, we suggest advantageous competitive strategy for each of the two firms engaged in asymmetric R&D competition. Analytical outcomes under the conditions of zero-sum and non-zero-sum games are as follows: Regardless of patent acquisition probability, the superior Firm 1 gets higher R&D incentives in zero-sum game. Thus, it is strategically favorable for the Firm 1 to make R&D investment under zero-sum game; the inferior Firm 2 conditionally gets higher strategic R&D incentives under nonzero-sum game. Comparison of symmetric and asymmetric models revealed that, when patent acquisition probability is low, symmetry is advantageous to Firm 1 to invest in R&D. On the other hand, to Firm 2, it is strategically advantageous for Firm 2 to do R&D competition in the asymmetric condition. Under the zero-sum game, the both firms has bigger R&D incentive in the asymmetric competition regardless of patent acquisition probability for Firm 1 and under the condition where patent acquisition probability is low with less than 30% for Firm 2.

4.1 Introduction

No one will doubt that R&D investment is a driving force of economic development for the country, and an important factor to develop new technology and the growth for a firm. Nevertheless, firms cannot easily decide to invest in R&D, because they know that they can suffer from unexpected investment loss in the midst of patent competition which happens inevitably among investment firms trying to protect their investment profits. In the recent market situation, we can notice an increasing number of winner-less war among firms where, as R&D investment of firms leads to excessive patent competition among them, many all the competing firms suffer loss. And, as the number of firms which, avoiding R&D investment and patent competition, try to get profits by the tricky use of non-infringing imitation goes up, people are more concerned about strategic R&D investment and patent disputes.

Over the past thirty years, the decreasing profits of R&D investment have been pointed out by economists and international associations like the WIPO (World Intellectual Property Organization) as one of the problems which should be tackled. A recent article in WSJ on the case of NOKIA[58] highlights the importance of cautious strategy in R&D investment. That is, since high proportion of R&D investment guarantees neither patent acquirement, nor investment profits, a firm needs to make decisions about R&D investment time matching the economic situation, and about investment in consideration of strategies of other firms. Reflecting such situations, there are active researches on R&D investment and patent race. As it is not clear whether a R&D investment of a firm will lead to good results, and it is not possible to get back the invested money, the failure in a R&D investment may negatively affect ongoing or planned

[58] According to the data reported in the WSJ article, the amount of R&D investment expenses NOKIA has spent during the last decade reaches as high as 40 billion dollars, 4 times of what APPLE has spent. Even if NOKIA holds over 10,000 patents, they do not guarantee profits to NOKIA(Source: http://online.wsj.com)

projects of the firm. Especially, given the attribute of patent (Weeds, 2002) as the winner-take-all system, in the investment competition stage, it is impossible to know which firm will acquire the patent right. It is also impossible to control completely leakage of technology information in the process of R&D investment and patent competition, even though intellectual property should be protected. Therefore, there are motives for firms to try to keep their technologies secretly rather than to get patents for them (Hall and Ziedonis, 2001; Gallini, 1992; Matutes et al., 1996; Horstmann et al., 1985).

R&D investment and patent race contain various kinds of uncertainty. The uncertainty may vary depending on the degree and speed of the development of a new product, and the incentive for R&D investment of a firm can change depending on the position of the other firm in the competition process (Zizzo, 2002). There have been various efforts to develop realistic models to reduce such uncertainty. But, it is necessary to notice the fact that the market situations have changed more rapidly and in more complex ways than the speed in which models have been developed. Furthermore, though firms generally secure profits by developing products and prohibiting their competitors from imitating them (Robert, 2001), unexpected outcomes can occur in the real market. It is commonly assumed that patent protects intellectual property, and, through such protection, development of products is activated. But, Bessen and Maskin(2006) proved that innovation is more active in industries where imitations are wide-spread. While it seems logical to apply for patent to secure profits from R&D investment, there are cases where firms do not apply for patent because patent application is equal to exposing its technology information to its competing firms. A firm can strategically leave even a patent it already applied as sleeping patent (Weeds, 2002). As such, even if patent is dealt with on many research models, the research outcomes can vary depending on hypothesized conditions. For example, the outcomes were different for the following two cases: the case where the firm holding the patent right of a product enjoys 100% protection of the patent (Chowdhury, 2005), and the case where non-infringing imitation is recognized in any way (Mukherjee, 2006).

It is impossible to eradicate uncertainty (Keith, 1989) caused by changeability of parameters, model algorithm, data, model structure and hypotheses. But, what many studies have pursued was to devise decision-making models minimizing uncertainty included in R&D competition and patent competition, and to maximize profits by predicting competitors' decision-making and devising strategic investment time and methods. As part of such efforts, this study, using the game theory, analyzes uncertainties of various R&D investment strategies of two firms competing with each other over the same product. Especially, unlike existing studies which determine patent acquisition probability in advance, this study constructs a model including two random variables of patent acquisition and non-infringing imitation under the bilateral R&D investment situation affecting strategic R&D incentives of the two firms in the asymmetric R&D competition model, and examines strategies to promote R&D investment of the two competing firms through sensitivity analysis.

4.2 Probabilistic Patent Acquisition model

We construct an asymmetric R&D investment model using the game theory, and assume a duopoly market where only the two firms producing the same product participate in. The two decide R&D investment at the same time (stage 1), and, then, are engaged in performance competition (stage 2) depending on patent competition and patent protection environment after the decisions on investment are made.

Following Chowdhury (2005), we let q_i be the output of firm and $f(q)$ be the inverse market demand function, where $q = q1 + q2$ and the equation satisfies $f' < 0$ and $f'(q) + q_i f''(q) < 0, \forall q, q_i$. We designate the cost function and the profit function of each firm i into cq and $\pi i(.,.)$, where the first argument shows Firm 1's marginal cost, and the second argument shows firm 2's marginal cost. The cost function of each firm can be improved by investing F (F>0) in R&D.

In the model, asymmetry was expressed by cost function of two firms. That is, we let the stronger firm have the better cost function, assuming that it is in the advantageous situation over the weaker one in existing distribution network and brand awareness. Lower cost means higher profits, and asymmetric hypothesis leads to the following ranking.

$$\pi_1(c'',c) = \pi_2(c,c'') > \pi_1(c',c) > \pi_1(\hat{c},c) > \pi_1(c,c)$$

and $$\pi_1(c'',c'') = \pi_2(c'',c'') \geq \pi_1(c',c') \geq \pi_1(\hat{c},\hat{c}) \geq \pi_1(c,c).$$

In the case where both firms decide to invest in R&D (Stage 1, Bilateral R&D case), if patent is not protected, each of the two firms are able to imitate the other's technology to the same level through mutual imitation regardless of patent acquisition, and if patent protection is provided, each firm can reduce the marginal cost up to the patent holder's cost by investing *I* with probability *z*. In other words, each firm improves its marginal cost to $c''q$ without patent protection in a bilateral R&D situation where two firms invest in R&D. And, the firm reduces its cost to; $c''q$ (Firm 1) or $c'q$ (Firm 2), and knowledge spillover reduces the non-innovating firm's cost to $\hat{c}q$ when there is no patent protection and a unilateral R&D situation in which only one firm invests in R&D. Furthermore, when, given the concept of non-infringing imitation[59], the non-patent holder can have the patented technology without infringement with probability z.

This study assumed that it is impossible to completely protect information, given the fact that, since technology information is leaked in the process of applying for patent, firms try to protect new technology through secrecy and lead time (Cohen at el., 2000; Levin et al., 1987) rather than through patent. That is, it assumed that even in the case where patent is protected, the firm not possessing patent can enhance its profits partly by new investment I and non-infringing imitation of patented technology to the extent of z probability. The situation where only one firm invests in R&D (unilateral-R&D-case) can be divided into two cases: the case where patent is protected, and the case where it is not. That is, in the case where patent is protected, a firm can gain profits (by decreasing its marginal cost to $\hat{c}$ with probability $z \in (0,1)$ only through additional cost (I) to steal the technology information. But, in the case where patent is not protected, the firm which does not invest in R&D can gain profits without paying additional cost by imitating technology information of the firm which invests in R&D. [60]

If two firms decide to invest in R&D, they are inevitably involved in patent competition except for the case where they choose the R&D cooperation option. But, in the stage where R&D investment is decided, it is impossible to predict which of the two will acquire the patent right. [61] It is also impossible to predict non-infringing imitation probability. Thus, it is necessary to make

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[59] Mukherjee(2006) assumes that two firms are in symmetric condition and that there is non-infringing imitation available.

[60] This is the case when the probability of non-infringing imitation(z) is 1.

[61] If patent acquisition can be explained by functions of R&D investment amount or difference of its scale compared with its competing company, the competition among companies will not occur from the beginning in rational judgement.

various payoff tables for different scenarios, and search for R&D investment strategies depending on the changes of patent acquisition and imitation probability variables through sensibility analysis. In addition, it is necessary to analyze how patent acquisition change, together with the change of non-infringing imitation, can be used in R&D investment strategies in various scenarios, by applying patent acquisition probability variable to asymmetric and symmetric R&D investment game models dealt with in chapter 2 and 3.

4.3 R&D investment strategy in nonzero-sum game environment

In the case where patent is not protected, since each of competing firms is able to imitate patented technology of the other firm completely (when the probability of non-infringing imitation is 1), patent acquisition probability does not affect payoff competition. But, in the market where patents are protected, performance of the two firms is affected by patent acquisition probability. If the probability of Firm 1 to acquire patent is ***p***, the probability of its competitor to acquire patent is 1-***p***. The performances of symmetric R&D investment under nonzero-sum game (NZ_Sym game hereafter) and asymmetric R&D investment under nonzero-sum game (NZ_Asy game hereafter) applying the above probabilities are decided as the following Table 4.1 and Table 4.2.

Table 4.1: Payoffs under Symmetric R&D investment game (NZ_Sym game).

Firm 1/2	R&D	No R&D
R&D	$z\pi_1(c',c')+(1-z)[p\pi_1(c',c)+(1-p)\pi_1(c,c')]-F-\frac{I}{2}$, $z\pi_2(c',c')+(1-z)[(1-p)\pi_2(c,c')+p\pi_2(c',c)]-F-\frac{I}{2}$	$z\pi_1(c',\hat{c})+(1-z)\pi_1(c',c)-F$, $z\pi_2(c',\hat{c})+(1-z)\pi_2(c',c)-I$
No R&D	$z\pi_1(\hat{c},c')+(1-z)\pi_1(c,c')-I$, $z\pi_2(\hat{c},c')+(1-z)\pi_2(c,c')-F$	$\pi_1(c,c),\pi_2(c,c)$

Table 4.2: Payoffs under Asymmetric R&D investment game (NZ_Asy game).

Firm 1/2	R&D	No R&D
R&D	$z[p\pi_1(c'',c'')+(1-p)\pi_1(c',c')]+(1-z)[p\pi_1(c'',c)+(1-p)\pi_1(c,c')]-kF-\frac{I}{2}$, $z[(1-p)\pi_2(c'',c'')+p\pi_2(c',c')]+(1-z)[(1-p)\pi_2(c,c')+p\pi_2(c'',c)]-F-\frac{I}{2}$	$z\pi_1(c'',\hat{c})+(1-z)\pi_1(c'',c)-kF$, $z\pi_2(c'',\hat{c})+(1-z)\pi_2(c'',c)-I$
No R&D	$z\pi_1(\hat{c},c')+(1-z)\pi_1(c,c')-I$, $z\pi_2(\hat{c},c')+(1-z)\pi_2(c,c')-F$	$\pi_1(c,c),\pi_2(c,c)$

As shown in the above Table 4.1 and Table 4.2, performances of the two firms in the bilateral-R&D-case are decided by non-infringing imitation probability (z) and patent protection acquisition probability (p). But, in the unilateral-R&D-case, since the firm which invests in R&D monopolizes the patent, the performance is not related with patent acquisition probability, but determined only by probability (z) through investment (I). The strategic R&D incentives of two firms calculated with the performance Table 4.1 & 4.2 above are summarized in Table 4.3.

Table 4.3: Strategic R&D incentives[62]in nonzero-sum game.

Sym/Asy_S(P)[63]	Strategic R&D incentives
$Sym\_S(P)_1$	$z[\pi_1(c',\hat{c})-\pi_1(c',c')]+(1-z)[p(\pi_1(c',c)-\pi_1(c,c'))]-F+\frac{I}{2}$
$Sym\_S(P)_2$	$z[\pi_2(\hat{c},c')-\pi_2(c',c')]+(1-z)[(1-p)(\pi_2(c,c')-\pi_2(c',c))]-F+\frac{I}{2}$
$Asy\_S(P)_1$	$z[p(\pi_1(c'',c'')-\pi_1(\hat{c},c'))+(1-p)(\pi_1(c',c')-\pi_1(\hat{c},c'))]+(1-z)[p(\pi_1(c'',c)-\pi_1(c,c'))]-kF+\frac{I}{2}$
$Asy\_S(P)_2$	$z[(1-p)(\pi_2(c'',c'')-\pi_2(c'',\hat{c}))+p(\pi_2(c',c')-\pi_2(c'',\hat{c}))]+(1-z)[(1-p)(\pi_2(c,c')-\pi_2(c'',c))]-F+\frac{I}{2}$

Intuitively, we can grasp that, when the probability of non-infringing imitation (z) is big, patent acquisition probability influences both firms, but, as probability (z) becomes smaller, only the patent acquisition probability of each firm affects its performance. That is, when z = 1, the equation calculating strategic R&D incentive includes patent acquisition probability p and 1-p, but, when z = 0, the equation only includes ***p*** (Firm 1) or 1-***p*** (Firm 2).

In the case where R&D cooperation is possible, since there is no possibility that R&D investment of competing firms leads to patent competition, the probability of acquiring patent right does not change payoffs of competing firms in the game model. But, in the case where technology licensing is possible, since patent acquisition can affect the profits of a firm greatly by the possibility of additional profits the patent right can generate, patent acquisition probability (P) critically affects performances of the two competing firms. Rockett (1990) argued that, since non-infringing imitation forces a firm to spend considerable expenses, imitation would not be profitable. But, we, assuming that, in the market where patent is protected, if the cost needed for

[62] S and (P) represent strategic R&D incentive and case when patent protection is provided.
[63] Sym_S(P) and Asy_S(P) represent strategic incentives for symmetric and asymmetric R&D investment game, respectively.

non-infringing imitation is smaller than the royalty the firm should pay to the patent-holding firm to use the patented technology, the firm is tempted to adopt the imitation strategy, include non-infringing imitation probability in the model in which licensing is added to.[64] Here, a licensing contract is assumed to be the one between the innovating firm and the non-innovating firm is per unit output royalty rather than up-front fixed fee. Consequently, the higher (the lower) the technology gap between two firms is and the higher the imitation probability is, the lower (the higher) additional profits through licensing gets.

The following Tables 4.4 and 4.5 show two competing firms' payoffs under symmetric and asymmetric R&D investment game regarding uncertain patent acquisition when a licensing option is added along with independent R&D investment, and Table 4.6 illustrates non-strategic and strategic R&D incentives when patent is protected.

Table 4.4[65]: Payoffs under symmetric R&D investment game with licensing (NZ_Sym game).

Firm 1/2	R&D	No R&D
R&D	$z\pi_1(c',c')+(1-z)[p\pi_1(c',c)+(1-p)\pi_1(c,c')+pR(c',c)]-F,$ $z\pi_2(c',c')+(1-z)[(1-p)\pi_2(c,c')+p\pi_2(c',c)+(1-p)R(c,c')]-F$	$z[\pi_1(c',\hat{c})+R(c',\hat{c})]+(1-z)[\pi_1(c',c)+R(c',c)]-F,$ $z\pi_2(c',\hat{c})+(1-z)\pi_2(c',c)-I$
No R&D	$z\pi_1(\hat{c},c')+(1-z)\pi_1(c,c')-I,$ $z[\pi_2(\hat{c},c')+R(c',\hat{c})]+(1-z)[\pi_2(c,c')+R(c,c')]-F$	$\pi_1(c,c),\pi_2(c,c)$

[64] Mukherjee (2006) assumes that non-infringing imitation isn't possible if technology licensing is available.

[65] In bilateral R&D case, the part of the payoff equation for firm 1 is calculated with the following step.
$z\pi_1(c',c')=z[p\pi_1(c',c')+(1-p)\pi_1(c',c')+pR(c',c')]$, cf) $R(c',c')=0$

Table 4.5: Payoffs under asymmetric R&D investment game with licensing (NZ_Asy game).

Firm 1/2	Payoffs
R&D / R&D	$z[p\pi_1(c'',c'')+(1-p)\pi_1(c',c')]+(1-z)[p\pi_1(c'',c)+(1-p)\pi_1(c,c')+pR(c'',c)]-kF-\frac{I}{2},$ $z[(1-p)\pi_2(c'',c'')+p\pi_2(c',c')]+(1-z)[(1-p)\pi_2(c,c')+p\pi_2(c'',c)+(1-p)R(c,c')]-F-\frac{I}{2}$
R&D / No R&D	$z(\pi_1(c'',\hat{c})+R(c'',\hat{c}))+(1-z)(\pi_1(c'',c)+R(c'',c))-kF,$ $z\pi_2(c'',\hat{c})+(1-z)\pi_2(c'',c)-I$
No R&D / R&D	$z\pi_1(\hat{c},c')+(1-z)\pi_1(c,c')-I,$ $z(\pi_2(\hat{c},c')+R(\hat{c},c'))+(1-z)(\pi_2(c,c')+R(c,c'))-F$
No R&D / No R&D	$\pi_1(c,c),\pi_2(c,c)$

Table 4.6: Strategic R&D incentives with licensing in nonzero-sum game.

Sym/Asy_S(PL)	Strategic R&D incentives with Licensing
$Sym\_S(PL)_1$	$z[\pi_1(c',\hat{c})-\pi_1(c',c')]+(1-z)[p(\pi_1(c',c)-\pi_1(c,c'))]-F+\frac{I}{2}$
$Sym\_S(PL)_2$	$z[\pi_2(\hat{c},c')-\pi_2(c',c')]+(1-z)[(1-p)(\pi_2(c,c')-\pi_2(c',c))]-F+\frac{I}{2}$
$Asy\_S(PL)_1$	$z[p(\pi_1(c'',c'')-\pi_1(\hat{c},c'))+(1-p)(\pi_1(c',c')-\pi_1(\hat{c},c'))]+(1-z)[p(\pi_1(c'',c)-\pi_1(c,c')+R(c'',c)]-kF+\frac{I}{2}$
$Asy\_S(PL)_2$	$z[(1-p)(\pi_2(c'',c'')-\pi_2(c'',\hat{c}))+p(\pi_2(c',c')-\pi_2(c'',\hat{c}))]+(1-z)[(1-p)(\pi_2(c,c')-\pi_2(c'',c)+R(c,c'))]-F+\frac{I}{2}$

4.4 R&D Investment Strategy in Zero-sum Game Environment

Observing the fact that, in the asymmetric R&D investment game where two firms compete over the same product, the zero-sum game environment where the total profit is fixed can force the two firms to change their competition strategies, we produced the two tables: Performance Table

4.7 in the symmetric R&D under zero-sum game environment (Z_Sym Game hereafter); Performance Table 4.8 in the Asymmetric R&D under zero-sum game environment (Z_Asy Game hereafter).

Table 4.7: Payoffs under symmetric R&D investment game (Z_Sym Game).

Firm 1/2	R&D	No R&D
R&D	$z\pi_1(c',c')+(1-z)[p\pi_1(c',c)+(1-p)\pi_1(c,c')]-F-\frac{I}{2}$, $z\pi_2(c',c')+(1-z)[(1-p)\pi_2(c,c')+p\pi_2(c',c)]-F-\frac{I}{2}$	$z\pi_1(c',\hat{c})+(1-z)\pi_1(c',c)-F$, $2z[\pi_2(c',c')-\frac{\pi_2(\hat{c},c')}{2}]+(1-z)\pi_2(c',c)-I$
No R&D	$2z[\pi_1(c',c')-\frac{\pi_1(c',\hat{c})}{2}]+(1-z)\pi_1(c,c')-I$, $z\pi_2(\hat{c},c')+(1-z)\pi_2(c,c')-F$	$\pi_1(c,c),\pi_2(c,c)$

Table 4.8: Payoffs under asymmetric R&D investment game (Z_Asy game).

Firm 1/2	Payoffs
R&D / R&D	$z[p\pi_1(c'',c'')+(1-p)\pi_1(c',c')]+(1-z)[p\pi_1(c'',c)+(1-p)\pi_1(c,c')]-kF-\frac{I}{2}$, $z[(1-p)\pi_2(c'',c'')+p\pi_2(c',c')]+(1-z)[(1-p)\pi_2(c,c')+p\pi_2(c'',c)]-F-\frac{I}{2}$
R&D / No R&D	$z\pi_1(c'',\hat{c})+(1-z)\pi_1(c'',c)-kF$, $z[\pi_2(c'',c'')+\pi_2(c',c')-\pi_2(\hat{c},c'')]+(1-z)[(1-p)(\pi_2(c,c')+\pi_2(c',c)-\pi_2(c,c''))+p\pi_2(c'',c)]-F-I$
No R&D / R&D	$z[\pi_1(c'',c'')+\pi_1(c',c')-\pi_1(c',\hat{c})]+(1-z)[(1-p)\pi_1(c,c')+p(\pi_1(c,c'')+\pi_1(c'',c)-\pi_1(c',c))]-kF-I$, $z\pi_2(\hat{c},c')+(1-z)\pi_2(c,c')-F$
No R&D / No R&D	$\pi_1(c,c),\pi_2(c,c)$

As shown in Table 4.7 and 4.8, in the unilateral-R&D-case, while the firm which invests in R&D can get the same performance as in the nonzero-sum model, the firm which does not invest in R&D can get profits of the total profits minus profits of patent-holding firm. Non-strategic and strategic R&D incentives calculated from the payoffs (Tables 4.7 and 4.8) are summarized in the following Table 4.9.

Table 4.9: Strategic R&D incentives in zero-sum game.

Sym/Asy_S(P)	Strategic R&D incentives
$Sym\_S(P)_1$	$z[\pi_1(c',\hat{c})-\pi_1(c',c')]+(1-z)[p(\pi_1(c',c)-\pi_1(c,c'))]-F+\frac{I}{2}$
$Sym\_S(P)_2$	$z[\pi_2(\hat{c},c')-\pi_2(c',c')]+(1-z)[(1-p)(\pi_2(c,c')-\pi_2(c',c))]-F+\frac{I}{2}$
$Asy\_S(P)_1$	$z[p(\pi_1(c',\hat{c})-\pi_1(c',c'))+(1-p)(\pi_1(c',\hat{c})-\pi_1(c'',c'')]+(1-z)[p(\pi_1(c',c)-\pi_1(c,c''))]+\frac{I}{2}$
$Asy\_S(P)_2$	$z[(1-p)(\pi_2(\hat{c},c'')-\pi_2(c',c'))+p(\pi_2(\hat{c},c'')-\pi_2(c'',c''))]+(1-z)[(1-p)(\pi_2(c,c'')-(\pi_2(c,c'))]+\frac{I}{2}$

Except for the case where imitation probability through *I* investment is 100%, patent-holding firm can get additional profits through licensing. That is, the lower the imitation probability gets, the royalty profit (R) gets larger between patent holder and non-patent holder (Bilateral-R&D-case) or between innovating firm and non-innovating firm (Unilateral-R&D-case). Table 4.10 and Table 4.11 summarize the performance of the case where technology licensing is added to in the asymmetric R&D investment game, and the strategic R&D incentives are summarized in Table 4.12.

Table 4.10: Payoffs under symmetric R&D investment game with licensing (Z_Sym Game).

Firm 1/2	R&D	No R&D
R&D	$z\pi_1(c',c')+(1-z)[p\pi_1(c',c)+(1-p)\pi_1(c,c')+pR(c',c)]-F,$ $z\pi_2(c',c')+(1-z)[(1-p)\pi_2(c,c')+p\pi_2(c',c)+(1-p)R(c,c')]-F$	$z[\pi_1(c',\hat{c})+R(c',\hat{c})]+(1-z)[\pi_1(c',c)+R(c',c)]-F,$ $2z[\pi_2(c',c')-\frac{(\pi_2(\hat{c},c')+R(\hat{c},c'))}{2}]+(1-z)\pi_2(c',c)-I$
No R&D	$2z[\pi_1(c',c')-\frac{(\pi_1(c',\hat{c})+R(c',\hat{c}))}{2}]+(1-z)\pi_1(c,c')-I,$ $z[\pi_2(\hat{c},c')+R(c',\hat{c})]+(1-z)[\pi_2(c,c')+R(c,c')]-F$	$\pi_1(c,c),\pi_2(c,c)$

Table 4.11: Payoffs under asymmetric R&D investment game with licensing (Z_Asy game).

Firm 1/2	Payoffs
R&D / R&D	$z[p\pi_1(c'',c'')+(1-p)\pi_1(c',c')]+(1-z)[p\pi_1(c'',c)+(1-p)\pi_1(c,c')+pR(c'',c)]-kF-\frac{I}{2},$ $z[(1-p)\pi_2(c'',c'')+p\pi_2(c',c')]+(1-z)[(1-p)\pi_2(c,c')+p\pi_2(c'',c)+(1-p)R(c,c')]-F-\frac{I}{2}$
R&D / No R&D	$z(\pi_1(c'',\hat{c})+R(c'',\hat{c}))+(1-z)(\pi_1(c'',c)+R(c'',c))-kF,$ $z[\pi_2(c'',c'')+\pi_2(c',c')-\pi_2(\hat{c},c'')-R(\hat{c},c'')]+(1-z)[p\pi_2(c'',c)+(1-p)[\pi_2(c',c)+\pi_2(c,c')-\pi_2(c,c'')+R(c,c')-R(c,c'')]-F-I$
No R&D / R&D	$z[\pi_1(c'',c'')+\pi_1(c',c')-\pi_1(c',\hat{c})-R(c',\hat{c})]+(1-z)[(1-p)\pi_1(c,c')]+p[R(c'',c)-R(c',c)+\pi_1(c'',c)+\pi_1(c,c'')-\pi_1(c',c)]-kF-I,$ $z(\pi_2(\hat{c},c')+R(\hat{c},c'))+(1-z)(\pi_2(c,c')+R(c,c'))-F$
No R&D / No R&D	$\pi_1(c,c),\pi_2(c,c)$

Table 4.12: Strategic R&D incentives with licensing in zero-sum game.

Sym/Asy_S(PL)	Strategic R&D incentives with Licensing
$Sym\_S(PL)_1$	$z[\pi_1(c',\hat{c})-\pi_1(c',c')+R(c',\hat{c})]+(1-z)[p(\pi_1(c',c)-\pi_1(c,c')+R(c',c))]-F+I$
$Sym\_S(PL)_2$	$z[\pi_2(\hat{c},c')-\pi_2(c',c')+R(\hat{c},c')]+(1-z)[(1-p)(\pi_2(c,c')-\pi_2(c',c)+R(c,c'))]-F+I$
$Ays\_S(PL)_1$	$z[p(\pi_1(c',\hat{c})-\pi_1(c',c')+R(c',\hat{c}))+(1-p)\pi_1(c',\hat{c})-\pi_1(c'',c'')+R(c',\hat{c})]$ $+(1-z)[p(\pi_1(c',c)-\pi_1(c,c'')+R(c',c))]+\frac{I}{2}$
$Asy\_S(PL)_2$	$z[(1-p)(\pi_2(\hat{c},c'')-\pi_2(c',c')+R(\hat{c},c''))+p(\pi_2(\hat{c},c'')-\pi_2(c'',c'')+R(\hat{c},c''))]$ $+(1-z)[(1-p)(\pi_2(c,c'')-\pi_2(c',c)+R(c,c''))]+\frac{I}{2}$

4.5 Sensitivity analysis regarding probabilities of Patent Acquisition and Non-infringing Imitation

Those we treat as variables in the competition model of two firms are non-infringing imitation probability (***z***) and patent acquisition probability (***p***). As it is difficult to define uncertainty of two variables as a specific function, we assume uniform distribution for ***z*** and ***p***. [66] By applying values which can occur in predictable other situations instead of hypotheses and values applied for the first time to the major variables used in the prediction of outcomes of the R&D investment game model through sensitivity analysis, we comparatively analyze how R&D incentive strategies can change depending on investment decision and patent competition. In addition, by making environmental situations into different scenarios ㅡ whether the competition environment is symmetric or asymmetric; whether the profits are determined by zero-sum game

[66] Future work will apply various probabilities distribution regarding features of non-infringing imitation and patent acquisition in reality.

or by non-zero-sum game — and, by examining the change range of R&D incentives in each scenario, we overcome the limits of simple prediction technique which analyzes only the single scenario, and indirectly evaluate risk levels of decision-making of competing firms.

The values of two variables are uniformly distributed, where the value of ***p*** is the value when the range from 0 to 1 is divided into 10 equal parts, and the value of the non-infringing imitation probability is that of six division of the range from 0 to 1. Applying the cost function hierarchy assumed above, we listed 32 kinds of profit functions ($\pi_i(.,.)$ where, $i = 1, 2$) which can take place in R&D competition of two firms, and assumed the value of the highest profit function ($\pi_1(c'', c) = \pi_2(c, c'')$) as 1,000.[67] Even if the profit functions of two firms also form a hierarchy, in many cases, it is impossible to do intuitive interpretation through the formulae included in the payoff table per scenario because linearity[68] between profit functions is not assumed. Accordingly, after generating enough random numbers matching hypotheses based on given values of $\pi_1(c'', c) = \pi_2(c, c'')$, we listed R&D incentives with ***p***, ***z*** values per scenario in Table 4.13 below.

4.5.1 Scenario-based R&D Incentives Comparison: Nonzero-sum Game VS Zero-sum Game

Zero-sum or nonzero-sum game (environmental) conditions have great effects on the results of R&D competition. Through the comparison of strategic-R&D incentives per scenario, we analyze under what condition each of the two firms engaged in asymmetric R&D investment competition can get higher achievement from its R&D investment. Here, based on R&D

[67] Scenario-based results should be fractionally interpreted based on the given value of $\pi_1(c'', c) = \pi_2(c, c'')$.
[68] Future work will also include the linear relationship between profit functions.

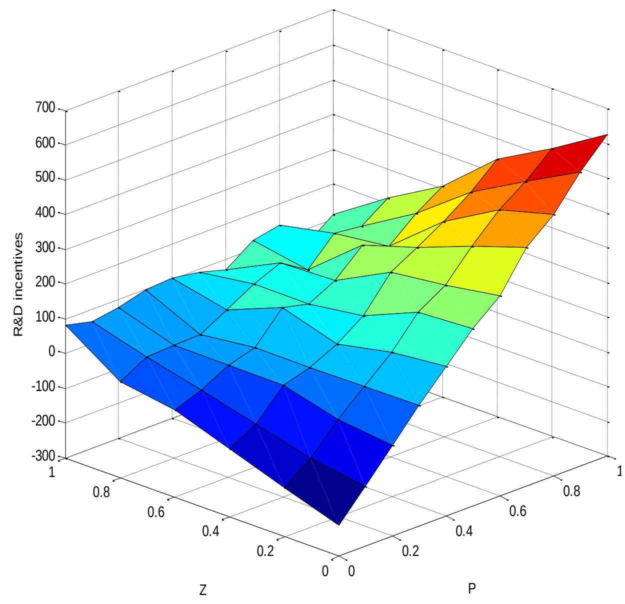
incentive table per scenario (Table 4.13), we comparatively analyzed strategic R&D incentives of the two firms as shown in Figure 4.1[69], 4.2, and 4.3. Figure 4.1 presents strategic R&D incentive changes depending on the changes of patent acquisition and imitation probabilities under the conditions of nonzero-sum and zero-sum as three-dimensional graph. Figure 4.2 and 4.3 show two scenarios for each of the firm to do comparative analysis of scenarios under the nonzero-sum and zero-sum game conditions.

[69] NZ and Z indicate non-zero sum and zero-sum game, respectively.

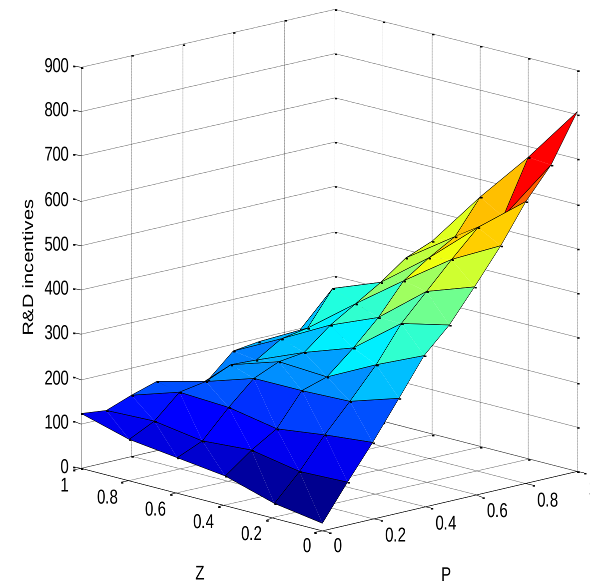
Table 4.13: Scenario-based R&D incentives regarding probabilities of ***p*** and ***z*** .

		S(P) in NonZerosum				S(PL) w/ Licensing in NonZerosum				S(P) in Zerosum				S(PL) w/ Licensing in Zerosum			
		Symmetric R&D game		Asymmetric R&D game		Symmetric R&D game		Asymmetric R&D game		Symmetric R&D game		Asymmetric R&D game		Symmetric R&D game		Asymmetric R&D game	
P	Z	Sym_S(P)1	Sym_S(P)2	Asy_S(P)1	Asy_S(P)2	Sym_S(PL)1	Sym_S(PL)2	Asy_S(PL)1	Asy_S(PL)2	Sym_S(P)1	Sym_S(P)2	Asy_S(P)1	Asy_S(P)2	Sym_S(PL)1	Sym_S(PL)2	Asy_S(PL)1	Asy_S(PL)2
0	0	-61.3	657.8	-211.3	681.3	-61.3	657.8	-211.3	762.1	-61.3	657.8	13.7	145.4	-61.3	738.6	13.7	239.4
	0.2	-31.0	527.6	-158.3	641.3	-31.0	527.6	-158.3	707.4	-31.0	527.6	31.8	163.4	-17.2	607.5	45.6	255.2
	0.4	14.4	411.6	-102.3	536.2	14.4	411.6	-102.3	582.4	14.4	411.6	66.8	250.3	40.6	484.1	93.1	338.9
	0.6	38.6	338.9	-49.3	529.6	38.6	338.9	-49.3	564.8	38.6	338.9	77.8	237.9	83.9	419.3	123.0	330.8
	0.8	123.3	262.5	-24.9	456.5	123.3	262.5	-24.9	473.0	123.3	262.5	94.0	374.8	180.4	336.1	151.0	466.0
	1	99.6	99.6	83.9	387.9	99.6	99.6	83.9	387.9	99.6	99.6	122.8	353.8	171.1	171.1	194.3	443.3
0.1	0	11.8	553.0	-126.3	627.6	11.8	553.0	-116.7	703.1	11.8	553.0	95.1	125.8	20.2	628.6	19.2	212.0
	0.2	24.3	477.7	-104.3	556.4	24.3	477.7	-97.0	614.8	24.3	477.7	90.8	147.8	44.5	549.9	56.7	230.7
	0.4	59.7	389.6	-61.5	490.6	59.7	389.6	-55.8	533.9	59.7	389.6	111.1	243.2	93.3	461.6	113.9	330.4
	0.6	59.7	296.4	-20.3	485.0	59.7	296.4	-16.6	515.5	59.7	296.4	103.7	249.3	104.4	368.1	131.2	335.9
	0.8	80.8	194.7	20.0	415.5	80.8	194.7	21.9	430.0	80.8	194.7	119.9	302.2	138.7	265.5	170.1	389.5
	1	97.8	97.8	62.2	374.9	97.8	97.8	62.2	374.9	97.8	97.8	117.1	331.8	166.2	166.2	180.1	416.7
0.2	0	89.0	525.8	-39.2	558.2	89.0	525.8	-20.1	625.6	89.0	525.8	172.1	105.8	105.8	593.2	18.4	181.9
	0.2	90.8	433.4	-19.2	512.9	90.8	433.4	-4.2	565.3	90.8	433.4	159.6	163.9	117.9	499.7	77.0	241.8
	0.4	93.1	357.1	21.5	505.6	93.1	357.1	32.8	545.5	93.1	357.1	146.5	190.9	132.0	425.9	119.4	271.4
	0.6	119.5	287.0	21.9	465.2	119.5	287.0	29.4	491.5	119.5	287.0	166.8	258.1	170.0	357.3	183.3	341.1
	0.8	136.2	226.5	23.3	408.6	136.2	226.5	27.1	422.4	136.2	226.5	173.7	313.9	198.0	298.5	219.9	400.3
	1	112.0	112.0	75.2	344.3	112.0	112.0	75.2	344.3	112.0	112.0	139.3	334.1	181.4	181.4	198.2	419.4
0.3	0	170.3	472.5	49.7	499.5	170.3	472.5	77.8	558.1	170.3	472.5	256.9	87.2	195.5	531.1	18.7	152.7
	0.2	142.8	364.7	47.3	448.6	142.8	364.7	70.5	494.8	142.8	364.7	222.3	162.8	176.9	425.1	91.6	234.9
	0.4	142.1	308.8	42.4	431.2	142.1	308.8	58.7	465.1	142.1	308.8	216.7	189.7	184.9	370.9	160.6	262.2
	0.6	161.1	279.1	46.1	386.1	161.1	279.1	57.5	409.4	161.1	279.1	217.7	281.7	213.6	345.0	219.5	362.0
	0.8	136.8	189.7	25.6	346.9	136.8	189.7	31.2	357.8	136.8	189.7	181.9	302.0	196.0	255.2	219.6	382.0
	1	119.2	119.2	98.2	384.8	119.2	119.2	98.2	384.8	119.2	119.2	155.3	368.8	193.7	193.7	212.7	462.4
0.4	0	247.6	399.7	132.8	425.2	247.6	399.7	170.8	476.9	247.6	399.7	339.6	71.2	282.1	451.4	18.4	128.2
	0.2	203.9	315.6	116.0	383.3	203.9	315.6	145.6	422.1	203.9	315.6	289.6	147.7	243.4	368.1	113.3	209.7
	0.4	151.8	230.9	81.9	368.9	151.8	230.9	105.3	399.6	151.8	230.9	237.2	162.5	202.4	291.8	159.3	233.3
	0.6	176.8	237.5	129.4	410.3	176.8	237.5	144.5	430.8	176.8	237.5	242.9	236.6	234.4	301.9	228.6	312.9
	0.8	175.2	204.4	68.2	339.7	175.2	204.4	75.8	349.6	175.2	204.4	208.9	314.9	237.1	269.5	241.7	395.4
	1	71.5	71.5	103.2	446.8	71.5	71.5	103.2	446.8	71.5	71.5	109.9	258.9	148.8	148.8	161.6	349.9
0.5	0	296.3	296.3	211.1	318.8	296.3	296.3	258.3	359.6	296.3	296.3	393.8	84.8	337.1	337.1	20.1	132.0
	0.2	293.0	293.0	201.8	338.2	293.0	293.0	240.7	372.2	293.0	293.0	370.1	144.4	341.2	341.2	136.3	201.3
	0.4	205.8	205.8	134.1	295.8	205.8	205.8	162.3	319.7	205.8	205.8	287.1	184.0	258.2	258.2	188.4	247.2
	0.6	177.7	177.7	112.1	329.9	177.7	177.7	130.8	346.6	177.7	177.7	250.7	236.5	236.2	236.2	225.4	308.9
	0.8	147.7	147.7	114.4	349.7	147.7	147.7	123.8	357.7	147.7	147.7	204.4	296.7	210.9	210.9	230.4	376.4
	1	76.3	76.3	89.2	371.6	76.3	76.3	89.2	371.6	76.3	76.3	132.6	290.8	148.4	148.4	175.5	378.7
0.6	0	363.0	221.6	278.8	241.3	363.0	221.6	333.1	273.0	363.0	221.6	467.5	57.6	410.7	253.4	13.8	93.8
	0.2	335.7	217.7	251.1	269.8	335.7	217.7	296.2	296.5	335.7	217.7	428.1	119.2	389.8	258.4	142.1	167.1
	0.4	264.1	179.1	230.1	285.6	264.1	179.1	264.7	305.0	264.1	179.1	344.6	162.3	321.9	227.3	209.1	219.9
	0.6	221.4	168.1	149.7	285.2	221.4	168.1	172.2	297.7	221.4	168.1	299.4	237.2	281.5	222.0	264.2	302.7
	0.8	171.1	143.4	146.6	318.3	171.1	143.4	157.9	325.0	171.1	143.4	238.4	250.5	239.8	208.8	259.3	327.8
	1	134.1	134.1	69.9	328.2	134.1	134.1	69.9	328.2	134.1	134.1	182.9	348.6	203.0	203.0	222.0	435.3
0.7	0	431.7	149.5	386.6	166.0	431.7	149.5	452.1	189.6	431.7	149.5	545.3	57.8	486.6	173.0	12.8	85.9
	0.2	394.3	158.3	334.6	201.1	394.3	158.3	387.1	220.7	394.3	158.3	486.0	116.7	453.2	191.2	154.5	156.6
	0.4	330.9	154.0	273.3	246.9	330.9	154.0	313.6	262.2	330.9	154.0	413.3	150.5	397.3	200.1	248.0	203.5
	0.6	262.4	150.5	223.2	261.1	262.4	150.5	249.4	271.0	262.4	150.5	333.8	207.8	329.8	204.6	285.9	272.7
	0.8	177.7	123.4	97.1	246.1	177.7	123.4	110.4	250.9	177.7	123.4	250.2	322.7	240.6	180.0	263.1	398.9
	1	137.7	137.7	126.0	367.0	137.7	137.7	126.0	367.0	137.7	137.7	191.9	312.1	213.8	213.8	228.3	403.0
0.8	0	516.5	87.0	452.6	96.9	516.5	87.0	526.9	113.3	516.5	87.0	631.0	40.4	582.2	103.4	18.8	59.0
	0.2	446.7	95.4	410.6	144.0	446.7	95.4	471.3	157.1	446.7	95.4	545.5	93.4	513.0	122.3	164.9	125.9
	0.4	361.0	95.9	318.5	195.4	361.0	95.9	362.8	205.5	361.0	95.9	450.5	144.8	429.8	134.6	254.2	191.5
	0.6	281.9	110.0	190.6	210.4	281.9	110.0	221.1	217.1	281.9	110.0	366.3	236.2	350.6	158.6	301.8	298.1
	0.8	249.6	163.6	171.8	277.6	249.6	163.6	187.1	281.0	249.6	163.6	326.0	287.7	323.6	227.5	338.6	363.5
	1	99.3	99.3	140.0	374.0	99.3	99.3	140.0	374.0	99.3	99.3	161.3	290.2	171.4	171.4	187.9	379.1
0.9	0	586.0	13.5	545.1	18.2	586.0	13.5	629.8	26.4	586.0	13.5	702.6	29.1	659.9	21.8	17.0	38.5
	0.2	462.5	30.1	463.7	67.8	462.5	30.1	530.3	73.8	462.5	30.1	556.8	92.5	529.2	48.8	166.4	116.3
	0.4	389.4	45.0	376.0	144.5	389.4	45.0	426.3	149.3	389.4	45.0	483.3	148.6	459.3	76.7	263.7	189.1
	0.6	318.6	87.1	257.4	196.2	318.6	87.1	290.5	199.5	318.6	87.1	408.7	215.3	391.3	133.5	329.9	272.3
	0.8	173.5	64.6	164.9	233.6	173.5	64.6	181.8	235.2	173.5	64.6	257.6	255.2	244.4	122.3	258.2	328.6
	1	107.8	107.8	58.1	332.7	107.8	107.8	58.1	332.7	107.8	107.8	179.9	328.7	178.5	178.5	202.0	416.6
1	0	659.8	-53.1	625.3	-53.1	659.8	-53.1	720.0	-53.1	659.8	-53.1	808.9	21.9	743.0	-53.1	21.9	21.9
	0.2	570.2	-24.1	527.2	12.5	570.2	-24.1	604.0	12.5	570.2	-24.1	678.6	75.0	652.7	-9.8	193.6	92.8
	0.4	467.4	8.8	443.2	120.6	467.4	8.8	499.4	120.6	467.4	8.8	561.7	128.3	548.8	38.5	302.6	164.4
	0.6	340.1	55.8	307.9	187.4	340.1	55.8	345.1	187.4	340.1	55.8	432.3	201.3	416.4	99.2	341.9	254.7
	0.8	193.5	60.4	214.9	239.5	193.5	60.4	233.5	239.5	193.5	60.4	284.0	229.4	264.6	115.7	278.7	298.7
	1	69.2	69.2	112.5	344.0	69.2	69.2	112.5	344.0	69.2	69.2	144.2	300.1	135.9	135.9	157.3	386.5

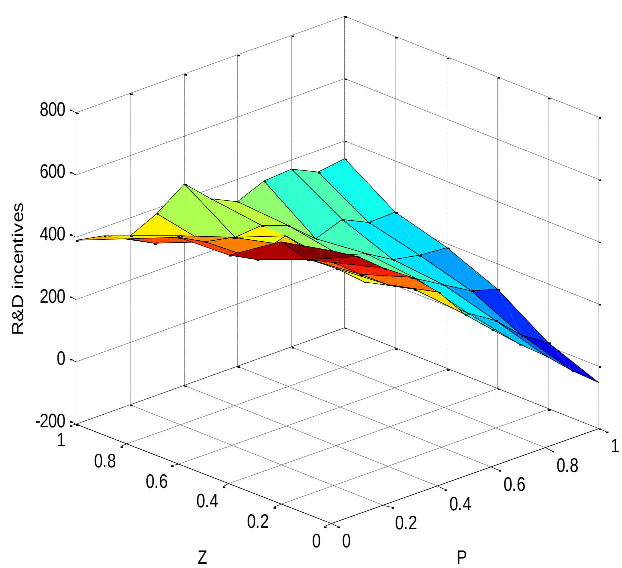
Nonzero-sum game VS Zero-sum game



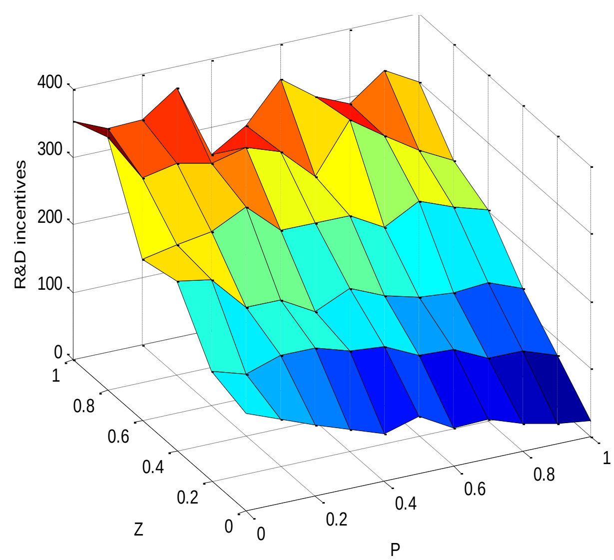
NZ_Asy_S(P)1



Z_Asy_S(P)1



NZ_Asy_S(P)2



Z_Asy_S(P)2

Figure 4.1: Asy_S(P) comparison between nonzero-sum and zero-sum game environment.

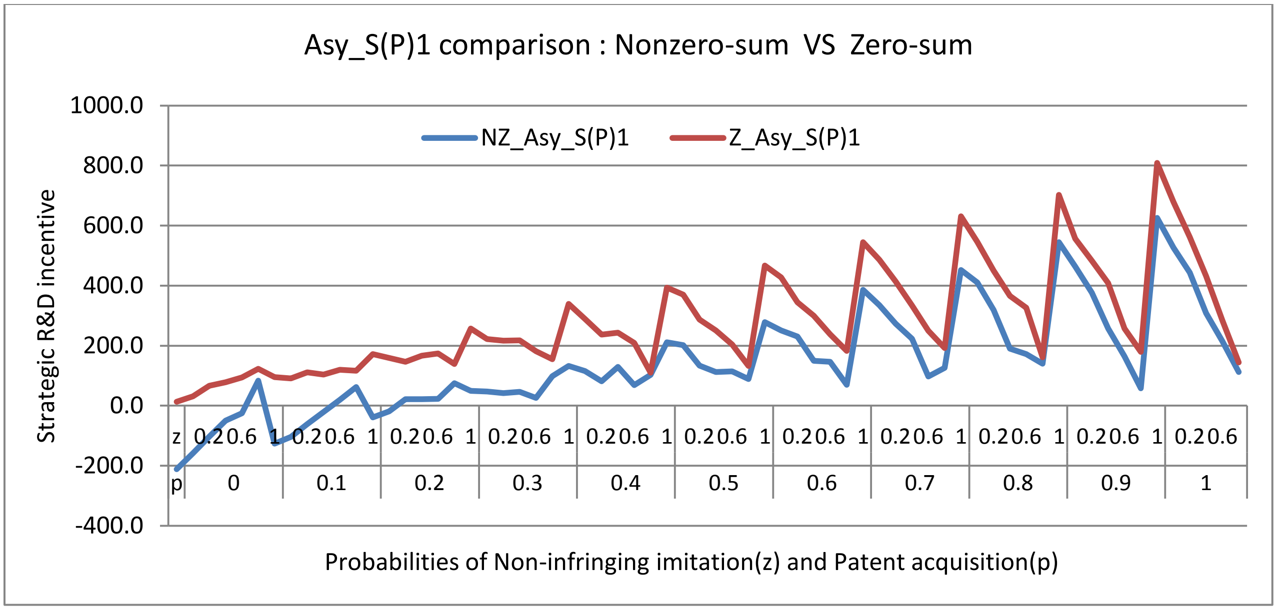


Figure 4.2: Asy_S(P)$_1$ comparison regarding ***p*** and ***z*** between nonzero-sum and zero-sum game.

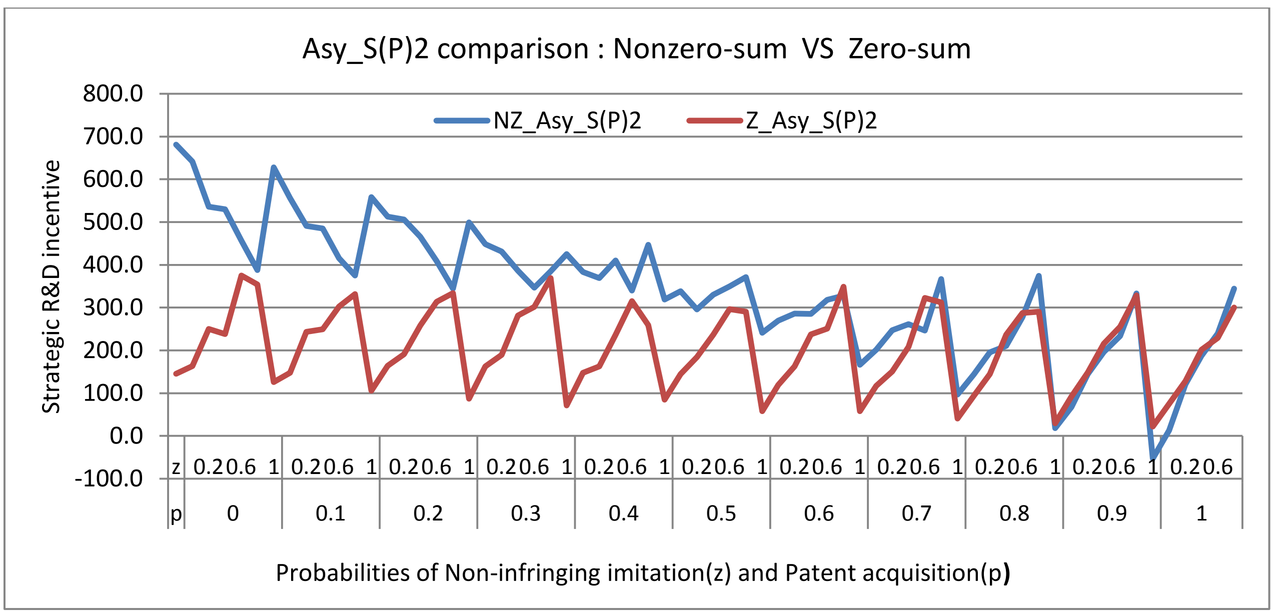


Figure 4.3: Asy_S(P)$_2$ comparison regarding ***p*** and ***z*** between nonzero-sum and zero-sum game.

As shown in Figure 4.1 and Figure 4.2, under the asymmetric competition, the superior Firm 1 has higher strategic R&D incentives in all sections when it is zero-sum game (rather than when it is nonzero-sum game). When patent acquisition probability of Firm 1 is from 0 to 30%, there is positive relationship between non-infringing imitation and R&D incentives, and, when it goes over 50%, the relationship between non-infringing imitation and R&D incentives becomes negative in both nonzero-sum and zero-sum game conditions. This indicates that, under the condition where patent acquisition probability of Firm 1 is low, as non-infringing imitation probability goes up, R&D investment becomes attractive and patent acquisition probability of Firm 1 is high, as non-infringing imitation probability goes down, R&D investment becomes good to make.

In the zero-sum (nonzero-sum) game environment, after patent acquisition probability goes over 30% (50%), as non-infringing imitation probability becomes larger, R&D incentive begins to decline.[70] The fact that, as patent acquisition probability goes up, decline slope becomes steeper (see Figure 4.2) indicates that, as patent acquisition probability of Firm 1 goes up, the effect of imitation probability of its competitor on the willingness of Firm 1 to invest in R&D gets larger. Especially, in the case of Firm 1, patent acquisition probability is low ($0 \leq \boldsymbol{p} \leq 20\%$), and imitation probability of its competitor is also low, it shows minus R&D incentive. In that case, it is advantageous for Firm 1 not to invest in R&D.

Under the asymmetric R&D competition, in the sections where patent acquisition probability of the inferior Firm 2 is high, R&D incentive values are higher in nonzero-sum game than those in zero-sum game (see Figure 4.3). In the sections where patent acquisition probability of Firm 1 is high ($\boldsymbol{p} \geq 50\%$), the smaller the probability of non-infringing-imitation is, the higher strategic R&D incentive gets (negative relationship. see Figure 4.2.). On the other hand, for Firm 2, under

[70] The pattern of negative relationship between non-infringing imitation probabilities and R&D incentives begins earlier in zero-sum than nonzero-sum game environment, because duopoly firms have more sensitive interdependent relationship in zero-sum game.

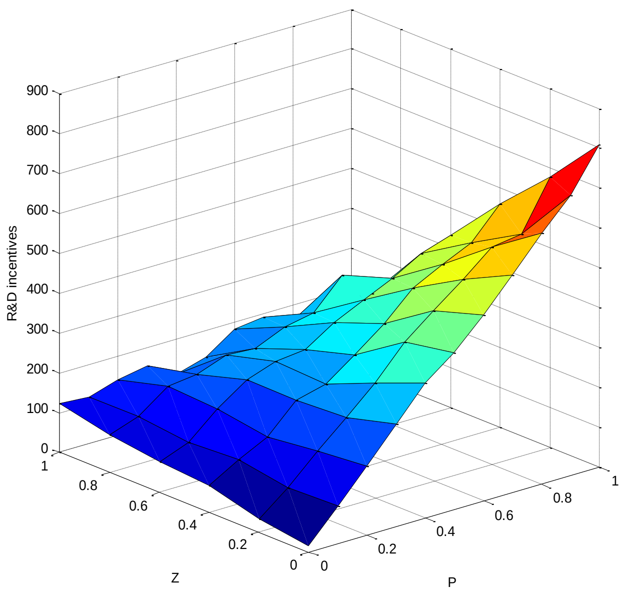
zero-sum game condition, R&D incentives and non-infringing-imitation probability show a certain positive pattern in all the sections. That is, in the section where ***p*** is 0%~30%, the pattern between NZ_Asy_S(P)2 and Z_Asy_S(P)2 shows contrasting one.

In nonzero-sum condition, when patent acquisition probability of Firm 1 is high (***p*** ≥ 50%), the higher the imitation probability gets, the steeper the incentive growth becomes, which means that the more evident the probability that the superior Firm 1will acquire patent, the more dependent Firm 2 will be on imitation of it, and the greater R&D incentive on non-infringing imitation grows.

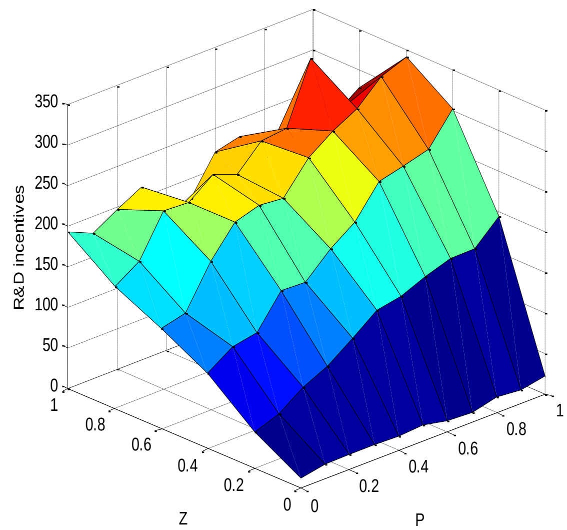
In summary, between non-zero-sum game and zero-sum game, since Firm 1 gets higher R&D incentive in zero-sum game regardless of patent acquisition probability, it is strategically advantageous for Firm 1 to compete in zero-sum game. On the other hand, for Firm 2, when patent acquisition probability is relatively high, it is more advantageous to invest in R&D in non-zero-sum game.

Figure 4.4, Figure 4.5, and Figure 4.6 show R&D incentives when licensing option is added in nonzero-sum game and zero-sum game under the asymmetric R&D competition.

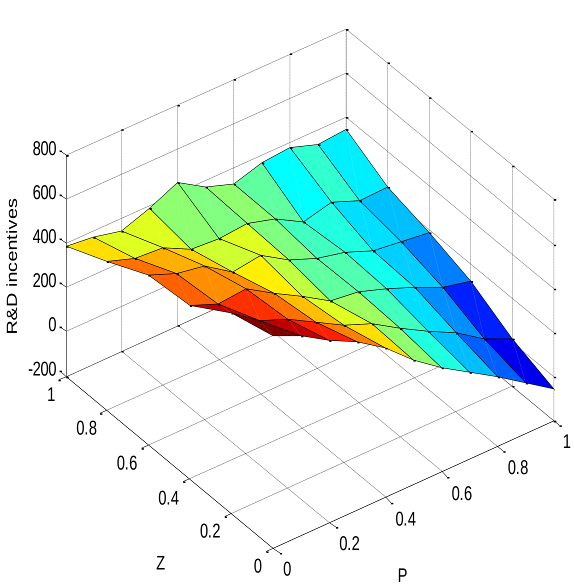
Non-zerosum game VS Zerosum game with licensing



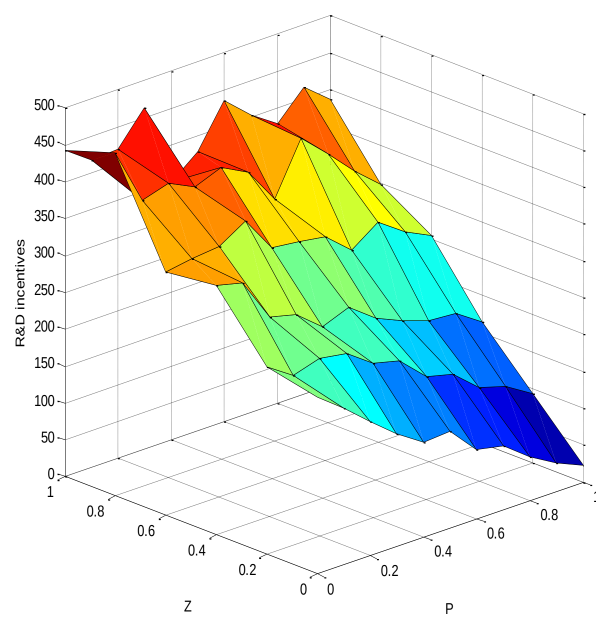
NZ_Asy_S(PL)1



Z_Asy_S(PL)1



NZ_Asy_S(PL)2



Z_Asy_S(PL)2

Figure 4.4: Asy_S(PL) comparison between nonzero-sum and zero-sum game environment.

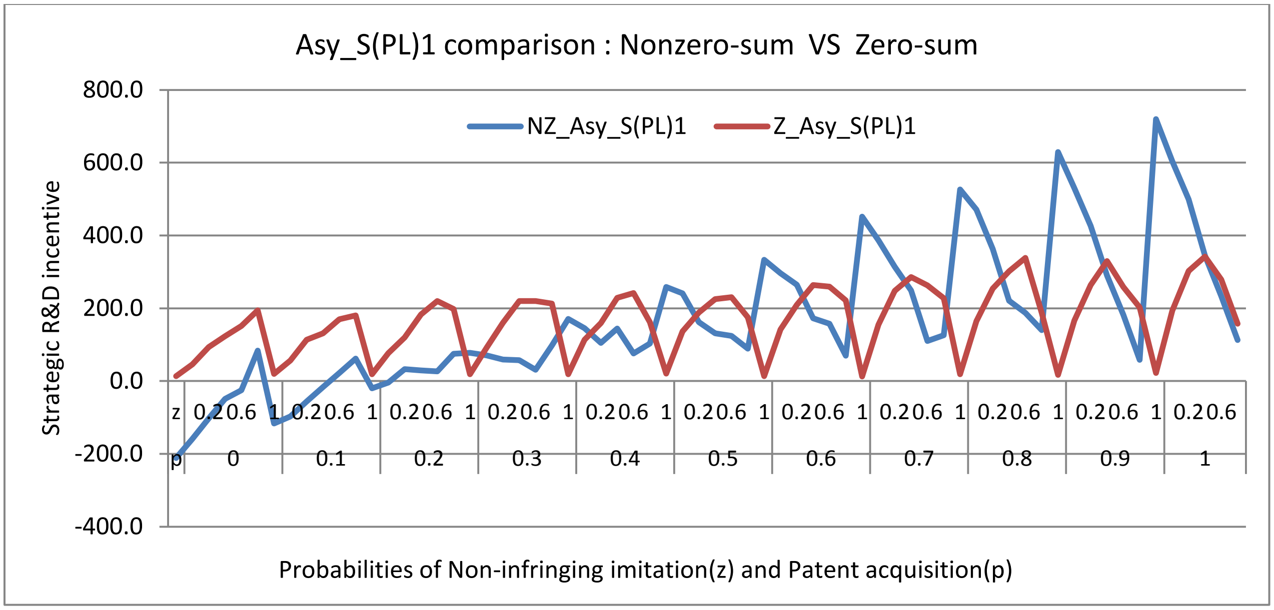


Figure 4.5: Asy_S(PL)$_1$ comparison regarding ***p*** and ***z*** between nonzero-sum and zero-sum game.

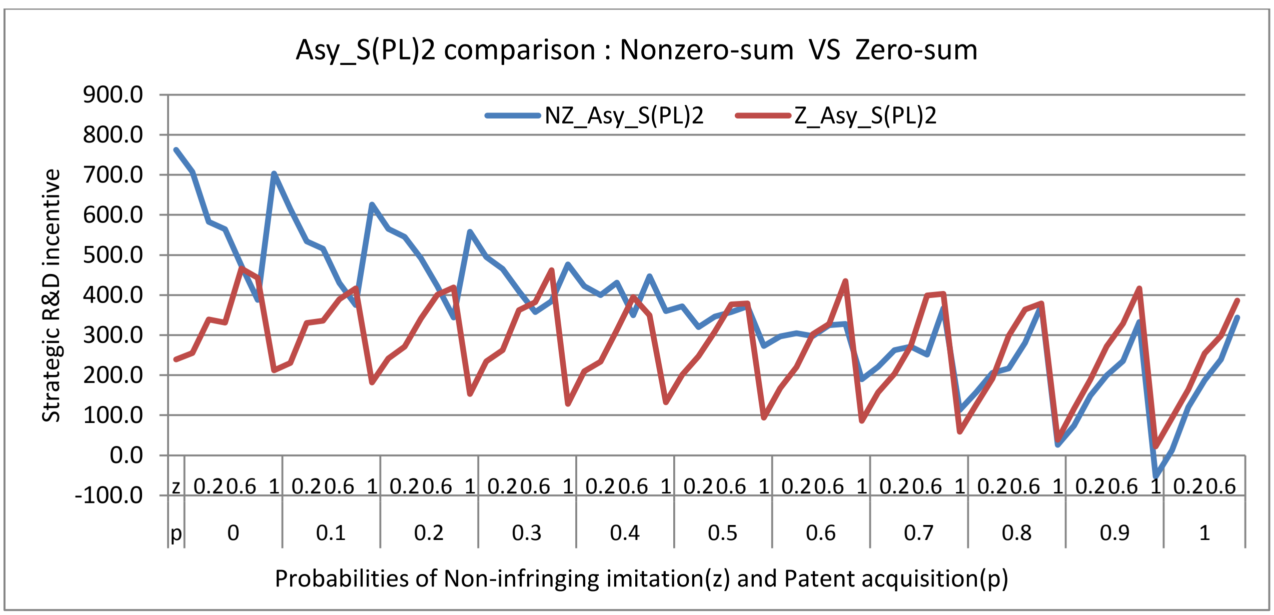


Figure 4.6: Asy_S(PL)$_2$ comparison regarding ***p*** and ***z*** between nonzero-sum and zero-sum game.

In Figure 4.4, we can identify that in the Z_Asy_S(PL)1 graph (upper right), R&D incentive values rise up and fall down along the changes of non-infringing imitation probabilities like a upside down bell. Figure 4.5 shows it more specifically. In the zero-sum game condition, when technology licensing option is added, regardless of patent acquisition probability, as non-infringing imitation grows, R&D incentive values rise up and fall down. On the other hand, in the nonzero-game condition, when patent acquisition probability goes up over 50% ($\boldsymbol{p} \geq 50\%$), since non-infringing imitation probability of its competitor becomes threat to expected benefits of R&D investment, R&D incentive decreases.

In the section where patent acquisition probability is low ($\boldsymbol{p} \leq 30\%$), R&D incentive gets bigger in zero-sum game than in nonzero-sum game. It means that even if the Firm 1 fails to acquire patent, there is still R&D allurement. But, in nonzero-sum game, R&D incentive value becomes negative. So, it is better not to invest in R&D.

In Figure 4.3, R&D incentives are high in all sections in nonzero-sum game, regardless of patent acquisition probability. But, in Figure 4.6 in which licensing option is added, we can identify that two graphs cross-over in a section. That is, when non-infringing imitation probability is low, Firm 2 has higher R&D incentive in nonzero-sum game. But, when imitation probability approaches 100%, R&D incentive in zero-sum game gets bigger than the case of non zero-sum game. By this, we can identify that licensing option becomes more favorable for R&D incentives in zero-sum game.

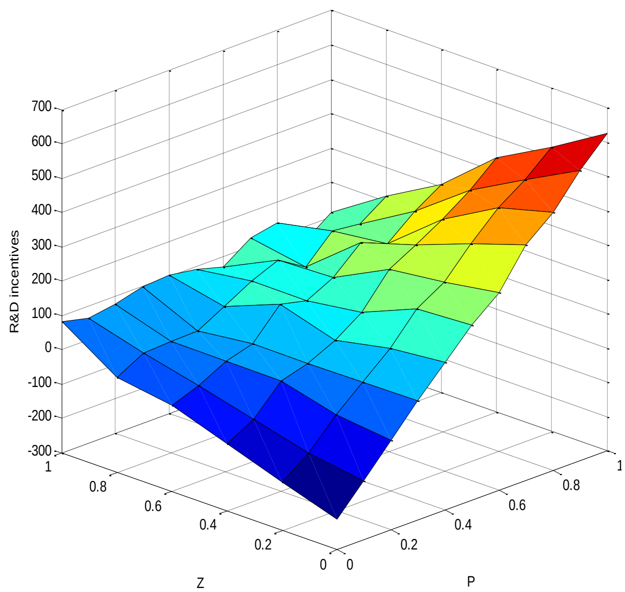
By comparing graphs of Firm 1 and Firm 2, we can analyze changes of R&D incentives depending on changes of patent acquisition probability, and changes of R&D incentives (slope) depending on changes of non-infringing imitation probability, and can find out that Firm 1 responds more sensitively to patent acquisition probability and non-infringing imitation probability than Firm 2.

In summary, in the case where technology licensing is available, Firm 1 can get higher R&D incentives in zero-sum (nonzero-sum) game when patent acquisition probability is low (high). For Firm 2, when patent acquisition probability is high, it is advantageous to invest in R&D in nonzero-sum game.

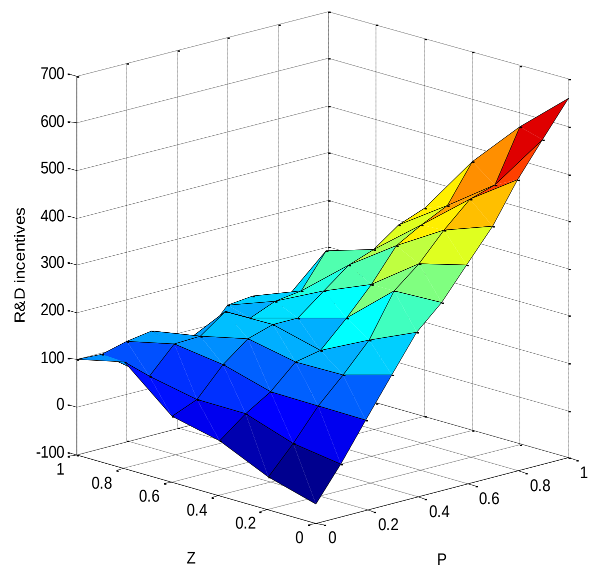
4.5.2 Scenario-based R&D Incentives Comparison: Asymmetry VS Symmetry

Asymmetric or symmetric competition condition is an important element affecting R&D incentive. Thus, it is necessary to compare R&D incentives in asymmetric R&D competition model and symmetric R&D competition model assuming the differences of cost (benefit) functions of two firms under nonzero-sum and zero-sum game conditions. Figure 4.7, Figure 4.8, and Figure 4.9 show R&D incentive changes of Firm 1 and Firm 2 depending on patent acquisition probability and non-infringing imitation probability in nonzero-sum game.

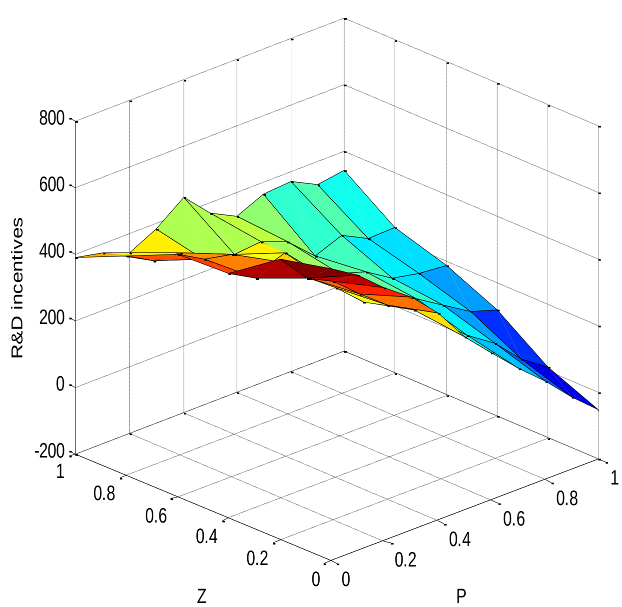
Asymmetry VS Symmetry in Nonzero-sum game



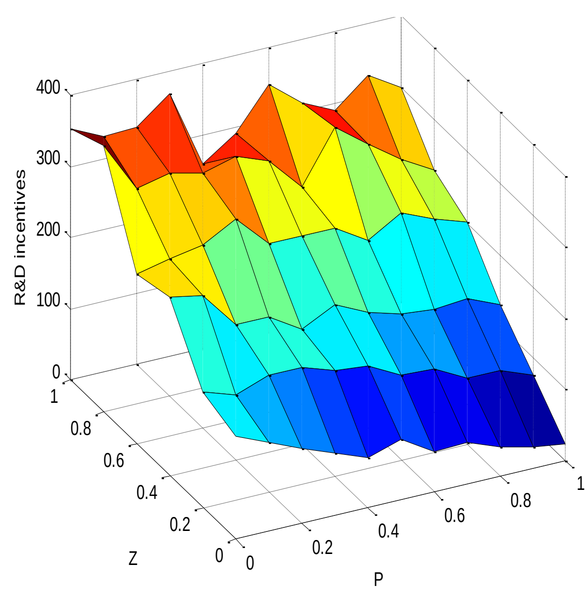
NZ_Asy_S(P)1



NZ_Sym_S(P)1



NZ_Asy_S(P)2



NZ_Sym_S(P)2

Figure 4.7: S(P) comparison between Asymmetry and Symmetry in nonzero-sum game.

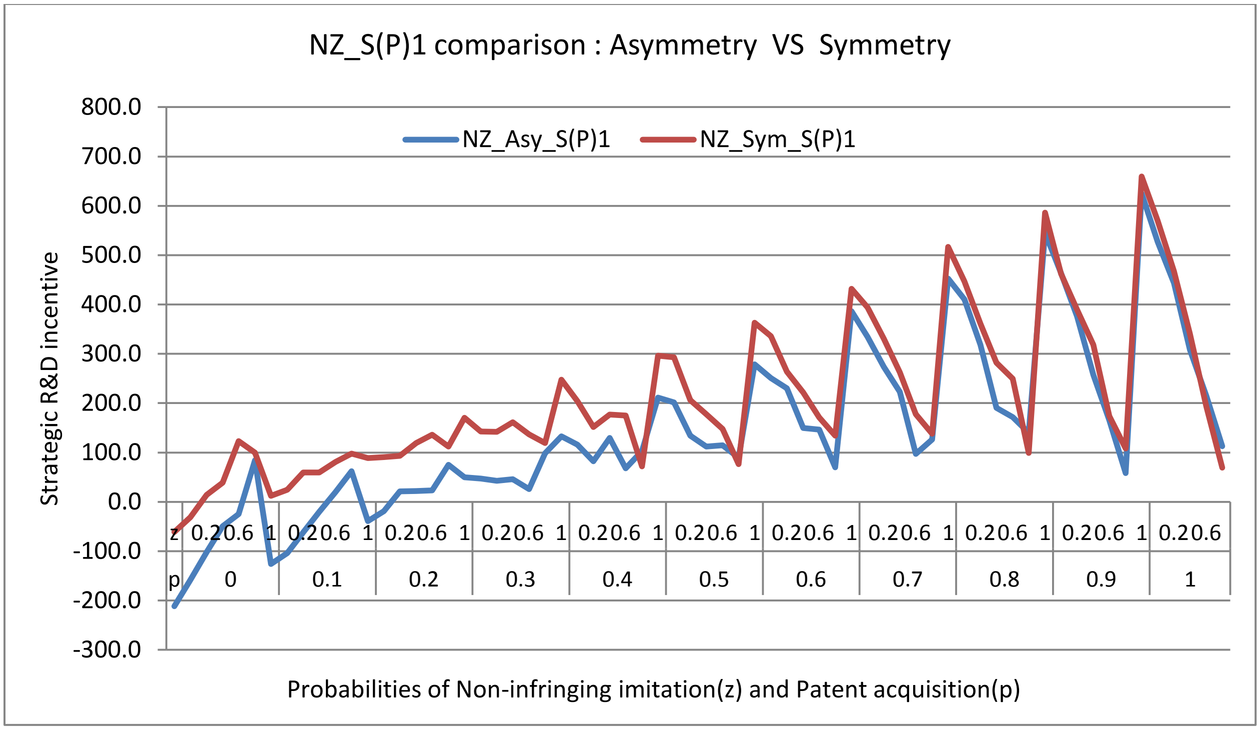


Figure 4.8: $NZ\_S(P)_1$ comparison regarding ***p*** and ***z*** between Asymmetry and Symmetry.

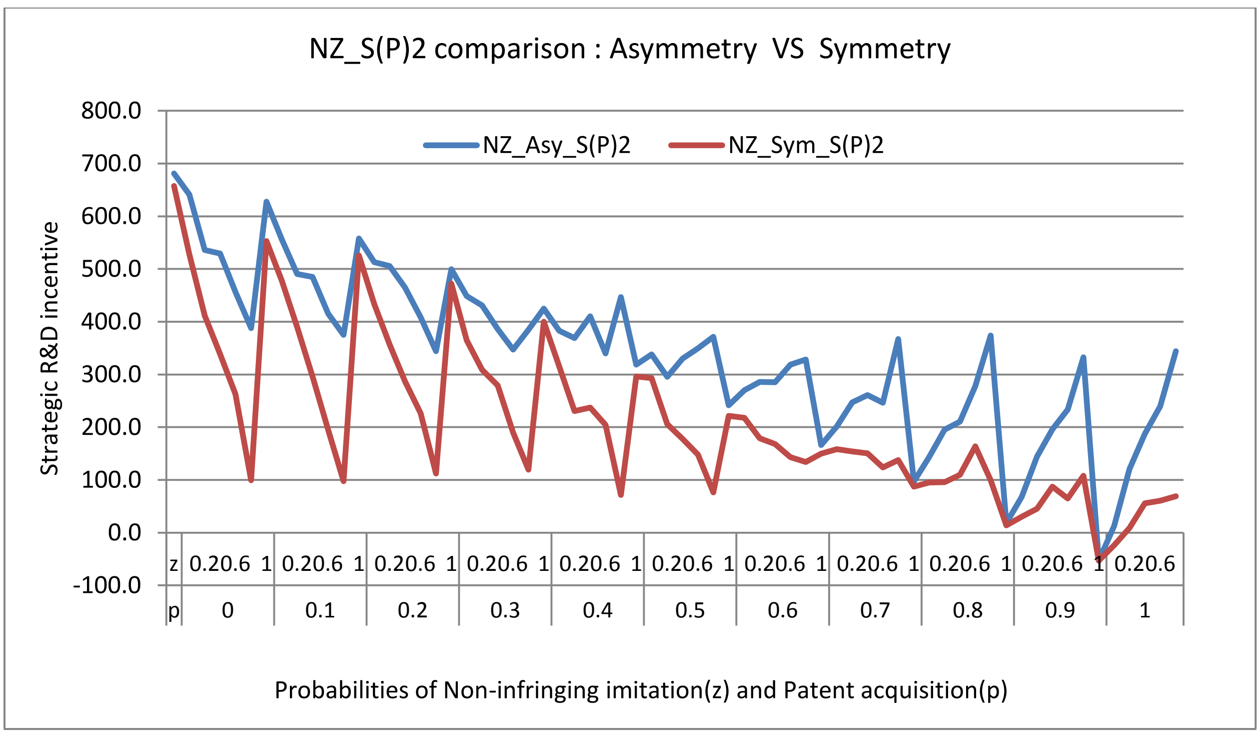


Figure 4.9: $NZ\_S(P)_2$ comparison regarding ***p*** and ***z*** between Asymmetry and Symmetry.

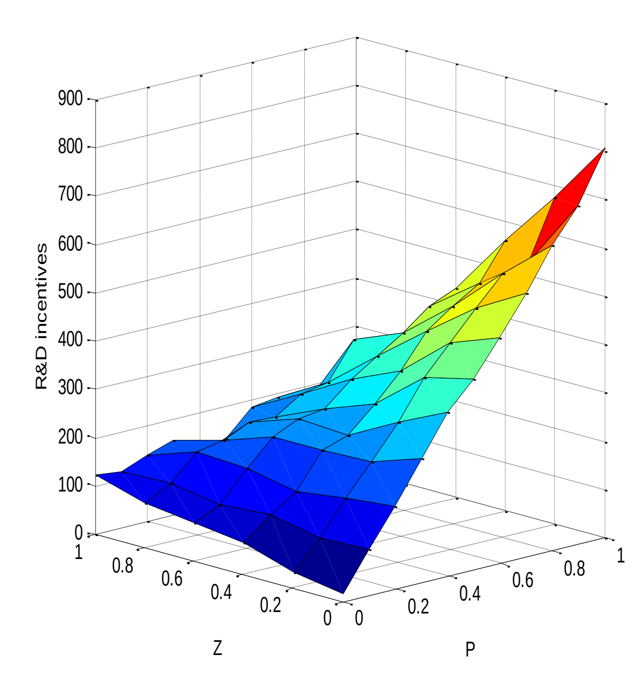
As shown in Figure 4.7 and Figure 4.8, we can identify that under nonzero-sum game, R&D incentives change in similar patterns in symmetric and asymmetric competitions. And, the phenomenon that as patent acquisition probability gets higher, non-infringing imitation probability and R&D incentive values go down is normal, and the phenomena happen in both firms (Figure 4.8, and Figure 4.9).

In nonzero-sum game, in the section where patent acquisition probability of Firm 2 is high, as non-infringing imitation probability gets bigger, R&D incentives go down rapidly, which means that it responds more sensitively to damage by imitation in symmetric model. In asymmetric competition game, even if non-infringing imitation probability goes up, R&D incentives do not go down rapidly (see Figure 4.9). That is because, for Firm 2, it is strategically advantageous to infringe on technology by imitation from the superior Firm 1. And, since Firm 2 can expect higher incentive in asymmetric R&D competition game (than in symmetric R&D competition game) regardless of patent acquisition probability, it is strategically advantageous to select asymmetric R&D competition in nonzero-sum game.

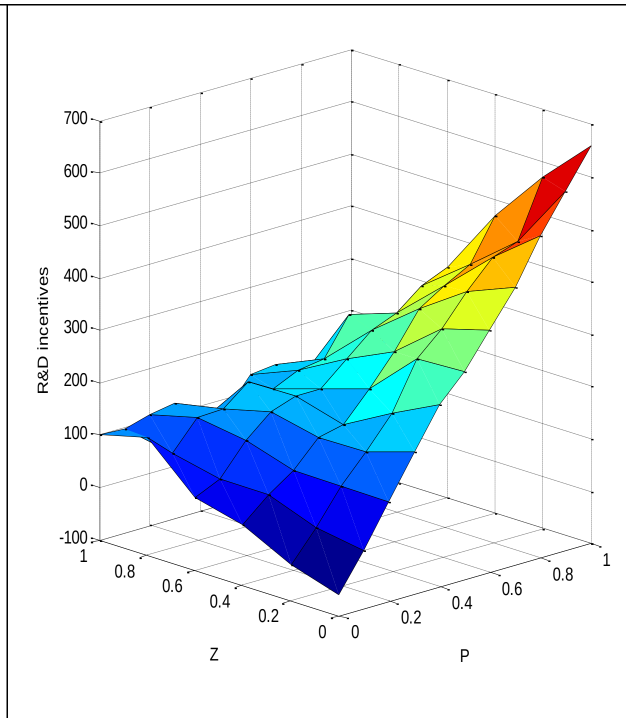
In summary, when patent acquisition probability of Firm 1 is low in nonzero-sum game, symmetric R&D competition game where the firm can expect higher R&D incentives is more advantageous to it. On the other hand, for Firm 2, R&D incentive values are high in all sections of asymmetric R&D competition game, and it is strategically advantageous for the firm to select asymmetric R&D competition.

To compare results from nonzero-sum game to ones from zero-sum game condition, we analyze R&D incentives in symmetric competition model and asymmetric competition model under zero-sum game as shown in Figure 4.10, Figure 4.11, and Figure 4.12.

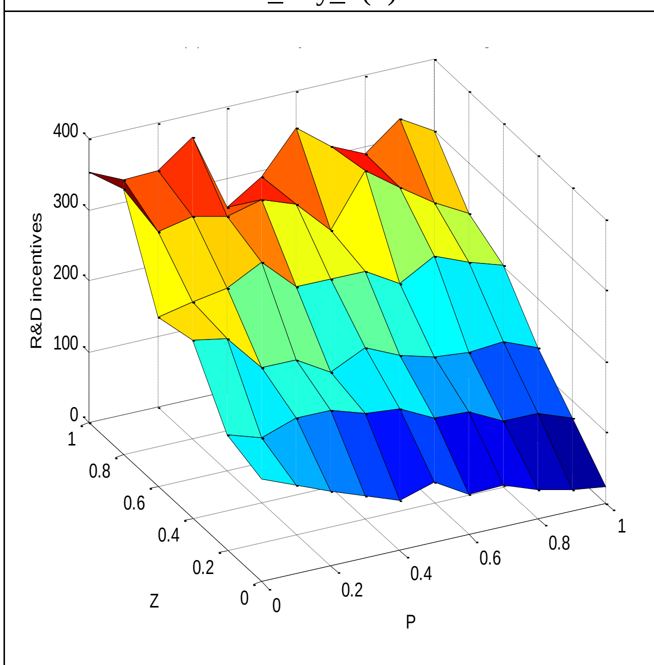
Asymmetry VS Symmetry in Zero-sum game



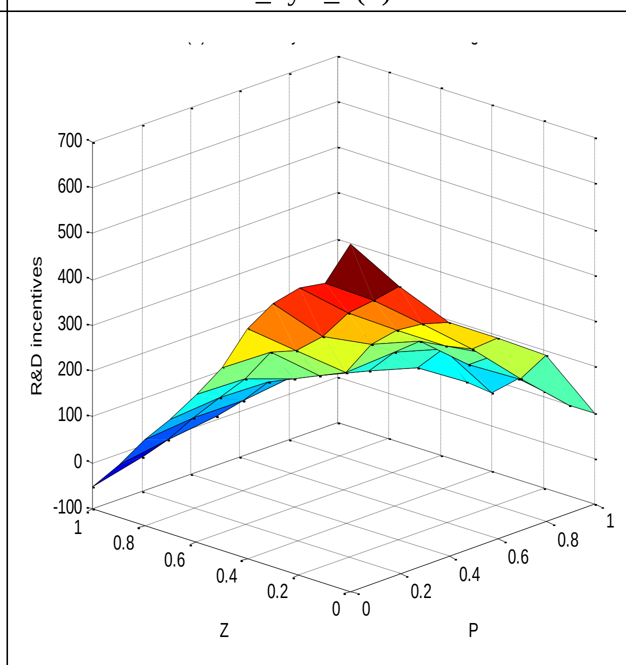
Z_Asy_S(P)1



Z_Sym_S(P)1



Z_Asy_S(P)2



Z_Sym_S(P)2

Figure 4.10: S(P) comparison between Asymmetry and Symmetry in zero-sum game.

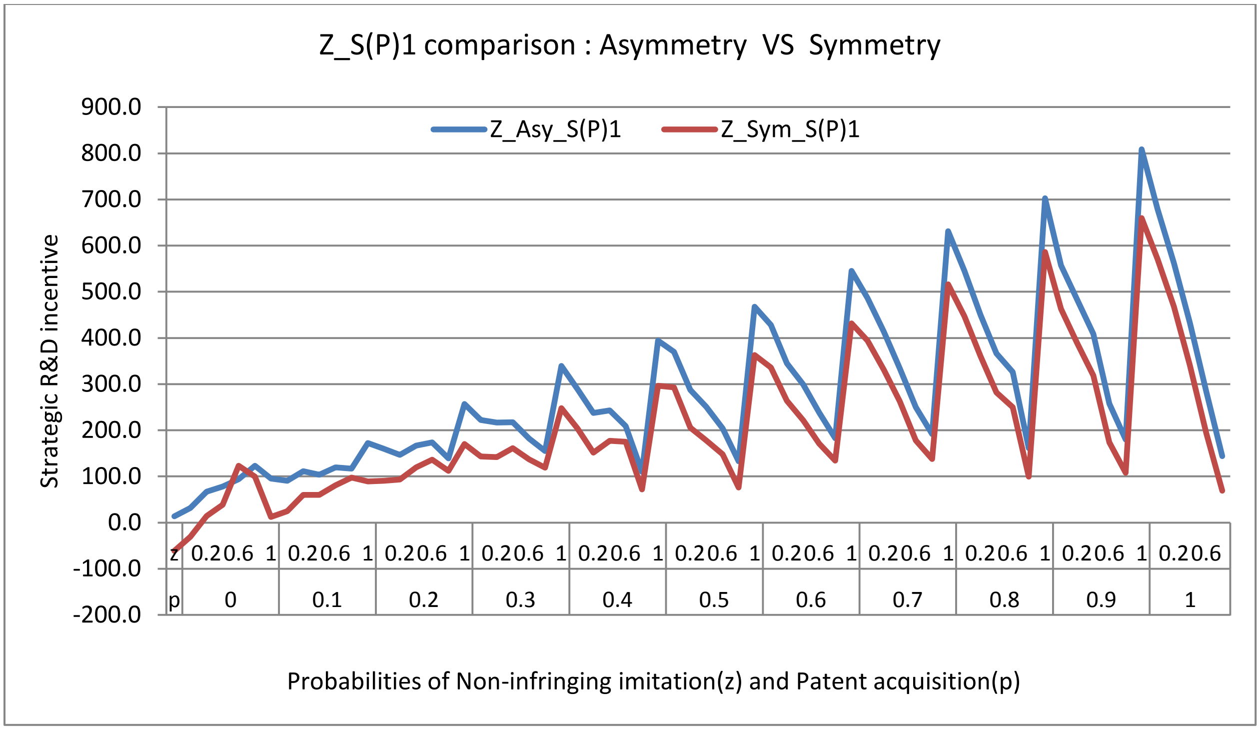


Figure 4.11: $Z\_S(P)_1$ comparison regarding ***p*** and ***z*** between Asymmetry and Symmetry.

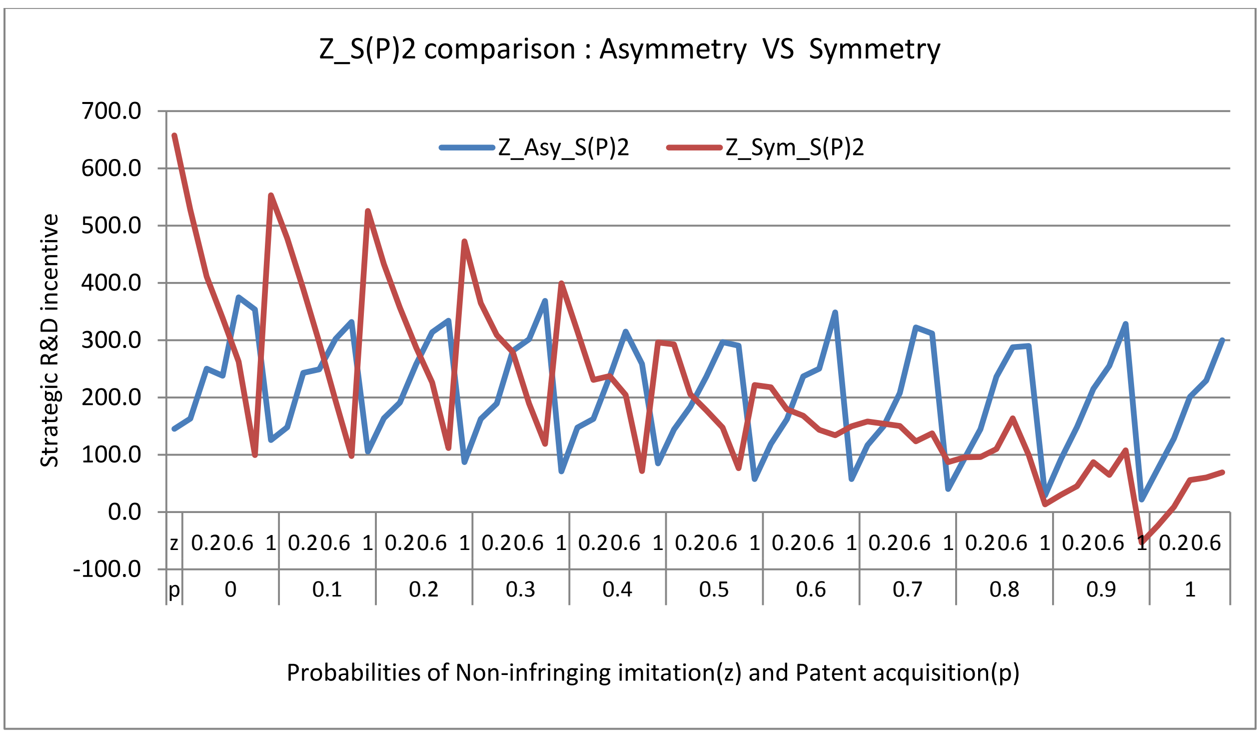


Figure 4.12: $Z\_S(P)_2$ comparison regarding ***p*** and ***z*** between Asymmetry and Symmetry.

In the case of Firm 1, we can identify that, in zero-sum game, R&D incentives are high in asymmetric game, unlike in the non-zero-sum game (see Figure 4.10 and Figure 4.11).

From the point where ***p*** goes up over 30%, the relationship between ***z*** and R&D incentives gets negative, which means that, when ***p*** is over 30%, Firm 1 becomes increasingly sensitive to as non-infringing imitation probability. Since expected profits go up along with patent acquisition probability, R&D incentives go down more rapidly because of the non-infringing imitation probability.

In the case of Firm 2, we can notice that R&D incentives in symmetric and asymmetric models change differently depending on imitation probability (see Figure 4.10). That is, while moving-average values of R&D incentives go up in asymmetric model, they do no change much in symmetric model.

In symmetric competition, as patent acquisition probability of Firm 2 goes up, imitation probability and R&D incentives go down. And they decline rapidly (see Figure 4.12). In asymmetric competition, the relationship between imitation probability and R&D incentives is positive, regardless of patent acquisition probability of Firm 2.

In conclusion, in zero-sum game, Firm 1 gets bigger R&D incentives in asymmetric model regardless of its patent acquisition probability. Meanwhile, Firm 2 can expect bigger R&D incentives in asymmetric model only when its patent acquisition probability is lower than 30% (***p*** ≤ 30%). Intuitively, in asymmetric model, high imitation probability becomes advantageous to the inferior firm. Especially, when patent acquisition probability of the inferior firm is low, it is more tempted to favor asymmetric competition. The results we analyzed under nonzero-sum game and zero-sum game are summarized in Table 4.14.

Table 4.14: Preferred R&D competition scenario for each firm.

Preference	Nonzero-sum game	Zero-sum game
Firm 1	Symmetric (when p < 0.5)	Asymmetric
Firm 2	Asymmetric	Asymmetric (when p > 0.7)

4.6 Conclusion

In bilateral-R&D investment, it is very likely that R&D competition can inevitably lead to patent competition if R&D-cooperation is excluded. In this process, the effect of changes of as patent acquisition probability and non-infringing imitation probability on R&D investment is very big. In order to seek an investment strategy generating the highest strategic R&D incentives among various competition scenarios, we reconstruct the two variables - patent acquisition probability (p) and non-infringing imitation probability (z) - as probabilistic model, and conduct sensitivity analysis depending on the two variables. The analysis reveals that, regardless of patent acquisition probability, Firm 1 gets higher R&D incentives in zero-sum game. Thus, it is advantageous for Firm 1 to play zero-sum game. However, if technology licensing is available, and patent acquisition probability is high, nonzero-sum game provides higher R&D incentives. Therefore, it is necessary to choose different strategies depending on scenarios.

For Firm 2, only when patent acquisition probability is higher than its competitor, regardless of licensing option, it can get higher strategic R&D incentives in nonzero-sum game.

Comparison of symmetric and asymmetric models revealed that, when patent acquisition probability is low, Firm 1 can get bigger R&D incentive in the symmetric model under the condition of nonzero-sum game. So, symmetry is advantageous to Firm 1 to invest in R&D. On the other hand, to Firm 2, R&D incentive value is higher in the asymmetric competition, regardless of p. So, it is strategically advantageous for Firm 2 to do R&D competition in the asymmetric condition. Under the zero-sum game, Firm 1 has bigger R&D incentive in the asymmetric competition regardless of patent acquisition probability. For Firm 2, under the condition where patent acquisition probability is low with less than 30%, it can get higher strategic R&D incentive if it selects asymmetric competition.

Chapter 5

R&D Investment Game Strategies Revisited by Decision-Tree with R&D incentives

ABSTRACT

Through the decision-making tree analysis, this research analyzes factors influencing decisions on R&D investment of two competing companies (duopoly), draws expected profits and R&D incentives along decision-making paths, and analyzed the best and second-best strategies of the two firms in an asymmetric competition situation. The best strategy analyzed through DT using payoffs and R&D incentives for both companies is to compete through R&D investment and technology licensing decision, and the second-best strategy is to choose no-R&D decision for the superior Firm 1, and R&D cooperation for inferior Firm 2.

5.1 Introduction

It is true that one of core elements to decide innovation of companies is R&D investment (Parthasarthy and Hammond, 2002). However, since a wrong decision on investment can lead to the survival of a firm, it is necessary for a firm to make strategic decisions on R&D investment considering various elements such as the market situation affecting the success and failure of the investment and strategies of competitors, etc. But, it is difficult for a specific firm to decide on R&D investment not only because of the risks involved in the possibility of the newly developed technology and its product to succeed in the market, but also because of the uncertainties about the R&D performance caused by R&D competition and inevitably accompanying patent competition with its competitors. "Strategic" decision-making in game theory is the decision-making in an interdependent situation where one person's behavior affects others' behaviors. It is a concept suitable to the R&D investment game where two companies compete over the same product without information about the competitor.

There have been active researches on strategic R&D investment in a wide range from researches on quantitative analysis on R&D investment performance (Li, 2001) to those on firm competition patterns through strategic and dynamic models (Lim, 1998; Li, 2011; Reinganum, 1982). As the competition patterns among firms become increasingly complicated, and, as it has become difficult to explain them with existing simple models, the necessity to do more realistic research has increased. Dixit and Pindyck (1994), which explained various characteristics of firm investment through game theories and real options (Martzoukos and Zacharias, 2013; Pawlina and Kort 2006; Schwartz, 2004; Weeds 2002), has become the basis of this research on which various models to explain competition could be developed. Especially, this research upgraded the conditions assumed in existing researches for simplifying the model (Mukherjee 2006; Pawlina and Thijssen 2004), and made efforts to strategically use patent along with R&D (Judd, Schmedders and Yeltekin, 2012; Weeds 2000). As part of such efforts, we, in Chapter 2, established a game model where two companies are involved in R&D and patent competition in an asymmetric duopoly situation, and sought strategies where those firms can get the best R&D incentives in various competitive environments. In addition, we applied the R&D investment game model to Decision-Tree[71](DT hereafter), and suggested the best strategy per scenario. Especially, through DT analysis using not only payoff but strategic and non-strategic R&D

[71] Due to its comprehensive nature, DT is very useful in making into model and understand various environment-based processes (Murthy, 1997), and, in data mining, it is considered as one of the most important classification techniques. (Hastie, 2009).

incentives[72], we structured various variables included in the asymmetric R&D investment game model, and compared decision-making process based on expected values of decision-making nodes and changes of R&D incentives.

5.2 Decision Setting

If two firms competing over a specific product decide to invest in R&D simultaneously, the two are involved in competition of patent over the new technology or product, which determines the competition performance of the two firms. It is assumed that, regardless of decision on R&D, the two firms are asymmetry in cost and benefit functions in scale, distribution network, and brand reputation, etc. Since it is competition over a single product, if any of the two firms with symmetric sizes increases R&D investment amount of money, the relationship becomes asymmetric. Decision-makings on R&D cooperation and technology licensing option are added, and firms can share R&D cost by such R&D cooperation, and reduce risks related with patent competition and patent application, and, instead of taking patent competition risk, can expect additional benefit through technology licensing after acquiring the patent right. If, in the first stage, decisions are made on asymmetry, additional option (licensing vs cooperation) as well as R&D, in the second stage, probabilistic competitive environment is provided. That is, in DT, chance nodes regarding the situation of the profit structure being nonzero-sum or zero-sum game and the case of patent protection is or isn't realized are included, and the decision-making process is illustrated in the following Figure 5.1.

[72] Strategic or non-strategic R&D incentives are the payoff difference between R&D decisions as to whether the firm invests in R&D or not, including the situations where a competing firm invests in R&D or does not invest in R&D.

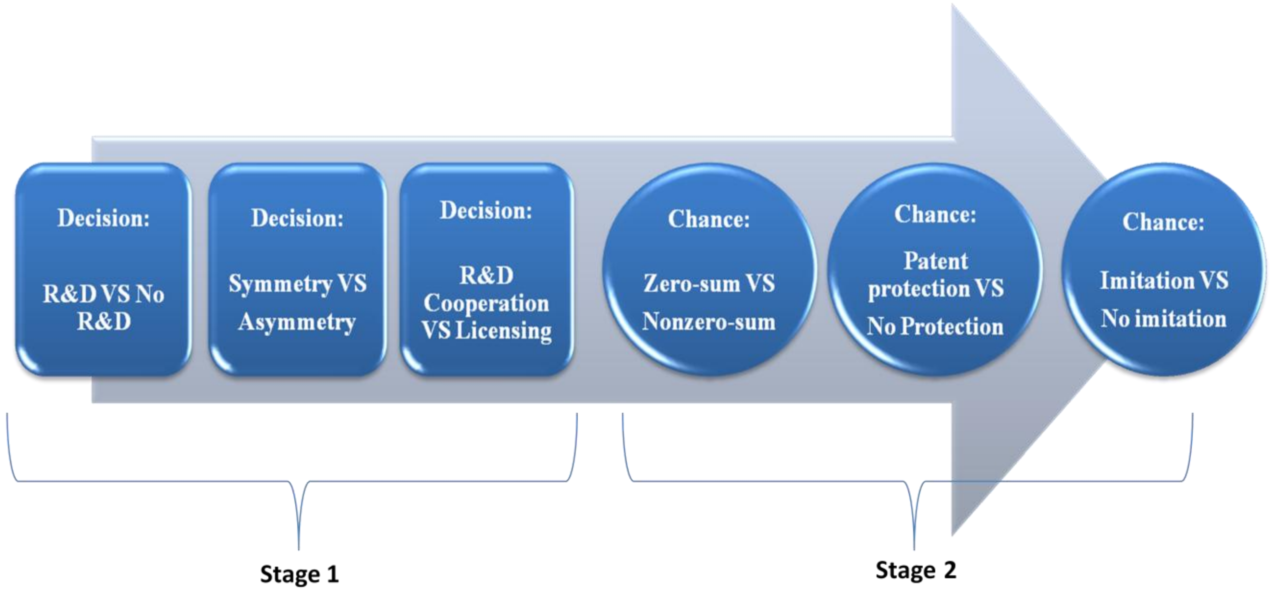


Figure 5.1: Decision Process for two-stage R&D investment game.

5.3 Decision-tree Analysis with Payoffs

5.3.1 Firm 1 (Superiority)'s R&D Investment Strategy based on DT

The R&D investment competition strategy using DT includes R&D game competition models and hypotheses treated in chapter 2, and, when new hypotheses (e.g. patent acquirement variable) are included, it can be shown by adding decision or chance nodes. Among various scenarios, we hypothesized asymmetric R&D competition (Superiority-Inferiority), and analyzed it through DT. In the final chance node, payoff function including non-infringing imitation or no-imitation was added. In the game model, payoff is decided interdependently with its competitor. Thus, it is possible to seek decision-making per scenario through DT analysis on each of R&D investment decisions of its competitor. Figure 5.2 shows DT of Firm 1 along with payoff function in the case of Firm 2 investing in R&D.

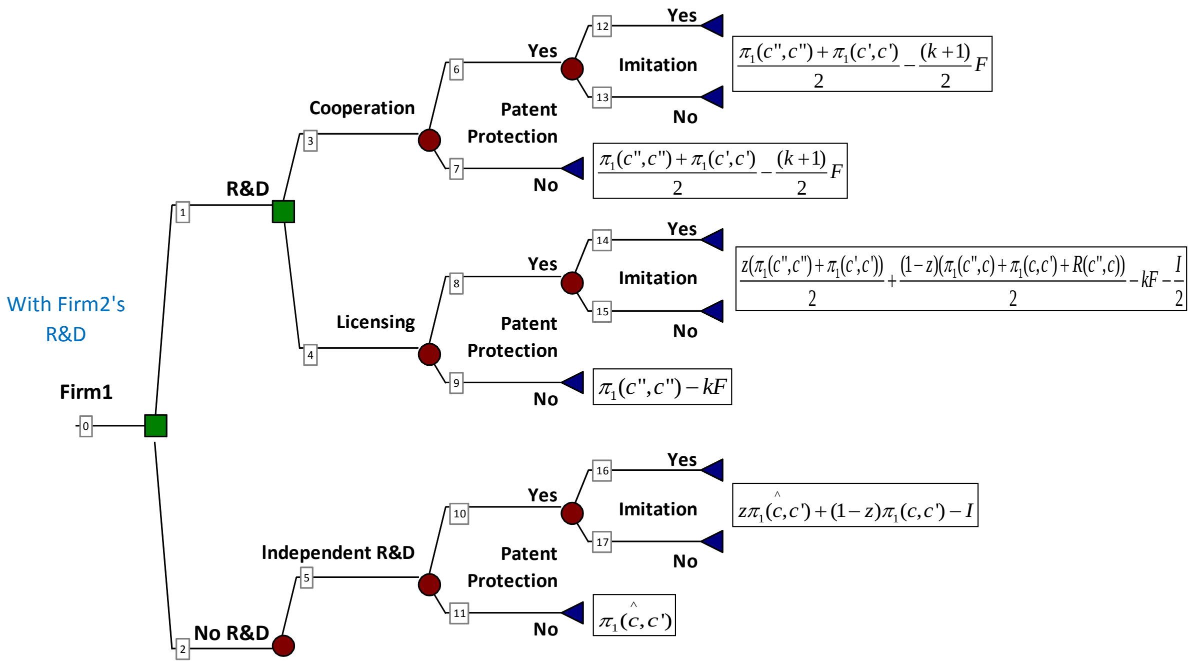


Figure 5.2: Decision-Tree diagram for Firm 1's payoff-functions with Firm2's R&D.

As shown in Figure 5.2, Firm 1 arrives at payoff going through various stages of decision-making process. If the firm decides on the initial investment, it becomes possible to make cooperative R&D or technology licensing with its competitor. But, if Firm 1 decides not to invest in R&D, it becomes the unilateral R&D condition. So, R&D cooperation or licensing changes from decision node to chance node, and, since it is unilateral R&D case, only independent R&D by Firm 2 is possible and R&D cooperation is impossible. Afterwards, the path is divided depending on whether there are patent protection and non-infringing imitation or not. On each path, related payoff function is added. If there is no patent protection, it is possible to imitate it 100%. So, in such a case, payoff is not divided into two nodes depending on non-infringing imitation probability. And, if patent is protected, each node has unique value depending on probability of non-infringing imitation (z). For instance,

$\frac{z(\pi_1(c'',c'')+\pi_1(c',c'))}{2}+\frac{(1-z)(\pi_1(c'',c)+\pi_1(c,c')+R(c'',c))}{2}-kF-\frac{I}{2}$ in the R&D-licensing node 14 and 15 have the payoff values of the case where the values of non-infringing imitation (z) are 1 and 0, respectively.

Asymmetry of competing firms were hypothesized as differences in cost functions (see Chapter 2), which generates 16 benefit function combinations for each firm (32 functions in total). Figure 5.1 displays the hierarchy of 16 benefit functions from $\pi_1(c'',c)=\pi_2(c,c'')$, benefit in the best competition scenario to $\pi_1(c,c'')=\pi_2(c'',c)$, benefit in the worst competition scenario of Firm 1 (2). Based on the hierarchy condition of profit-functions and benefit assumption in bilateral R&D ($\pi(c',c')-\pi(c,c)\geq F$ and $\pi(c'',c'')-\pi(c,c)\geq kF$), end nodes of DT were completed, [73] and, the optimal decision-path of Firm 1 (when Firm 2 is expected to invest in R&D) is shown in Figure 5.3.

[73] As shown in Table 2.15, we made numerical payoff per scenario by generating conditional random numbers satisfying hypotheses on profit functions and bilateral R&D through VBA. By assuming 1,000 for $\pi_1(c'',c)=\pi_2(c,c'')$, Profit function at the top, it is possible to interpret payoff values for remaining profit functions proportionally.

Profit Order	**Firm 1**	**Firm 2**
1	$\pi_1(c'', c)$	$\pi_2(c, c'')$
2	$\pi_1(c'', \hat{c})$	$\pi_2(c, c')$
3	$\pi_1(c', c)$	$\pi_2(\hat{c}, c'')$
4	$\pi_1(c'', c')$	$\pi_2(c, \hat{c})$
5	$\pi_1(c', \hat{c})$	$\pi_2(\hat{c}, c')$
6	$\pi_1(\hat{c}, c)$	$\pi_2(c', c'')$
7	$\pi_1(c'', c'')$	$\pi_2(c'', c'')$
8	$\pi_1(c', c')$	$\pi_2(c', c')$
9	$\pi_1(\hat{c}, \hat{c})$	$\pi_2(\hat{c}, \hat{c})$
10	$\pi_1(c, c)$	$\pi_2(c, c)$
11	$\pi_1(c', c'')$	$\pi_2(\hat{c}, c)$
12	$\pi_1(\hat{c}, c')$	$\pi_2(c', \hat{c})$
13	$\pi_1(c, \hat{c})$	$\pi_2(c'', c')$
14	$\pi_1(\hat{c}, c'')$	$\pi_2(c', c)$
15	$\pi_1(c, c')$	$\pi_2(c'', \hat{c})$
16	$\pi_1(c, c'')$	$\pi_2(c'', c)$

Table 5.1: Profit function hierarchy for duopoly R&D investment game.

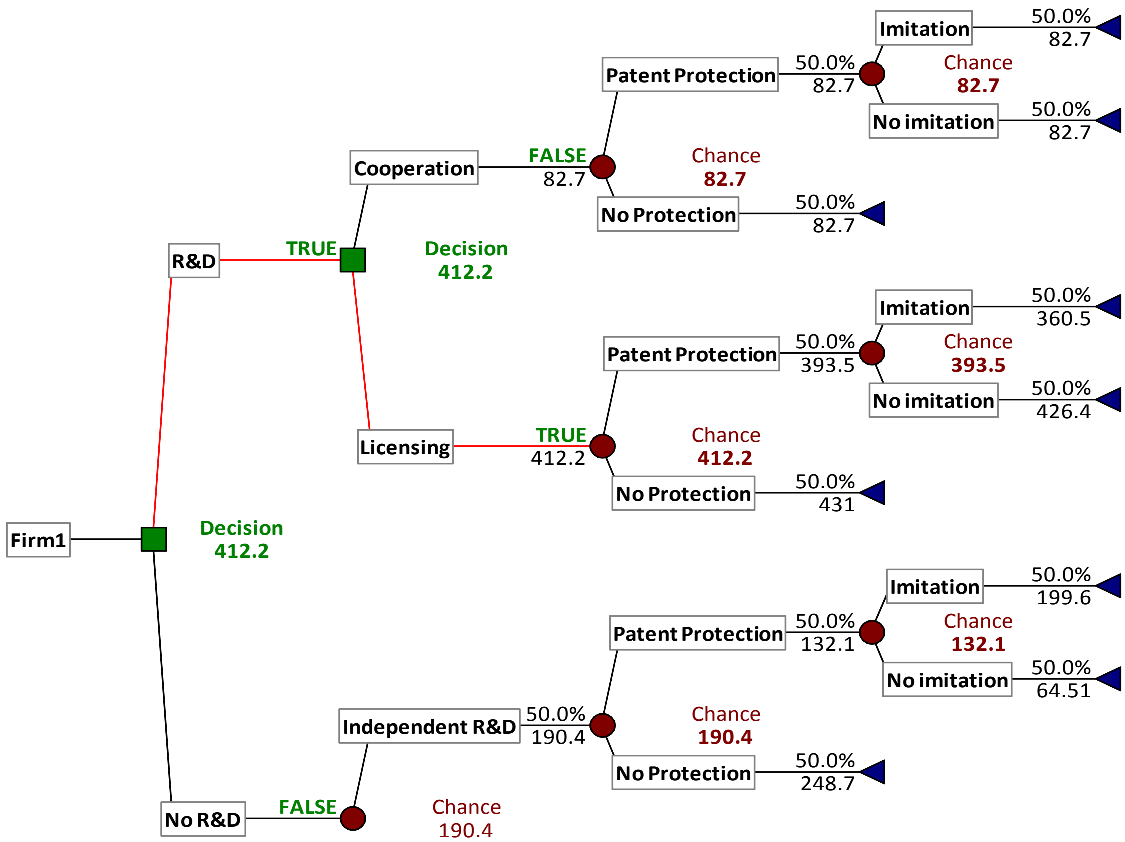


Figure 5.3: Firm 1's optimal decision path when Firm2 invests in R&D.

In the R&D investment strategy using DT, it is the most desirable to choose a path which generate the highest payoff through decision-making process through decision (chance) nodes of the firm. Consequently, the superior Firm 1, when it expects that the inferior Firm 2 will invest in R&D, decides on bilateral-R&D investment, and achieves the optimal decision-making[74] by

[74] The reason why Firm 1 can get higher expected profits in the case of choosing no-R&D than in the case of R&D-Cooperation means that imitating technology patent of its competitor is better than to share cost and benefit safety through R&D cooperation.

selecting technology licensing. Especially, there is small possibility of R&D-cooperation, given that its expected profit is only 8% compared with the profit in the best scenario.[75]

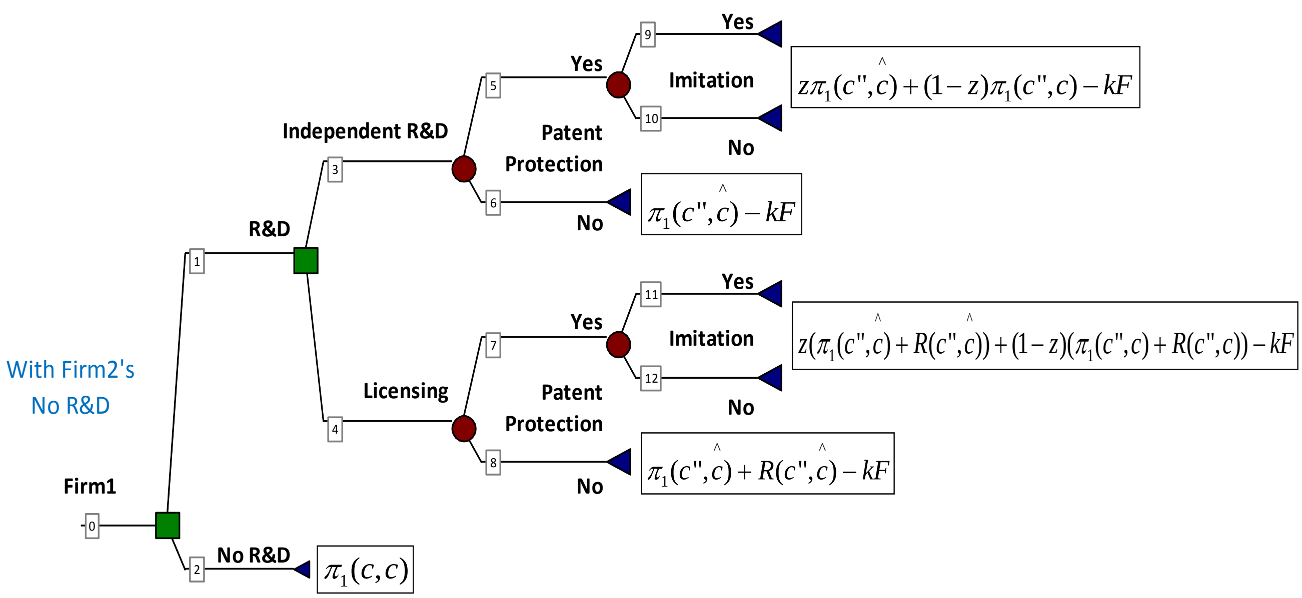


Figure 5.4: Decision-Tree diagram for Firm 1's payoff-functions with Firm2's No R&D.

In the same way, DT of Firm 1, in the case where Firm 2 will not invest in R&D, is shown in Figure 5.4. Given no-R&D decision by Firm 2, R&D investment of Firm 1 will be the unilateral R&D case, and only technology licensing and independent R&D are possible. Intuitively, if its competitor does not invest in R&D, Firm 1 will never fail to invest in R&D, and try to do licensing its patented technology. On the other hand, in the case where Firm 1 also decides not to invest in R&D, R&D cooperation or licensing decision node disappears. In such a case, there is no technology or product, payoff function is determined as $\pi_1(c,c)$, without influence of patent

[75] As we hypothesized that in the best scenario $\pi_1(c'',c) = \pi_2(c,c'') = 1{,}000$, it is possible to calculate expected profits of the two firms in percentiles under the hierarchy.

protection and non-infringing imitation related elements. The optimal decision-making path of Firm 1 (given no-R&D of Firm 2) is shown in Figure 5.5, using numerical payoff.

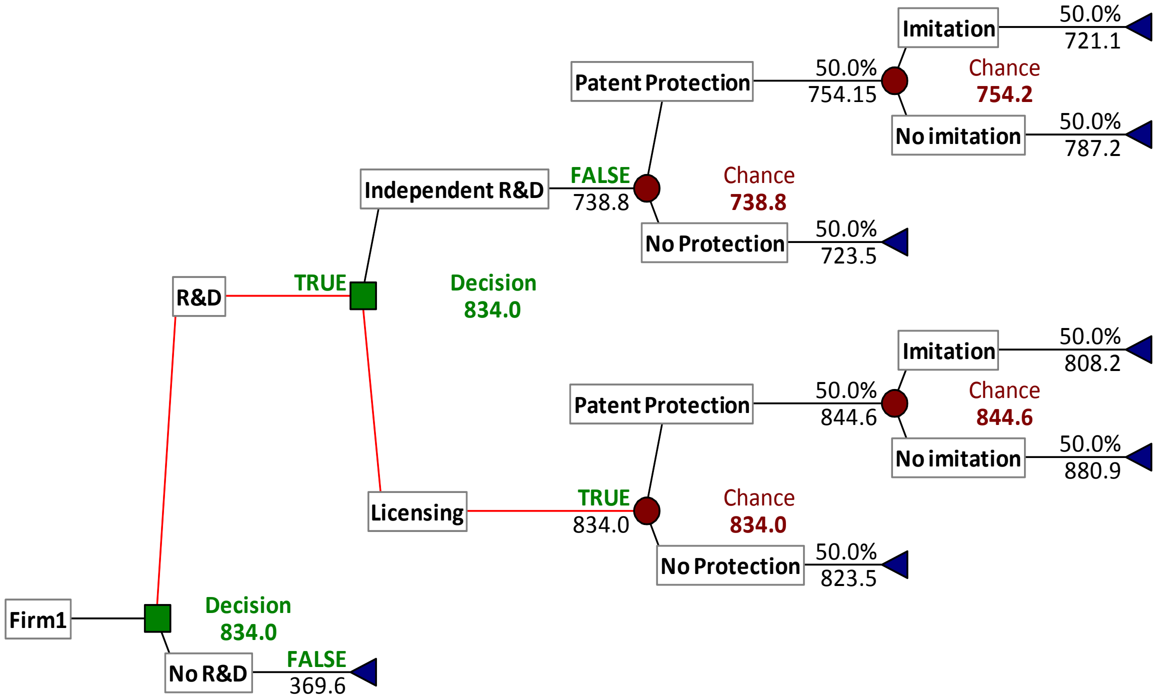


Figure 5.5: Firm 1's optimal decision path when Firm2 doesn't invest in R&D.

Based on the optimal-DT, we can find that, given no-R&D of Firm 2, it is good for Firm 1 to decide to invest in R&D, and Firm 1 can expect profits of patent technology through licensing of it. Accordingly, it is the optimal decision-making maximizing expected profits for the superior Firm 1 to make R&D investment, regardless of R&D investment of Firm 2. In this case, it prefers licensing generating higher expected profits to cooperation.

5.3.2 Firm 2 (Inferiority)'s R&D Investment Strategy based on DT

In the asymmetric R&D investment competition game, one firm is in inferior status to the other firm(s). In this paragraph, Firm 1 in the superior status analyzes DT of the inferior Firm 2 in the same method of DT analysis of Firm 1, and compares the results of the games. Figure 5.6 illustrates DT of Firm 2 with Payoff functions given the R&D investment of Firm 1. Figure 5.7 displays the optimal decision-path of Firm 2 with numerical payoff.

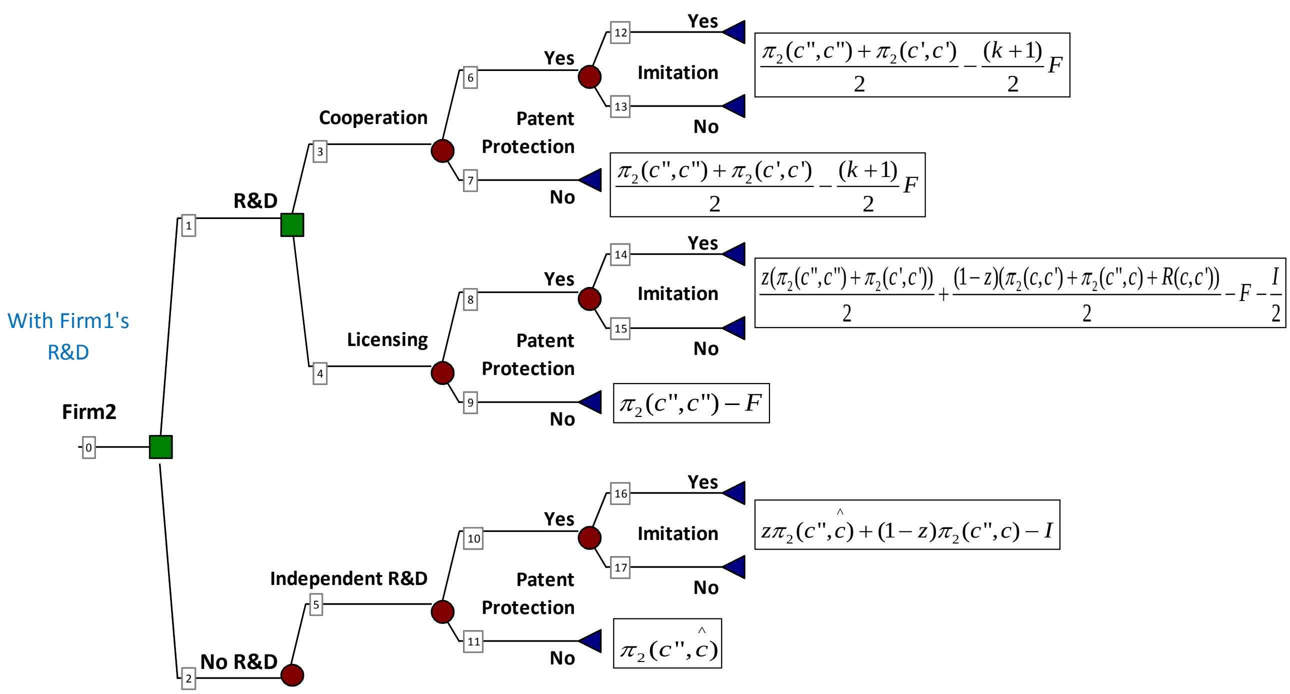


Figure 5.6: Decision-Tree diagram for Firm 2's payoff-functions with Firm1's R&D.

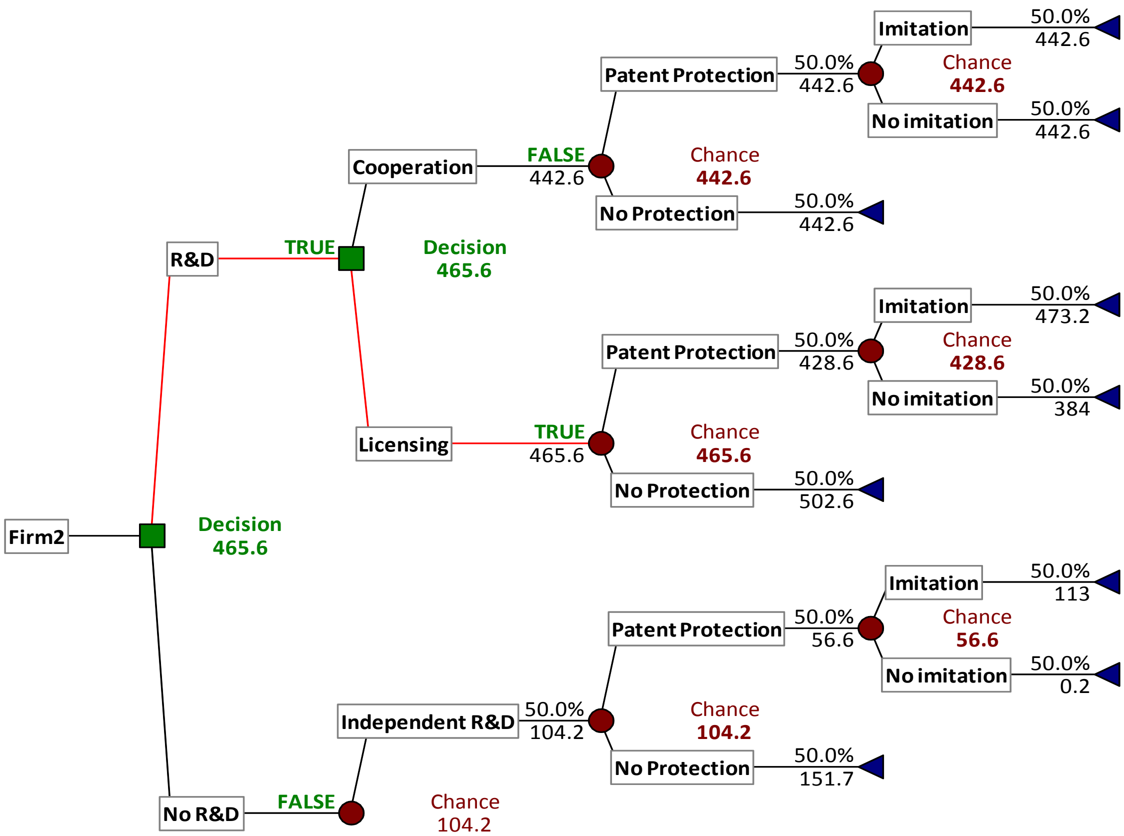


Figure 5.7: Firm 2's optimal decision tree when Firm1 invests in R&D.

As shown in Figure 5.7, in the current scenario where the possibility of acquiring patent is 50% for Firm 2, the optimal decision-making of Firm 2 is R&D investment and licensing. But, what should be noted is the fact that, since the difference of expected profits of Firm 2 between cooperation and licensing is small, 2%, it is possible to upgrade the quality of strategic analysis by finding variables having big effects on decision-making (sensitivity analysis). For example, little increase of non-infringing imitation probability will decrease expected profits of licensing decision-path, and change the best decision-making into R&D cooperation. It is also deeply related with the basic strategy of the inferior firm. Intuitively, in the situation where the possibility of acquiring patent is uncertain, if imitation probability also decreases, expected profits from imitation decreases as well. Thus, it should be a wise strategy for the inferior firm to reduce patent competition risk and R&D investment cost by seeking R&D cooperation with the superior firm.

In the case where no-R&D of Firm 1 is expected, DT of Firm 2 is shown in Figure 5.8 with Payoff functions, and Figure 5.9 as the optimal decision-path respectively.

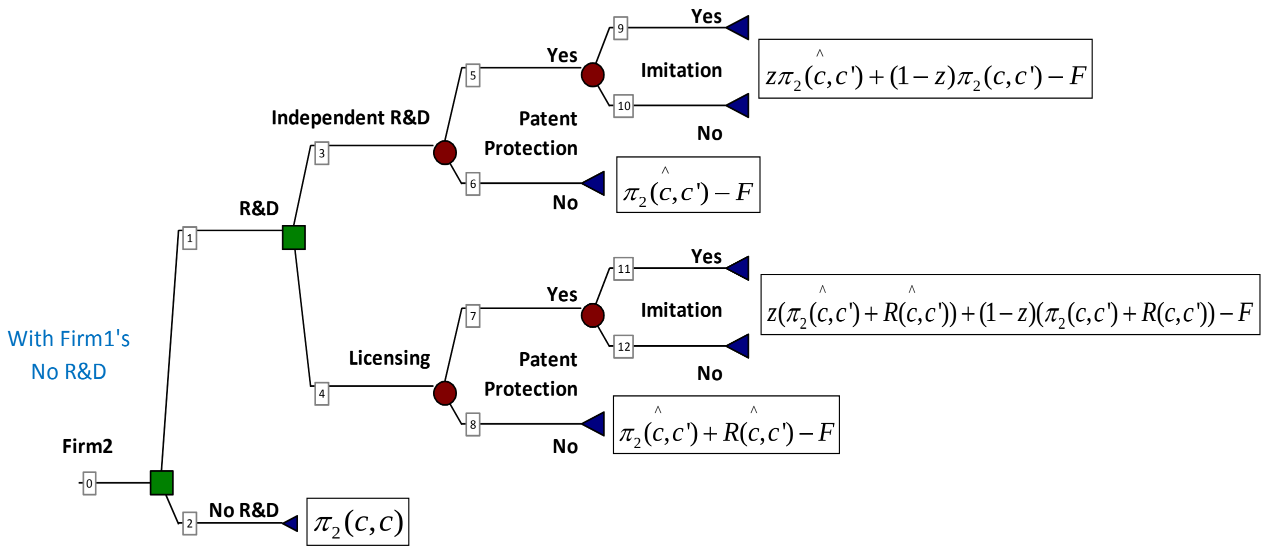


Figure 5.8: Decision-Tree diagram for Firm 2's payoff-functions with Firm1's No R&D.

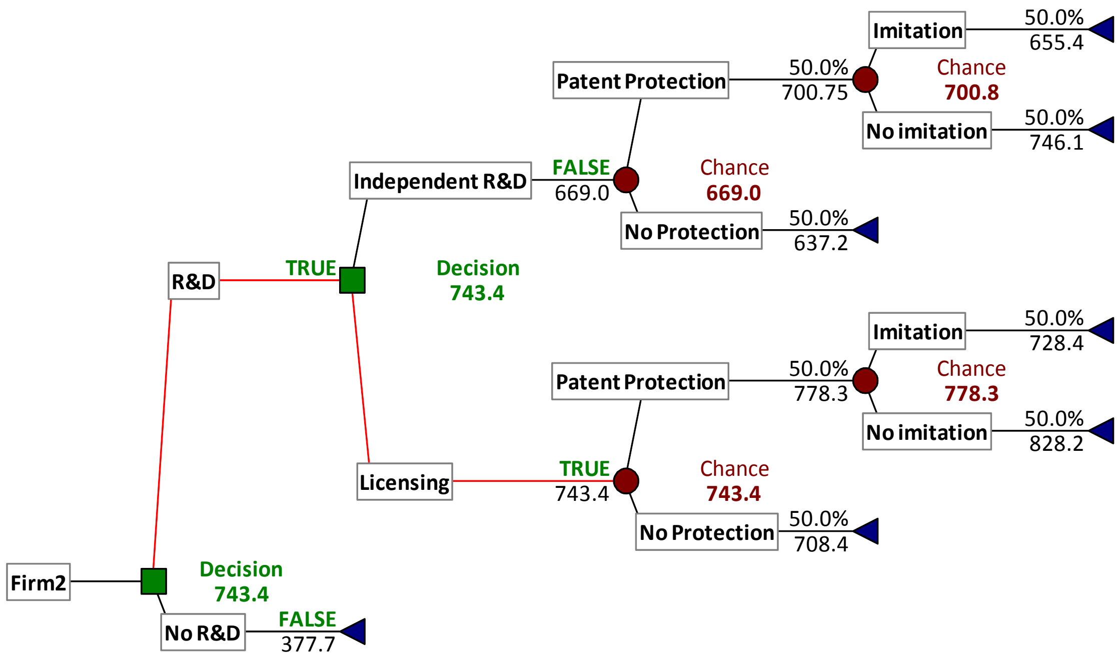


Figure 5.9: Firm 2's optimal decision tree when Firm1 doesn't invest in R&D.

As shown in Figure 5.9, Firm 2, when it expects no-R&D investment of Firm 1, after deciding R&D investment, can maximize its expected profits through technology licensing. Like the case of Firm 1, it is the optimal decision-making for Firm 2 to invest in R&D if it expects no-R&D investment of Firm 1 (unilateral R&D case).

Based on optimal decision-paths of Firm 1 and Firm 2 calculated above, we identified that, if the two firms select R&D investment decisions generating higher expected profits under each predicts the other's strategy as the best strategy, equilibrium can be formed. Especially for the inferior Firm 2, when a change happens in prediction on patent protection and non-infringing imitation probabilities, R&D cooperation, the second-best strategy, can be a new optimal decision-making.[76] But, we can notice that, for Firm 1, No-R&D, rather than cooperation, can be the second-best strategy.

5.4 Decision-tree Analysis Utilizing R&D Incentives

Basically, the strategy to maximize one's profits can be the best strategy. However, some firms may prefer strategies which can minimize profits and maximize risks of competitors to their own profits. Especially, in the duopoly R&D investment game this research deals with, various strategies depending on scenarios are possible, and, there is high probability that the other side predicts one's strategy of maximizing the profits, and strategically obstructs one's choice. Consequently, in this chapter, we compare the strategy focusing on the difference of expected profits[77] depending on R&D investment decision of the other side rather than one's expected profits and the strategy using payoff, and examine how they can be used in R&D investment games.

Unlike the case of R&D investment game model we showed in Chapter 2, DT analysis requires one to construct DT consisting of independent decision and chance nodes depending on decision-making of the other side, and to make decisions to choose a path providing high expected payoff. However, if the selection options of the other side are two, one (firm) also has two optimal decisions (Four optimal decisions in total take place in Firm 1 and Firm 2). So, the optimal decisions of players can be complex depending on situations, and it is not easy to know whether there is a dominant strategy or equilibrium. Thus, in this paragraph, we analyze and suggest a new investment decision-making strategy of firms using R&D incentive under the uncertainty of

[76] Intuitively, an inferior firm has motive to reduce risk caused by failure to acquire patent rights and R&D investment cost, through R&D cooperation with a superior firm.
[77] R&D incentives

R&D investment of the other side. If R&D incentive, rather than payoff, is used in DT, it is possible to find the optimal decision-making not through the path increasing my expected performance, but through the path minimizing R&D incentive of the other side. This strategy (of minimizing R&D incentive) allows one to choose a path where the difference of expected profits acquired from the two decision-makings is the smallest, and minimizes the effect of strategies of the competitor with whom one has interdependent relationship. Especially, when R&D incentive is used, one need not assume decision-making of the other side, making it possible to analyze it only with half times the number of DTs as the number of DTs when payoff is used, which increases computational efficiency, and making it possible to do competition strategy analysis with a new perspective.

First, let us examine DT for Firm 1. Figure 5.10 shows DT of Firm 1, using its R&D incentive without assumption about R&D investment decision of the other side (Firm 2). Initial R&D investment decision, licensing or cooperation decision and chance nodes depending on whether there are patent protection and non-infringing imitation are arranged in order, and the R&D incentive depending on decision-making path is added on the end nodes.

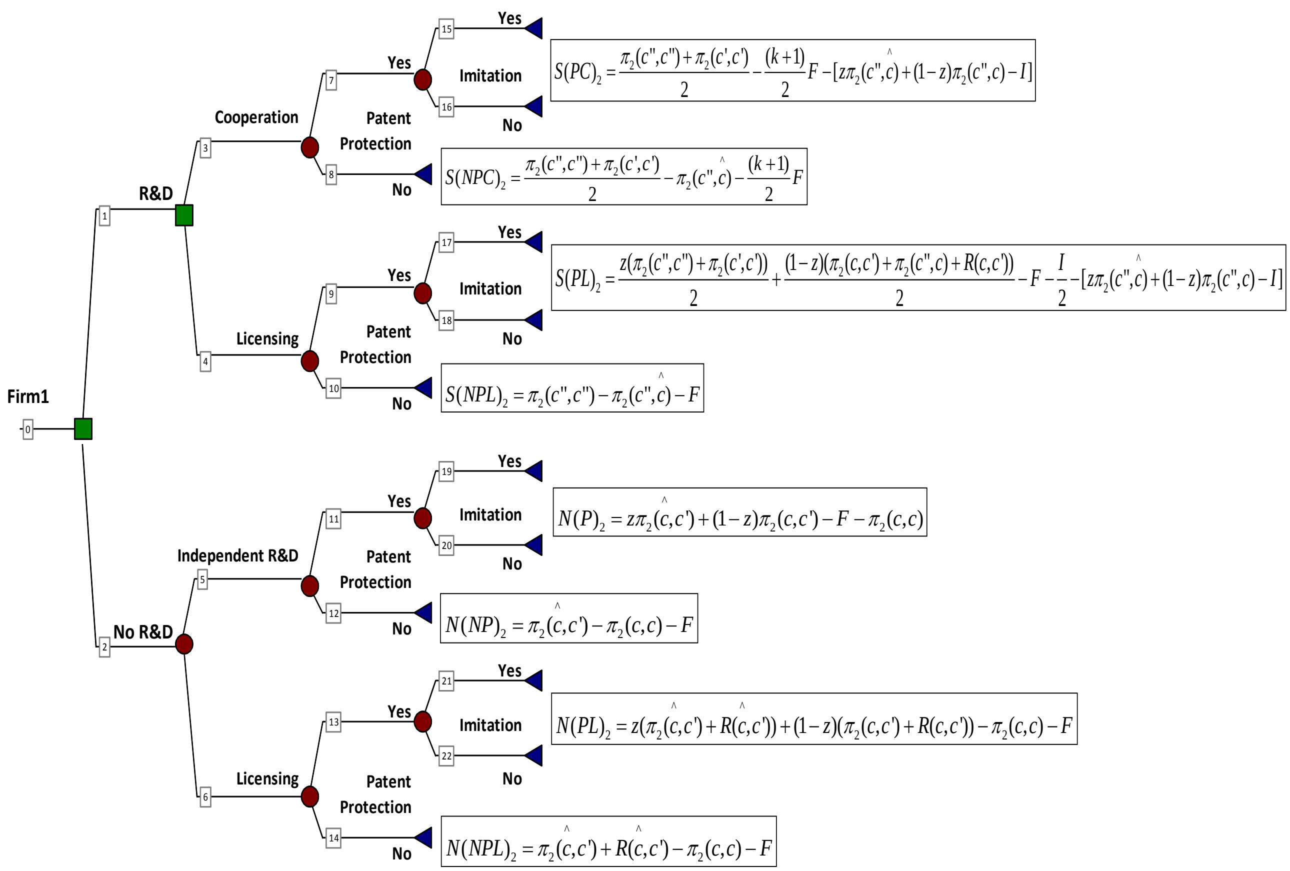


Figure 5.10: Decision-Tree diagram for Firm1 with Non-strategic and Strategic R&D incentives.

As shown in Figure 5.10, on the end nodes of DT, strategic and non-strategic R&D incentives[78] suitable to the related path are attached. For example, at the ends of paths (1-3-7-15), $S(PC)_2 = \frac{\pi_2(c'',c'') + \pi_2(c',c')}{2} - \frac{(k+1)}{2}F - [z\pi_2(c'',\hat{c}) + (1-z)\pi_2(c'',c) - I]$ is placed. $S(PC)_2$ is the strategic R&D incentive Firm 2 can get through R&D cooperation under the condition where patent is protected. Since the function contains non-infringing imitation (z), when z=1 and z=0, it has the value suitable to paths 1-3-7-15 and 1-3-7-16 respectively. Under the case of R&D (no-R&D)

[78] N refers to non-strategic whereas S means strategic incentive, and P(NP), PC(NPC) and PL(NPL) in parentheses indicate (no) patent protection with independent R&D, cooperative R&D and technology licensing.

decisions of Firm 1, it is possible to calculate strategic and non-strategic R&D incentive values of Firm 2. By generating numerical R&D incentives satisfying requirements assumptions of function, we made the DT shown in Figure 5.11.

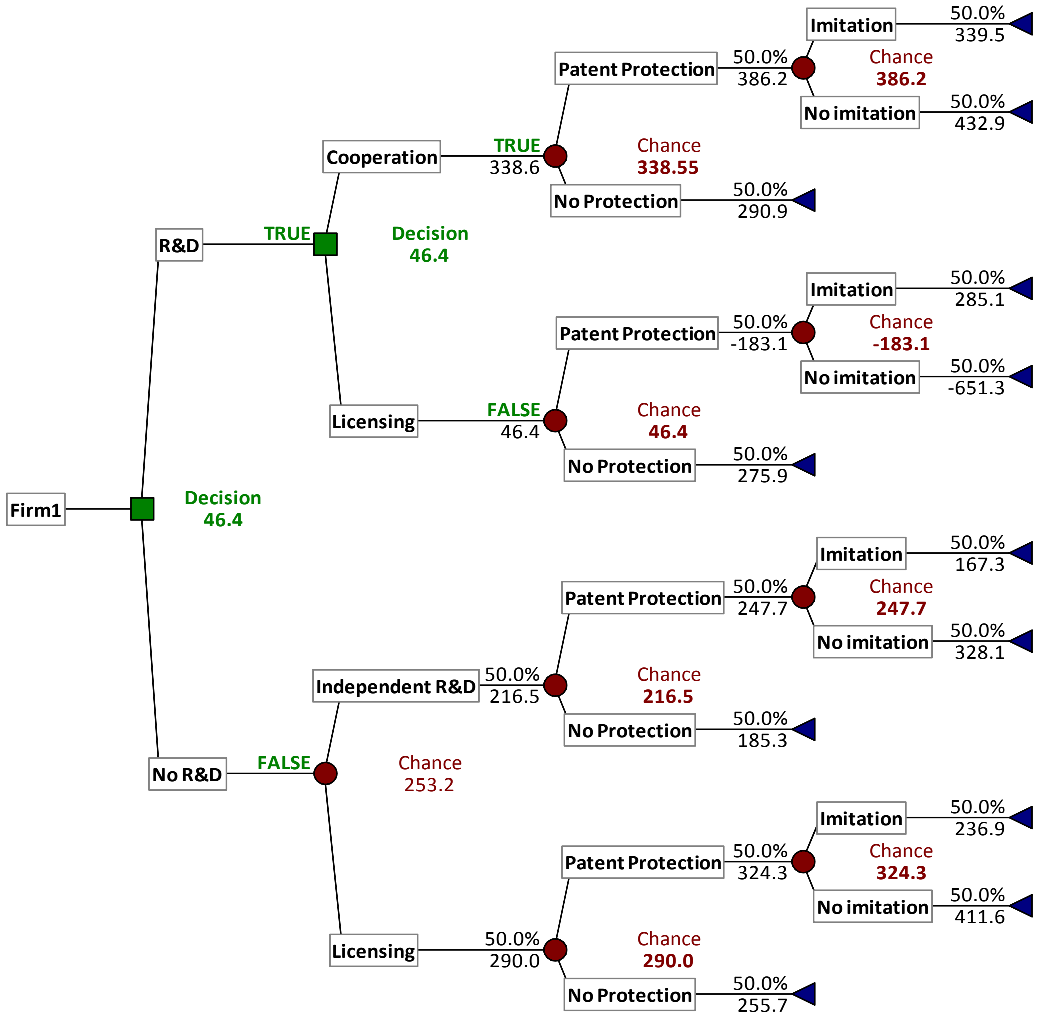


Figure 5.11: Firm1's optimal decision tree with non-strategic and strategic R&D incentives.

Unlike the strategy of choosing path creating the highest payoff, the DT using R&D incentive chooses the strategy to choose the path creating the smallest R&D incentive. That is, by choosing a strategy minimizing expected R&D incentive of its competitor, the DT wants to minimize the effect of the strategy of its competitor in the interdependent game. [79] In addition, the DT using R&D incentive makes it possible to know the path creating the biggest R&D incentive of its competitor, and to analyze the strategy beneficial to one and the strategy beneficial to one's competitor. For example, it is highly possible that the strategic choice of Firm 2 is R&D cooperation in which R&D incentive is the highest. Given such possibility, it is beneficial to Firm 1 to evade R&D cooperation. In addition, when Firm 1 selects R&D cooperation, expected R&D incentive of Firm 2 is 338.6. On the other hand, when Firm 1 does not select R&D, expected R&D incentive of Firm 2 is 290.0 even if it chooses patent licensing. Thus, the second-best strategy of Firm 1 is no-R&D[80] by which it can force low R&D incentive to its competitor, rather than R&D cooperation.

DT and Optimal-DT of Firm 2 using R&D incentive with the same method are shown in Figure 5.12 and Figure 5.13.

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[79] If there is no difference in expected profits from R&D investment and from no-R&D, it is wiser not to invest in R&D, considering the investment cost.

[80] In the case of no-R&D, it is possible to adopt strategy to reduce R&D investment cost, remove risks involved in patent acquisition competition, and create around-invention through non-infringing imitation.

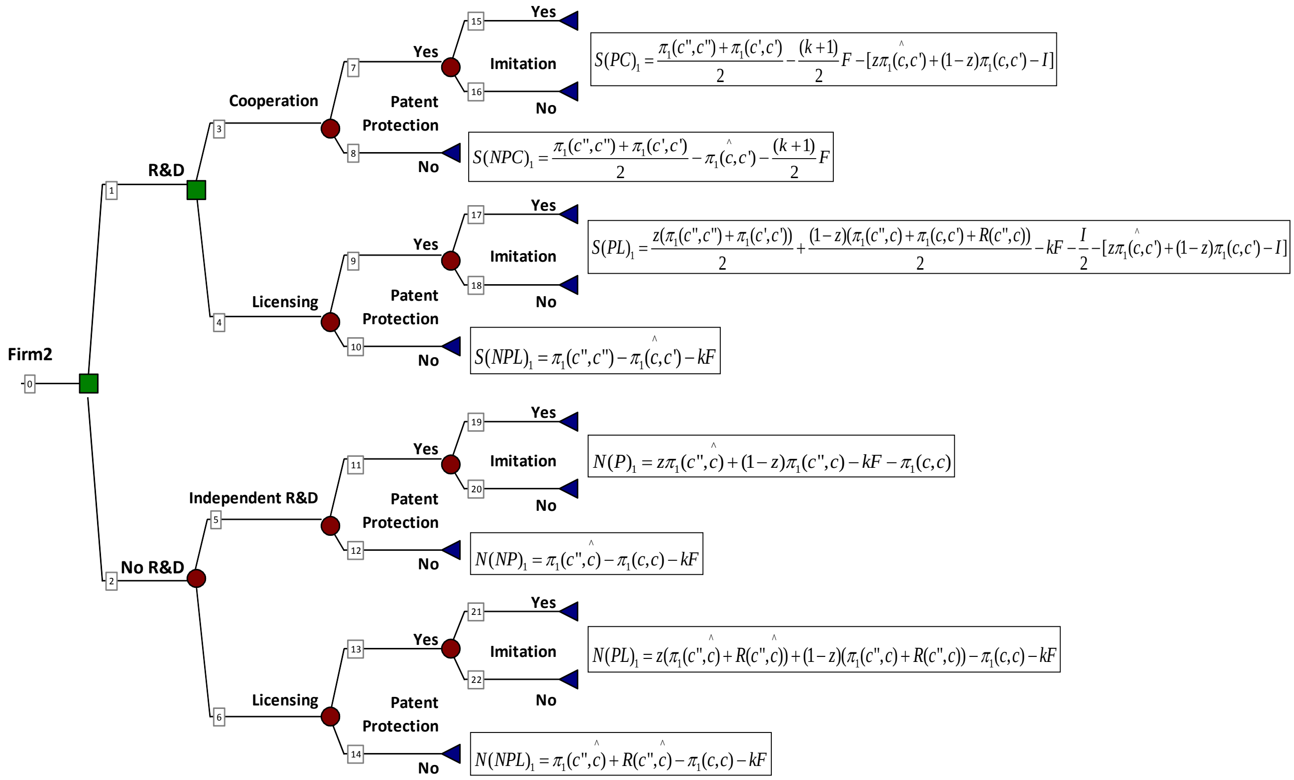


Figure 5.12: Decision-Tree diagram for Firm2 with non-strategic and strategic R&D incentives.

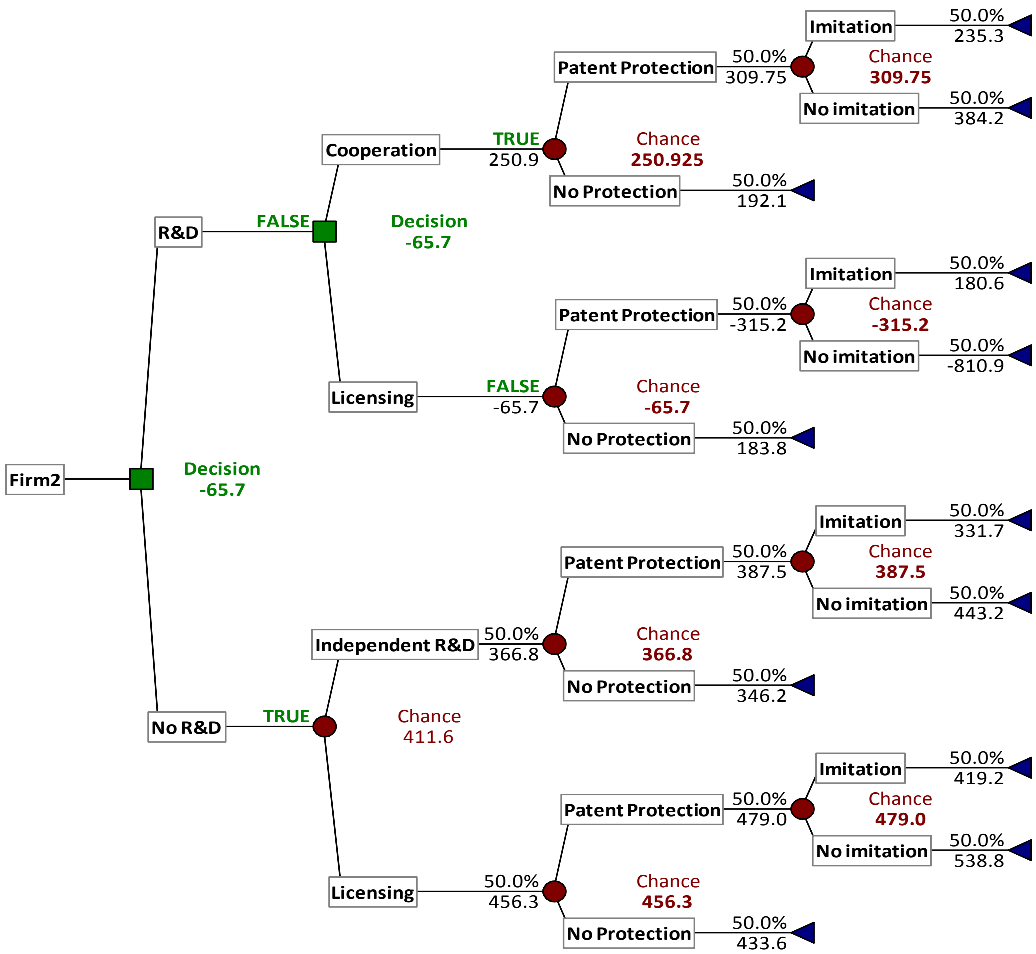


Figure 5.13: Firm2's optimal decision tree with non-strategic and strategic R&D incentives.

As shown in Figure 5.13, we can identify that, to the inferior Firm 2, it is the best strategy to choose R&D licensing, the path minimizing R&D incentive of its competitor. When Firm 2 decides on no-R&D investment, since the expected R&D incentive of its competitor goes up, it is wise for Firm 2 to make R&D investment decision in the way of minimizing the possibility of Firm 1's R&D investment. Especially, unlike Firm 1 whose second-best strategy is to choose no-R&D, the second-best strategy for Firm 2 is R&D-cooperation. Given no-R&D of Firm 2, Firm 1's expected R&D incentive is 411.6, higher than the value it can get when it chooses R&D-cooperation. So, it prefers R&D cooperation. Consequently, when the two firms choose the best strategies, equilibrium is formed in bilateral R&D investment, which is the same result with decisions using payoff.

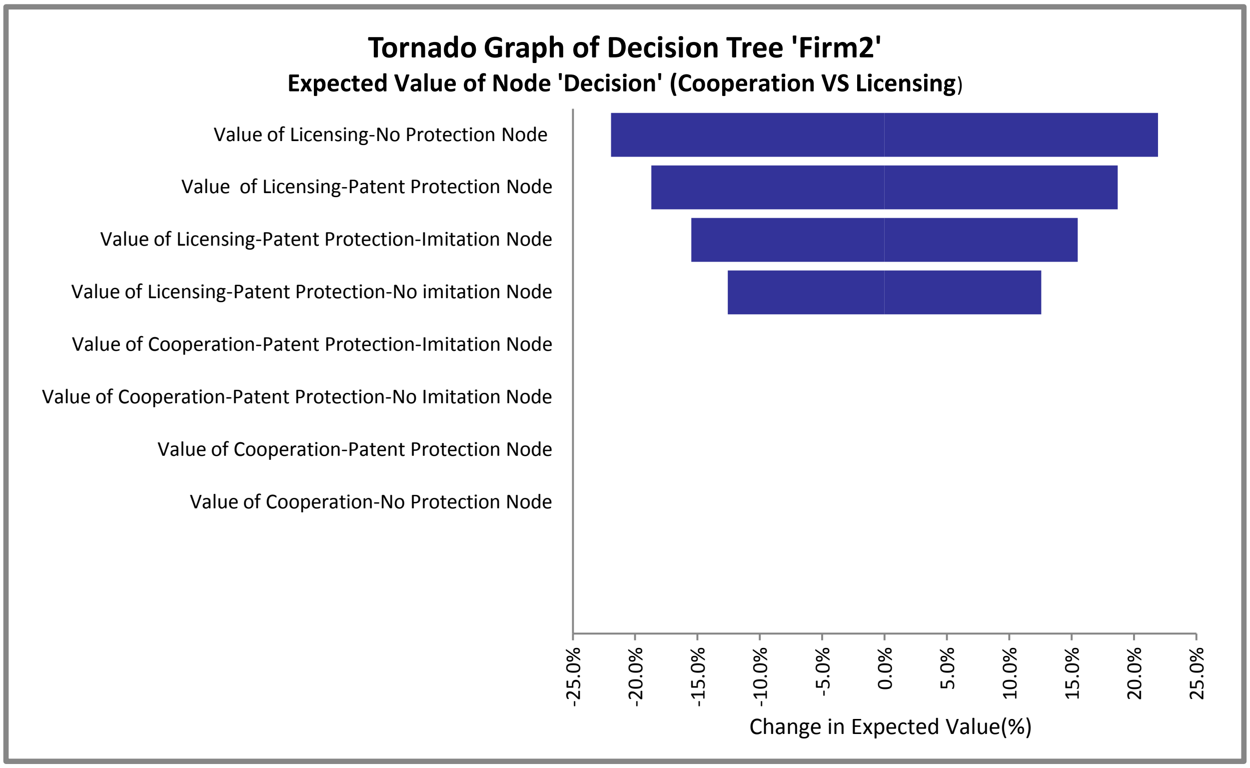
5.5 Sensitivity Analysis for Patent Protection and Non-infringing Imitation

In the asymmetric R&D investment competition model, patent protection and non-infringing imitation are core elements in decision-making. But, since it is unknown to what extent such environmental elements may occur in real competition, we build the chance node with 50% probability in the basic model. But, in the view of decision-maker, since it is possible to reduce uncertainty in competition and make better quality decision by analyzing effects which affect the decision-making, it is necessary to conduct sensitivity analysis. In this paragraph, we will conduct sensitivity analysis on various variables in R&D investment decisions of the two firms, and examine changes of what variables firms should pay attention to.

In the DT of Firm 1, R&D investment through licensing is the best decision, and its second-best decision is to avoid R&D cooperation and win the competition by no-R&D and non-infringing imitation. Especially, for the superior Firm 1, expected profit in the R&D-licensing path is much higher than other decision-making nodes, leading it to stably maintain decision-making on competitive environment changes. On the other hand, to the inferior Firm 2, while R&D investment is beneficial than no-R&D, the difference of expected benefits between licensing and cooperation paths is not big, which we judged as a signal of big effects of variables. To identify this, we do one-way sensitivity analysis using precision tree[81]. Figure 5.14 displays nodes which

[81] A decision-tree software developed by Palisade Corporation, Ithaca, NY, 14850.

affect R&D investment decisions, the best decision, to the greatest extent in the form of tornado graph in the order of sensitivity ranking.



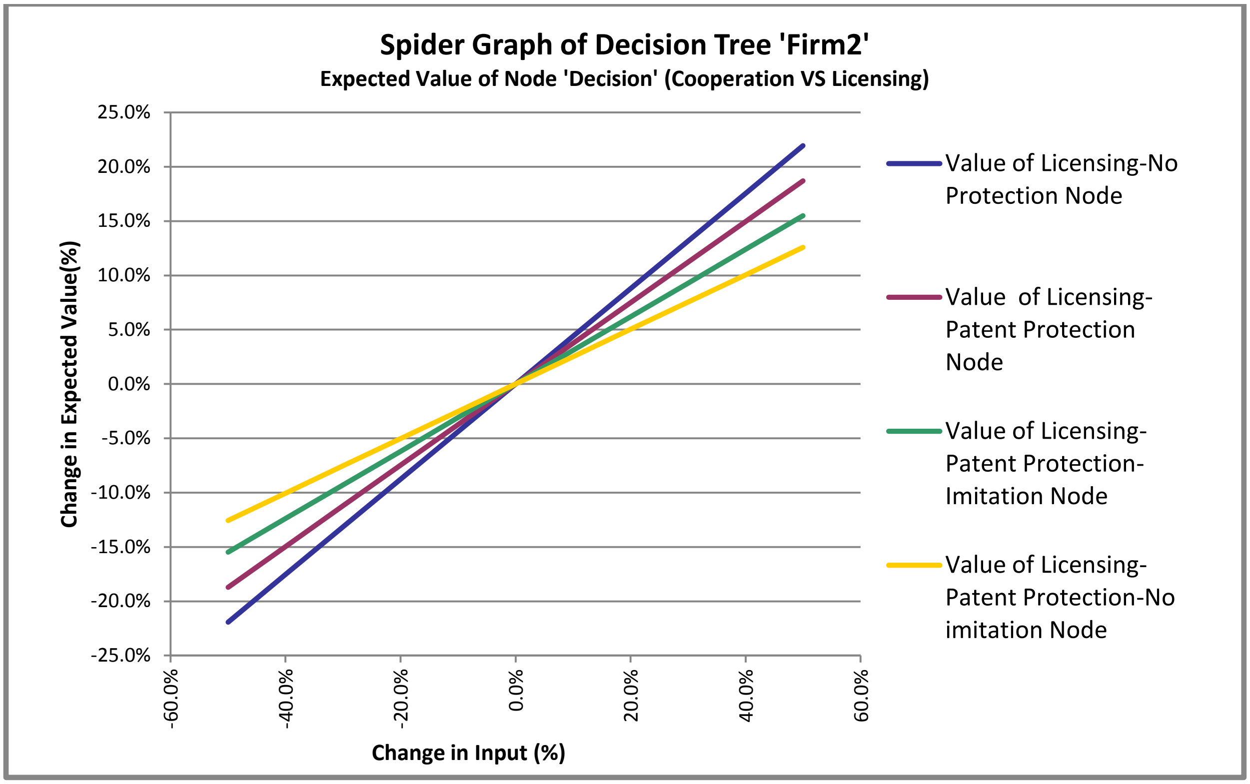
Tornado Graph Data

Decision Tree 'Firm2' (Expected Value of Node 'Decision' (Cooperation VS Licensing)

			Minimum			Maximum		
			Output		Input	Output		Input
Rank	Input Name	Cell	Value	Change (%)	Value	Value	Change (%)	Value
1	Value of Licensing-No Protection Node	F35	894.2	-21.94%	251.3	1396.8	21.94%	753.9
2	Value of Licensing-Patent Protection Node	F29	931.2	-18.71%	214.3	1359.8	18.71%	642.9
3	Value of Licensing-Patent Protection-Imitation Node	G27	968.05	-15.49%	236.6	1322.95	15.49%	709.8
4	Value of Licensing-Patent Protection-No imitation Node	G31	1001.5	-12.57%	192	1289.5	12.57%	576
5	Value of Cooperation-Patent Protection-Imitation Node	G15	1145.5	0.00%	221.3	1145.5	0.00%	221.3
6	Value of Cooperation-Patent Protection-No Imitation Node	G19	1145.5	0.00%	221.3	1145.5	0.00%	221.3
7	Value of Cooperation-Patent Protection Node	F17	1145.5	0.00%	221.3	1145.5	0.00%	221.3
8	Value of Cooperation-No Protection Node	F23	1145.5	0.00%	221.3	1145.5	0.00%	221.3

Figure 5.14: Tornado Chart with Data for Firm2's decision (Cooperation VS Licensing).

In Figure 5.14, we can notice that the upper four nodes: Licensing & No Patent Protection → Licensing & Patent Protection → Licensing & Patent protection & Imitation → Licensing & Patent protection & Imitation. Spider chart (Figure 5.15) precisely displays information about the changes in input (node) variation and output variation of elements highly influential to the tornado chart.



Spider Graph Data

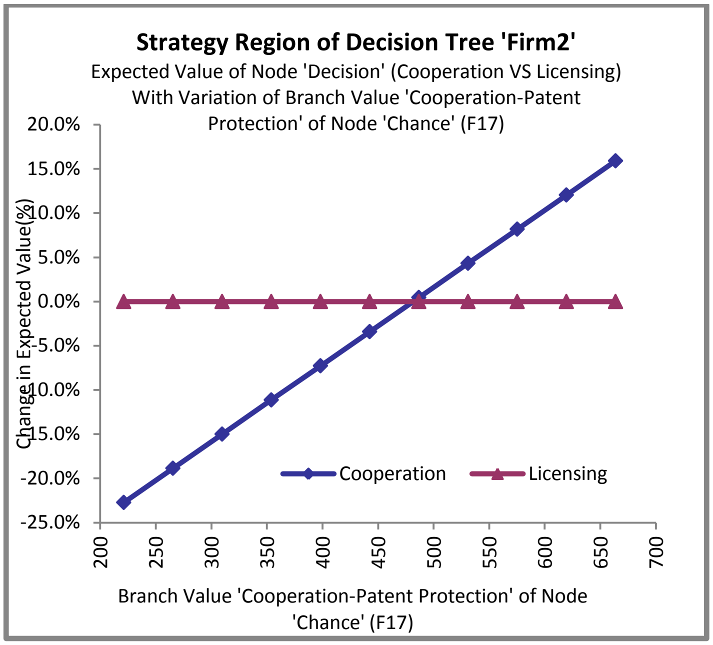
Decision Tree 'Firm2' (Expected Value of Node 'Decision' (Cooperation VS Licensing))

			Input Variation			Output Variation		
Input Name	**Cell**	**Step**	**Value**	**Change**	**Change (%)**	**Value**	**Change**	**Change (%)**
Value of Licensing-No Protection Node	F35	1	251.3	-251.3	-50.00%	894.2	-251.3	-21.94%
		2	301.56	-201.04	-40.00%	944.46	-201.04	-17.55%
		3	351.82	-150.78	-30.00%	994.72	-150.78	-13.16%
		4	402.08	-100.52	-20.00%	1044.98	-100.52	-8.78%
		5	452.34	-50.26	-10.00%	1095.24	-50.26	-4.39%
		6	502.6	0	0.00%	1145.5	0	0.00%
		7	552.86	50.26	10.00%	1195.76	50.26	4.39%
		8	603.12	100.52	20.00%	1246.02	100.52	8.78%
		9	653.38	150.78	30.00%	1296.28	150.78	13.16%
		10	703.64	201.04	40.00%	1346.54	201.04	17.55%
		11	753.9	251.3	50.00%	1396.8	251.3	21.94%

Value of Licensing-Patent Protection Node	F29	1	214.3	-214.3	-50.00%	931.2	-214.3	-18.71%
		2	257.16	-171.44	-40.00%	974.06	-171.44	-14.97%
		3	300.02	-128.58	-30.00%	1016.92	-128.58	-11.22%
		4	342.88	-85.72	-20.00%	1059.78	-85.72	-7.48%
		5	385.74	-42.86	-10.00%	1102.64	-42.86	-3.74%
		6	428.6	0	0.00%	1145.5	0	0.00%
		7	471.46	42.86	10.00%	1188.36	42.86	3.74%
		8	514.32	85.72	20.00%	1231.22	85.72	7.48%
		9	557.18	128.58	30.00%	1274.08	128.58	11.22%
		10	600.04	171.44	40.00%	1316.94	171.44	14.97%
		11	642.9	214.3	50.00%	1359.8	214.3	18.71%
Value of Licensing-Patent Protection-Imitation Node	G27	1	236.6	-236.6	-50.00%	968.05	-177.45	-15.49%
		2	283.92	-189.28	-40.00%	1003.54	-141.96	-12.39%
		3	331.24	-141.96	-30.00%	1039.03	-106.47	-9.29%
		4	378.56	-94.64	-20.00%	1074.52	-70.98	-6.20%
		5	425.88	-47.32	-10.00%	1110.01	-35.49	-3.10%
		6	473.2	0	0.00%	1145.5	0	0.00%
		7	520.52	47.32	10.00%	1180.99	35.49	3.10%
		8	567.84	94.64	20.00%	1216.48	70.98	6.20%
		9	615.16	141.96	30.00%	1251.97	106.47	9.29%
		10	662.48	189.28	40.00%	1287.46	141.96	12.39%
		11	709.8	236.6	50.00%	1322.95	177.45	15.49%
Value of Licensing-Patent Protection-No imitation Node	G31	1	192	-192	-50.00%	1001.5	-144	-12.57%
		2	230.4	-153.6	-40.00%	1030.3	-115.2	-10.06%
		3	268.8	-115.2	-30.00%	1059.1	-86.4	-7.54%
		4	307.2	-76.8	-20.00%	1087.9	-57.6	-5.03%
		5	345.6	-38.4	-10.00%	1116.7	-28.8	-2.51%
		6	384	0	0.00%	1145.5	0	0.00%
		7	422.4	38.4	10.00%	1174.3	28.8	2.51%
		8	460.8	76.8	20.00%	1203.1	57.6	5.03%
		9	499.2	115.2	30.00%	1231.9	86.4	7.54%
		10	537.6	153.6	40.00%	1260.7	115.2	10.06%
		11	576	192	50.00%	1289.5	144	12.57%

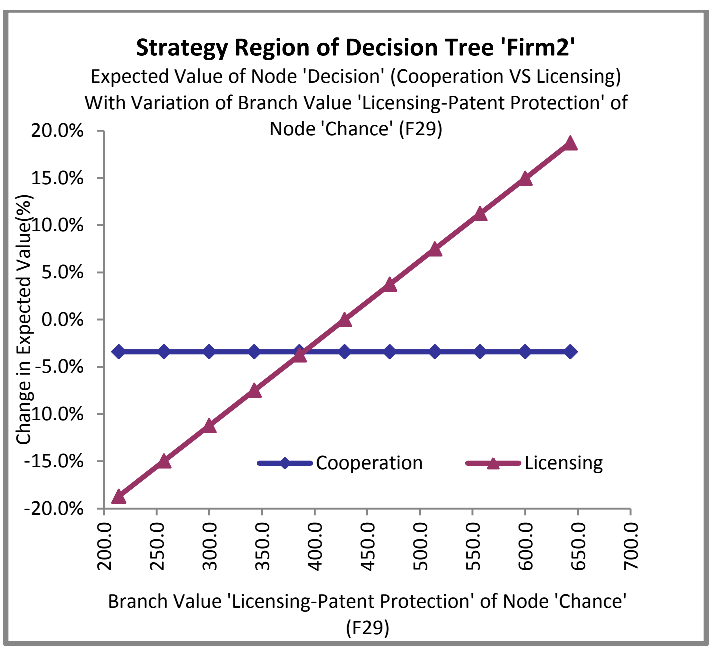
Figure 5.15: Spider Chart with Data for Firm2's decision (Cooperation VS Licensing).

In Figure 5.14, the Licensing & No-protection node at the top of the tornado chart shows the steepest positive slope creating 21.94% of the outcome of input change, followed by Licensing & Patent Protection (18.71%), Licensing & Patent Protection & Imitation (15.49%), and Licensing & Patent Protection & No Imitation (12.57%) in descending order. Based on this, we can identify changes of strategic regions of firms depending on the changes of Patent Protection values which have the greatest effect on decision-making. Figure 5.16 and Figure 5.17 show the outcome values of R&D cooperation and licensing nodes. And, Figure 5.18 shows changing patterns of expected value of decision (Cooperation VS Licensing) values depending on input changes of the two variables - Patent protection and Non-infringing imitation in two-way sensitivity analysis.



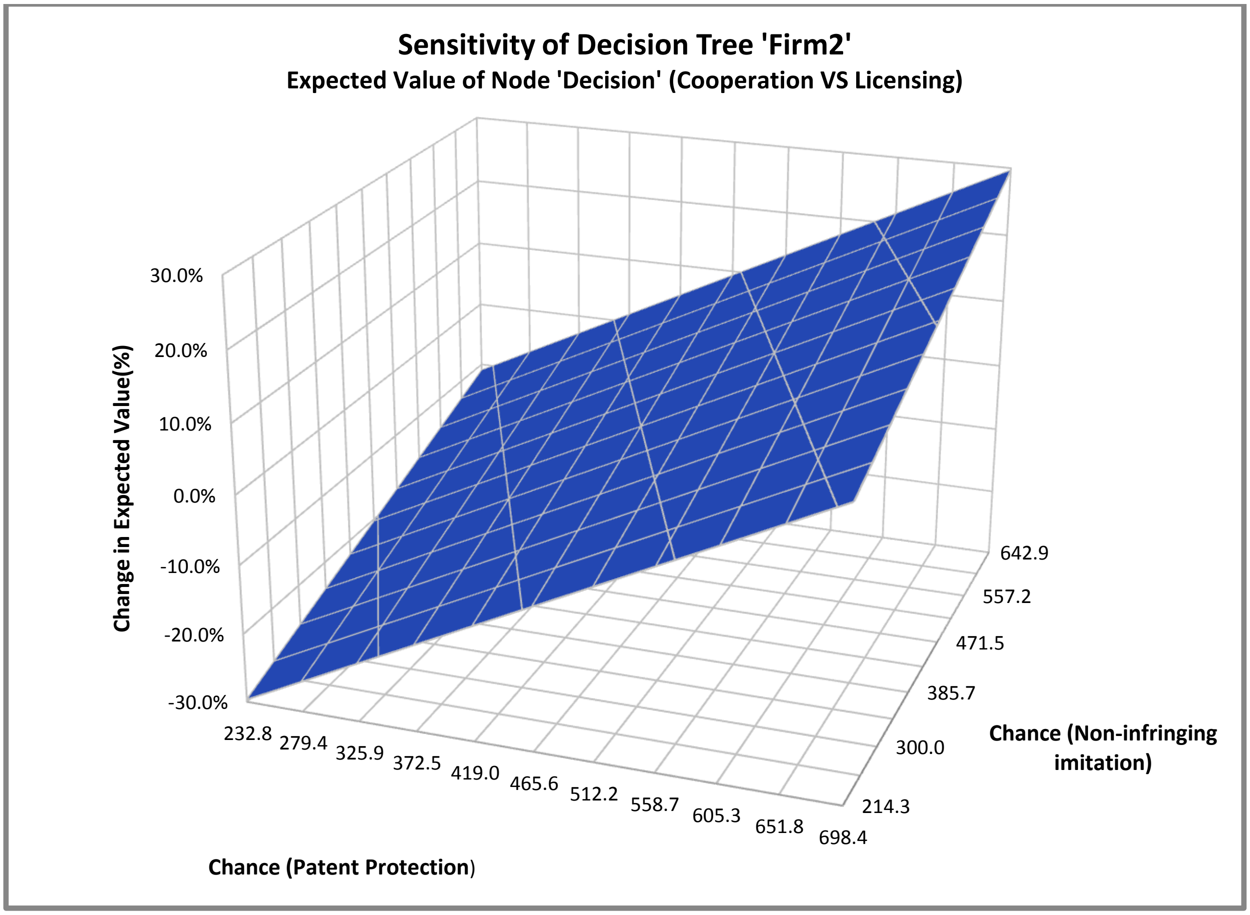
Strategy Region Data						
	Input		Cooperation		Licensing	
	Value	Change (%)	Value	Change (%)	Value	Change (%)
#1	221.3	-50.00%	885.2	-22.72%	1145.5	0.00%
#2	265.56	-40.00%	929.46	-18.86%	1145.5	0.00%
#3	309.82	-30.00%	973.72	-15.00%	1145.5	0.00%
#4	354.08	-20.00%	1017.98	-11.13%	1145.5	0.00%
#5	398.34	-10.00%	1062.24	-7.27%	1145.5	0.00%
#6	442.6	0.00%	1106.5	-3.40%	1145.5	0.00%
#7	486.86	10.00%	1150.76	0.46%	1145.5	0.00%
#8	531.12	20.00%	1195.02	4.32%	1145.5	0.00%
#9	575.38	30.00%	1239.28	8.19%	1145.5	0.00%
#10	619.64	40.00%	1283.54	12.05%	1145.5	0.00%
#11	663.9	50.00%	1327.8	15.91%	1145.5	0.00%

Figure 5.16: Strategy region with variation of Cooperation-Patent protection node.



Strategy Region Data						
	Input		Cooperation		Licensing	
	Value	Change (%)	Value	Change (%)	Value	Change (%)
#1	214.3	-50.00%	1106.5	-3.40%	931.2	-18.71%
#2	257.2	-40.00%	1106.5	-3.40%	974.06	-14.97%
#3	300.0	-30.00%	1106.5	-3.40%	1016.92	-11.22%
#4	342.9	-20.00%	1106.5	-3.40%	1059.78	-7.48%
#5	385.7	-10.00%	1106.5	-3.40%	1102.64	-3.74%
#6	428.6	0.00%	1106.5	-3.40%	1145.5	0.00%
#7	471.5	10.00%	1106.5	-3.40%	1188.36	3.74%
#8	514.3	20.00%	1106.5	-3.40%	1231.22	7.48%
#9	557.2	30.00%	1106.5	-3.40%	1274.08	11.22%
#10	600.0	40.00%	1106.5	-3.40%	1316.94	14.97%
#11	642.9	50.00%	1106.5	-3.40%	1359.8	18.71%

Figure 5.17: Strategy region with variation of Licensing-Patent protection node.



Two-Way Sensitivity Data of Decision Tree 'Firm2' (Expected Value of Node 'Decision' (Cooperation VS Licensing))
With Variation of Chance (Patent Protection) and Chance (Non-infringing imitation)

		Chance (Patent Protection)										
		232.8	**279.4**	**325.9**	**372.5**	**419.0**	**465.6**	**512.2**	**558.7**	**605.3**	**651.8**	**698.4**
Chance (Non-infringing imitation)	**214.3**	-29.677%	-25.6124%	-21.5478%	-17.4832%	-13.4186%	-9.354%	-5.2894%	-1.2248%	2.8398%	6.9044%	10.969%
	257.2	-27.8062%	-23.7416%	-19.677%	-15.6124%	-11.5478%	-7.4832%	-3.4186%	0.646%	4.7106%	8.7752%	12.8398%
	300.0	-25.9354%	-21.8708%	-17.8062%	-13.7416%	-9.677%	-5.6124%	-1.5478%	2.5168%	6.5814%	10.646%	14.7106%
	342.9	-24.0646%	-20.0%	-15.9354%	-11.8708%	-7.8062%	-3.7416%	0.323%	4.3876%	8.4522%	12.5168%	16.5814%
	385.7	-22.1938%	-18.1292%	-14.0646%	-10.0%	-5.9354%	-1.8708%	2.1938%	6.2584%	10.323%	14.3876%	18.4522%
	428.6	-20.323%	-16.2584%	-12.1938%	-8.1292%	-4.0646%	0.0%	4.0646%	8.1292%	12.1938%	16.2584%	20.323%
	471.5	-18.4522%	-14.3876%	-10.323%	-6.2584%	-2.1938%	1.8708%	5.9354%	10.0%	14.0646%	18.1292%	22.1938%
	514.3	-16.5814%	-12.5168%	-8.4522%	-4.3876%	-0.323%	3.7416%	7.8062%	11.8708%	15.9354%	20.0%	24.0646%
	557.2	-14.7106%	-10.646%	-6.5814%	-2.5168%	1.5478%	5.6124%	9.677%	13.7416%	17.8062%	21.8708%	25.9354%
	600.0	-12.8398%	-8.7752%	-4.7106%	-0.646%	3.4186%	7.4832%	11.5478%	15.6124%	19.677%	23.7416%	27.8062%
	642.9	-10.969%	-6.9044%	-2.8398%	1.2248%	5.2894%	9.354%	13.4186%	17.4832%	21.5478%	25.6124%	29.677%

Figure 5.18: Sensitivity graph with variation of patent protection and non-infringing imitation.

In the current scenario, while Firm 2 expects the highest expected profits through R&D-licensing, we can notice that it needs to change its strategies for the changes of patent protection values which play the most important role in decision-making on investment. That is, in cooperation node, if the input changes go over 10% in the current condition, at the time when expected value changes in cooperation go over licensing, the strategy of Firm 2 changes from licensing to cooperation (Figure5.16), and the strategic changes occur also in licensing node depending on patent protection changes (Figure5.17).

In Figure5.18, if we fix the patent protection (horizontal) axle, and see the changes of decision-making expected values on the imitation (vertical) axle, we can identify about 19% changes. On the contrary, if we fix the vertical axle, and see only changes in horizontal axle, we can see 40% changes. So, we can identify that patent protection plays the most important role in determining expected values in cooperation and licensing strategies.

5.6 Conclusion

In this research, we, using DT, analyze what the decision-making maximizing one's own expected profits is, given that one can predict strategies of one's competitor among two firms which are playing an R&D investment competition game in the interdependent environment. Especially, we apply numerical payoff and R&D incentive satisfying hypotheses of profit functions hierarchy and bilateral R&D to DT, and, based on this, we draw the best decision-makings of firms. DT using R&D incentive enables us to analyze the best and the second-best strategies of firms with half times as many as the number of DT needed in using payoff, enhancing computational efficiency. In the DT analysis using Payoff and R&D incentive, the best strategies for both firms are to compete through R&D investment and technology licensing. We also identify that the second-best strategy for Firm 1 is to choose no-R&D, and that for Firm 2 is to choose R&D cooperation.

Chapter 6

Conclusion

Using the game theory, we construct an asymmetric R&D competition model, and apply it to various competition models. The game consists of two stages: in the stage 1, the two firms decide R&D investment; in stage 2, patent acquisition is determined. We develop as many as possible competition scenarios by the combination of various variables and environments (conditions) such as patent acquisition, non-infringing-imitation probability, R&D-cooperation option, licensing option, zero-sum, and non-zero-sum game conditions, etc. By applying various analytical methods such as sensitivity analysis, scenario analysis, and decision-making model analysis, etc., we develop and suggest strategies per scenario by which firms can secure high expected profits through R&D investment.

First, we examine strategic R&D investment decisions for two competing firms using game theory. In doing so, we generate a series of possible competition scenarios describing anticipated payoffs and higher R&D incentives. It is shown that bilateral R&D competition under patent protection can create higher strategic R&D incentive for R&D cooperation than independent R&D investment. Also we find that if non-infringing imitation is less likely, R&D cooperation with patent protection achieve higher strategic R&D incentives. With patent protection, technology licensing creates higher R&D incentives for both strategic and non-strategic situations, when compared with the situations without licensing for the two competing firms. Furthermore, firms in asymmetric competition expect higher strategic R&D incentives through the R&D cooperation.

Second, we study R&D investment game strategies with the assumption of zero-sum under a saturated market competition. By generating a series of possible competition scenarios focusing on expected payoffs and better R&D incentives to achieve, we compared two models with and without non-infringing imitation. From the study, we find that patent protection always increases non-strategic R&D incentive, but strategic R&D incentive increases (decreases) when there is (not) non-infringing imitation available. In the R&D cooperation circumstance, patent protection increases non-strategic R&D incentive while decreasing strategic R&D incentive. We also find that cooperative R&D can always expect higher strategic R&D incentive than independent R&D investment regardless of the existence of patent protection when there is non-infringing imitation available, whereas cooperative R&D (independent R&D) achieves higher R&D incentive with (without) patent protection when there is no imitation available. Furthermore, technology licensing generates higher non-strategic R&D incentive than R&D cooperation can generate whether or not patent protection is available.

Third, we construct R&D competition game as a probabilistic model and investigate the changes of patent acquisition probabilities and imitation possibilities of the two firms by doing sensitivity analysis. From the analytical outcomes under the conditions of zero-sum and non-zero-sum games, we find that it is strategically favorable for the Firm 1 to make R&D investment under zero-sum game regardless of patent acquisition probability and the inferior Firm 2 has a chance to get higher strategic R&D incentives only under nonzero-sum game. Comparison of symmetric and asymmetric models reveals that, under the nonzero-sum game, symmetry condition is advantageous to Firm 1 to invest in R&D. On the other hand, it is strategically advantageous for Firm 2 to do R&D competition in the asymmetric condition.

Last, we utilize decision-tree (DT) model to analyze what the decision-making maximizing one's own expected profits is, given that one can predict strategies of one's competitor among two firms which are playing an R&D investment competition game in the interdependent environment. Especially, we apply numerical payoff and R&D incentive satisfying hypotheses of profit functions hierarchy and bilateral R&D to DT, and, based on this, we draw the best decision-makings of firms. In the DT analysis using Payoff and R&D incentive, the best strategies for both firms are to compete through R&D investment and technology licensing. We also identify that the second-best strategy for Firm 1 is to choose no-R&D, and that for Firm 2 is to choose R&D cooperation.

Despite various efforts, this research has various limits. First, even if we suggested realistic conditions such as asymmetry of two firms, non-infringing-imitation probability, and changes of incentives depending on changes of patent acquisition probability, in order to suggest a model resembling reality, the assumption in stage 1 that two firms determine to invest in R&D at the same time is not very realistic. However, if we assume that two firms decide on R&D sequentially in duopoly situation, uncertainties such as the firm which decides to invest later can acquire information about technology and investment of the firm which decide to invest first, and market preoccupation, etc. increase. Thus it is inevitable to add many unrealistic assumptions. Consequently, our game model which can minimize additional assumptions by assuming a simultaneous-move game – We do not necessarily mean simultaneous decisions, but include the competition type where players play the game without having information about competitor – is different from existing research methods.

The second limit is that in analyzing investment strategies, it is difficult to explain rationally selection of node order and constituting elements. This research constituted DT in the order of R&D investment decision of two firms-decision of licensing and cooperation options-patent protection or not-imitation or not. But, when the order of chance nodes is changed or new nodes are added, the model becomes less reliable. It has limits in the sense that when a new node is added, the assumption of the initial model should be changed, and so everything should be reconstructed. Consequently, we focused on suggesting various analytical methods of asymmetric R&D competition models, and emphasized the easiness of expansion and transformation of the model. Finally, this research did not consider time concept. There can be considerable gap between the first stage (decision on R&D investment) and stage 2 (decision on payoff), and such gap can be an important element in decision on R&D investment. But, since the time gaps among R&D, patent competition, and performance decision in various industries, firms, and competing items are different (e.g. in the pharmaceutical industry, R&D investment consists of various stages, and it is difficult to concretize time until performance is determined). So, it can be applied in the research for a specific industry.

This research can be expanded in various directions. The current game model is one-shot game not including time concept, because R&D investment decision is made in stage 1, and patent is determined, and related profits of the two firms are also determined in stage 2. However, in the R&D investment consisting of multiple stages including time concept like the R&D process in the pharmaceutical industry, it is better to analyze by repeated game method. In this case, it is necessary to distinguish the case where decision-making of each stage is independent and the case where it is dependent, and to add assumptions on the effects of sequential R&D investment decisions on the possibility of patent acquisition per each stage. And, it would be more interesting if Bayesian analytical method is used and information on decisions made in each stage is updated, and related competitions are analyzed. It would be also interesting if concept of utility theory for decision-makers to formally classify their willingness is used. If the elements which were not included in this research (e.g. competition model including 3 and more firms, and decision-making including utilities of competing firms), the model will explain the reality more efficiently.

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