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THREE ESSAYS ON R&D CHOICE WITH COMPATIBILITY EXTERNALITY

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Abstract

This dissertation consists of the three essays on R&D project choice in the presence of compatibility externality.

In the first essay we consider a R&D contest between two firms who can choose to concentrate their research in one of two avenues or approaches. In the R&D contest, firms compete in two stages. In the first stage, firms choose which approach they will investigate, after which they endogenously select optimal effort level given firms' choice of approach in the second stage. There are compatibility externalities if they choose the same approach. However, there is also greater probability of simultaneous discovery which may cause harmful results to both firms. We examine 2 situations with different payoff structures by considering the Bertrand R&D game and the equal sharing R&D game. The equilibrium avenue choice in each game depends on the size of compatibility externality and it may exhibit too much differentiation or too much duplication. The equilibrium effort choice conditional on duplication is inefficiently high in the equal sharing R&D game, while the equilibrium effort choice is efficient when firms choose different research avenues. The result of the excess differentiation and the efficient investment choice in the Bertrand R&D game suggest that the lump-sum investment subsidy may need to be implemented in the US wireless mobile phone industry to reduce inefficiency involved in excess differentiation without distorting efficient investment choice.

In the second essay we consider firms' R&D choice problem where firms may choose the same research approach only through forming a research alliance. When firms agree on forming a research alliance, they play an equal sharing R&D game for the stand-alone value of R&D success, while they split the network value of R&D success according to a certain proportion specified under the research alliance contract. Since firms share the network value of R&D success, firms have an incentive to free-ride on the other firm's investment. But, due to the payoff structure in which firms receive rewards for its second discovery, firms also have excessive incentive for investment. The interplay of such conflicting incentives result in non-monotonic inefficiency in equilibrium

investment choice. Especially it turns out that the excessive incentive for investment outweighs the insufficient incentive for investment when compatibility externality is low enough, which results in excess duplication in site choice.

In the third essay we consider firms' dynamic R&D project choice problem in the presence of compatibility externality. Firms which engage in R&D based on risky fundamental technologies (sites) face two kinds of uncertainties: the uncertainty involved in the fundamental technology (whether a treasure is buried in the site) and the uncertainty involved in its own R&D activity (whether R&D succeeds given that a treasure is buried in the site investigated). Each firm carries out two activities in the site that it chooses: production and research. There exists compatibility benefit in both per-period production revenue and the per-period R&D reward when firms choose the same site. Such compatibility benefit which the firms can't internalize and the nature of competition in the prospective product market interplay to result in over-duplication or over-differentiation in site choice in the equilibrium. The result of our numerical analysis of the two period game shows that the information benefit through experimentation causes the social optimum and the equilibrium in the two period game to be non-myopic where they involve in differentiation in site choice more often than in the one period game.

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Chapter I

Standard setting, compatibility externalities and R&D

I.1 Introduction

Many products have value only when the products are used in combination with other products. For example, in order to watch DVD, one needs a DVD player, ATM cards are useless without automatic teller machines. A cell phone by itself is of no use in the area where carrier's service is not provided. These are examples of products which need complementary goods in generating their values and they are described as forming "systems".[1] In such systems markets, compatibility or standardization among systems is of importance to consumers. Consumers may enjoy more benefits by purchasing goods from compatible systems than from an isolated incompatible system[2]. Especially in the presence of network externality in consumption of compatible goods, consumers may put higher value on products which are compatible across systems since compatibility increases the actual network size of each system to that of entire interconnected systems.[3]

However, whether compatibility is beneficial to firms is less clear. Some of benefits that consumers enjoy thanks to compatibility may be exploited by firms. Then, the consumers' compatibility benefits eventually feed back into firms' incentive to make their product compatible.[4] Firms can also benefit directly from compatibility. If the products are compatible, then economies of scale

[1] Katz & Shapiro(1994) define a system as a collection of two or more components together with an interface that allows the components to work together.

[2] If standardization reduces variety and consumers place much value on variety, welfare effect of standardization on consumers may be unclear. For the explicit analysis on tradeoff between efficiency and variety, see Farrell and Saloner (1986).

[3] Farrell & Saloner (1985) identify in detail benefits from compatibility or standardization occurring to consumers that include, but not restricted to : a market-mediated effect, as when a complementary good becomes cheaper and more readily available the greater the size of compatible systems ; a thicker second-hand(used) market, enhanced price competition among firms.

[4] We use compatibility benefit and network benefit interchangeably. Similarly, compatibility externality and network externality are used interchangeable in the rest of the paper.

may occur in the production process of the parts used in compatible products, resulting in lower prices of inputs. In some occasions, firms may enhance quality of their products or lower their production costs by sharing their compatible facilities.[5] When such benefits from compatibility is greater, firms has more incentive to choose a same standard, in which they compete within a standard. But, compatibility may bring about losses to firms, too. When products are compatible, consumers may not incur any switching cost in purchasing other compatible products, which may make competition within a standard very fierce[6]. In contrast, if products are incompatible and are considered to have different characteristics, then firms compete only for some fraction of the market which consists of consumers who are not in the installed base of any standard.[7] In such cases where price competition is dampened by firms' choosing different standards, firms may prefer incompatibility, in which they compete with their own standards.

Foreseeing such situations in the product market, firms at the pre-R&D stage can choose between competition within a standard and competition with its own standard. Then, firms in such situations have a following trade-off. Seeking compatibility by engaging in R&D on the research avenue for similar compatible products, may yield greater rewards given an exclusive success in R&D, as long as the greater network benefits can be eventually captured by firms. But, on the other hand, it also entails the possibility that the R&D race may end up with simultaneous discovery, resulting in losses to all the firms who made discovery simultaneously.[8] How simultaneous discovery dissipates the rewards from R&D success may depend on how competitive the relevant industry is.

First consider the case in which all the rewards from R&D success are competed away when simultaneous discovery occurs. One good example in such extreme case can be found in the airplane

[5] The wireless communication service industry offers one good example. AT&T, Cingular and T-Mobile which adopt the same GSM technology, can share their networks in providing their service to customers. By doing so, they may construct the interconnected national GSM network so that each firm with incomplete network only, can provide seamless connection in any areas wherever some other GSM carrier has networks. This is the typical example of "physical" network externality(Oz, 2001).

[6] Even when products are almost compatible, firms often create artificial switching costs to build an installed base. For example, wireless telecommunication companies often charges a penalty fee to customers who discontinue the service before the contract expires. In such cases, the penalty fee which customers have to incur will be the switching cost. Mileage or points program used in many industries is another good example of artificial switching cost.

[7] If different incompatible products don't provide its intrinsic values, so consumers consider the products as just incompatible but almost identical, one standard may eventually win all the market, which is often called as "tipping". Since tipping occurs in favor of a firm with more installed base, competition for installed base is very fierce in the industries where tipping occurs. For examples of the industries where "tipping" have been observed, see Katz & Shapiro(1994).

[8] If there are several technologies possible for a standard and network benefits is large enough to outweigh the loss resulting from competition within a standard no matter which technology is standardized, then all the firms would always prefer compatibility to incompatibility. In that case, choice between compatibility vs incompatibility wouldn't be an issue any more. Instead a new issue would arise : which standard is chosen in equilibria and which standard is socially efficient? See Farrell & Saloner(1985) for more in detail.

manufacturer industry. In the 1960s, Douglas and Lockheed introduced the Douglas DC-10 and the Lockheed L-1011 respectively within months of each other. Both of them being the similar wide-bodied three-engined jet airliners, both Douglas and Lockheed made great losses from the simultaneous discovery (The Economist(1985)). Such an extreme case where all the rewards from R&D success are bid away in the case of simultaneous discovery can be captured by the "Bertrand payoff" structure (winner-take-all and no reward in the event of simultaneous discovery). Second, in some industries where competition doesn't dissipate the R&D rewards completely, firms often split the rewards from R&D success when simultaneous discovery occurs. For example, Sega and Nintendo, the two dominant providers in the video game market, have split the market since the development of their own standards. Third, in some industries, firms form a certain type of research alliances through which they cooperate in creating compatibility benefit by agreeing on the same standard or in reducing competition by agreeing on sharing each other's technologies.[9] Consider the example of the anti-ulcer drug market in Australia where Tagamat developed by Smith Kline and Zantac developed by Glaxo were the two dominant brands in early 1980's. Smith Kline and Glaxo have had a joint-patent on Tagamat and Zantac, by which they agreed not to sue the other for breach of prior patent when they engaged in their R&D independently. With such a joint-patent, Smith Kline and Glaxo could reap externality from each other's technologies without causing intense competition. In all the cases mentioned above, simultaneous discovery reduces the reward from R&D success, thereby giving firms the incentive to engage in R&D on different incompatible systems(or different products).[10] If the prospective products from different incompatible research avenues have their own intrinsic values, then simultaneous successes in different R&D avenues(or R&D sites) will not impair each other's payoffs.[11] How much investments firms make is also affected by the possibility of simultaneous discovery because firms may have less incentive for investment as simultaneous discovery dissipates more of the reward from R&D success. Hence, given that such negative effect on firms' payoffs of simultaneous discovery may result in distortion in firms' incentive structure for optimal site choice and optimal investment choice, we might have the following questions : do firms seek compatibility and herd on the same type of R&D avenues in the expectation of capturing compatibility benefits or compatibility externalities? Or, do firms seek incompatibility and diversify their research fearing simultaneous discovery? Are firms' non-

[9] There are various forms of research alliance each of which has different contents of cooperation. If they agree to share all the R&D rewards, then it is no different from a merged firm, while firms cooperate to a very limited extent, exchange of some information.

[10] Even when firms form a research alliance, it is clear that a firm would be better off with an exclusive discovery.

[11] The research avenues are referred to as"site" following the analogy in the "the buried treasure problem". Hereafter, we use both terms interchangeably.

cooperative R&D choices socially efficient? Are firms' R&D intensities given site choice efficient? If not, what kind of intervention may improve the social welfare? Which standard regime would work between the mandatory single standard regime and the multiple standard regime? [12]

In the theoretical literature on standards and network externality, the focus has been mainly on adoption of new products, not on how new technologies come into existence in the first place : the R&D avenue choice. We provide a simple static R&D model in which two firms compete in R&D race in two stages for new generation technologies where two different R&D avenues are available, each being for different technologies incompatible with each other. In the first stage, firms sequentially choose which site to investigate. In the second stage, observing the result of the site choice, firms choose its optimal probability of success(or effort) given site choice.[13] When firms duplicate R&D avenue choice, the reward from an exclusive success is bigger than the reward from R&D success when firms differentiate in the research avenue choice. But if firms duplicate in the research avenue choice, firms bear the risk of simultaneous discovery, which might result in losses to both firms. Firms can choose to differentiate their research avenue choice and avoid the possibility of simultaneous discovery even though the rewards from R&D is smaller than the rewards from an exclusive R&D success given duplication in research avenue choice. In order to capture various results of simultaneous discovery, we consider 2 extreme noncooperative games each of which captures the 2 different situations mentioned earlier : **the Bertrand R&D game** where simultaneous discovery on the same site results in dissipation of all the rewards from R&D success, **the equal sharing R&D game** in which each firm gets a half of the R&D rewards in the event of simultaneous discovery.

The results we obtain are as follows.

First, in the Bertrand R&D game, the equilibrium effort level or investment conditional on site choice is efficient both when firms choose different sites(differentiation) and when firms choose the same site(duplication). Such efficiency outcome results from the coincidence between the private incentive for increase in effort and that of the social planner : a firm has less incentive for duplication in proportion to the more effort exerted by its rival firm since the increase in the rival firm's effort raises the probability of simultaneous discovery, thereby reducing the expected payoff from R&D. In the social optimum, as one firm's probability of success in R&D is higher, the marginal contribution of the other firm's effort is less, so the increase in one firm's effort should be accompanied by the

[12] We assume that the simultaneous discovery in different sites doesn't dissipate the reward from R&D success by either firm, which is discussed in more detail in the section of 2.2.1. Hereafter, simultaneous discovery means simultaneous discovery on the same site unless specified.

[13] Hereafter, we use effort and probability of success in R&D interchangeably.

decrease in the other firm's effort in the social optimum. But, the equilibrium site choice may exhibit too much differentiation for certain set of value of compatibility externality since when it chooses a different site, firms don't consider the network benefits which would occur to the rival firm in choosing the same site.

Second, in the equal sharing R&D game, firms equilibrium effort level conditional on duplication is inefficiently high since firms receive the reward for its second discovery which doesn't add the social welfare. Such excessive incentive for effort also causes firms to choose the same site too much when compatibility externality has intermediate value, resulting in excess duplication.

Third, the optimal policy mix to reduce inefficiencies involved in site choice and effort choice depends on the size of compatibility externality. Without sufficient information on the size of compatibility externality, choosing a mandatory single standard bears risk of loss in additional innovation, lowering the social welfare. However, if the prospective product market is expected to be very competitive so that the relevant industry is close to the case of Bertrand R&D game, then there may occur excess differentiation in site choice in the multiple standard regime, which suggests that the lump-sum investment subsidy may need to be implemented in the US wireless mobile phone industry to reduce inefficiency involved in excess differentiation without distorting efficient investment choice.

As mentioned earlier, the existing theoretical literature in economics on standards and network externality, has mainly focused on the issues regarding introduction of new products which are developed already.

Farrell and Saloner(1985) analyze the sources of inefficiency inherent in standardization where firms choose between incompatible standards in a dynamic setting. They find that excess inertia may occur due to the failure of coordination among firms adopting a new superior standard when information on firm's preferences on standards is incomplete.

Katz and Shapiro(1985) analyze network externality effects under oligopolistic competition on market equilibrium. In their model, consumers' foresight on the potential size of the networks, determine effective networks. Since the rationality restriction on the expectations of consumers allow many sets of expectations in the equilibria, there exist multiple fulfilled expectations equilibria. In their analysis of the firms' incentives to produce compatible goods, they find that firms with good reputations or large existing networks tend to be against compatibility while firms with weak reputation or small existing networks tend to favor compatibility.

Farrell and Saloner(1988) discuss a coordination problem in a finite period model in which firms with different preferences on technologies, seek to agree on one technology. The payoff structure in their model is as follows : a firm is best off if all the firms agree on the technology which it prefers. But, a firm would rather agree on the technology less preferred by it than be incompatible. This payoff structure allows Farrell and Saloner to ignore the case where incompatibility may arise in equilibria. Then, firms play a battle of sexes game each period. In their model, Farrell and Saloner examine three different coordination process: the committee as a pre-play communication mechanism, the market or bandwagon process and a hybrid mechanism in which firms use both bandwagon and committee strategies. They obtain the result that the committee unambiguously outperforms the bandwagon system and the hybrid game gives strictly greater payoffs than the pure committee system.

Katz and Shapiro (1992) consider a market with network externalities where an incumbent with existing installed base competes with an entrant with lower costs but having the disadvantage of no installed base. In their dynamic model, with the crucial assumption of exponential growth of market, they analyze the situation that incumbent's advantage of installed base may not be important when compared to "future" installed base. In those situations, consumers' expectations play a critical role and many fulfilled expectations equilibria exist, one of which involves "insufficient friction". They show that an entrant has the incentive to seek incompatibility unilaterally if licensing contracts as side-payment system is not perfect.

Even though Katz and Shapiro(1985, 1992) identify some of firms' incentives to seek compatibility or incompatibility, they don't capture firms' motives to seek incompatibility fearing simultaneous discovery since all the products in their models are already developed and no R&D issue arises. Also, in their model, firms have conflicting incentives for compatibility, which are determined by asymmetry in position in market structure. Firms with larger installed base favor incompatibility while firms with smaller installed base favor compatibility. In our model, symmetric firms have the same preference toward compatibility where the preference toward compatibility is determined by conflicting forces : compatibility externality and simultaneous discovery.

Among few attempts to thoroughly discuss the effect of compatibility externality or network benefits on the R&D competition, Kristiansen(1998) is noteworthy. Kristiansen(1998) analyzes the situation in which two firms engage in R&D race in a dynamic setting where introducing technology earlier incurs more costs. He finds that firms' incentive to win over installed base brings firms to play the game of prisoners' dilemma so that the firms may introduce new incompatible technologies in the equilibrium earlier than in the Pareto Optimum. His model differs from our model in many ways as follows. First, the concept of "R&D site" isn't explicitly considered in Kristiansen's model. So firms' competition in site choice can't be captured in his model, while it is one of the main issues in our model. Second, in his model the new technologies developed by each firm is assumed to be incompatible with each other in the basic model. Hence, compatibility isn't a choice in his model, while compatibility choice is one of firms' main strategies in our model. Third, he considers standard agreement and compulsory licensing to avoid excessive differentiation. This is essentially discussing the "social planner's optimum" in our model. In his model, the social optimum cannot arise from a non-cooperative game. In our model, it sometimes can. Fourth, in his model, the stand-alone value of the product developed from R&D is realized from an *ex ante* identical distribution function across firms with no mass in it. Since a firm with higher stand-alone value wins the R&D race, the situation close to simultaneous discovery in our model may occur only when the two firms' stand-alone value is identical, which occurs with zero probability in his model. Hence the problem of simultaneous discovery that is our main issue can't be captured in his model. Fifth, there is no R&D in his model in a strict sense since there is no probability of failure in R&D in Kristiansen's model.

Another paper which is close to our paper is Chatterjee and Evans (2003). They analyze firms' R&D avenue or site choice problem in a dynamic setting where there's only one right site with the prize buried in it. As in our model, they incorporate the case of simultaneous discovery into their discrete time model. Even though firms prefer to avoid simultaneous discovery, herding on the more promising project may occur in equilibria since there's only one right site. Also, they analyze firms' strategic incentives to induce the rival to choose the different site through influencing the rival's belief on the probabilities of each site's being the right one. The main difference between our model and their model is that, in their model, the projects are perfectly correlated. Since there is only one right project, if the belief on one site's being the right one, increases, then, the belief on the other site's being the right one, decreases. In our model, the treasures are buried with probability one in both sites. Another difference is that they don't model network or compatibility benefit which is the main source of incentive for firms to seek duplication in R&D avenue choice in our model. In their model, if firms duplicate on a particular site, then that's because the probability of the prize being buried in that project is high enough to offset more than the expected loss caused by possible simultaneous discovery. The last big difference is that they only consider the Bertrand R&D game, while we consider the equal sharing R&D game and the research alliance game as well so that we may derive a policy implication on standard setting.

I.2 Model

I.2.1 Description of model

There are two "sites" or research avenues on technologies, S_1 and S_2, available to the two symmetric firms, A and B. One may consider the sites as research paths in which firms engage in R&D for the new generation of technology.[14] Let S_A be the site chosen by the firm A and S_B by the firm B. For simplicity, assume that the reward from R&D success is not site-specific. Let $V(n)$ represent the reward from R&D success with n being the number of the firm(s) choosing the same site. Denote by (S_l, S_k) with $S_l, S_k \in \{S_1, S_2\}$ the profile of firms' site choice where the firm A and the firm B choose the site S_l and the site S_k respectively. Denote by $V_i(S_l, S_k)$ the firm i's expected revenue from R&D when the firms' site choice is (S_l, S_k). There occurs *compatibility externality* in firms' reward from R&D success when firms choose the same site, which implies $V(2) > V(1)$. Firms incur the R&D activity cost, c of which level is endogenously chosen by firms. In each site, a firm succeeds in R&D activity with π, the probability of success which depends on the level of c, the R&D activity cost. We call π, the probability of success as "effort" since π captures general characteristics of effort in the sense that raising π increases the expected value of R&D activity, but it costs to raise π. Then, specifically we assume that π has an one-to-one functional relation with c that the cost of obtaining π is $c(\pi)$ where $c(\pi)$ is assumed to be strictly convex and smooth.

Firms move in two stages : In the first stage, firms sequentially choose sites to investigate. In the second stage, after observing each other's site choice, firms simultaneously choose the level of R&D activity cost to determine the optimal effort level(hence the probability), after which they engage in R&D.

Note that firms' different site choices in the first stage are followed by the corresponding different subgames in the second stage where firms solve the following the optimal effort choice problem,

$$\max_{\pi_i}\{V_i(S_i, S_j) - c_i(\pi_i)\} \text{ for given } (S_i, S_j)$$

where $i, j \in \{A, B\}$ with $i \neq j$. Then, foreseeing optimal effort choices in each subgame, firms can figure out what its optimal site is by using typical backward induction in solving the following optimal site choice problem,

$$\max_{S_i \in \{S_1, S_2\}}\{V_i(S_i, S_j^*) - c_i\}$$

[14] We define a "site" in a broad sense that several slightly different research projects may be available in each site. With such interpretation, the model can capture the case that even when each project is well protected under a patent, the fundamental technologies, i.e., the "site" which the projects are based on, is not protected but available to all firms without any legal restriction. For another aspect in definition of the site, see 2.2.1.

where S_j^* is the site chosen by the firm j in the equilibrium. Then, the profile of each firm's choice of the optimal site and effort level, $((S_A^*, \pi_A^*), (S_B^*, \pi_B^*))$ constitutes the subgame perfect Nash equilibrium in the game.

We consider 2 different kinds of games in the main section : the Bertrand R&D game and the equal Sharing R&D game. The 2 games differ in the expected revenue from R&D success when duplication in site choice is followed by simultaneous discovery, resulting in different $V_i(S_i, S_j)$ for $i \in \{A, B\}$ with $S_i = S_j$. For example, suppose both firms choose the site S_1. Then, in the Bertrand R&D game, the firm i's expected revenue from R&D success conditional on both firms being on S_1, is

$$V_i(S_1, S_1) = \pi_i^S(1 - \pi_j^S)V(2),$$

where π_i^S is the firm i's effort level conditional on both firms being on the same site. In the equal sharing R&D game,

$$V_i(S_1, S_1) = [\frac{1}{2}\pi_i^S\pi_j^S + \pi_i^S(1 - \pi_j^S)]V(2).$$

I.2.2 Discussion of model

I.2.2.1 Independency between the different sites in R&D rewards

We assume that the rewards from R&D success in different sites are independent in the sense that simultaneous discovery in different sites doesn't affect the value of R&D success in each site.[15] The assumption relates to how we define the "site". We define the site such that the products developed from the different sites have their intrinsic values targeted for groups of consumers with differentiated preferences. Then, each discovery captures different segments of the market so that simultaneous discovery in different sites doesn't reduce the value of R&D success in either site. Even when consumers don't find much difference in products, technological distinction between the incompatible products developed from different sites, may be perceived by the producers of complementary goods which play another key role in forming incompatible systems. In that situation, if the two technologies are expected to be almost equally promising, then both technologies may capture more than the critical mass of producers of complementary goods at the same time. Then, the simultaneous discovery in different sites may lead to no "tipping" as in the case discussed by Quelin et al(2001). Recall the example in the second generation wireless telecommunication market in US where both GSM technology and CDMA technology were introduced around 1997. Even though

[15] With the assumption, we exclude the case that simultaneous discovery in different sites hurts R&D success as much as simultaneous discovery in the same site does, in which firms site choice problem becomes trivial since firms' dominant strategy is choosing the same site due to compatibility externality.

consumers don't have specific preference for one technology over the other, both standards seem to have won the critical mass of producers of complementary goods such as handset manufacturers, so tipping will be unlikely to occur.

On the contrary, we assume that simultaneous discovery in the same site reduces the value of R&D success, which is one of the key assumption in our model.[16] How simultaneous discovery in the same site hurts each firm depends on the situation of the relevant industries, some of which may be captured in our analysis of 3 different R&D games.

I.2.2.2 (Backward) compatibility externality

We assume that even when only one firm's R&D is successful and the other's not, still the value of R&D success is increased due to compatibility externality as long as the two firms chose the same site in the first stage.[17] Such assumption could well fit the industries where technology evolves in a way that the next generation technology is backward compatible with the current generation technology. In that case, when a firm makes an exclusive discovery of new technology, it may easily win over the rival firm's customers since the rival firm's customers can switch to the firm with the new technology without significant switching cost. Consider again the example of wireless telecommunication industry in which firms engage in R&D for next generation of technologies. If all the firms choose the same site, say GSM, followed by exclusive R&D success by one firm, then, new services and new products from R&D success may be backward compatible with the existing systems of the rival firms. Then rival firms' customers may want to switch to the firms with new technology because they can continue to use old handsets and accessories, not having to buy new ones. Moreover, the firm with new technology may not have to incur additional interconnection cost when its new technology is compatible with the rival's old technology, which is another source of compatibility externality.[18]

Besides the compatibility externality directly occurring in the production process, there may be another compatibility benefit which arises in technology adoption process, a part of which eventually is captured by the firms who invent the technology. Suppose that both incompatible technologies

[16] If simultaneous discovery in the same site results in no loss, firms' site choice problem becomes trivial in that firms' dominant strategy is choosing the same site because of compatibility externality.

[17] In our main model, with the definition of the "sites", the case that compatibility externality arises even when firms choose different sites is excluded. But, in some cases, different standards which were originally incompatible become compatible after installing "adapters" at some costs, of which case is discussed in the first part of the Discussion section.

[18] This production side compatibility externality was the major factor in many wireless communication service operator's choosing the same 2nd generation wireless communication technologies. For details, see Fernando Saurez, 3G : Technology To Competitive Advantage, London School of Business.

are invented simultaneously, then adoption of technologies may be delayed until the intrinsic values of the two technologies turn out to be substantial enough that the producers of complementary goods are sure that both will survive.[19] However, if both firms investigate the same site so that the technologies developed from the site are early known to be compatible, then the suppliers of complementary goods would have no fear of being stranded, so there will be no delay in adoption, which is another source of compatibility externality.[20]

I.3 The Bertrand R&D game

In this section, we consider the Bertrand R&D game where firms compete away the reward from R&D success in the case of simultaneous discovery following firms' choosing the same site.

I.3.1 Firms' optimal effort choice (2nd stage)

First we examine firms' equilibrium effort choice conditional on site choice determined in the first stage. Then, there are 4 different cases for site choices : $(S_1, S_1), (S_1, S_2), (S_2, S_1), (S_2, S_2)$. But, since sites are symmetric, firms' choice problem of the optimal effort level given the site choice (S_1, S_1) is identical to that given the site choice (S_2, S_2). By the same reason, the optimal effort choice problem given (S_1, S_2) is identical to that given (S_2, S_1) for both firms. Hence it suffices to analyze only the two cases, $(S_1, S_1), (S_1, S_2)$, each of which we call as duplication and as differentiation respectively in the rest of the paper.

I.3.1.1 Subgame following duplication

Now suppose both firms choose S_1. Then, the firm i' payoff maximization problem, conditional on both firms being at S_l is

$$Max_{\pi_i^S}\{\pi_i^S(1-\pi_j^{S*})V(2) - c(\pi_i^S)\}$$

where $i \in \{A, B\}$ with $i \neq j$ and π_j^{S*} solves the firm j's maximization problem for given $V(2)$, conditional on duplication.[21] Then, the first order condition for the firm i's maximization problem is solved by π_i^{S*} as

$$(1-\pi_j^{S*})V(2) = c'(\pi_i^{S*}).$$

[19] As mentioned earlier, the failure of the AM stereo standards provides one example that the adoption delay due to lack of compatibility may be huge, implying that no delay due to compatibility may be huge.

[20] For example, in Europe where GSM was determined by ETSI for a single wireless telecommunication standard, all the European operators have adopted GSM without significant delay. In contrast, in the US where multiple standards were allowed, the 2nd generation technologies were introduced far later than in Europe.

[21] Since when a firm chooses its optimal effort level, it considers its rival's effort level, $\pi_j^{S*}$is the best response to π_i^{S*}, the rival's equilibrium effort level for given $V(2)$.

The left-hand side of the first order condition represents the firm i's marginal revenue from increase in effort conditional on duplication, while the right-hand side of the condition represents the firm i's marginal cost of increase in effort. Note that the firm i's marginal revenue consists of the two parts, $(1-\pi_j^{S*})$ and $V(2)$, where $(1-\pi_j^{S*})$ is the probability of an exclusive discovery given the firm i's R&D success. It shows that in the Bertrand R&D game where simultaneous discovery yields no reward to any firm, a firm has less incentive to increase its effort as the rival firm's effort level is higher because the rival firm's higher effort level (hence probability of success) leads to simultaneous discovery with higher probability, which in turn results in less probability of an exclusive discovery, thereby yielding less marginal revenue from the same effort level.

But note that π_j^{S*} should be equal to π_i^{S*} in the equilibrium by symmetry between firms. Hence it follows that $(1-\pi_j^{S*})V(2) = (1-\pi_i^{S*})V(2)$, which is decreasing in π_i^{S*} in the equilibrium. Using this fact, we can analyze the firm i's equilibrium effort choice using Figure I.1.

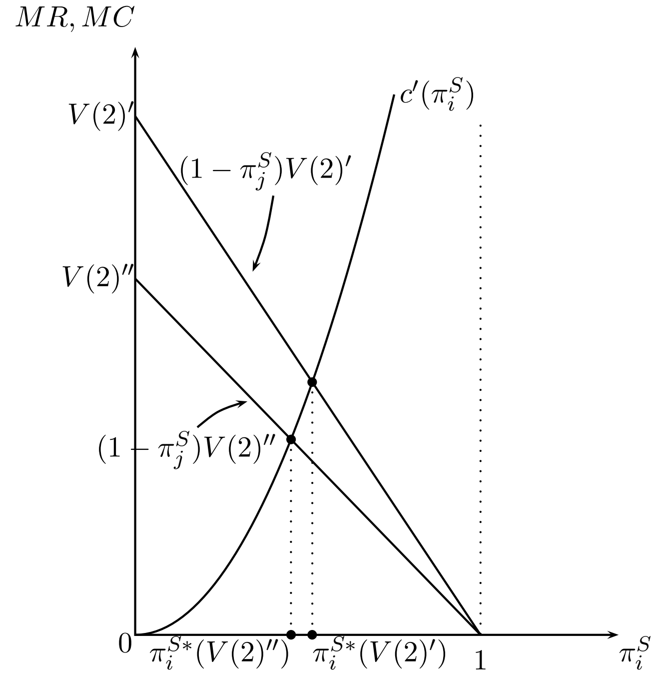

Figure I.1: π_i^{S*} increases in $V(2)$

In Figure I.1, the vertical axis intercept of the straight line representing $(1-\pi_j^S)V(2)$ is $V(2)$. The figure shows that the marginal revenue for given π_i is increasing in $V(2)$ so that π_i^{S*} also should be increasing in $V(2)$ with the increasing marginal cost function.

Now consider the social planner's choice problem on the efficient effort level, conditional on both being at S_1, which is

$$Max_{\pi_A^S,\pi_B^S}\{[1-(1-\pi_A^S)(1-\pi_B^S)]V(2)-c(\pi_A^S)-c(\pi_B^S)\}.$$

Then, the first order conditions for the social planner's problem are solved by π_i^{S**} as

$$(1-\pi_j^{S**})V(2)=c'(\pi_i^{S**}) \text{ for } i,j\in\{A,B\} \text{ with } i\neq j,$$

where $(\pi_A^{S**},\pi_B^{S**})$ solves the social planner's maximization problem for given $V(2)$, conditional on duplication. The left-hand side of the condition represents the social marginal revenue from increase in effort in the firm i's R&D activity conditional on duplication, while the right-hand side of the condition represents the social marginal cost of increase in effort in the firm i's R&D activity. Note that $(1-\pi_j^{S**})V(2)$, the social marginal revenue from increasing π_i^{S**} decreases in π_j^{S**} ; as the other firm j is more likely to succeed in R&D, the social value of the firm i's effort is less since the firm i's success in R&D yields no social value given the firm j's success in R&D.

Now compare the equilibrium effort level with the socially optimal effort level using the corresponding first order conditions. Note that the strict convexity of $c(\cdot)$ ensures the uniqueness of π_i^{S*} and π_i^{S**} for given $V(2)$ in each of the first order conditions. Then, it follows that $\pi_i^{S*}=\pi_i^{S**}$ for $i\in\{A,B\}$ since π_i^{S*} and π_i^{S**} are the unique solutions of the identical equations. Therefore, the firms' equilibrium effort levels are efficient when firms duplicate site choice.

I.3.1.2 Subgame following differentiation

Now denote by π_i^D the firm i's effort level (hence the probability) when firms choose different sites. Suppose that the firm A chooses S_1 and the firm B chooses S_2. Then, the firm A's payoff maximization problem conditional on the firm B being at S_2 is

$$Max_{\pi_A^D}\{\pi_A^D V(1)-c(\pi_A^D)\}.$$

Then, π_A^{D*}, the firm A's equilibrium effort level conditional on differentiation solves the first order condition of the firm A's problem as

$$V(1)=1=c'(\pi_A^{D*}).$$

The left-hand side of the condition represents the firm A's marginal revenue from increase in effort conditional on the firm B's being at the different site, while the right-hand side of the condition represents the firm A's marginal cost of increase in effort. Since firms are symmetric, π_B^{D*}, the firm

B's equilibrium effort level solves the first order condition for the firm B's payoff maximization problem as

$$V(1) = 1 = c'(\pi_B^{D*}).$$

Note that being different from the duplication case, the probability of an exclusive discovery is 1. Given assumption on $V(1)$, the marginal revenue from increase in effort is constant so that $V(1)$ and the marginal cost combine to determine π_i^{D*} as in Figure I.2.

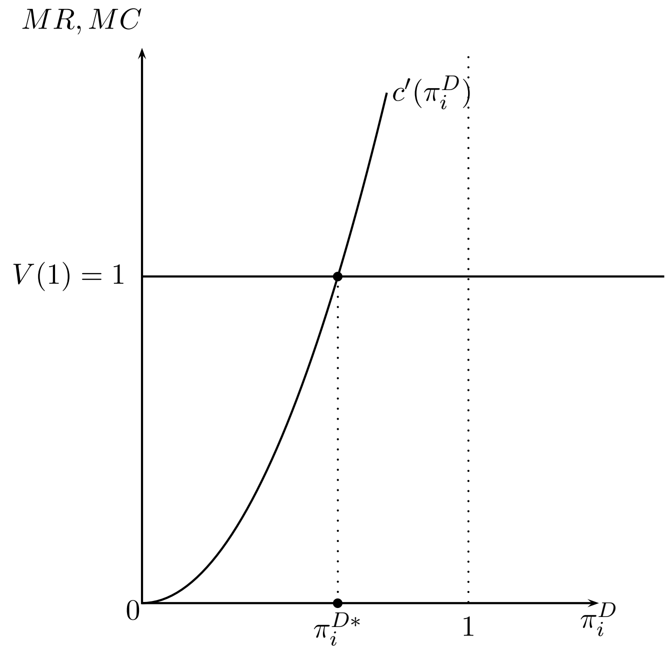

Figure I.2: π_i^{D*} is uniquely determined by $c(\cdot)$ and $V(1) = 1$.

Now consider the social planner's optimal effort choice problem conditional on the firms' being at different sites, which is

$$Max_{\pi_A^D, \pi_B^D}\{\pi_A^D V(1) + \pi_B^D V(1) - c(\pi_A^D) - c(\pi_B^D)\}.$$

Then, π_i^{D**} for $i \in \{A, B\}$ for given $V(1)$, solves the first order conditions for the social planner's problem as

$$V(1) = 1 = c'(\pi_i^{D**}) \text{ for } i, j \in \{A, B\} \text{ with } i \neq j.$$

Then, by the same argument used to demonstrate the efficiency of the equilibrium effort conditional on duplication, we have $\pi_i^{D*} = \pi_i^{D**}$ for $i \in \{A, B\}$, so the firms' equilibrium effort levels are efficient when firms differentiate site choice.

The efficiency result in the equilibrium effort in the subgames is summarized as in the following proposition.

Proposition 1 ***(Efficient effort)*** *In the subgame of the Bertrand R&D game, where firms choose the optimal effort level given site choice, the equilibrium effort levels are efficient conditional on the site choice both when firms duplicate site choice and when firms differentiate site choice.*

The efficiency result in the equilibrium effort choice in the duplication subgame is caused by the unique incentive structure inherent in the Bertrand R&D game and is in contrast to the typical result of over-investment in R&D which is found in Loury (1979), Reinganum (1979, 1982) and Dasgupta and Stiglitz (1980).

I.3.1.3 Comparison between the two subgames

Now compare the equilibrium effort level conditional on firms' being at different sites to that conditional on firm's being at the same site. Then, we need to compare the corresponding first order conditions,

$$(1-\pi_j^{S*})V(2) = c'(\pi_i^{S*}) \text{ and } V(1) = 1 = c'(\pi_i^{D*}).$$

Since $c'(\cdot)$ is strictly convex, it suffices to compare the left-hand side of each equation. Now, refer to $V(2)$ as $V(2)^*_{BR}$ if $V(2) = \frac{1}{(1-\pi_i^{D*})}$. Then, Figure I.3 shows that $V(2)^*_{BR}$ is unique with increasing $c'(\pi_i)$.

Note that π_i^{S*} depends on the magnitude of $V(2)$, while π_i^{D*} is fixed for given $c'(\cdot)$ and for given $V(1) = 1$. Then, the following claim provides the condition under which we can compare π_i^{S*} to π_i^{D*}.

Claim 1 *In the subgame of the Bertrand R&D game, where firms choose the optimal effort level given site choice, the equilibrium effort level conditional on duplication is greater than that conditional on differentiation if and only if* $V(2) > V(2)^*_{BR}$ *where* $V(2)^*_{BR} = \frac{1}{(1-\pi_i^{D*})}$.

Proof. See Appendix. ■

Given fixed π_i^{D*}, the result in Claim 1 implies that π_i^{S*} increases in $V(2)$. It is very intuitive in that with higher compatibility externality, the marginal effort revenue conditional on duplication rises accordingly so that it may more than offset the expected loss from the possibility of simultaneous discovery, yielding higher equilibrium effort level.

The result of Claim 1 differs from the result of Chatterjee and Evans (2003) and Loury (1979), in which research intensity falls as the number of rival firms increases. But, their results without

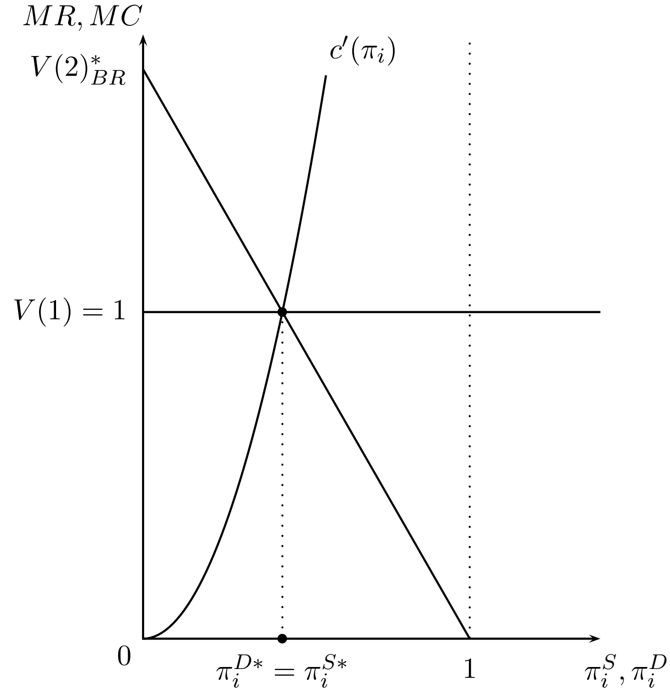

Figure I.3: $\pi_i^{D*} = \pi_i^{S*}$ as $V(2) = V(2)^*_B$

compatibility externality can be captured as a special case of our model by putting $V(2) = 1$. Since $V(2) = 1 < \frac{1}{(1-\pi_i^{D*})}$, it follows that $\pi_i^{S*} < \pi_i^{D*}$ according to Claim 1, as same as in Chatterjee and Evans(2003) and in Loury (1979). But our model shows that such results in Chatterjee and Evans(2003) and in Loury (1979) may not be true with big enough compatibility externality, in which R&D intensity may rise with the number of firms if compatibility externality increases in the number of firms.

I.3.2 Firms' optimal site choice (1st stage)

Denote by $W_i(S_k, S_l)$ the firm i's expected payoff from choosing the site S_k where all the firms choose the optimal effort level conditional on the site choice (S_k, S_l) where $i \in \{A, B\}$ and $S_k, S_l \in \{S_1, S_2\}$. Denote by $W(S_k, S_l)$ the social value of the site choice, (S_k, S_l) where the effort level in each site is efficient conditional on the site choice (S_k, S_l). Since $\pi_i^{S*} = \pi_j^{S*}$ in the equilibrium due to symmetry between firms, we let π_{BR}^{S*} the equilibrium effort level in the Bertrand R&D game when both firms choose the same site where $\pi_i^{S*} = \pi_j^{S*} = \pi_{BR}^{S*}$. Denote by π^{S**} the socially optimal effort level when firms choose the same site.[22] Similarly, denote by π^{D*} and π^{D**} the equilibrium effort level and the socially optimal effort level respectively when firms choose different sites.

Then, consider first $W(S_1, S_1)$ and $W(S_1, S_2)$ where

$$
\begin{aligned}
W(S_1, S_1) &= \pi_1^{S**}(2 - \pi_1^{S**})V(2) - 2c(\pi_1^{S**}) \text{ and} \\
W(S_1, S_2) &= \pi_1^{D**} + \pi_2^{D**} - c(\pi_1^{D**}) - c(\pi_2^{D**}).
\end{aligned}
$$

Also consider $W_B(S_1, S_1)$ and $W_B(S_1, S_2)$ where

$$
\begin{aligned}
W_B(S_1, S_1) &= \pi_1^{S*}(1 - \pi_1^{S*})V(2) - c(\pi_1^{S*}) \text{ and} \\
W_B(S_1, S_2) &= \pi_2^{D*} - c(\pi_2^{D*}).
\end{aligned}
$$

Note that $W(S_l, S_l)$ with $S_l \in \{S_1, S_2\}$ depends on the magnitude of $V(2)$, while $W(S_l, S_k)$ with $l \neq k$ is independent of $V(2)$. Especially, $W(S_l, S_l)$ is strictly increasing in $V(2)$. Similarly, $W_i(S_l, S_l)$ with $i \in \{A, B\}$ is strictly increasing in $V(2)$, while $W_i(S_l, S_k)$ with $i \in \{A, B\}$ is independent of $V(2)$. Then, the result on the equilibrium of the Bertrand R&D game is summarized in Proposition 2.

Proposition 2 *In the subgame perfect Nash equilibrium of the Bertrand R&D game, (i) if compatibility externality is small enough that $V(2) < V(2)^*_{BR}$, then firms choose different sites in the first stage and exert π^{D*} in the second stage, (ii) if compatibility externality is big enough that $V(2) > V(2)^*_{BR}$, then firms choose the same site in the first stage and exert π^{S*}_{BR} in the second stage.*

Proof. See Appendix. ■

Proposition 2 shows that if compatibility externality is big enough, then firms prefer duplication regardless of possibility of simultaneous discovery in the equilibrium.

Now denote by $V(2)^{**}$ the reward from R&D success conditional on both firms being on the same site for which $W(S_l, S_l) = W(S_l, S_k)$ for $S_l \in \{S_1, S_2\}$ with $l \neq k$. Then, the social optimum depends on $V(2)$ as summarized in the following proposition.

Proposition 3 *In the stoical optimum of the Bertrand R&D game, (i) if compatibility externality is small enough that $V(2) < V(2)^{**}$, then firms choose different sites in the first stage and exert*

[22] Since the social planner's problem is identical across different games, the socially optimal effort level conditional on site choice is identical across different games, too. So we have one notation for the socially optimal effort level. Similarly, the payoff conditional on differentiation is identical across different games, so we have one notation for the equilibrium effort level conditional on differentiation.

π^{D**} *in the second stage, (ii) if compatibility externality is big enough that* $V(2) > V(2)^{**}$*, then firms choose the same site in the first stage and exert* π^{S**} *in the second stage.*

Proof. See Appendix. ■

Proposition 2 and Proposition 3 shows that both in the equilibrium and in the social optimum, site choice is monotone in $V(2)$ in the sense that as compatibility externality becomes greater, duplication is not only more socially desirable but also more preferred by firms. Now, we have the following result on the relation between $V(2)^*_{BR}$ and $V(2)^{**}$.

Lemma 1 *For given* $c(\cdot)$, $V(2)^*_{BR}$ *is strictly greater than* $V(2)^{**}$.

Proof. See Appendix. ■

Due to such discrepancy between $V(2)^{**}$ and $V(2)^*_{BR}$ as in Lemma 1, the equilibrium site choice exhibits too much differentiation as summarized in Proposition 4.

Proposition 4 ***(Excess differentiation)*** *Suppose that compatibility externality is such that* $V(2)^{**} < V(2) < V(2)^*_{BR}$*. Then, in the Bertrand R&D game, the equilibrium is inefficient due to excess differentiation in site choice even though the equilibrium effort level given duplication is efficient.*

Proof. See the Appendix. ■

The excess differentiation is caused by the following discrepancy between the private incentive and the social incentive in site choice : When a firm decides to choose another site, it doesn't consider the other firm's loss in expected payoff from foregone compatibility externality. But if $V(2) > V(2)^*_{BR}$, then compatibility externality is big enough to more than offset the gap between the private incentive for duplication and that of the social planner, so firms choose the same site even from noncooperative motive.

I.4 The equal sharing R&D game

In this section, we consider the equal sharing R&D game where firms share a half of the reward from R&D success in the case of simultaneous discovery. The equal sharing R&D game may capture the industries in which instant imitations follows initial innovations. For example, consider the industries where the relevant intellectual property right(IPR hereafter)s are not well defined and competing firms have enough ability for instant R&D. In such industries, one firm's success in

R&D may induce competing firms to instantly engage in R&D whenever firms know that instant imitations will not lead to dissipation of all the firms' profits.[23]

I.4.1 Firms' optimal effort choice (2nd stage)

I.4.1.1 Subgame following duplication

Suppose both firms choose S_1. Then, the firm i's maximization problem, conditional on both firms being at S_1 is

$$Max_{\pi_i^S}\{[\frac{1}{2}(\pi_i^S)(\pi_j^{S*}) + \pi_i^S(1-\pi_j^{S*})]V(2) - c(\pi_i^S)\} \text{ for } i,j \in \{A,B\} \text{ with } i \neq j$$

where π_j^{S*} solves the firm j's maximization problem for given $V(2)$. Then, the first order condition for the firm i's problem conditional on both being at S_1 is

$$[\frac{1}{2}(\pi_j^{S*}) + (1-\pi_j^{S*})]V(2) = [1 - \frac{1}{2}\pi_j^{S*}]V(2) = c'(\pi_i^{S*}) \text{ for } i,j \in \{A,B\} \text{ with } i \neq j.$$

Now, recall that the difference in the payoff structure between the Bertrand R&D game and the equal sharing R&D game lies only in the difference in the firms' payoffs in the occasion of simultaneous discovery. Hence, the social planner's effort choice problem conditional on both being at S_1 is same as in the Bertrand R&D game, which is

$$Max_{\pi_A^S,\pi_B^S}\{[1-(1-\pi_A^S)(1-\pi_B^S)]V(2) - c(\pi_A^S) - c(\pi_B^S)\},$$

as in the Bertrand R&D game. Accordingly the first order conditions with respect to π_i^S, are also same as in the Bertrand R&D game and

$$(1-\pi_j^{S**})V(2) = c'(\pi_i^S) \text{ for } i,j \in \{A,B\} \text{ with } i \neq j.$$

Note that $[1 - \frac{1}{2}\pi_j^{S*}]V(2)$, the firm i's the marginal effort revenue is always greater than $(1 - \pi_j^{S**})V(2)$ for each π_i and given $V(2)$ in the equilibrium. Hence, it follows that $\pi_i^{S**} < \pi_i^{S*}$ for given $V(2)$ as shown in Figure I.4.

I.4.1.2 Effort choice following differentiation

The equilibrium effort level conditional on firms' choosing different sites is same as in the Bertrand R&D game. So the relevant first order condition is

$$V(1) = 1 = c'(\pi_i^{D*}) \text{ for } i,j \in \{A,B\} \text{ with } i \neq j.$$

[23] For the R&D race in which one firm's innovation induces another firms' participation in R&D race in a different setting, see Choi(1991).

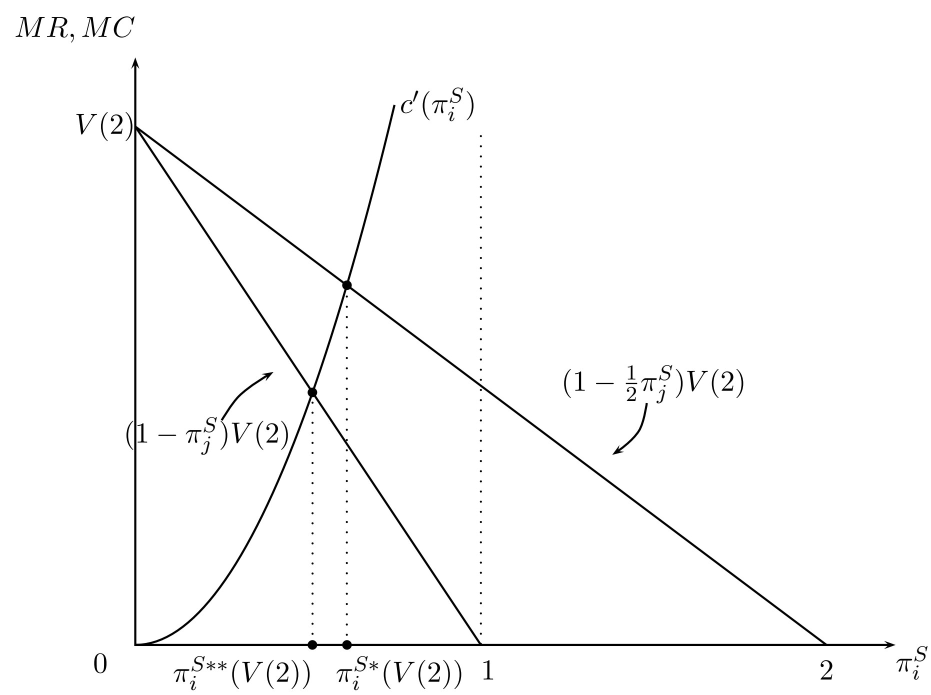

Figure I.4: $\pi_i^{S**} < \pi_i^{S*}$ for given $V(2)$

Hence as in the Bertrand R&D game, it follows that $\pi_i^{D*} = \pi_i^{D**}$ for $i \in \{A, B\}$.

The results on the equilibrium effort level in the subgames of the equal sharing R&D game is summarized in the following proposition.

Proposition 5 *(**Excessive effort**) In the equal sharing R&D game, the equilibrium effort level is inefficiently high in the subgame where firms choose the same site, while the equilibrium effort level is efficient in the subgame where firms choose different sites.*

The inefficiency in the equilibrium effort level conditional on duplication is in contrast to the efficiency result in the Bertrand R&D game. Such inefficiency result is caused by the over-rewarding structure in the equal sharing R&D game as follows. Note that the social marginal revenue from increase in the firm i's effort is $(1 - \pi_j)V(2)$, implying the firm i's marginal contribution to R&D success is worth only to the extent that it backs up the other firm's investigation. But, in the equal sharing R&D game, each firm gets $(1 - \frac{1}{2}\pi_j)V(2) = \frac{1}{2}V(2) + (1 - \pi_j)V(2)$ for its marginal effort revenue, which implies that each firm is over-rewarded by $\frac{1}{2}V(2)$, creating excessive incentive for duplication.

I.4.1.3 Comparison between the two subgames

Now we examine the difference between the equilibrium effort level conditional on firms' choosing the same site and that conditional on firms' choosing different sites. As in the previous section on the Bertrand R&D game, we need to compare the left-hand sides of the first order conditions : $[1-\frac{1}{2}\pi_j^{S*}]V(2)$ and $V(1)=1$. Now refer to $V(2)$ as $V(2)^*_{ES}$ such that $V(2)=\frac{1}{1-\frac{1}{2}\pi^{D*}}$. Also denote by π^{S*}_{ES} the equilibrium effort level in the equal sharing R&D game. Then, the following claim provides the condition under which we can compare π^{D*} to π^{S*}_{ES}.

Claim 2 *In the subgame of the equal sharing R&D game, π^{D*}, the equilibrium effort level conditional on differentiation is greater than π^{S*}_{ES}, the equilibrium effort level conditional on duplication if and only if $V(2)<V(2)^*_{ES}$ where $V(2)^*_{ES}=\frac{1}{1-\frac{1}{2}\pi^{D*}}$.*

Proof. See Appendix. ■

I.4.1.4 Firms' optimal site choice (1st stage)

As in the Bertrand R&D game, the social planner's expected payoffs from duplication and from differentiation are respectively

$$\begin{aligned} W(S_l,S_l) &= \pi_l^{S**}(2-\pi_l^{S**})V(2)-2c(\pi_l^{S**}) \text{ and} \\ W(S_l,S_k) &= \pi_l^{D**}+\pi_k^{D**}-c(\pi_l^{D**})-c(\pi_k^{D**}). \end{aligned}$$

The firm i's expected payoff from differentiation and duplication are respectively

$$\begin{aligned} W_i(S_l,S_l) &= \frac{1}{2}\pi_l^{S*}(2-\pi_l^{S*})V(2)-c(\pi_l^{S*}) \text{ and} \\ W_i(S_l,S_k) &= \pi_l^{D*}-c(\pi_l^{D*}). \end{aligned}$$

when the firm i chooses the site S_l. The results on the equilibrium in the equal sharing R&D game is summarized in Proposition 6.

Proposition 6 *In the subgame perfect Nash equilibrium of the equal sharing R&D game, (i) if compatibility externality is small enough that $V(2)<V(2)^*_{ES}$, then firms choose different sites in*

the first stage and exert π^{D*} in the second stage, (ii) if compatibility externality is big enough that $V(2) > V(2)^*_{ES}$, then firms choose the same site in the first stage and exert π^{S*}_{ES} in the second stage.

Proof. See Appendix. ■

Proposition 6 shows that in the equal sharing R&D game, site choice is monotone in $V(2)$ in the sense that duplication is more preferred and more desirable as compatibility externality becomes greater as in the Bertrand R&D game.

Now, we have the following result on the relation between $V(2)^{**}$ and $V(2)^*_{ES}$.

Lemma 2 *For given $c(\cdot)$, $V(2)^*_{ES}$ is strictly smaller than $V(2)^{**}$.*

Proof. See Appendix. ■

Then, with Lemma 2, we have the following excess duplication result on the equilibrium of the equal sharing R&D game.

Proposition 7 ***(Double inefficiency)*** *Suppose that compatibility externality is such that $V(2) > V(2)^*_{ES}$. In the equal sharing R&D game, the equilibrium is inefficient as follows. (1) For $V(2)$ with $V(2)^{**} < V(2)$, the equilibrium site choice is efficient but the equilibrium effort level given duplication is higher than in the social optimum. (2) For $V(2)$ with $V(2)^*_{ES} < V(2) < V(2)^{**}$, the equilibrium exhibits both excess duplication in site choice and excess effort level given duplication.*

Proof. See Appendix. ■

From Proposition 7, one can see that even when compatibility externality is big enough that firms' site choice of duplication is efficient, the inefficiency involved in excessive effort still remains in the equilibrium. This comes from the over-rewarding payoff structure for simultaneous discovery in the equal sharing R&D game as shown in Proposition 5. However, if compatibility externality has a intermediate value such that firms find it optimal to duplicate, but it is still not big enough for duplication for the social planner, then excess duplication in site choice worsens the inefficiency problem.

I.5 Policy implications on standardization

Since compatibility externality isn't often internalized in firms' private incentive, thereby resulting in inefficient allocations, most of research on compatibility externality has suggested a certain type of intervention of government agency to reduce such inefficiency. Few literature, however, has dealt with the effect of public policy on firms' R&D project choice with compatibility externality. In this section, the effects on equilibria in each noncooperative game of the various public policy devices are reviewed and the efficacy of each policy is discussed with a regard to a standard-setting issue.

First consider Corollary 1 in which the thresholds of compatibility externality in each game and that of the social planner are compared and put in order.

Corollary 1 *The threshold of compatibility externality in each game is ordered as follows.*

$$V(2)^*_{ES} < V(2)^{**} < V(2)^*_{BR}.$$

Proof. Recall from Lemma 1 that $V(2)^{**} < V(2)^*_{BR}$. But from Lemma 2 we have $V(2)^*_{ES} < V(2)^{**}$. Hence we have $V(2)^*_{ES} < V(2)^{**} < V(2)^*_{BR}$ from the two results. ■

In the following, we consider the various cases each of which corresponds to different sets of compatibility externality. In this section, the effects on equilibria in each noncooperative game of the various public policy devices are reviewed and the efficacy of each policy is discussed with a regard to a standard-setting issue.[24]

The case that $V(2) < V(2)^*_{ES}$

In this case, firms choose different standards in both games, which is efficient. Moreover, since the equilibrium investment level conditional on differentiation is also efficient, no efficiency problem arises when compatibility externality is small enough that $V(2) < V(2)^*_{ES}$. Hence, there's no need for intervention of government agency for standardization, and the multiple standard regime in which firms are free to develop products based on different incompatible standards is desirable. On the contrary, a mandatory single standard regime which might be implemented with over estimation of compatibility externality lowers the social welfare by making foregone the chance of additional innovation.

The case that $V(2)^*_{ES} < V(2) < V(2)^{**}$

In this case, if the relevant industry situation is close to the one characterized by the Bertrand R&D game, then firms will choose different standards, which is efficient. But, if the relevant industry

[24] In the following analysis of each case corresponding to the different set of compatibility externality, we omit the case that compatibility externality equals to threshold values since such case occurs with the probability of measure zero.

situation is close to the one characterized by the equal sharing R&D game, firms will choose the same standard, which is inefficient.

Since the equilibrium investment level conditional on duplication is inefficiently high in the equal sharing R&D game as proven in Double Inefficiency Proposition (Proposition 7), the policy intervention promoting differentiation could substantially increase the social welfare when the payoff structure of the relevant industry is closed to that of the equal sharing R&D game. Consider the case in which instant mimicking is easily attained and it's profitable to entrants, which implies that the simultaneous discovery doesn't dissipate all the reward from R&D success. In such case, if the second mover's choosing the same standard occurs due to weak protection of fundamental technologies, more strict implementation of intellectual property right(hereafter IPR) protection policy on fundamental technologies would induce the second mover to choose another fundamental technology or standard, which relieves the problem of excess duplication problem and thereby excess investment problem as well. Alternatively, per-unit investment tax which is imposed on marginal revenue from increase in investment conditional on duplication may also reduce the incentive to duplicate standard choice.[25]

The case that $V(2)^{**} < V(2) < V(2)^{*}_{BR}$

In this case, if the payoff structure of the relevant industry is closer to that of the Bertrand R&D game, there may arise excess differentiation in firms' standard choice. Then, the inefficiency involved in standard choice in the Bertrand R&D game can be easily reduced by establishing the mandatory single standard regime. Moreover, especially in the industries characterized by the Bertrand payoff structure, the equilibrium investment level given duplication is also efficient. So, all the inefficiency problem is completely resolved with the mandatory single standard regime. Alternatively, the lump-sum subsidy for firms choosing a particular standard may be implemented to increase the firms' incentive for duplication, thereby decrease excess duplication problem.[26] The subsidy should be of a lump-sum form so that it won't distort efficient investment incentive structure given duplication in the Bertrand R&D game.

In the industries which can be captured by the equal sharing R&D game, even though firms'

[25] For example, τ of per-unit investment tax reduces the firms' marginal revenue from increase in investment from $(1-\frac{1}{2}\pi)V(2)$ to $(1-\frac{1}{2}\pi-\tau)V(2)$ in the equal sharing R&D game. Since the excess duplication result occurs due to the over-rewarded marginal revenue conditional on duplication, such per-unit investment would cause firms to have less incentive to duplicate standard choice in the first stage.

[26] In the current model, both sites are ex ante complectly identical. But, if sites are asymmetric and one site is better than the other in terms of the stochastic dominance, then the lump-sum subsidy should be given to the firms choosing the better site.

standard choice is efficient, the equilibrium investment level given duplication is too high. The excess equilibrium investment problem may be relieved by introduction of per-unit investment tax as discussed in the previous cases. However, the strict implementation of IPR protection policy should not be used since it may induce the second firm to choose different standard, which might result in excess differentiation.

The case that $V(2) > V(2)^*_{BR}$

In this case, firms choose the same standard in both games, which is efficient. In the Bertrand R&D game, the equilibrium investment level is efficient, so there's no need for any intervention of government agency.

But, in the equal sharing R&D game, excess investment problem remains, so the per-unit investment tax needs to be imposed to reduce firms private incentive for investment down to the level of the social planner's incentive for investment.

I.6 Discussions

I.6.1 Single standard regime vs. Multiple standard regime

In previous section, we have reviewed how the inefficiency involved in standard choice and investment choice in each game can be relieved by several public polices. But, if the information on the magnitude of compatibility externality and the payoff structure of the relevant industry is not available, then what the optimal policy mix is would not be clear.

Especially, establishing the mandatory single standard regime could be risky in that it might preclude the chance of another innovation, which could decrease social welfare in the case that $V(2) < V(2)^{**}$. Recall that the mandated single standard regime may increase social welfare only when the relevant market is very competitive that it is close to the Bertrand R&D game and compatibility externality has intermediate value that $V(2)^{**} < V(2) < V(2)^*_{BR}$. In that case, the mandated single standard regime can reduce inefficiency from excess differentiation and no other policy device is needed. However, if the relevant market is close to the case of the equal sharing R&D game, over investment arises due to the discrepancy between firms' incentive for investment and that of the social planner. Since such inefficiencies still remain in the mandated single standard regime, other policy devices should be implemented to reduce inefficiencies involved in investment choice.[27]

[27] If the government is interested in the amount of output rather than social welfare, for example, in the arms-race, then the over-investment in the equal sharing R&D game may not be a critical issue so that no other policy tool is

Now consider the market based multiple standard regime. With the market based multiple standard regime, there's no loss involved in preclusion of another innovation. But, if the relevant market is close to that of the Bertrand R&D game and the size of compatibility externality is such that $V(2)^{**} < V(2) < V(2)^{*}_{BR}$, then there may arise excess differentiation. No inefficiency problem involved in investment choice arises in the market which is close to the Bertrand R&D game. But, if the relevant market is close to the case of the equal sharing R&D game, then inefficiencies involved in investment choice arise, which can be reduced only by implementation of other policy tools.

Now consider the example of the second generation wireless telecommunication market in the US and the European countries where the European countries have adopted the mandated single standard regime and the US has adopted the market based multiple standard regime. Given that it is probable that the second generation wireless telecommunication market could be very competitive, if compatibility externality is expected to be big enough, then it would be socially desirable to choose the mandated single standard regime, which seems to be the reason for the European countries's choice of the mandated single standard regime. On the contrary, if compatibility externality is not substantial or the cost of constructing an adaptor is not so big, then the socially desirable standard regime would be the market based multiple standard regime as in the case of the US.[28] But if the cost of constructing an adaptor is not so big as in Gandal & Salant(2003), then the market-based multiple standard regime has more benefits, which supports the US choice of the market based multiple standard regime. Moreover, even when the cost of constructing an adaptor is big enough, the inefficiencies from excess differentiation can be reduced with the market based multiple standard regime by implementing a lump-sum investment subsidy, while any other policy instrument can't make up for the loss of foregone innovation with the mandated single standard regime.

I.6.2 Ex post standardization with costly adapter

One of the main assumptions in the model is that compatibility can be attained only through choosing the same standard, so prospective products from different standards are incompatible. It means that compatibility decision can be made only ex ante and making compatible ex post products from different standard is too costly, so virtually impossible. But, in some cases, installing adapters incurs only some reasonable cost, so originally incompatible products may become ex post compatible with adapters. Then, compatibility can be obtained both through duplication

needed.

[28] The issue related to constructing an adaptor is discussed in the next subsection.

and through differentiation. However there are two main differences between the two ways. The first difference lies in what risk or cost firms should take besides R&D activity cost when firms want their products compatible. When firms choose to make their products compatible through duplication in site choice, then the firms bear the risk of possible loss from simultaneous discovery. If firms choose to make their products compatible through differentiation in site choice followed by construction of an adapter, then firms don't have to bear the risk of simultaneous discovery but they have to incur the cost of installing adapter after the development of products.[29] The second difference lies in the timing of standardization. Ex ante standardization is achieved when firms choose the same site, while ex post standardization is achieved firms construct an adapter after the development of products. Now consider firms' expected payoff following differentiation which is

$$W_i((S_l, S_k); V(2), A) = \pi_i[V(2) - A] - c(\pi_i)$$

where A is the cost of installing adaptor. Note that $W_i((S_l, S_k); V(2), A)$ increases by π_i for the marginal increase in $V(2)$, while $W_i((S_l, S_l); V(2))$ increases by $\pi_i(1-\pi_i)$ for the marginal increase in $V(2)$ in the Bertrand R&D game. Hence, it follows that ex post standardization is more attractive compared to ex ante standardization as compatibility externality is bigger because the cost of constructing a adapter is independent of compatibility externality, while the value of expected loss from simultaneous discovery is increasing in compatibility externality. Then, the equilibrium site choice is monotone as Proposition 2 in the main model. But the direction is opposite.

Since in the equal sharing R&D game there remains the discrepancy between firms incentive for investments and that of the social planner, inefficiency in effort choice still remains accordingly. So it does with the firms' standard choice, too.

I.7 Concluding remarks

We build a simple R&D choice model in which two firms compete in R&D race in two stages for new generation technologies where two different R&D avenues are available, each being for different technologies incompatible with each other. Existence of compatibility externality gives firms an incentive to choose a single standard. But the possibility of simultaneous discovery gives firms an incentive to choose different standards. The interplay of the two conflicting incentives result in discrepancy between firms' private incentive and the social planner's incentive in both site choice problem and effort choice problem, the detail of which depends on how R&D reward is dissipated

[29] Recall that products from different sites serve different segments of the market so that the simultaneous discovery in the different site doesn't dissipate the value of R&D success in each site.

in the case of simultaneous discovery. In the Bertrand R&D game, firms' equilibrium site choice may exhibit excess differentiation, but the equilibrium effort choice is optimal. In the equal sharing R&D game, for some set of compatibility externality, there occurs double inefficiency problem with which firms choose the same site too much and make too much investments in the equilibrium.

The interesting extensions of our model are as follows. First, a multi-period model which may capture firms' dynamic behavior, can be considered where there exists positive possibility that the treasure may not be buried in the site. With the probability that there exists no treasure, firms R&D may end up with failure even when they make maximum investments. In that case, firms should form a belief on each site's having a treasure, which should be updated every period based on observation of the result of all firms' R&D experiment on each site.

Second, in our model, the probability of success is assumed to be determined by the R&D activity cost without uncertainty. But one can consider the model with uncertainty in the way that the R&D activity cost determines not the probability of success itself, but its distribution as in Bhattacharya & Mookherjee (1986).

Chapter II

R&D choice through a research alliance in the presence of compatibility externality

II.1 Introduction

In this paper we consider firms' R&D choice for the development of applied technologies with compatibility externality where a fundamental technology associated with each applied technology is proprietary. Consider the following situation. There are two firms, the firm A and the firm B which sequentially choose a research approach or a fundamental technology which the relevant applied technologies should be based on where the firm A chooses first by which it obtains exclusive legal rights on the relevant fundamental technologies.[1] In the situations like this, the firm B can choose the same fundamental technology chosen by the firm A only when the firm A allows the firm B to do so. However, if there exists compatibility externality big enough, the firm A may find it better to exploit compatibility externality by allowing the firm B to choose the same fundamental technology when its advantage as a first mover is properly rewarded.[2] Then, one of the possible ways of both firms' agreeing on choosing the same fundamental technology would be forming a research alliance under a contract by which the firm B is allowed to choose the same fundamental technology already chosen by the firm A and the firm A is compensated some payoffs for giving up its exclusive legal rights on the fundamental technology. We examine such problem with the research alliance formation game in which firms cooperate in the choice of fundamental technology by forming a

[1] For example, in the pharmaceutical industries many laboratories have patents on some "compounds" where compounds(fundamental technologies) are the substances which could be potentially used for the development of new drugs(final products or applied technologies).

[2] For example, in their choosing 2nd generation wireless telecommunication standard, the leading firms among the European operators in the cellular phone industry could boost consumers' demand by their agreeing on the same standard, GSM where they had to share their proprietary technologies with small compensation.

research alliance and then compete in R&D by investigating the fundamental technology or site independently.[3]

In the existing literature on coalition formation with externality such as Bloch (1995), Yi (1998), and Yi & Shin (2000), they focus on the case that the incentive for forming a coalition arises from the reduction of R&D cost within a coalition. Our model differs from theirs in the following points. First, we examine the coalition formation problem of the firms in the R&D stage where the possibility of simultaneous discovery may induce firms to choose the different fundamental technologies, while most cost-reducing coalition formation literature deal with already developed products that the issue of simultaneous discovery is irrelevant. Second, in our model we capture the first mover's advantage more explicitly so that how the interplay of compatibility externality and first mover's advantage determine firms' standard choice can be examined in a more stylized way.

Using the research alliance model in our paper, we found that firms don't consider its own investment's beneficial effect on the rival firm, which creates the discrepancy between the private incentive for investment and that of social planner where firms have less incentive for investment than the social planner. But, due to the payoff structure in which firms receive rewards for its second discovery, firms also have excessive incentive for investment. The interplay of such conflicting incentives result in non-monotonic inefficiency in equilibrium investment choice. Especially it turns out that the excessive incentive for investment outweighs the insufficient incentive for investment when compatibility externality is low enough, which results in excess duplication in site choice.

II.2 Model

There are two "sites" or fundamental technologies, S_1 and S_2, available to the two symmetric firms, A and B where the firms wish to develop applied technologies based on either fundamental technology. Let S_A be the site chosen by the firm A and S_B by the firm B. Denote by (S_l, S_k) with $S_l, S_k \in \{S_1, S_2\}$ the profile of firms' site choice where the firm A and the firm B choose the site S_l and the site S_k respectively.

Let $V(n)$ represent the value of R&D success with n being the number of the firm(s) choosing the same site. For simplicity, assume that the value of R&D success is not site-specific. Denote by $V_i(S_l, S_k)$ the firm i's expected revenue from R&D activity when the firms' site choice is (S_l, S_k). There occurs *compatibility externality* in the value of R&D success when firms choose the same site,

[3] Hereafter we refer to the research approach or the fundamental technology for each applied technologies as a site by analogy with a well-known "the buried treasures problem". See, for example, Ross(1983).

which implies $V(2) > V(1)$ where $V(1)$ is normalized to be 1. Firms incur the R&D activity cost, c of which level is endogenously chosen by firms. In each site, a firm succeeds in R&D activity with π, the probability of success which depends on the level of c, the R&D activity cost. We call π, the probability of success as "effort" since π captures general characteristics of effort in the sense that raising π increases the expected value of R&D activity, but it costs to raise π. Then, specifically we assume that π has an one-to-one functional relation with c that the cost of obtaining π is $c(\pi)$ where $c(\pi)$ is assumed to be strictly convex and smooth.

The game proceeds as follows. In the first stage, firms sequentially choose sites to investigate. Without a loss of generality, the firm A is assumed to choose a site to investigate first. If the firm B finds it optimal to choose the same site chosen by the firm A, then the two firms make a contract by which they form a research alliance. In the second stage, given the site choice determined in the first stage, firms simultaneously choose the level of R&D activity cost to determine the optimal effort level(hence the probability of R&D success), after which they engage in R&D.

Each firm's payoff within a research alliance is as follows. Suppose that after both firms choose the same site within a research alliance, the firm i with $i \in \{A, B\}$ makes an exclusive discovery that $V(2)$ is realized from its R&D success. Then, the reward to the firm i given its exclusive discovery consists of the following two parts. The first part of the reward is $V(1)$, referred to as the **stand-alone value of R&D success**, which is given to whoever firm makes an exclusive discovery. The second part is the firm i's share of $V(2) - V(1)$, the increase in the value of R&D success created by firms choosing the same site, referred to as the **network value of R&D success**. As the compensation for giving up its property rights on the site, the firm A receives $\frac{1+\lambda}{2}[V(2) - V(1)]$ for its share of network value of R&D success, while the firm B receives $\frac{1-\lambda}{2}[V(2) - V(1)]$ for its share of network value of R&D success where λ is the sharing parameter in $[0, 1]$.[4] More specifically, if firms agree on $\lambda > 0$, then it implies that the firms agree on the firm A being compensated for giving up its property rights on the site. If firms agree on $\lambda < 1$, then it implies that the firms agree on the firm B being compensated for its contribution to creation of compatibility externality by its choosing the same site. Suppose that the firm A is the sole discoverer, then it receives $V(1)$, the stand-alone value of R&D success for the reward for its exclusive discovery and $\frac{1+\lambda}{2}[V(2)-V(1)]$ for the compensation for its share of network value of R&D success, while the firm B receives only its share of network value of R&D success, $\frac{1-\lambda}{2}[V(2) - V(1)]$. If the sole discoverer is the firm B, then it receives $V(1)$, the stand-alone value of R&D success for the reward for its exclusive discovery

[4] For given $V(2)$, the upper bounds and lower bounds of $\lambda^* \in [0, 1]$, the equilibrium sharing proportion are analyzed in this paper. But the firms' detailed bargaining process determining λ^* is not analyzed in this paper.

and $\frac{1-\lambda}{2}[V(2)-V(1)]$ for its share of network value of R&D success, while the firm A receives only $\frac{1+\lambda}{2}[V(2)-V(1)]$, its share of the network value of R&D success. If both firms succeed in R&D, then the firms split the stand-alone value of R&D success so that each firm receives $\frac{1}{2}V(1)$ for its reward for simultaneous discovery besides its share of the network value of R&D success. If both firms fail, then both firms get no reward. So, one can see that in the research alliance game, the firms play an equal sharing R&D game in the competition for the stand-alone value of R&D success, while they share the network value of R&D success according to the sharing parameter λ which is predetermined when firms agree on forming the research alliance.[5] Then, for example, each firm's expected revenue from R&D on S_1 within a research alliance which captures all the possible results of R&D activity is as follows .

$$
\begin{aligned}
V_A(S_1,S_1) &= [\pi_A(1-\pi_B)+\frac{1}{2}\pi_A\pi_B]V(1)+ \\
&\quad \frac{1+\lambda}{2}[\pi_A(1-\pi_B)+\pi_B(1-\pi_A)+\pi_A\pi_B][V(2)-V(1)] \\
&= \frac{1}{2}\pi_A(2-\pi_B)+\frac{1+\lambda}{2}(\pi_A+\pi_B-\pi_A\pi_B)[V(2)-1], \text{ and} \\
V_B(S_1,S_1) &= [\pi_B(1-\pi_A)+\frac{1}{2}\pi_B\pi_A]V(1)+ \\
&\quad \frac{1-\lambda}{2}[\pi_A(1-\pi_B)+\pi_B(1-\pi_A)+\pi_A\pi_B][V(2)-V(1)] \\
&= \frac{1}{2}\pi_B(2-\pi_A)+\frac{1-\lambda}{2}(\pi_A+\pi_B-\pi_A\pi_B)[V(2)-1],
\end{aligned}
$$

where $\lambda \in [0,1]$. The first term in each firm's expected revenue represents the expected reward of a stand-alone value of R&D success. The second term in each firms's expected revenue represents the expected reward of its share in a network value of R&D success, reflecting the first mover's advantage. For example, with $\lambda = 1$, the firm A enjoys the first mover's advantage in full and gets all the network value of R&D success, while with $\lambda = 0$ there's no first mover's advantage and each firm shares the network value equally.

Using the research alliance model with such two-part reward structure, we can also analyze the case where firms are allowed to choose the same site non-cooperatively without any explicit contract but compatibility externality is captured by all the firms choosing the same site no matter which firm discovers, given R&D success in the site. Consider the case that there exists indirect(or virtual) network effects such that firms' choosing a same standard result in a larger set of complementary goods, which in turn cause a positive feedback on the firms' own goods. Then, such benefits from a larger set of complementary goods will occur to all the firms whose products are compatible.

[5] For the details of the equal sharing R&D game, see Lee(2003).

For example, suppose one firm succeeds in the development of a hardware of the next generation based on a specific standard, which induces more developments of softwares compatible with the standard. Then, assuming that there doesn't occur much cost for the software companies to make their products to be backward compatible, the firms other than the discoverer also would receive the benefit of more variety of softwares compatible with their current generation of hardware.[6] In this case, $\lambda \neq 0$ implies that firms' benefit from compatibility externality is not same even when firms don't make the binding contract that specifies payoffs asymmetric to firms. One of the examples of such case is that the firms choosing the same site differ from each other in market share to which the benefit of compatibility externality is beneficial to each firm in proportion. Then $\lambda > 0$ represents the firm A's being in the market leader in the industry.

The payoff structure in our research alliance model captures the following features which are found in many industries. First, even when firms form a research alliance, they still compete against each other. In our research alliance model, firms cooperate by forming a research alliance in creating compatibility externality to increase the value of R&D success, but they still compete for the stand-alone value of R&D success by investigating the site independently. Second, compatibility externality can be captured by every firm choosing the same standard even when the success in R&D is made by another firm.[7] This case can be captured by allowing λ to be strictly smaller than 1 in our model. Third, the first mover's advantage is acknowledged in sharing the value of R&D success. This case can be captured by allowing λ to be strictly greater than 0 in our model.

Notice that firms' site choices in the first stage are followed by the corresponding subgames in the second stage where firms solve the following the optimal effort choice problem,

$$\max_{\pi_i}\{V_i(S_i, S_j) - c_i(\pi_i)\} \text{ for given } (S_i, S_j)$$

where $i, j \in \{A, B\}$ with $i \neq j$. Then, foreseeing optimal effort choices in each subgame, firms can figure out what its optimal site is by using typical backward induction in solving the following optimal site choice problem,

$$\max_{S_i \in \{S_1, S_2\}}\{V_i(S_i, S_j^*) - c_i\}$$

where S_j^* is the site chosen by the firm j in the equilibrium. Then, the profile of each firm's choice of the optimal site and effort level, $((S_A^*, \pi_A^*), (S_B^*, \pi_B^*))$ constitutes the subgame perfect Nash equilibrium in the game.

[6] If there are essential common parts which are used both in the current generation of products and the next generation of products, the success of the next generation of products may result in the reduction in the cost of the parts used commonly, which can be another example that non-discoverers may receive the benefit of compatibility externality given R&D success by another firm.

[7] As discussed earlier, this can be applicable to the case that firms don't make a explicit contract.

II.3 Firms' optimal effort choice (2nd stage)

First we consider the firms' effort choice in each subgame.

II.3.1 Subgame following duplication

Suppose that in the first stage firms have formed a research alliance to investigate S_l with $S_l \in \{S_1, S_2\}$ in which they split the network value of R&D success according to the predetermined sharing parameter λ. Then, for given $V(2)$ the firm A's maximization problem conditional on its being the first mover in the research alliance is

$$Max_{\pi_A^S}\{\pi_A^S(1-\pi_B^{S*})+\frac{1}{2}\pi_A^S\pi_B^{S*}]+\frac{1+\lambda}{2}[(\pi_B^{S*}+(1-\pi_B^{S*})\pi_A^S)][V(2)-1]-c(\pi_A^S)\}$$

where π_B^{S*} solves the firm B's maximization problem for given λ. Then, π_A^{S*}, the firm A's optimal effort level should solve the following first order condition,

$$(1-\frac{1}{2}\pi_B^{S*})+\frac{1+\lambda}{2}(1-\pi_B^{S*})[V(2)-1]=c'(\pi_A^S). \tag{II.1}$$

Now consider the firm B's maximization problem.

$$Max_{\pi_B^S}\{[\pi_B^S(1-\pi_A^{S*})+\frac{1}{2}\pi_B^S\pi_A^{S*}]+\frac{1-\lambda}{2}[\pi_A^{S*}+\pi_B^S(1-\pi_A^{S*})][V(2)-1]-c(\pi_B^S)\}.$$[8]

Then, π_B^{S*}, the firm B's optimal effort level should solve the following first order condition,

$$(1-\frac{1}{2}\pi_A^{S*})+\frac{1-\lambda}{2}(1-\pi_A^{S*})[V(2)-1]=c'(\pi_B^S). \tag{II.2}$$

The social planner's effort choice problem conditional on both being at S_l is

$$Max_{\pi_A^S,\ \pi_B^S}\{[1-(1-\pi_A^S)(1-\pi_B^S)]V(2)-c(\pi_A^S)-c(\pi_B^S)\},$$

and its corresponding first order condition is

$$(1-\pi_j^{S**})V(2)=c'(\pi_i^S) \text{ for } i,j\in\{A,B\} \text{ with } i\neq j. \tag{II.3}$$

Then, by comparing the left hand side of the equation II.1, II.2 and that of the equation II.3, one can compare the equilibrium effort level to the socially optimal effort level conditional on duplication.

[8] If we allow firms to choose the effort level sequentially, i.e., the firm A chooses its optimal effort level first and the firm B choose its own optimal effort level later, then the subgame reduces down to the Stackelberg game where π_B^{S*} is the function of π_A^{S*}.

II.3.2 Subgame following differentiation

Now denote by π_i^D the firm i's effort level (hence the probability of R&D success) when firms choose different sites. Then, the firm i's payoff maximization problem conditional on the firm j's choosing the different site is

$$Max_{\pi_i^D}\{\pi_i^D V(1) - c(\pi_i^D)\}.$$

Then, π_i^{D*}, the firm i's equilibrium effort level conditional on differentiation solves the first order condition of the firm i's problem as

$$V(1) = 1 = c'(\pi_i^{D*}). \tag{II.4}$$

The left-hand side of the condition represents the firm i's marginal revenue from increase in effort conditional on the firm j's being at the different site, while the right-hand side of the condition represents the firm i's marginal cost of increase in effort.

Now consider the social planner's optimal effort choice problem conditional on the firms' being at different sites, which is

$$Max_{\pi_A^D,\pi_B^D}\{\pi_A^D V(1) + \pi_B^D V(1) - c(\pi_A^D) - c(\pi_B^D)\}.$$

Then, π_i^{D**} for $i \in \{A, B\}$ for given $V(1)$, solves the first order conditions for the social planner's problem as

$$V(1) = 1 = c'(\pi_i^{D**}) \text{ for } i, j \in \{A, B\} \text{ with } i \neq j. \tag{II.5}$$

Then, by comparing the left hand side of the equation II.4 and that of the equation II.5, one can see that $\pi_i^{D*} = \pi_i^{D**}$ for $i \in \{A, B\}$, implying that the firms' equilibrium effort levels are efficient when firms differentiate site choice.

II.3.3 Inefficiency in equilibrium effort choice

Refer to the value of R&D success as $V(2)^*_{BR}$ if $V(2) = \frac{1}{(1-\pi_i^{D*})}$. Also denote the value of R&D success by $V(2)^*_{RA}$ such that $W_i((S_l, S_l); V(2)^*_{RA}, \lambda = 0) = W_i(S_l, S_k)$ where

$$\begin{aligned} W_i(S_l, S_k) &= (\pi_l^{D*} + \pi_k^{D*}) - [c(\pi_l^{D*}) + c(\pi_k^{D*})] \text{ and} \\ W_i((S_l, S_l); V(2), \lambda = 0) &= [\pi_i^{S*}(1 - \pi_j^{S*})] + \frac{1}{2}[\pi_i^{S*} + \pi_i^{S*} - (\pi_i^{S*}\pi_j^{S*})][V(2) - 1] - c(\pi_i^{S*}). \end{aligned}$$

with the abuse of notation that π_l^{D*} represents the equilibrium effort in the site S_l when the firms choose the different sites.[9] So, given symmetry between firms as $\lambda = 0$, the firms are indifferent

[9] Notice that $W_i(S_l, S_k)$ and $W_i((S_l, S_l); V(2), \lambda = 0)$ are the maximized payoffs from the corresponding site choice where in the second stage the firms make the equilibrium effort level given the site choice made in the first stage.

between duplication in site choice and differentiation in site choice when $V(2) = V(2)^*_{RA}$. Denote the value of R&D success by $V(2)^{**}$ such that $W((S_l, S_l); V(2)) = W(S_l, S_k)$ where

$$\begin{aligned} W(S_l, S_k) &= (\pi^{D**} + \pi^{D**}) - [c(\pi^{D**}) + c(\pi^{D**})] \text{ and} \\ W((S_l, S_l); V(2)) &= \pi^{S**}(2 - \pi^{S**})V(2) - 2c(\pi^{S**}). \end{aligned}$$

So, given symmetry between the sites, the social planner is indifferent between duplication on either site and differentiation in site choice when $V(2) = V(2)^{**}$. Then, we have the following lemma on the magnitude of $V(2)^*_{RA}$.

Lemma 3 *In the research alliance game,* $V(2)^*_{RA} < V(2)^{**} < V(2)^*_{BR}$.

Proof. See the Appendix. ∎

The equilibrium effort choice following duplication in site choice is summarized in the following proposition.

Proposition 8 ***(Asymmetric and non-monotonic effort choice)*** *Suppose that firms have formed the research alliance with the two-part reward structure in the first stage in the research alliance game. Then, the firms' equilibrium effort choices in the second stage are as follows.*
(1) If $V(2) > V(2)^*_{BR}$, *then* $\pi_B^{S*} < \pi^{S**}$ *for* $\forall\ \lambda \in [0, 1]$, *while* π_A^{S*} *may be higher or lower than* π^{S**}, *depending on* λ *for given* $V(2)$.
(2) If $V(2)^*_{RA} < V(2) < V(2)^*_{BR}$, *then* $\pi_A^{S*} > \pi^{S**}$ *for* $\forall\ \lambda \in [0, 1]$, *while* π_B^{S*} *may be higher or lower than* π^{S**}, *depending on* λ *for given* $V(2)$.

Proof. See the Appendix. ∎

The asymmetric inefficiency in the equilibrium effort choice follows from the asymmetry in the payoff structure caused by the first mover's advantage. Since firms are symmetric in the cost structure, the asymmetric investment resulting from the asymmetric payoff structure causes inefficiency. However, notice that the equilibrium effort level is inefficient in an non-monotonic way in the sense that excessive effort are more probable to be made in the equilibrium for $V(2)$ with $V(2) < V(2)^*_{BR}$, while insufficient efforts are more probable to be made in the equilibrium for $V(2)$ with $V(2) > V(2)^*_{BR}$. This non-monotonic pattern of inefficiency is caused by the interplay of the over-rewarding for simultaneous discovery and the free-riding on spill-over in the payoff structure in the research alliance. Recall that even though the reward of a stand-alone value of R&D success is allocated to the discoverer, a part of the expected reward of a network value of R&D success may be allocated to a non-discoverer since it is shared according to the pre-determined λ regardless of who discovers. Such reward system creates an incentive to free-ride on the rival's effort, which could potentially results in insufficient equilibrium effort as occurring when $V(2) > V(2)^*_{BR}$. However, notice that there exists another force working in the opposite way, which is related to the equal sharing payoff structure for the stand-alone value of R&D success. Since firms play an equal sharing R&D game for a stand-alone value of R&D success, there's potential incentive for excessive effort. Those conflicting forces offset each other when $V(2) = V(2)^*_{BR}$. And when $V(2) < V(2)^*_{BR}$, the incentive for excessive effort dominates, while the incentive for insufficient effort dominates when $V(2) > V(2)^*_{BR}$.

When it comes to the case without the first mover's advantage, the asymmetric inefficiency between the firms' equilibrium effort level disappears and only the non-monotonic inefficiency remains. Then, the case without the first mover's advantage provides the necessary and sufficient condition for duplication in site choice as shown in the following lemma.

Lemma 4 *For given $V(2)$, firms choose the same site in the equilibrium if and only if $W_B(S_l, S_l; V(2), \lambda = 0) \geq W_B(S_l, S_k)$.*[10]

Proof. See the Appendix. ■

The necessary and sufficient condition for duplication in Lemma 4 follows from the fact that the firm A can find some $\lambda \in [0, 1]$ such that both firms find it better off to form a research alliance whenever $W_B(S_l, S_l; V(2), \lambda = 0) \geq W_B(S_l, S_k)$. Then, the inefficiency in the firm's equilibrium effort choice in the case with $\lambda = 0$ can be summarized as follows.

Claim 3 ***(Non-monotonic effort choice without first mover's advantage)*** *Suppose there doesn't exist the first mover's advantage, i.e. $\lambda = 0$, then firms' equilibrium effort choice in the research alliance exhibits the non-monotonic inefficiency as follows.*
(1) $\pi_i^{S*} > \pi_i^{S**}$ for all $V(2) \in [V(2)^*_{RA}, V(2)^*_{BR})$ and $i \in \{A, B\}$;
(2) $\pi_i^{S*} < \pi_i^{S**}$ for all $V(2)$ with $V(2) > V(2)^*_{BR}$ and $i \in \{A, B\}$.

Proof. See the Appendix. ■

Since the firms' effort incur R&D activity cost which can be considered as investment, we have the following insufficient investment result from Proposition 8 and Claim 3.

Corollary 2 ***(Under-investment with big compatibility externality)*** *Suppose that compatibility externality is big enough that $V(2) > V(2)^*_{BR}$. If the first mover's advantage is not big enough*

[10] We assume that firms choose the same site if $W_B(S_l, S_l; V(2), \lambda = 0) = W_B(S_l, S_k)$.

so that the two firms share the network value of R&D success almost equally, the firms' equilibrium investment choice exhibits under-investment.

As discussed earlier, when compatibility externality is big enough, then the incentive for free-riding on the rival firm's effort outweighing the incentive for excessive effort inherent in the equal-sharing payoff structure, which results in the under-investment result as in Corollary 2.

II.4 Firms' optimal site choice (1st stage)

Recall that for given $V(2)$ the social planner's expected payoffs from duplication and the expected payoffs from differentiation are respectively

$$\begin{aligned} W((S_l, S_l); V(2)) &= \pi_l^{S**}(2 - \pi_l^{S**})V(2) - 2c(\pi_l^{S**}) \text{ and} \\ W(S_l, S_k) &= \pi_l^{D**} + \pi_k^{D**} - c(\pi_l^{D**}) - c(\pi_k^{D**}), \text{ while} \end{aligned}$$

the firm i's expected payoff in the research alliance and the payoff conditional on differentiation are respectively

$$\begin{aligned} W_A(S_l, S_l) &= \pi_A^{S*}(1 - \frac{1}{2}\pi_B^{S*}) + \frac{1+\lambda}{2}[(\pi_B^{S*} + (1 - \pi_B^{S*})\pi_A^{S*})][V(2) - 1] - c(\pi_A^{S*}), \\ W_B(S_l, S_l) &= \pi_B^{S*}(1 - \frac{1}{2}\pi_A^{S*}) + \frac{1-\lambda}{2}[(\pi_A^{S*} + (1 - \pi_A^{S*})\pi_B^{S*})][V(2) - 1] - c(\pi_B^{S*}) \text{ and} \\ W_i(S_l, S_k) &= \pi_l^{D*} - c(\pi_l^{D*}). \end{aligned}$$

According to Lemma 4, whenever $V(2) > V(2)^*_{RA}$, the first mover finds it optimal to form the research alliance and capture the network value of R&D success by offering low enough λ to the firm B. Then, the equilibrium site choice in the research alliance game can be summarized as in the following proposition.

Proposition 9 *In the subgame perfect Nash equilibrium of the research alliance game,*
(1) if compatibility externality is big enough that $V(2) \geq V(2)^*_{RA}$, then firms form a research alliance in the first stage and exert π_i^{S*} with $i \in \{A, B\}$ for some $\lambda \in [0,1]$ in the second stage.
(2) if compatibility externality is small enough that $V(2) < V(2)^*_{RA}$, then firms choose different sites in the first stage and exert π^{D*} in the second stage.

Proof. See the Appendix. ■

Now recall from Lemma 3 that $V(2)^*_{RA} < V(2)^{**} < V(2)^*_{BR}$ from which we have the following excess duplication result on the equilibrium site choice of the research alliance game.

Proposition 10 ***(Excess duplication)*** *In the research alliance game, the equilibrium exhibits the following inefficiencies.*

(1) For $V(2)$ with $V(2)^*_{RA} \leq V(2) < V(2)^{**}$, the firms choose the same site too much and both firms make over-investment for low enough λ.

(2) For $V(2)$ with $V(2)^{**} < V(2) < V(2)^*_{BR}$, the firms' choosing the same site is efficient, but the firms make over-investment for low enough λ.

(3) For $V(2)$ with $V(2) > V(2)^*_{BR}$, firm's choosing the same site is efficient, but the firms make under-investment for low enough λ.

Proof. See the Appendix. ■

Notice that the third result of Proposition 10 is in contrast to the typical result of over-investment which has been found in most R&D literature such as Loury(1979) and Reinganum(1982). The under-investment result follows from the characteristics of the payoff structure of the research alliance in which firms have incentive for free-riding on each other's investment since they share the network value of the R&D success even when the rival is the sole discoverer.

II.5 Policy implications on standardization

Since compatibility externality isn't often internalized in firms' private incentive, thereby resulting in inefficient allocations, most of research on compatibility externality has suggested a certain type of intervention of government agency to reduce such inefficiency. Few literature, however, has dealt with the effect of public policy on firms' R&D project choice with compatibility externality. In this section, the effects on equilibria in each noncooperative game of the various public policy devices are reviewed and the efficacy of each policy is discussed with a regard to a standard-setting issue.

First recall from Lemma 3 that

$$V(2)^*_{RA} < V(2)^{**} < V(2)^*_{BR}.$$

In the following, we consider the possible policy tools to relieve the inefficiencies occurring in each case which corresponds to the different level of compatibility externality. In this section both efforts and investments are used interchangeably and sites and standards are used interchangeably.

The case that $V(2) < V(2)^*_{RA}$

In this case, firms choose different standards, which is efficient. Moreover, since the equilibrium investment level conditional on differentiation is also efficient, no efficiency problem arises when compatibility externality is small enough that $V(2) < V(2)^*_{RA}$. Hence, there's no need for intervention of government agency for standardization, and the multiple standard regime in which firms are free to develop products based on different incompatible standards is desirable. On the contrary, a mandatory single standard regime which might be implemented with over estimation of compatibility externality, lowers the social welfare by making foregone the chance of additional innovation.

The case that $V(2)^*_{RA} < V(2) < V(2)^{**}$

In this case, firms choose the same standard, which is inefficient. The excess duplication and the over-investment problem arises, so the policy intervention promoting differentiation such as more strict implementation of intellectual property right(hereafter IPR) protection policy or per-unit investment tax can be implemented to increase the social welfare.[11]

The case that $V(2)^{**} < V(2) < V(2)^*_{BR}$

In this case, firms choose the same standard in the equilibrium, which is efficient. However, firms' equilibrium investment level within a research alliance is too high. Then, the intervention of government agency should be a mix of two different competition-fostering policies because the equilibrium in the research alliance game exhibits two types of inefficiencies each of which needs a separate policy intervention. First, notice that the asymmetric inefficiency involved in investment choice worsens as the first mover's advantage is greater (λ is closer to 1). Since the first mover's footing in determining λ depends on how proprietary the fundamental technology the first mover has chosen is, a lenient IPR policy fundamental technologies could strengthen the second mover's footing in determining λ, thereby relieves the asymmetric inefficiency problem in investment choice. Second, the per-unit investment tax needs to be implemented in order to reduce firms' incentive for over-investment as discussed earlier. But, the per-unit investment tax should be minimal so that it won't induce firms to choose different standards.

The case that $V(2) > V(2)^*_{BR}$

In this case, firms choose the same standard, which is efficient. However, the equilibrium investment level may be too low, which needs another policy mix : a lenient IPR policy on fundamental technologies and per-unit investment subsidy. The lenient IPR policy can be used to reduce asymmetric

[11] For example, τ of per-unit investment tax reduces the firms' marginal revenue from increase in investment from $(1-\frac{1}{2}\pi)V(2)$ to $(1-\frac{1}{2}\pi-\tau)V(2)$ in the equal sharing R&D game. Since the excess duplication result occurs due to the over-rewarded marginal revenue conditional on duplication, firms has less incentive to duplicate standard choice in the first stage.

inefficiency as discussed before. Now recall that firms' incentive for investment in the research alliance is smaller than that of the social planner for all $V(2)$ with $V(2) > V(2)^*_{BR}$ when both firms almost equally split the network value of R&D success(Claim 3). Hence, the per-unit investment subsidy which increase firms' marginal revenue up to that of the social planner would reduces inefficiency arising from under-investment.

II.6 Concluding remarks

We build a simple R&D choice model in which two firms compete in R&D race in two stages for development of applied technologies where the same fundamental technologies can be chosen only through a research alliance. Existence of compatibility externality gives firms an incentive to choose a single standard. But the possibility of simultaneous discovery as well as the first mover's advantage gives firms an incentive to choose different standards. The interplay of these incentives result in discrepancy between firms' private incentive and the social planner's incentive in both site choice problem and effort choice problem that firms equilibrium site choice may exhibit too much duplication and the equilibrium effort choice may be insufficient or excessive, depending on the magnitude of compatibility externality.

Since our model doesn't analyze explicitly how λ is determined, the immediate extension of our model would be the model with the bargaining process in the first stage. But, notice that the threshold value for duplication in site choice should be $V(2)^*_{RA}$ no matter which bargaining process is considered. So the qualitative aspect of the over-duplication result in our model wouldn't be changed in the model with a more specified bargaining process.

Chapter III

Dynamic R&D choice with compatibility externality

III.1 Introduction

In the theoretical literature in economics on R&D, much research effort has been devoted to exploring the effect of various distortions inherent in the nature of R&D on the scales of R&D investments(Reinganum(1979), Loury(1979), Dasgupta and Maskin(1987)). But in many systems market with competing technologies, not only the scale of R&D investment but also the allocation of research effort across competition technologies has been a critical issue.[1] For example, in the wireless communication industry where GSM standard and CDMA standard are competing for the next generation technology, all the relevant industry producers such as carriers, equipment producers and handset manufacturers should choose which technology their products will be based on. In their decision on which technology their products should be based on, the firms in the relevant industries may consider the various factors which can give conflicting incentives in their technology choice. Especially if the competing technologies develop in the evolution pattern where each competing technologies are upgraded in the fashion that the new generation product are backward compatible with the previous generation products, then the typical systems market as described above may share the following features.

First, two kinds of uncertainties may be involved in R&D of applied technologies if the fundamental technologies on which the applied technologies are based are risky, too. In the example of the wireless communication industry, the carriers who want to develop the applied technologies based on either GSM platform or on CDMA platform, should take the risk that its chosen platform might turn out to be a "wrong" fundamental technology which applied technologies for marketable

[1] Katz & Shapiro(1994) define a system as a collection of two or more components together with an interface that allows the components to work together.

products can't be developed from.[2] With such two kinds of uncertainties, when firms fail in R&D of applied technologies, firms may not know whether the failure is caused by the problem associated with its R&D activity only or the problem associated with the fundamental technology that it chose. Second, there could be substantial compatibility benefit which firms may want to exploit by choosing same technology. In the example of the wireless communication industry, if there exists substantial compatibility benefit, then when firms choose the same technology, say, GSM, handset makers and equipment producers can enjoy economies of scale. Moreover operators can interconnect other operators' compatible network without incurring the cost of installing adapters.[3] Third, how competitive the relevant market is affects firms' decision on their technology choice in R&D. If there are many firms whose prospective products from their R&D success aren't much differentiated and there is strict possibility of simultaneous discovery, then the firms engaging in R&D take into account how much competitive prospective product market will be in the case of simultaneous discovery. Especially, firms expect the prospective product market to be very competitive, then firm may want to choose different technologies which might serve different segments of market between which competition is less severe.

This paper addresses the question on how firms decide on which fundamental technology to choose for their R&D of applied technologies in an environment with the features described above : there are two kinds of uncertainties that firms face in their R&D of applied technologies where there exists strict possibility of simultaneous discovery in the presence of network externality within compatible technologies.[4]

Although there has been abundant literature in economics on R&D, most of them has focused on the scale of R&D investments as mentioned in the beginning. Only a few papers, notably Bhattacharya and Mookherjee (1986), Fershtman and Rubinstein (1997) and Chatterjee and Evans (2004) have examined the issue of allocation of research efforts across competing technologies.

Bhattacharya and Mookherjee (1986) investigate on how firms choose research projects, which affect the riskiness and the correlation of their research performance. In their model, firms choose a strategy from a closed interval, which determines a distribution where the realization of research performance is a real-valued random variable. They analyze the impact of the winner-take-all feature of patent race on the choice of research projects and find that both the non-cooperative

[2] Or equivalently it may take too much time for development, which can be interpreted as failure in R&D for given fixed time period.

[3] Actually compatibility benefit was the main reason for ETSI to determine GSM for a single standard in Europe's wireless telecommunication industry in early 1980's.

[4] We interchangeably use a fundamental technology and a "site" by analogy with a well-known "the buried treasures problem". See, for example, Ross(1983).

equilibrium and the social optimum involves extremes specialization.

Chatterjee and Evans (2003) analyze firms' R&D avenue or "site" choice problem in a dynamic setting where there's only one "right" site with a prize buried in it. As in our model, they incorporate the case of simultaneous discovery into their discrete time model. Even though firms prefer to avoid simultaneous discovery, herding on the more promising project may occur in equilibria since there's only one "right" site. Also, they analyze firms' strategic incentives to induce the rival to choose the different site through influencing the rival's belief on the probabilities of each site's being the right "one". The main difference between our model and their model is that in their model the projects are perfectly correlated. Since there is only one right project, if the belief on one site's being the right one increases, then the belief on the other site's being the right one decreases accordingly. In our model, both sites could be "right" ones with some positive beliefs where beliefs on treasures being buried in each site are uncorrelated with each other. Another difference is that they don't model network or compatibility benefit which is the main source of incentive for firms to seek duplication in R&D avenue choice in our model. In their model, if firms duplicate on a particular site, then it occurs because the probability of the prize being buried in that project is high enough to offset more than the expected loss caused by possible simultaneous discovery.

This paper also is related to the literature on the vein of network externality such as Katz and Shapiro (1985, 1992) and Kristiansen (1998).

Katz and Shapiro (1985) analyze network externality effects under oligopolistic competition on market equilibrium. In their model consumers' foresight on the potential size of the networks determine effective networks. Since the rationality restriction on the expectations of consumers allow many sets of expectations in the equilibria, there exist multiple fulfilled expectations equilibria. In their analysis of the firms' incentives to produce compatible goods, they find that firms with good reputations or large existing networks tend to be against compatibility, while firms with weak reputation or small existing networks tend to favor compatibility.

Katz and Shapiro (1992) consider a market with network externalities where an incumbent with existing installed base competes with an entrant with lower costs but having the disadvantage of no installed base. In their dynamic model, with the crucial assumption of exponential growth of market, they analyze the situation that incumbent's advantage of installed base may not be important when compared to "future" installed base. In those situations, consumers' expectations play a critical role and many fulfilled expectations equilibria exist, one of which involves "insufficient friction". They show that an entrant has the incentive to seek incompatibility unilaterally if licensing contracts as side-payment system is not perfect. Even though Katz and Shapiro (1985, 1992) identify some of firms' incentives to seek compatibility or incompatibility, they don't capture firms' motives to seek incompatibility in order to avoid possible contention following simultaneous discovery of compatible products since all the products in their models are already developed and no R&D issue arises. Hence, Katz and Shapiro (1992)'s model considers only the stage after R&D is done which is one of the subgames we consider in our model.

While existing theoretical literature in economics on network externality including Katz and Shapiro(1985, 1992) has mainly focused on the issues regarding introduction of new products without uncertainties, Kristiansen (1998) is one of few attempts to thoroughly discuss the effect of compatibility or network benefits on the R&D avenue choice. Kristiansen (1998) analyzes the situation in which two firms engage in R&D race in a dynamic setting with costs decreasing in time. Although under social optimum both firms should introduce products later, firms' noncooperative incentive to win over installed base brings firms to play the game of prisoners' dilemma so that the firms may introduce new incompatible technologies early in the equilibrium. But Kristiansen assumes that the firm whose quality realization is higher wins the R&D race where quality realization is drawn from a continuous distribution function. So, in his model the probability of simultaneous discovery is measure zero under usual distributions without mass in it, which causes his model unable to capture firms' considering the possibility of simultaneous discovery. In our model in which the possibility of simultaneous discovery is captured, the degree of competitiveness in the prospective product market is a well-defined variable which is taken into account in firms' decision on which technology they choose.

The main results we obtain are as follows: First, without externality in the production activity, when compatibility externality in reward from R&D success is not big enough, there always exists some set of beliefs (on the chosen fundamental technologies' being "right" one for development of applied technologies) for which over-duplication in site choice occurs or over-differentiation in site choice occurs in the equilibrium, depending on the degree of competitiveness in the prospective product market. Especially, over-differentiation is more likely to occur as the prospective product market is more competitive, while over-duplication is more likely to occur as the prospective product market is less competitive. Second, with externality in the production activity, both over-differentiation and over-duplication may arise for different sets of beliefs when the magnitude of compatibility benefit in the reward from R&D success is not big enough and the prospective product market is competitive enough. Such coexistence of the sets of beliefs for which different kinds of inefficient site choice occurs may create difficulty in determining standard regime since both a single standard regime and a multiple standard regime may end up with resulting in an inefficient standard choice. Third, since there exists the information benefit from experimentation through differentiation due to the independence between the sites, both the social optimum and the equilibrium may be non-myopic where they involve in more specialization in the two period game than in the one period game especially when the belief on treasures being buried in either site is very high and compatibility externality in the reward from R&D success is not very high. Fourth, since the rival firm's information benefit from experimentation through differentiation isn't internalized by a firm, the firms has less incentive for differentiation than the social planner, which results in over-duplication in the first period site choice of the two period game.

This paper is organized as follows. In Section 2 we explain the basic structure of the problem and its features. Section 3 contains the social optimum in the one period game and the two period game. Section 4 considers the non-cooperative equilibrium in the one period game and the two period game where its efficiency is examined. Section 5 contains the extensions and concluding remarks.

III.2 Model

III.2.1 Description of model

III.2.1.1 Basic structure of the game

III.2.1.1.1 R&D environment : two incompatible sites There are two "sites" or research avenues on fundamental technologies, S_1 and S_2, from each of which many applied technologies can be developed potentially. The sites themselves are not proprietary even though all the applied technologies developed from the sites are proprietary. With such public nature of the sites, the situation that firms choose the same site can be well captured. The sites are incompatible with each other in the sense that any applied technologies developed from the different sites are incompatible with each other, while they are compatible with each other if they are developed from the same site. The applied technologies progress from one generation to the next generation according to an backward compatible evolution pattern within each site. Hence, applied technologies of the next generation are backward compatible with the ones of the current generation(but not in the other direction) only if the applied technologies of both generations are from the same site. In that sense, the sites are research "paths". We consider the situation that all the applied technologies of the current generation are available at a minimal cost which is normalized to be 0, while the applied technologies of the next generation can be acquired only from the success in R&D activity which incurs a per-period cost, c.

III.2.1.1.2 Uncertainties involved in R&D activity When firms choose a site to investigate, they face two kinds of uncertainty : the uncertainty on whether treasures are buried in the site and the uncertainty on whether R&D will succeed when treasures are buried in the site. The second uncertainty can be expressed by π, the probability of R&D success conditional on treasures being buried in the site. For simplicity we assume π is exogenously given and same in both sites.[5] The first uncertainty can be expressed by p_l^s with $l \in \{1, 2\}$ and $p_l^s \in (0, 1]$ where p_l^s represents the (updated) belief that treasures are buried in the site after s number of R&D experiments have failed in the site S_l with $s \in \{0, 1, 2\}$. With such two kinds of uncertainty, when firms fail in R&D, it could be due to the following two possibilities. The first possibility is that there is no treasure buried in the site. The second possibility is that treasures are buried in the site but the R&D activity was not successful, which is possible with $1 - \pi$ for every R&D experiment. Hence, with the initial belief p_l^0, after one R&D experiment in S_l ends up with a failure, the firms update to p_l^1 their beliefs that treasures are buried in S_l by the Bayesian updating rule as follows ;

$$p_l^1 = \frac{p_l^0(1-\pi)}{p_l^0(1-\pi) + (1-p_l^0)} = \frac{p_l^0(1-\pi)}{1-p_l^0\pi}.$$

Similarly, p_l^2 the updated posterior belief that treasures are buried in S_l after two R&D experiments in the site ending up with a failure can be obtained by the Bayesian updating rule as follows ;

$$p_l^2 = \frac{p_l^1(1-\pi)}{p_l^1(1-\pi) + (1-p_l^1)} = \frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2 + (1-p_l^1)}.$$ [6]

As is clear in the above expressions, it's obvious that the posterior belief is revised downward whenever the R&D experiment ends up with a failure, implying that treasures are more likely not to be buried in the site as R&D experiment keeps failing. But, if a firm makes a discovery in the site S_l in the current period, then the posterior belief in the next period on treasures being buried in the site S_l is updated to be 1.

III.2.1.1.3 Firms' two activities : Production and R&D There are two symmetric firms, A and B which make revenues from two activities over two periods : production activity using the applied technology of the current generation and R&D activity for the next generation applied

[5] For the R&D choice model with compatibility externality in which the provability of success is endogenously chosen by firms, see Lee(2003).

[6] The detailed proof is provided in Appendix.

technology. Both activities should be carried out on one site, meaning that the applied technology of the next generation should be from the same fundamental technology on which the applied technology of the current generation is based. Moreover, the two activities are inseparable, implying that the firms should carry out both activities at the same time and can't carry out either activity only.

III.2.1.1.4 Payoffs from the two activities An individual firm's net per-period revenue from production activity is denoted by $v(n)$ with n representing the number of firms choosing the same site. The per-period social value of R&D success is denoted by $V(n)$ with n representing the number of firms choosing the same site regardless of whether only one firm was successful in its R&D or two firms were successful in their R&D.[7] Hence, the social value of either firm's exclusive discovery and that of simultaneous discovery by two firms are both $V(2)$ if the two firms have chosen the same site before R&D.[8]

For simplicity, we assume that $v(1) = 0$, implying that when firms choose different site, without the payoff from R&D activity, firms would make only zero economic profit from the production activity using the applied technology of the current generation.[9] We normalize V(1) to be 1 for simplicity. We also assume that $v(2) > v(1)$ and $V(2) > V(1)$, implying that there exists compatibility externality in the net revenue from production activity and in the value of R&D success respectively.[10]

Especially, for simplicity $v(2)$ is assumed to be equal to c, the R&D activity cost, implying that firms are guaranteed to get at least zero economic profit when they choose the same site since their R&D activity cost is offset by the payoff from production activity which is high enough due to compatibility externality even when they fail in the R&D.

But when firms choose the same site, how much portion of $V(2)$ an individual firm gets from R&D success depends on whether the discovery is exclusive or simultaneous, and the degree of competition in the prospective product market in the case of simultaneous discovery. Especially the

[7] Since the benefit of R&D success occurs in every period, the firms find it profitable to begin R&D activity in the first period even though there's no discounting in this model. So the issue of delaying R&D doesn't arise in our problem.

[8] Or equivalently one can consider that the social planner's payoff from R&D success following duplication in site choice is the greater of the value of either firm' s R&D success, i.e., $max\{x_A, x_B\}$ where x_i with $i \in \{A, B\}$ is the value of the firm i's R&D success and x_A is assumed to be equal to x_B.

[9] This assumption together with the assumption that the applied technology of the current generation is available at a minimal cost implies that the relevant industry only with the applied technology of the current generation is competitive in the sense that there's no supernormal economic profit to induce firms outside the relevant industry.

[10] We interchangeably use "compatibility externality" and "network externality" although we use "compatibility externality" in most cases.

nature of competition is described by $\theta \in [0, 1/2]$ in the case of simultaneous discovery with θ representing how much competitive the prospective product market is. The case of $\theta = 0$ corresponds to the situation in which firms play the Bertrand game in the prospective product market that firms compete away surplus from R&D success. The case of $\theta = 1/2$ corresponds to the situation in which competition in the prospective product market is not so severe that firms equally share the revenue from R&D success.[11] Then each firm's reward from R&D success following simultaneous discovery in the same site is $\theta V(2)$, while the reward of the firm making an exclusive discovery following both firms' choosing the same site is $V(2)$. Denote by (S_l, S_k) with $S_l, S_k \in \{S_1, S_2\}$ the profile of firms' site choice where the firm A and the firm B choose the site S_l and the site S_k respectively. Denote by (p_1^s, p_2^t) with $s, t \in \{0, 1, 2\}$ the profile of the beliefs on treasures being buried in S_l and S_k respectively where s number of R&D experiment has failed in S_1 and t number of R&D experiment has failed in S_2. Now denote by $V((S_l, S_k); (p_1^s, p_2^t))$ the social planner's one period payoff where the firms' site choice is (S_l, S_k) and the set of beliefs on each site is (p_1^s, p_2^t) with $s, t \in \{0, 1, 2\}$. Then, $V((S_l, S_k); (p_1^0, p_2^0))$ denotes the social payoff from R&D activity in the first period. Denote by $W((S_l, S_k); (p_l^0, p_k^0))$ the social planner's total expected payoff over two periods where the firms' site choice in the first period is (S_l, S_k), the set of the initial beliefs on treasures being buried in the sites is (p_l^0, p_k^0) and at the beginning of the second period the social planner makes the site choice which is optimal for the subgame corresponding to the realized outcome of the R&D activity in the first period. The social planner's objective is to maximize the sum of the value created by the two firms' activities. We assume that the social planner has lexicographic preference for duopoly over a monopoly. Hence the second mover's opting out of R&D competition due to the first mover's site choice is considered to be inefficient if the social payoff from both firms staying in business is positive. Now denote by $V_i((S_l, S_k); (p_l^s, p_k^t))$ the firm i's one period expected payoff where the firms' site choice is (S_l, S_k) and the set of beliefs are (p_l^s, p_k^t) with $s, t \in \{0, 1, 2\}$. Denote by $W_i((S_l, S_k); (p_l^0, p_k^0))$ the firm i's total payoff over two periods where the firms' site choice in the first period is (S_l, S_k), the set of initial beliefs is (p_l^0, p_k^0) and at the beginning of the second period the firms play the action prescribed by the equilibrium strategy for the subgame corresponding to the realized outcome of the R&D activity in the first period.

III.2.1.1.5 The process of R&D competition The game proceeds as follows. At the beginning of the first period, firms sequentially choose the site to investigate. Without a loss of generality

[11] Note that θ can't exceed 1/2 since the sum of all the firms' producer surplus can't exceed the total social surplus. All the externality arising from firms choosing the same research path is expressed by $V(2)$ and $v(2)$ where $V(2) > V(1)$ and $v(2) > v(1)$.

we assume that the firm A first chooses the site to investigate. Due to the limitation on investment capacity, the firms can choose only one site each period. The choice of sites and the result of R&D are observable to both firms without any noise. For the remaining of the first period, the firms engage in both production activity and R&D activity. At the end of the first period, the result of R&D activity is revealed, after which the revenue from production activity and the R&D reward depending on the result of R&D activity are realized. At the beginning of the next period, with the publicly available information on the result of R&D, both firms update their beliefs on treasures being buried in the sites according to the history of investigation in the previous period. With the updated posterior beliefs, firms decide which site to choose at the beginning of the second period. We assume that a switching cost is prohibitively high if a firm has succeeded in the first period, while a firm incur a negligible switching cost if it has not succeeded in the first period.[12] Hence, at the beginning of the second period a firm which has failed in R&D in the first period can switch to the other site if it wants, while the firm which has succeeded in R&D in the first period should continue to choose the same site which it chose in the first period. For example, if both firms have succeeded in R&D in the first period, then the firms' site choice in the second period will be same as in the first period. If neither firm has succeeded in R&D in the first period, then the firms face basically the same problem that they had in the first period, but with updated posterior beliefs. If either firm has succeeded in the first period, then the firm which failed in the first period weighs continual investigation in the site it chose in the first period with switching to the other site, while the firm which has succeeded in the first period continues to choose the site it chose in the first period.

III.2.1.2 Strategies and Equilibria

Now consider firms' strategy in the game. First denote by $\mathcal{P}_l \subseteq [0,1]$ with $l \in \{1,2\}$ the set of belief on treasures being buried in the S_l. Similarly denote by $\mathcal{P} = \mathcal{P}_1 \times \mathcal{P}_2$ the set of the profiles of beliefs on treasures being buried in the S_1 and S_2 respectively. Denote by $\mathcal{S}_i$ with $i \in \{A, B\}$ the set of the sites that the firm i chooses. Notice that in our simple model, selection of the site to investigate is the firms' sole action variable in each period.

Then, in the one period game with the set of initial beliefs (p_1^0, p_2^0), the firm i's pure strategy is a function $s_i : \mathcal{P} \times \mathcal{S}_j \rightarrow \mathcal{S}_i$ which assigns a site to choose for the set of initial beliefs and for the

[12] With this assumption about switching costs we restrict our analysis to the situation that firms invest in substantial amount of production facilities only after they succeed in the development of applied technologies.

rival firm's site choice. Especially in the Nash equilibrium it solves

$$max_{s_i} V_i((S_l, S_k); (p_1^0, p_2^0)) \text{ for } i \in \{A, B\},\ l \in \{1, 2\} \text{ for given } S_{-i}.$$

Now consider the two period game in which the firms' site choice in the second period depends on the result of R&D activity in the first period, where each of different results of R&D activity is followed by the corresponding different subgames. Denote by (S_l^s, S_k^f) with $l, k \in \{1, 2\}$ the profile of the outcome of R&D such that the firm A's R&D in the site S_l was successful but the firm B's R&D in the site S_k was not.[13] Similarly (S_l^f, S_k^s) denotes the outcome of R&D such that the firm A's R&D in the site S_l was not successful but the firm B's R&D in the site S_k was successful. (S_l^f, S_k^f) and (S_l^s, S_k^s) are similarly defined. Then, for example the set

$$\mathcal{H}_{(l,k)} \equiv \{(S_l^s, S_k^s), (S_l^f, S_k^f), (S_l^s, S_k^f), (S_l^f, S_k^s)\} \text{ with } l, k \in \{1, 2\}$$

is the set of all the histories following (S_l, S_k), each history initiating its corresponding subgame.

Then, for each firm the pure strategy in the two period game is defined as a function $\hat{s}_i : \mathcal{P} \times \mathcal{S}_j \times \mathcal{H} \rightarrow \mathcal{S}_i \times \mathcal{S}_i$ which assigns a choice of a site in each period for the set of initial beliefs (p_1^0, p_2^0), the rival firm's site choice and the history of R&D activities where $\mathcal{H}$ is the set of all the histories available at the beginning of the second period . Then, since the firms' site choice and the result of the R&D activity are observable and the equilibrium strategy should induce a Nash equilibrium in every subgame, the proper solution concept for the equilibrium in the two period game should be a subgame perfect Nash equilibrium in which the firm i's equilibrium strategy solves

$$max_{\hat{s}_i \times \hat{s}_i} W_i((S_l, S_k); (p_1^0, p_2^0)) \text{ for } i \in \{A, B\} \text{ for } l, k \in \{1, 2\} \text{ for given } S_{-i}.$$

III.2.2 Discussion of model

III.2.2.1 Inseparability of R&D activity and production activity

We assume that the firms' R&D activity and production activity are inseparable. Hence engaging in either R&D activity only or production activity only is an option neither to the firms nor to the social planner.[14] With this assumption we focus on the situation which has the following features. First, the firms' primary activity is R&D activity and production activity is a minor activity where the most of revenue comes from R&D activity and the revenue from production activity can recoup

[13] We don't preclude the case that $k = l$ unless it's explicitly stated.

[14] Without this assumption, for some set of initial beliefs which are extremely low, the firms would find it more profitable to conduct production activity only, not doing R&D activity after they chose the same site, which is efficient also.

at most the R&D activity cost. Second, in the R&D for the technology of the next generation it's crucial for the firms to have a full command of the technology of the current generation which is acquired through production activity.

III.2.2.2 Independence between the different sites in R&D rewards

We assume that the two sites are independent in the sense that simultaneous discovery in different sites doesn't affect the value of R&D success in each site. Such assumption may fit well the situation that the products developed from different sites have their intrinsic values targeted for groups of consumers with differentiated preferences. Then, each discovery in the different sites captures different segments of the market so that simultaneous discovery in the different sites doesn't reduce the value of R&D success in either site. On the contrary, when simultaneous discovery occurs in the same site, it affects each firm's payoff from R&D success, depending on the degree of competitiveness in the prospective product market.

III.2.2.3 (Backward) compatibility externality or indirect compatibility externality

We assume that if the two firms chose the same site in the first stage, then due to compatibility externality the value of R&D success is increased regardless of whether both firms are successful in their R&D or only either firm is successful in its R&D. One can see that such phenomenon may happen in the following two cases.

First, consider that competing technologies develop following the evolution pattern that the next generation products are backward compatible with the current generation products. Then, when a firm makes an exclusive discovery of new technology, it may easily win over the rival firm's customers since the rival firm's customers can switch to the firm with the new technology (of the rival firm whose R&D was successful) without significant switching cost.

Alternatively, if there exists indirect(or virtual) compatibility externality within the relevant systems market, then the news itself that firms have agreed on a single standard would create a bigger set of complementary goods of more variety. If such complementary goods are of the next generation, then the benefit from the bigger set of complementary goods will be captured by the firm whose R&D was successful regardless of whether the rival firm's R&D was successful.

III.3 Social optimum

In this section, we consider the characterization problem of the social optimum. Since the social planner solves the maximization problem of the sum of the value of the firms' R&D activity and production activity, the social planner's problem is equivalent to the problem of a monopolist's optimal R&D portfolio choice in which the firm runs two laboratories where there are two incompatible R&D projects available. For a benchmark case we consider the one period game first.

III.3.1 One period game

III.3.1.1 When there exists production externality : $c = v(2) > v(1)$

First we consider the case with production externality. In this case, the firms have a sure incentive to duplicate site choice since the production payoff, $v(2)$ which is a sure payoff is big enough to offset c, the R&D activity cost. Now recall that the social optimum attains

$$max_{\{s_A,s_B\}}V((S_l,S_k);(p_1^0,p_2^0)) \text{ with } l,k \in \{1,2\} \text{ where}$$

$$\begin{aligned} V((S_l,S_k);(p_1^0,p_2^0)) &= [p_1^0\pi V(1)+v(1)-c]+[p_2^0\pi V(1)+v(1)-c] \\ &= (p_1^0+p_2^0)\pi V(1)-2c \text{ for } l\neq k \quad ; \qquad \text{(III.1)} \\ V((S_l,S_l);(p_1^0,p_2^0)) &= p_l^0[(\pi)^2+\pi(1-\pi)+(1-\pi)\pi]V(2)+2v(2)-2c \\ &= p_l^0\pi(2-\pi)V(2). \qquad \text{(III.2)} \end{aligned}$$

Then, since $V((S_1,S_2);(p_1^0,p_2^0)) = V((S_2,S_1;(p_1^0,p_2^0))$, the socially optimal site choice should be

$$argmax_{\{s_A,s_B\}}\{V((S_1,S_1);(p_1^0,p_2^0)),V((S_1,S_2);(p_1^0,p_2^0)),V((S_2,S_2);(p_1^0,p_2^0))\}.$$

Now denote by $P_{12} \subseteq \mathcal{P}$ the set of (p_1^0,p_2^0) such that

$$V((S_1,S_2);(p_1^0,p_2^0)) \geq max\{V((S_1,S_1);(p_1^0,p_2^0)),V((S_2,S_2);(p_1^0,p_2^0))\}.$$

P_{11} and P_{22} are defined similarly. Then, since

$$\begin{aligned} V((S_1,S_2);(p_1^0,p_2^0)) \geq V((S_1,S_1);(p_1^0,p_2^0)) \quad &\text{iff} \quad p_2^0 \geq p_1^0[(2-\pi)V(2)-1]+\frac{2c}{\pi} \text{ and} \\ V((S_1,S_2);(p_1^0,p_2^0)) \geq V((S_2,S_2);(p_1^0,p_2^0)) \quad &\text{iff} \quad p_2^0 \leq \frac{p_1^0\pi-2c}{\pi[(2-\pi)V(2)-1]}, \end{aligned}$$

so, P_{12} is the set of (p_1^0,p_2^0) such that

$$p_2^0 \geq p_1^0[(2-\pi)V(2)-1]+\frac{2c}{\pi} \text{ and } p_2^0 \leq \frac{p_1^0\pi-2c}{\pi[(2-\pi)V(2)-1]}.$$

Similarly, P_{11} is the set of (p_1^0,p_2^0) such that

$$p_2^0 \leq p_1^0[(2-\pi)V(2)-1]+\frac{2c}{\pi} \text{ and } p_2^0 \leq p_1^0,$$

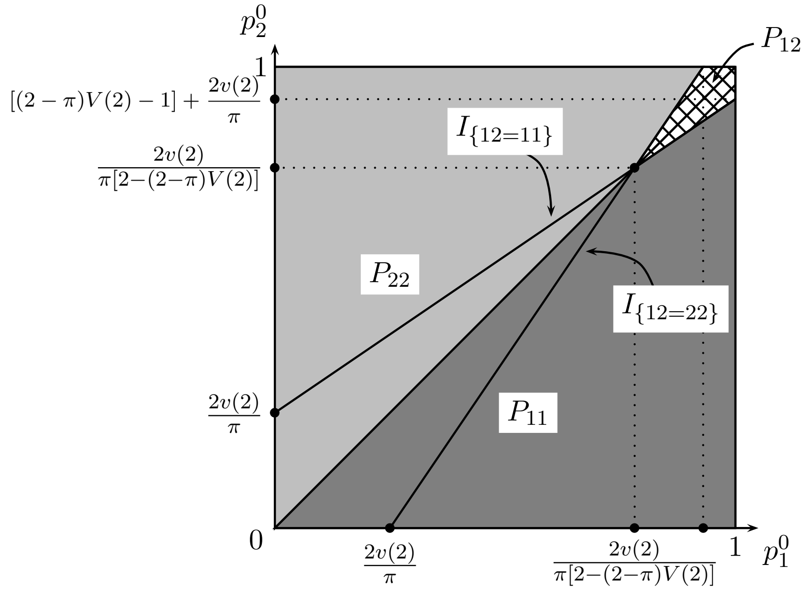

Figure III.1: Characterization of social optimum in the one period game : $V(2) < \widetilde{V}(2)$(P_{12} is nonempty)

and P_{22} is the set of (p_1^0, p_2^0) such that

$$p_2^0 \geq \frac{p_1^0\pi - 2c}{\pi[(2-\pi)V(2)-1]} \text{ and } p_2^0 \geq p_1^0.$$

Consider Figure III.1 where the socially optimal site portfolio for each of different (p_1^0, p_2^0) is shown. First denote by $I_{\{12=11\}} \subseteq \mathcal{P}$ the set of (p_1^0, p_2^0) such that $I_{\{12=11\}} = P_{12} \cap P_{11}$. Then, for every point of (p_1^0, p_2^0) in $I_{\{12=11\}}$,

$$\begin{aligned} p_2^0 &= p_1^0[(2-\pi)V(2)-1] + \frac{2c}{\pi} \\ &= p_1^0[(2-\pi)V(2)-1] + \frac{2v(2)}{\pi}. \end{aligned} \tag{III.3}$$

The term of $\frac{2v(2)}{\pi}$ in (III.3) reflects the relative advantage of (S_1, S_2) over (S_1, S_1) in payoff where $v(2)$ equals to c. Similarly, denote by $I_{\{12=22\}} \subseteq \mathcal{P}$ the set of (p_1^0, p_2^0) such that $I_{\{12=22\}} = P_{12} \cap P_{22}$. Then, for every point of (p_1^0, p_2^0) in $I_{\{12=22\}}$,

$$p_2^0 = \frac{p_1^0\pi - 2v(2)}{\pi[(2-\pi)V(2)-1]}. \tag{III.4}$$

Then, P_{12} is represented by the crosshatched area in Figure III.1 where $I_{\{12=11\}}$ is below $I_{\{12=22\}}$. For the rest area,

$$\mathcal{P}\backslash P_{12} = \begin{cases} P_{11} \text{ if } p_1^0 > p_2^0 \\ P_{22} \text{ if } p_1^0 < p_2^0, \end{cases}$$

are represented by the gray area and by the light gray area respectively in Figure III.1. Notice that the configuration of each set of P_{11}, P_{12} and P_{22} depends on the slopes and the intercepts of $I_{\{12=11\}}$ and $I_{\{12=22\}}$ where the slopes depend on $V(2)$ and the intercepts depend on $v(2)$. Especially, the slope of $I_{\{12=11\}}(I_{\{12=22\}})$ is increasing(decreasing) in $V(2)$.

Now let

$$\widetilde{V}(2) \equiv \frac{2(\pi - c)}{\pi(2-\pi)} \text{ for given } \pi \text{ and } c. \tag{III.5}$$

Then, the effect of $V(2)$ and $v(2)$ on the configuration of P_{ij} with $i, j \in \{1, 2\}$ can be summarized as in Claim 4.

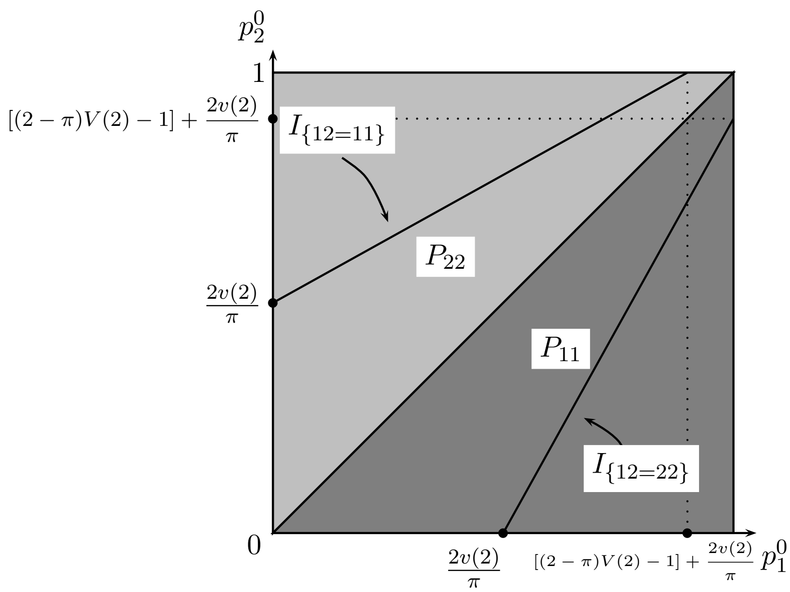

Figure III.2: Characterization of social optimum in the one period game : $V(2) > \widetilde{V}(2)$(P_{12} is empty)

Claim 4 *For given π and c, let $\widetilde{V}(2) \equiv \frac{2(\pi-c)}{\pi(2-\pi)}$. Then,*

(1) if $V(2) \leq \widetilde{V}(2)$, as $V(2)$ is greater, P_{11} and P_{22} get bigger in their sizes, while P_{12} gets smaller in its size.

(2) if $V(2) > \widetilde{V}(2)$, P_{12} is empty.

(3) With $v(2) = c$, as c is higher, P_{11} and P_{22} get bigger in their sizes, while P_{12} gets smaller in its size.

Proof. See the Appendix. ■

The result of Claim 4 is straightforward in that for a larger set of (p_1^0, p_2^0), the duplication in site choice is socially optimal as the magnitude of compatibility benefit grows. Further there should be a certain threshold over which only duplication in site choice is efficient for all $(p_1^0, p_2^0) \in \mathcal{P}$, which is $\widetilde{V}(2)$. Picture III.2 depicts the socially optimal site portfolio with $V(2) > \widetilde{V}(2)$ where there doesn't exist P_{12}, implying only duplication on the site with higher probability of treasures being buried is efficient.

III.3.1.2 When there's no production externality : $v(2) = v(1)$

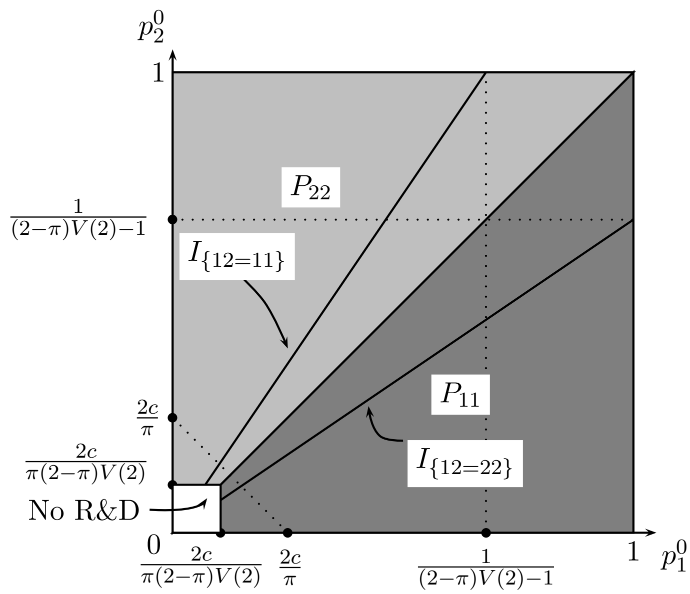

Figure III.3: Characterization of social optimum in the one period game without production externality : $V(2) > \widetilde{V}(2)_{\{v(2)=v(1)\}}$($P_{12}$ is empty)

Now we consider the case without production externality using Figure III.3 and Figure III.4. First, notice that without production externality the equation for $I_{\{12=11\}}$ and the equation for $I_{\{12=22\}}$ respectively becomes

$$p_2^0 = p_1^0[(2-\pi)V(2)-1]; \tag{III.6}$$

$$p_2^0 = \frac{p_1^0}{(2-\pi)V(2)-1}. \tag{III.7}$$

Now let $\widetilde{V}(2)_{\{v(2)=v(1)\}}$ such that

$$\widetilde{V}(2)_{\{v(2)=v(1)\}} = \frac{2}{2-\pi}.$$

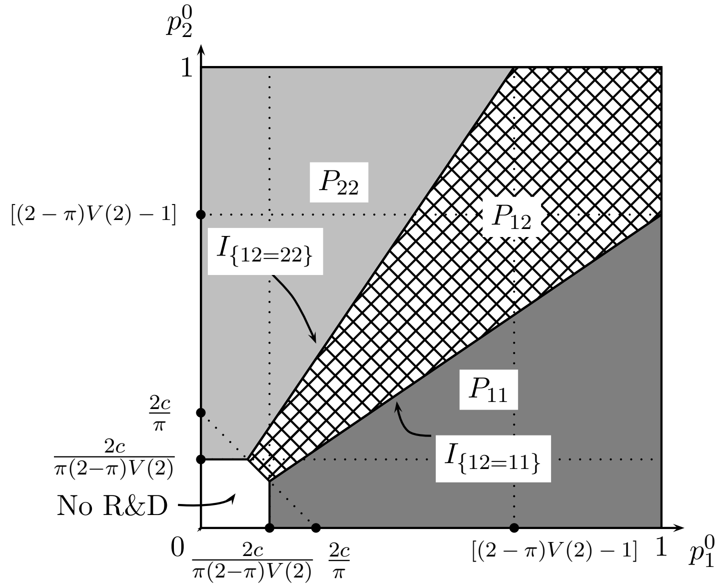

Figure III.4: Characterization of social optimum in the one period game without production externality : $V(2) < \widetilde{V}(2)_{\{v(2)=v(1)\}}$($P_{12}$ is nonempty)

Then, if $V(2) \geq \widetilde{V}(2)_{\{v(2)=v(1)\}}$, we have $P_{12} = \emptyset$ as shown in Figure III.3.[15] If $V(2) < \widetilde{V}(2)_{\{v(2)=v(1)\}}$, then there exists P_{12} as depicted in Figure III.4.

III.3.1.3 The role of production externality as a reservation site choice

Now we examine the role of production externality in configuration of socially optimal site portfolio when the expected payoff from R&D activity is low. Notice that without production externality, the R&D activity cost can be recouped only by the payoff from R&D success. So, for given R&D activity cost, if p_1^0 and p_2^0 is extremely low where $V(2) < \infty$, then the expected payoff from R&D activity would not be large enough to recoup the whole R&D activity cost, which results in the socially optimal site portfolio being involved in no R&D activity, as depicted by the white polygons in the bottom left corner in Figure III.1 and Figure III.2.[16] Especially, the polygons represent the set of (p_1^0, p_2^0) such that for given c and π,

$$V((S_1, S_2)) = (p_1^0 + p_2^0)\pi V(1) - 2c \leq 0 \text{ and} \tag{III.8}$$

$$V((S_l, S_l)) = p_l^0 \pi(2-\pi)V(2) - 2c \leq 0 \text{ for } l \in \{1, 2\}. \tag{III.9}$$

[15] Notice that $\widetilde{V}(2)_{\{v(2)=v(1)\}} \geq \widetilde{V}(2)$ with equality holding for $v(2) = v(1)$. So, whenever $V(2)$ is big enough to have no P_{12} without production externality, P_{12} is also empty with production externality.

[16] One might think of the situation that production activity only, not engaging in R&D activity could increase the payoff. For example, without R&D additivity, the social payoff from production activity only would be $2v(2) > 0$ if the firms choose the same site. But with the assumption that the two activities are inseparable, production activity only is not an option in our model.

But with production externality, such area of "no R&D activity" would be smaller. Especially, if production externality is big enough to recoup the whole R&D activity cost, the area of "no R&D activity" disappears as in Figure III.1 and in Figure III.2, which implies that duplication in site choice plays a role of a reservation choice available to firms when the separate R&D activity is likely not to pay off due to low probability of treasures being buried in the site. Such role of duplication in site choice as a reservation choice is summarized in Claim 5.

Claim 5 *For given $V(2)$,*
(1) without production externality, it's socially optimal for firms not to engage in R&D for (p_0^1, p_0^2) such that the condition (III.8) and the condition (III.9) are satisfied ;
(2) with production externality, as $v(2)$ grows, the set of (p_0^1, p_0^2) such that the condition (III.8) and the condition (III.9) are satisfied shrinks. If $v(2) \geq c$, there doesn't exist the set of (p_0^1, p_0^2) for which R&D isn't efficient.

Proof. See the Appendix. ■

Claim 5 implies that with production externality big enough, the duplication in site choice can be a reservation choice in R&D for low (p_0^1, p_0^2) for which the choice of no R&D would be optimal without production externality.

III.3.2 Two period game

In this section we first examine the socially optimal site choice in every possible subgame that firms may face at the beginning of the second period. By taking into account the expected payoffs of all the subgames and the probability of each subgame being played we can find the socially optimal search plan for each initial beliefs (p_1^0, p_2^0) over the two periods. Now denote by $p_l(t) \in (0, 1]$ with $l \in \{1, 2\}$ for $t = 1, 2$ the belief on treasures being buried in S_l at the beginning of the period t. Then, by the definition of the initial beliefs, $(p_1(1), p_2(1)) = (p_1^0, p_2^0)$ for $t = 1$. But, for $t = 2$, $p_l(2) \in \{p_l^0, p_l^1, p_l^2\}$ with $l \in \{1, 2\}$ depending on the history of the first period.

III.3.2.1 Optimal site portfolio in each subgame

In this section we explore the socially optimal site portfolio in each subgame where the optimal site portfolio depends on $(p_1(2), p_2(2))$. Then, since $(p_1(2), p_2(2))$ in turn depends on (p_1^0, p_2^0) according to the Bayesian updating rule, we can find the set of (p_1^0, p_2^0) for which the corresponding socially optimal site portfolio is assigned in each subgame. The characterization of the efficient site portfolio in each subgame in terms of (p_1^0, p_2^0) will be used to construct the two period payoff function, by which we can examine what the efficient site portfolio in the first period of the two period game for each (p_1^0, p_2^0) is.

III.3.2.1.1 Subgame following (S_l^s, S_k^s) or (S_l^s, S_l^s)

If the site choice in the first period was differentiation($l \neq k$) and the result is (S_l^s, S_k^s), that is, both firms succeeded in R&D, then the treasures turned out to be buried in both sites, so the set of the beliefs will be updated to $(p_1(2), p_2(2)) = (1, 1)$ at the beginning of the second period. If the site choice in the first period was duplication and the result is (S_l^s, S_l^s), then since the R&D experimentation was done on only S_l and it reveals that treasures are buried in S_l, the set of the beliefs will be updated to $(p_l(2), p_k(2)) = (1, p_k^0)$ with $l \neq k$ at the beginning of the second period.

However, since switching costs is prohibitively high when firms succeeded in R&D in the first period, no switching in site choice will occur at the beginning of the second period and both firms continue to choose the same site that each chose in the first period. Then, given the success in R&D in the first period, the social payoff in the second period is $V(2) + 2v(2)$ following (S_l^s, S_l^s) and $2V(1)$ following (S_l^s, S_k^s) respectively.

III.3.2.1.2 Subgame following (S_l^f, S_k^f) and (S_l^f, S_l^f)

In this subgame, the firms face the same situation that the firms had at the beginning of the first period except that the set of the beliefs will be updated to $(p_1(2), p_2(2)) = (p_1^1, p_2^1)$ following (S_l^f, S_k^f) with $l \neq k$ and updated to $(p_l(2), p_k(2)) = (p_l^2, p_k^0)$ following (S_l^f, S_l^f) with $l \neq k$ respectively.

Hence the problem that the social planner should solve at the beginning of the second period is the same problem in the one period game with the relevant updated set of the posterior beliefs as follows.

$$max\{V((S_1, S_1); (p_1(2), p_2(2))), V((S_1, S_2); (p_1(2), p_2(2))), V((S_2, S_2); (p_1(2), p_2(2)))\},$$

$$\text{where } (p_1(2), p_2(2)) = \begin{cases} (p_1^1, p_2^1) \text{ following } (S_l^f, S_k^f) & \text{with } l \neq k; \\ (p_l^2, p_k^0) \text{ following } (S_l^f, S_l^f) & \text{with } l \neq k. \end{cases}$$

First consider the subgame following (S_l^f, S_k^f). When each R&D experiment in the different sites fails in the first period, the social planner would continue to choose the different sites in the second period rather than choosing the same site S_l if the updated beliefs on treasures being buried in each site satisfies the condition that

$$\begin{aligned} V((S_1, S_2); (p_1^1, p_2^1)) &\geq V((S_l, S_l); (p_1^1, p_2^1))) \\ \Longleftrightarrow \qquad p_k^1 &\geq p_l^1[(2-\pi)V(2) - 1] + \frac{2c}{\pi} \text{ for } l \neq k.^{17} \end{aligned} \qquad \text{(III.10)}$$

Then, since

$$p_l^1 = \frac{p_l^0(1-\pi)}{1-p_l^0\pi} \text{ for } l \in \{1,2\},$$

we can compute the set of (p_1^0, p_2^0) satisfying the condition (III.10), which boils down to the condition that

$$p_k^0 \geq \frac{\pi p_l^0(1-\pi)[(2-\pi)V(2)-1] + 2v(2)(1-p_l^0\pi)}{\pi\{(1-p_l^0\pi)(1-\pi) + \pi p_l^0(1-\pi)[(2-\pi)V(2)-1] + 2v(2)(1-p_l^0\pi)\}}.$$

Now notice that $p_l^1 \geq p_k^1$ iff $p_l^0 \geq p_k^0$. Hence if $p_l^0 \geq p_k^0$ and the history of search in the first period is (S_l^f, S_k^f), then the optimal site choice in the second period should be either (S_l, S_k) or (S_l, S_l) since $V((S_l, S_l); (p_1(1), p_2(1))) \geq V((S_k, S_k); (p_1(1), p_2(1)))$ due to $p_l^1 \geq p_k^1$. The socially optimal site choice in the subgame following (S_l^f, S_k^f) is summarized in Lemma 5.

Lemma 5 *Suppose $p_l^0 > p_k^0$ with $l \neq k$. Then, after the history of (S_l^f, S_k^f), the socially optimal site choice in the second period is*

$$\begin{array}{ll} (S_l, S_k) & \text{if } p_k^0 \geq \frac{\pi p_l^0(1-\pi)[(2-\pi)V(2)-1]+2v(2)(1-p_l^0\pi)}{\pi\{(1-p_l^0\pi)(1-\pi)+\pi p_l^0(1-\pi)[(2-\pi)V(2)-1]+2v(2)(1-p_l^0\pi)\}}; \\ (S_l, S_l) & \text{otherwise.} \end{array} \tag{III.11}$$

Next consider the subgame following (S_l^f, S_l^f). When both R&D experiments in the same site S_l fail in the first period, the set of the updated beliefs is (p_l^2, p_k^0) where $p_l^2 < p_l^1 < p_l^0$. Then, the socially optimal site choice for each $(p_1(2), p_2(2))$ should solve

$$max\{V((S_1, S_2); (p_l^2, p_k^0)), V((S_l, S_l); (p_l^2, p_k^0))\} \text{ for } l \in \{1,2\}.$$

The socially optimal site portfolio following the history of (S_l^f, S_l^f) is summarized in Lemma 6.

Lemma 6 *Suppose that both firms fail in R&D at the same site S_l in the first period. Then, the socially optimal site portfolio in the second period is*

$$\begin{array}{ll} (S_l, S_l) & \text{if } p_k^0 < min\{\frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2+(1-p_l^0)}, \frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2+(1-p_l^0)}[(2-\pi)V(2)-1] + \frac{2v(2)}{\pi}\}; \\ (S_k, S_k) & \text{if } p_k^0 > max\{\frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2+(1-p_l^0)}, \frac{\frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2+(1-p_l^0)}\pi - 2v(2)}{\pi[(2-\pi)V(2)-1]}\}; \\ (S_l, S_k) & \text{Otherwise.} \end{array} \tag{III.12}$$

Proof. See the Appendix. ■

III.3.2.1.3 Subgame following (S_l^s, S_k^f) or (S_l^f, S_k^s)

In the subgame following (S_l^s, S_k^f), the beliefs are updated to be $(p_l(2), p_k(2)) = (1, p_k^1)$ and the site choice problem remains only for the firm B in the second period since the firm A has to continue to choose the site S_l. In the subgame following (S_l^f, S_k^s) with $l \neq k$, the posterior beliefs are updated to be $(p_l(2), p_k(2)) = (p_l^1, 1)$ and the site choice problem remains only for the firm A in the second period since the firm B has to continue to choose the site S_k. Suppose that the history of search in the first period is (S_1^s, S_2^f). Then, the social planner's problem at the beginning of the second period is

$$\begin{aligned}
max_{\{s_1,s_B\}}\{V((S_1,S_1);(p_1(2),p_2(2))), \quad & V((S_1,S_2);(p_1(2),p_2(2)))\}, \\
\text{where } (p_1(2),p_2(2)) &= (1,p_2^1), \\
V((S_1,S_1);(p_1(2),p_2(2))) &= \{p_1(2)[\pi V(2)+(1-\pi)V(2)]+2v(2)-c\} \\
&= V(2)+v(2) \text{ and} \\
V((S_1,S_2);(p_1(2),p_2(2))) &= \{p_1(2)[V(1)]+v(1)\}+\{p_2(2)\pi[V(1)]+v(1)-c\} \\
&= 1+p_2^1\pi-c.
\end{aligned}$$

Now suppose that the firm B switches its site to investigate in the second period from S_2 to S_1. Then, since the firm A's R&D in S_1 was already successful in the first period, the R&D-related social payoff is $V(2)$ regardless of whether the firm B's R&D in the second period is successful or not. Given the firm A's preceding R&D success in S_1, the social contribution of the firm B's R&D activity comes not from its R&D success but from its creating network externality by choosing the same site. Hence it follows that the social planner solves

$$\begin{aligned}
&max\{V(2)+v(2), V(1)+p_2^1\pi-c\} \text{ following } (S_1^s, S_2^f) \text{ and} \\
&max\{V(1)+p_1^1\pi-c, V(2)+v(2)\} \text{ following } (S_1^f, S_2^s).
\end{aligned}$$

The socially optimal site choice in the second period after the history of (S_l^s, S_k^f) is summarized in Lemma 7.

Lemma 7 *Suppose $p_l^0 > p_k^0$ with $l \neq k$. Then, after the history of (S_l^s, S_k^f), the socially optimal site choice in the second period is*

$$\begin{array}{ll} (S_l, S_k) & \text{if } p_k^0 > \frac{V(2)-1+2v(2)}{\pi[V(2)+2v(2)-\pi]}; \\ (S_l, S_l) & \text{otherwise.} \end{array} \tag{III.13}$$

III.3.2.1.4 Subgame following (S_l^s, S_l^f) or (S_l^f, S_l^s)

Suppose the history of search in the first period is (S_l^s, S_l^f). Then, the site choice problem remains only with the firm B and especially the social planner needs to solve

$$max[V(2) + 2v(2), V(1) + p_k(2)\pi V(1) - c].$$

Then, since we have $(p_l(2), p_k(2)) = (1, p_k^0)$, we have Lemma 8 on the socially optimal site choice in the second period after (S_l^s, S_l^f).

Lemma 8 *After the history of (S_l^s, S_l^f), the socially optimal site choice in the second period is*

$$\begin{array}{ll} (S_l, S_k) & \text{if } p_k^0 > \frac{V(2)-1+v(2)}{\pi}; \\ (S_l, S_l) & \text{otherwise.} \end{array} \tag{III.14}$$

III.3.2.2 Optimal site choice in the first period

Now we investigate the optimal site choice in the first period when all the subgames in the second period are take into account. For each (p_1^0, p_2^0), the socially optimal site choice is

$$\begin{aligned} & argmax\{W((S_1,S_2);(p_1^0,p_2^0)), W((S_1,S_1);(p_1^0,p_2^0)), W((S_2,S_2);(p_1^0,p_2^0))\} \\ = & \begin{cases} argmax\{W((S_1,S_2);(p_1^0,p_2^0)), W((S_1,S_1);(p_1^0,p_2^0))\} & \text{if } p_1^0 > p_2^0 \\ argmax\{W((S_1,S_2);(p_1^0,p_2^0)), W((S_2,S_2);(p_1^0,p_2^0))\} & \text{if } p_1^0 < p_2^0. \end{cases} \end{aligned} \tag{III.15}$$

The equality in the equation (III.15) follows from the fact that the firms and the sites are symmetric. Using such symmetry, hereafter our analysis focuses only on the case with $p_1^0 \geq p_2^0$ for the most of the discussions for simplicity and apply it to the result of the case with $p_1^0 < p_2^0$.

III.3.2.2.1 Total expected social payoff from differentiation in site choice in the first period

First we examine $W((S_1, S_2); (p_1^0, p_2^0))$, the total social expected payoff over the two periods when the set of the initial beliefs is (p_1^0, p_2^0) and the firms choose the different sties in the first period. Denote by $V^*((\cdot,\cdot); (p_1(2), p_2(2)))$ the maximized second period social payoff where the firms' site choice in the second period is socially optimal for the given history of search in the first period and $(p_1(2), p_2(2))$ the set of updated posterior beliefs. Then, given the payoffs in each subgame, $W((S_1, S_2); (p_1^0, p_2^0))$ can be expressed as

$$\begin{aligned} W((S_1,S_2);(p_1^0,p_2^0)) = & -2c + (p_1^0\pi)(p_2^0\pi)\{[2V(1)+2v(1)] + [2V(1)+2v(1)]\} \\ & + p_1^0\pi(1-p_2^0\pi)\{[V(1)+2v(1)] + [V^*((S_1,\cdot);(1,p_2^1))]\} \\ & + p_2^0\pi(1-p_1^0\pi)\{[V(1)+2v(1)] + [V^*((\cdot,S_2);(p_1^1,1))]\} \\ & + (1-p_1^0\pi)(1-p_2^0\pi)\{[2v(1)] + [V^*((\cdot,\cdot);(p_1^1,p_2^1))]\}, \text{ where} \end{aligned} \tag{III.16}$$

$$
\begin{aligned}
V^*((S_1,\cdot);(1,p_2^1)) &= max\{V(2)+2v(2)-c, V(1)+v(1)+p_2^1\pi V(1)+v(1)-c\}\ ; \\
V^*((\cdot,S_2);(p_1^1,1)) &= max\{V(2)+2v(2)-c, V(1)+v(1)+p_1^1\pi V(1)+v(1)-c\}\ ; \\
V^*((\cdot,\cdot);(p_1^1,p_2^1)) &= max\{V((S_1,S_2);(p_1^1,p_2^1)), V((S_1,S_1);(p_1^1,p_2^1)), V((S_2,S_2);(p_1^1,p_2^1))\}
\end{aligned}
$$

Each curly bracket corresponds to the different subgame where the coefficient before each curly bracket is the probability that each subgame is reached. The payoff in each curly bracket include all the payoffs which are realized from the end of the first period through the end of the second period. It consists of the two parts where the payoff in the first square bracket corresponds to the sure payoff in the first period given the corresponding subgame and the payoff in the second square bracket corresponds to the expected (net) payoff in the second period from the socially optimal site choice for the given corresponding subgame.

III.3.2.2.2 Total expected social payoff from duplication in site choice

Next we examine $W((S_l,S_l);(p_1^0,p_2^0))$, the total social expected payoff over the two periods when the set of the initial beliefs is (p_1^0,p_2^0) and the firms choose the same site in the first period. Then, given the payoffs in each subgame, $W((S_1,S_1);(p_1^0,p_2^0))$ can be expressed as

$$
\begin{aligned}
W((S_1,S_1);(p_1^0,p_2^0)) = -2c &+ p_1^0\pi^2\{[V(2)+2v(2)]+[V(2)+2v(2)]\} \\
&+ p_1^0\pi(1-\pi)\{[V(2)+2v(2)]+[V^*((S_1,\cdot);(1,p_k^0))]\} \\
&+ p_1^0(1-\pi)\pi\{[V(2)+2v(2)]+[V^*((\cdot,S_1);(1,p_k^0))]\} \\
&+ [p_1^0(1-\pi)^2+(1-p_1^0)]\{[2v(2)]+[V^*((\cdot,\cdot);(1,p_k^0))]\},\ \text{where}
\end{aligned}
\tag{III.17}
$$

$$
\begin{aligned}
V^*((S_1,\cdot);(1,p_k^0)) &= max\{V(2)+2v(2)-c, V(1)+v(1)+p_2^0\pi V(1)+v(1)-c\} \\
V^*((\cdot,S_1);(1,p_k^0)) &= max\{V(2)+2v(2)-c, V(1)++v(1)+p_2^0\pi V(1)+v(1)-c\} \\
V^*((\cdot,\cdot);(1,p_k^0)) &= max\{V((S_1,S_2);(p_1^2,p_2^0)), V((S_1,S_1);(p_1^2,p_2^0)), V((S_2,S_2);(p_1^2,p_2^0))\}.
\end{aligned}
$$

III.3.2.3 Numerical Analysis

In this subsection we explore the non-myopia of the social optimum. To compare the social optimum in the one period game to the social optimum in the two period game, we need to define $P_{12}^{(2)}$ as the set of (p_1^0,p_2^0) for which

$$W((S_1,S_2);(p_1^0,p_2^0)) \geq W((S_l,S_l);(p_1^0,p_2^0)) \text{ with } l\in\{1,2\}.$$

We define $P_{ll}^{(2)}$ with $l\in\{1,2\}$ similarly. Then, if $P_{12}^{(2)} \neq P_{12}$ (or equivalently $P_{ll}^{(2)} \neq P_{ll}$ with $l\in\{1,2\}$), the social optimum would be not myopic. However, notice that the comparison between

$P_{12}^{(2)}$ and P_{12} requires the calculation of $W((S_1, S_2); (p_1^0, p_2^0))$ and $W((S_l, S_l); (p_1^0, p_2^0))$ where each of $W((S_1, S_2); (p_1^0, p_2^0))$ and $W((S_l, S_l); (p_1^0, p_2^0))$ with $l \in \{1, 2\}$ have 4 subgames with each subgame having up to 3 possible outcomes, which implies that the comparison between $P_{12}^{(2)}$ and P_{12} for all the subset of $\mathcal{P}$ requires the calculation for more than 60 different cases. So, the closed-form solution to capture the non-myopia of the social optimum would be neither tractable nor attainable. Hence we conduct a numerical analysis for notable numerical examples from which we draw the result on the non-myopia in the social optimum.[18]

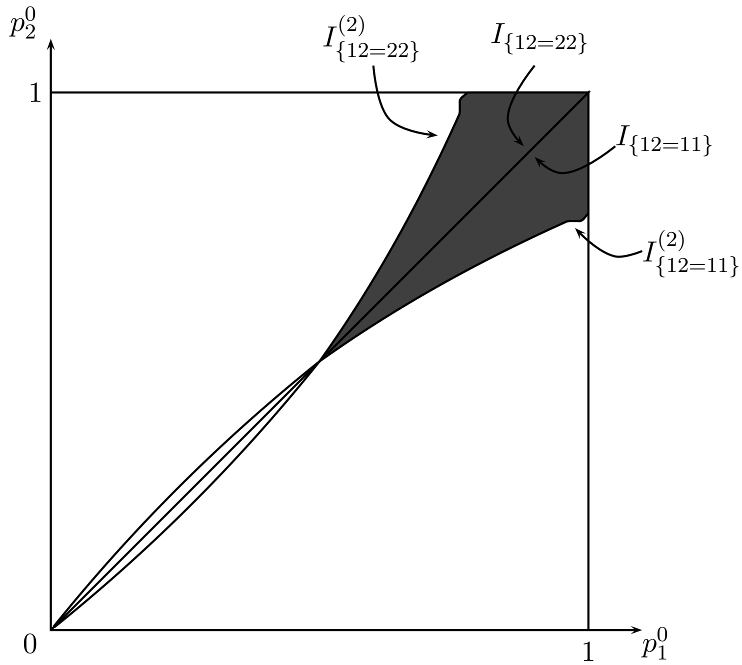

Figure III.5: Non-myopia in the first period efficient site choice in the two period game without production externality : $V(2) = \widetilde{V}(2)_{\{v(2)=v(1)\}}$

III.3.2.3.1 The case without production externality

For ease of exposition, we assume that R&D activity is always desirable, which relieves us of the discussion of the option of "no R&D". Also we focus only on the case of $V(2) \leq \widetilde{V}(2)_{\{v(2)=v(1)\}}$ without production externality and the case of $V(2) \leq \widetilde{V}(2)$ with production externality, for which

[18] The numerical analysis was conducted using Mathematica and the program code is available upon request.

there may occur diverse kinds of inefficient site choice in the equilibrium.[19]

Now consider Figure III.5 where compatibility externality in the reward from R&D success is such that $\widetilde{V}(2)_{\{v(2)=v(1)\}}$ so that the $I_{\{12=11\}}$ line and the $I_{\{12=22\}}$ line overlap because both indifference lines have the slope of 1.[20] First we denote by $I^{(2)}_{\{12=11\}}$ and $I^{(2)}_{\{12=22\}}$ the social planner's indifference curves between the relevant site choices in the first period where the expected payoff in the second period is taken into account. Since both the total social payoff from duplication in site choice and that from differentiation in site choice are non-linear in (p^0_1, p^0_2) as clear from equation (III.16) and equation (III.17), one can see that $I^{(2)}_{\{12=11\}}$ and $I^{(2)}_{\{12=22\}}$ are curves, while $I_{\{12=11\}}$ and $I_{\{12=22\}}$ are straight lines. In this case P_{12} is the set of (p^0_1, p^0_2) which constitute the straight line from $(0, 0)$ to $(1, 1)$. But, notice that $I^{(2)}_{\{12=11\}}$ and $I^{(2)}_{\{12=22\}}$ intersect at some (p^0_1, p^0_2) with $p^0_1 = p^0_2 < 1$ so that the interior set of $P^{(2)}_{12}$(dark gray area) is nonempty especially for the set of (p^0_1, p^0_2) where both beliefs are very high as shown in Figure III.5. Hence, such difference in the socially optimal site choice in the one period game and that in the first period of the two period game shows that $P_{12} \neq P^{(2)}_{12}$, implying that the social optimum is non-myopic. Especially it involves more differentiation in site choice when the 2nd period is taken into account. This result follows from the fact that the slope of $I^{(2)}_{\{12=11\}}(I^{(2)}_{\{12=22\}})$ is decreasing(increasing) in $p^0_1(p^0_2)$ for most of $p^0_1(p^0_2)$, implying the benefit of experimentation is greater relative to the cost of experimentation as the belief on treasures being buried in the site both firms' investigating is higher.

Now consider Figure III.6 in which compatibility benefit from R&D success is small that $V(2) < V(2)_{\{v(2)=v(1)\}}$.[21] In this figure, the clear difference is found for the set of (p^0_1, p^0_2) where either of two initial beliefs are high enough. For such beliefs the socially optimal site choice in the first period is differentiation in the two period game, while duplication in site choice is efficient in the one period game. The result is very intuitive in that in the two period game the firm whose R&D was unsuccessful in the first period can investigate the site in which the other firm's R&D was successful where such switching to the site in which R&D was successful is more efficient than in the first period since now the uncertainty regarding the site is resolved(i.e., treasures are certain to be buried). In this case, the expected benefit of experimentation is high enough for the social optimum to involve differentiation when the expected payoff in the second period enters the social planner's payoff function. But, one can see that the reverse phenomenon occurs for the set of

[19] For low enough θ with not big enough compatibility benefit, there may exist some set of (p^0_1, p^0_2) for which over-differentiation may occur as in the one period game(See Proposition 11 and Proposition 13). But, such case is similar to the case with low θ when $V(2) \leq \widetilde{V}(2)_{\{v(2)=v(1)\}}$ without production externality or $V(2) < \widetilde{V}(2)$ with production externality, so we omit the analysis of such cases.

[20] In the numerical example shown in Figure III.5 we have $\pi = .8$, from which $\widetilde{V}(2)_{\{v(2)=v(1)\}} \equiv \frac{2}{2-\pi} = 5/3$.

[21] In the numerical example shown in Figure III.6, we have $\pi = .8$ and $V(2) = 1.4 < 5/3 = V(2)_{\{v(2)=v(1)\}}$.

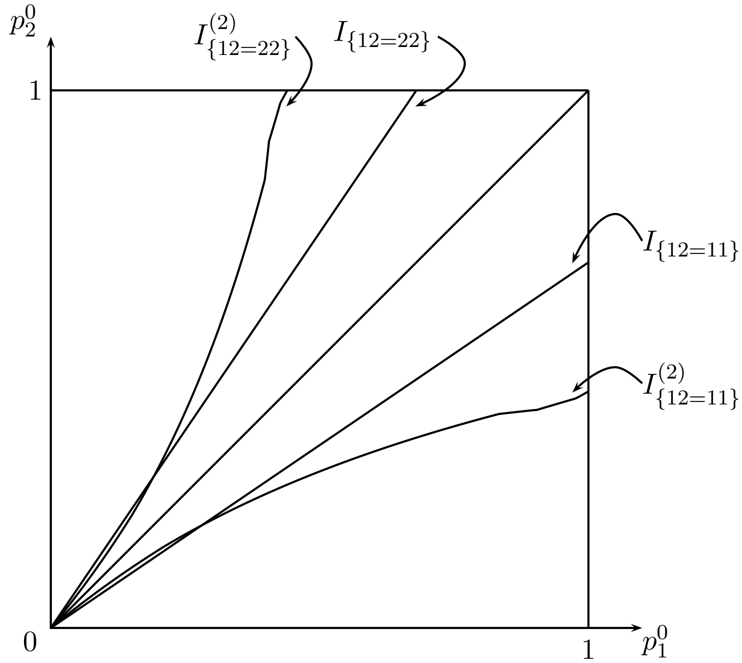

Figure III.6: Non-myopia in site choice in the Social Optimum of the two period game without production externality : $V(2) < V(2)_{\{v(2)=v(1)\}}$

(p_1^0, p_2^0) such that both initial beliefs are very low and very alike in their values. Such result is also very intuitive in that when it's very likely for neither firm to succeed in each site where two beliefs are much alike in their values, the expected benefit from differentiation in site choice is not big that duplication in site choice is socially optimal.

III.3.2.3.2 The case with production externality

The pattern of non-myopia in the social optimum in the two period game with production externality is very similar to the case without production externality. First consider Figure III.7 where $V(2) = \widetilde{V}(2)$. Recall from the definition of $\widetilde{V}(2)$ that $I_{\{12=11\}}$ and $I_{\{12=22\}}$ are straight lines and $P_{12} = \{(1,1)\}$ if $V(2) = \widetilde{V}(2)$. But as shown in the figure $I^{(2)}_{\{12=11\}}$ and $I^{(2)}_{\{12=22\}}$ are curves and intersect at some (p_1^0, p_2^0) with $p_1^0 = p_2^0 < 1$ so that the interior set of $P^{(2)}_{12}$ which is depicted as dark gray area is nonempty. Now consider Figure III.8 where $V(2) < \widetilde{V}(2)$. In the figure, the first period site choice in the two period game may involves differentiation in site choice for a larger set

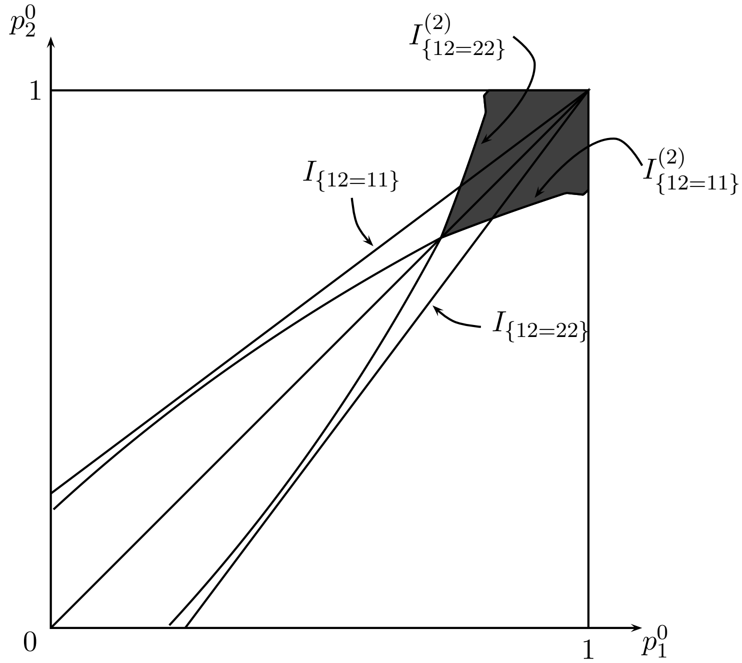

Figure III.7: Non-myopia in site choice in the Social Optimum of the two period game with production externality : $V(2) = \widetilde{V}(2)$

of (p_1^0, p_2^0) than in the one period game.

Then, the discussion hitherto regarding the non-myopia in the social optimum can be summarized in Claim 6 and Result 3.

Claim 6 *In the social optimum of the two period game $P_{12} \neq P_{12}^{(2)}$ and $P_{ll} \neq P_{ll}^{(2)}$ with $l \in \{1, 2\}$, implying that the social planner is non-myopic.*

Even though we don't have a closed-form solution but we still may draw the following result from our numerical analysis.

Result 3 *In the social optimum of the two period game both in the case with production externality and the case without production externality*
(1) most of P_{12} is included in $P_{12}^{(2)}$, implying that generally the first period site choice in the two period game involves more differentiation than in the one period game ;
(2) but there may exist some set of (p_1^0, p_2^0) with both beliefs being very low for which the first period

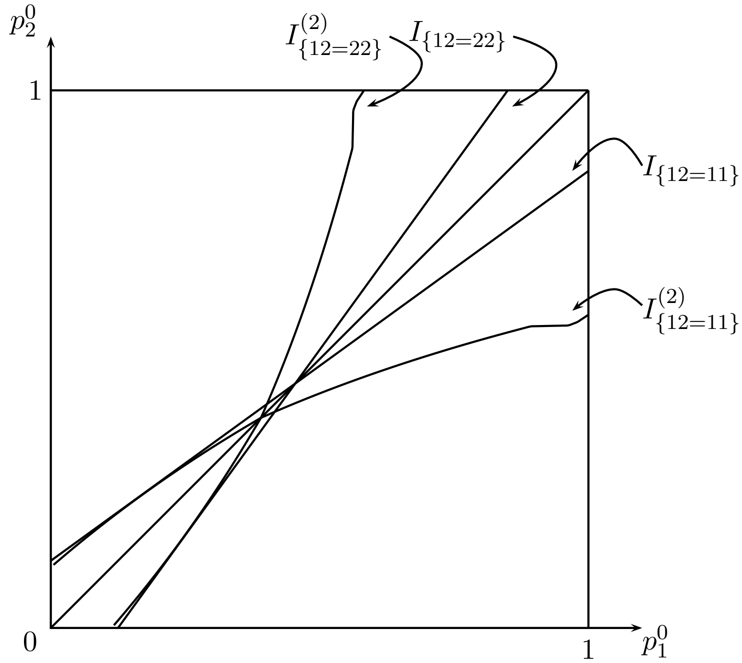

Figure III.8: Non-myopia in site choice in the Social Optimum of the two period game with production externality : $V(2) < \widetilde{V}(2)$

socially optimal site choice is duplication, while differentiation in site choice is socially optimal in the one period game.

III.4 Noncooperative Game

In this section, we examine the firms' equilibrium site choice where the firms don't take into account its effect on the rival firm's payoff when they choose the site to investigate. First, we examine the firms' equilibrium site choice in the one period game as a benchmark.

III.4.1 One period game

III.4.1.1 Characterization of Equilibrium

In the one period game, the firm i' expected payoff given the rival firm's choice of S_l and the set of initial beliefs (p_1^0, p_2^0) is

$$\begin{aligned} max_{S_i \in \{S_A, S_B\}} V_i((S_A, S_B);(p_1^0, p_2^0)) \quad & \text{for} \quad i \in \{A, B\},\ l,k \in \{1,2\} \text{ with } l \neq k, \\ \text{where } V_i((S_l, S_l);(p_1^0, p_2^0)) \quad &= \quad p_l^0 \pi[(1-\pi) + \pi\theta]V(2) + v(2) - c \text{ with } \theta \in [0, 1/2] \\ \text{and } V_i((S_k, S_l);(p_1^0, p_2^0)) \quad &= \quad p_k^0 \pi V(1) + v(1) - c. \end{aligned}$$

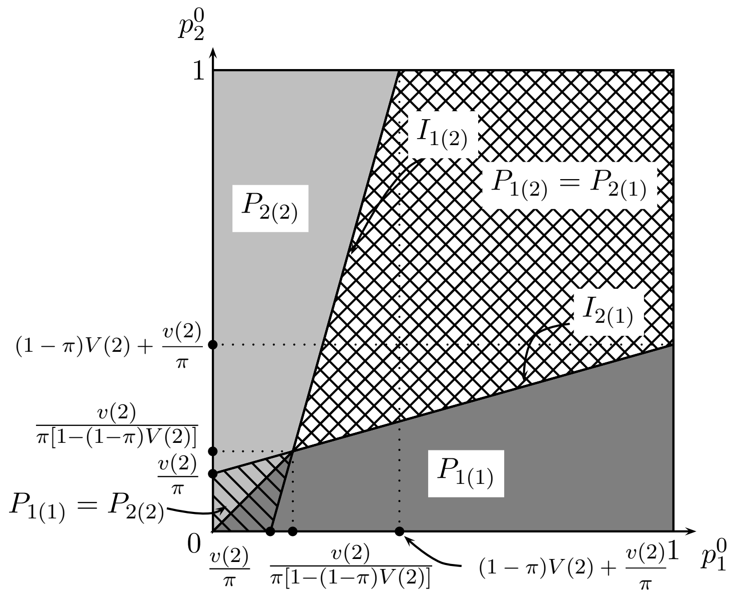

Figure III.9: Characterization of Nash equilibrium in the one period game : $\theta = 0$

Recall that with $\theta = 0$ firms play a Bertrand game in the prospective product market when the firms make a simultaneous discovery following duplication in site choice, while with $\theta = 1/2$ the firms paly an equal sharing game in the prospective product market. Now denote by $P_k(p_l^0) \subseteq \mathcal{P}_k$ with $l, k \in \{1,2\}$ and $l \neq k$ the set of p_k^0 such that for given p_l^0 and θ

$$V_B((S_l, S_k);(p_l^0, p_k^0)) \geq V_B((S_l, S_l);(p_l^0, p_k^0)) \text{ where } S_A = S_l.$$

Then, by definition of $P_k(p_l^0)$, for given p_l^0, θ and $S_A = S_l$,

$$V_B((S_l, S_k);(p_l^0, p_k^0)) < V_B((S_l, S_l);(p_l^0, p_k^0)) \text{ for } \forall\ p_k^0 \in \mathcal{P}_k \backslash P_k(p_l^0).$$

Now denote by $I_{k,\{p_l^0\}} \in P_k(p_l^0)$ a singleton of p_k^0 such that for given the rival firm's choice of S_l, the initial belief p_l^0 and θ,

$$\begin{aligned} V_B((S_l,S_k);(p_l^0,p_k^0)) &= V_B((S_l,S_l);(p_l^0,p_k^0)) \\ \Longleftrightarrow p_k^0\pi V(1)+v(1)-c &= p_l^0\pi[(1-\pi)+\pi\theta]V(2)+v(2)-c \\ \Longleftrightarrow \qquad p_k^0 &= p_l^0[1-(1-\theta)\pi]V(2)+\frac{v(2)}{\pi}. \end{aligned}$$

Then, we can construct $I_{k(l)} \subseteq \mathcal{P}$, the set of (p_k^0, p_l^0) such that

$$I_{k(l)} \equiv \{(I_{k,\{p_l^0\}}, p_l^0) | p_l^0 \in [0,1] \text{ for } l,k \in \{1,2\} \text{ with } l \neq k\}$$

where $I_{2(1)}$ is the set of (p_1^0, p_2^0) such that

$$p_2^0 = p_1^0[1-(1-\theta)\pi]V(2)+\frac{v(2)}{\pi}, \tag{III.18}$$

and $I_{1(2)}$ is the set of (p_1^0, p_2^0) such that

$$p_2^0 = \frac{\pi p_1^0 - v(2)}{\pi[1-(1-\theta)\pi]V(2)}. \tag{III.19}$$

Now denote by $P_{l(k)}$ with $l \neq k$ the set of (p_1^0, p_2^0) such that for given θ

$$V_i((S_l,S_k);(p_1^0,p_2^0)) \geq V_i((S_k,S_k);(p_1^0,p_2^0)),$$

where $P_{l(k)} = P_{k(l)}$ due to symmetry between the sites. Then, one can see that $P_{2(1)} = P_{1(2)}$ is the set of (p_1^0, p_2^0) such that for given θ

$$p_2^0 \geq p_1^0[1-(1-\theta)\pi]V(2)+\frac{v(2)}{\pi} \text{ and } p_2^0 \leq \frac{\pi p_1^0 - v(2)}{\pi[1-(1-\theta)\pi]V(2)}. \tag{III.20}$$

$P_{l(l)}$ with $l \in \{1,2\}$ is defined as the set of (p_1^0, p_2^0) such that for given θ

$$V_i((S_l,S_l);(p_1^0,p_2^0)) > V_i((S_k,S_l);(p_1^0,p_2^0)), \text{ which is satisfied when}$$

$$p_k^0 < p_l^0[1-(1-\theta)\pi]V(2)+\frac{v(2)}{\pi}. \tag{III.21}$$

Notice that the slope of $I_{2(1)}$ and $I_{1(2)}$ depend on θ, which in turn determines the configuration of $P_{2(1)}$ (and accordingly $P_{1(1)}$ and $P_{2(2)}$). Figure III.9 depicts one of the examples with the case of $\theta = 0$ and Figure III.10 depicts one of the examples with the case of $\theta = 1/2$.[22] One can see the clear difference in the size of $P_{1(2)}$ with $P_{1(2)} = P_{2(1)}$ between in Figure III.9 and in Figure III.10.

[22] Both Figure III.9 and Figure III.10 is based on the numerical example that

$$V(2) = 1.4,\ v(2) = c = 0.1,\ \pi = .8,\ v(1) = 0.$$

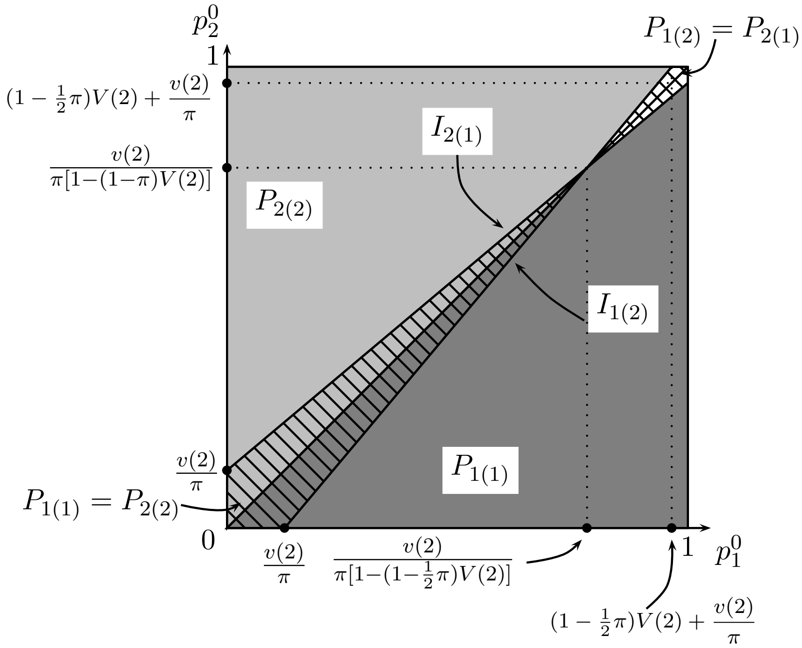

Figure III.10: Characterization of Nash equilibrium in the one period game : $\theta = 1/2$

In Figure III.9 with $\theta = 0$ corresponding to the Bertrand case, the firms have more incentive to differentiate in their site choice than in Figure III.10 with $\theta = 1/2$ corresponding to the equal sharing case, because the payoff from simultaneous discovery in the same site is zero in the Bertrand game while that in the equal sharing game is $\frac{1}{2}V(2)$, resulting in a larger set of $P_{1(2)}$ in the Bertrand game than in the equal sharing game.

How the characterization of the equilibrium depends on $V(2)$ for given $\theta \in [0, 1/2]$ is summarized in Claim 7.

Claim 7 *For given π, c and θ, let $\overline{V}(2)(\theta) \equiv \frac{\pi-c}{\pi[1-(1-\theta)\pi]}$. Then,*
(1) if $V(2) \leq \overline{V}(2)(\theta)$, as $V(2)$ is greater, $P_{1(1)}$ and $P_{2(2)}$ get bigger in their sizes, while $P_{1(2)}$ and $P_{2(1)}$ with $P_{1(2)} = P_{2(1)}$ gets smaller in its size.
(2) if $V(2) > \overline{V}(2)(\theta)$, $P_{l(k)}$ with $l \neq k$ is empty.
(3) With $v(2) = c$, as c is higher, $P_{1(1)}$ and $P_{2(2)}$ get bigger in their sizes, while $P_{1(2)}$ and $P_{2(1)}$ with $P_{1(2)} = P_{2(1)}$ gets smaller in its size.

Proof. See the Appendix. ■

The result of Claim 7 is straightforward in that for given θ the second mover finds it profitable to choose the same site chosen by the first mover for a larger set of (p_1^0, p_2^0) as the magnitude of compatibility benefit grows. Further for given θ there should be a certain threshold over which for $\forall$ $(p_1^0, p_2^0) \in \mathcal{P}$, only duplication in site choice occurs in the equilibrium where we denote it by $\overline{V}(2)(\theta)$.

III.4.1.2 Efficiency of equilibrium : when there's no production externality ($c > v(2) = v(1)$)

Now we examine whether the equilibrium coincides to the social optimum for each (p_1^0, p_2^0). First recall that the firm's expected payoff from duplication in site choice depends on how competitive the prospective product market is, which is expressed by the magnitude of θ with $\theta \in [0, 1/2]$. To highlight the effect of θ, first we consider the case with no production externality.

Given symmetry between the sites, notice that the inefficiency involved in the equilibrium site choice can be visualized with the difference between P_{12} and $P_{l(k)}$ with $l \neq k$, which is determined by the difference between the slope of $I_{\{12=11\}}(I_{\{12=22\}})$ and the slope of $I_{2(1)}(I_{1(2)})$ when both curves have 0 for the values of the intercept without production externality. Now notice from the equation (III.19) and the equation (III.3) that the slope of $I_{1(2)}$ is $[(1-\pi) + \pi\theta]V(2)$, while the slope of $I_{\{12=11\}}$ is $[(2-\pi)V(2) - 1]$. For given $V(2)$, denote by $\theta^*_{\{v(2)=v(1)\}}(V(2))$ such that

$$\begin{aligned} [(1-\pi) + \pi\theta^*_{\{v(2)=v(1)\}}]V(2) &= [(2-\pi)V(2) - 1] \\ \Longleftrightarrow \qquad \theta^*_{\{v(2)=v(1)\}} &= \frac{V(2)-1}{\pi V(2)}, \end{aligned} \tag{III.22}$$

where $\theta^*_{\{v(2)=v(1)\}}(V(2))$ is increasing in $V(2)$.[23] Then, since the slope of $I_{1(2)}$ is increasing in θ, it's obvious that for $\forall$ $\theta > \theta^*_{\{v(2)=v(1)\}}$, the firms have more incentive for duplication in site choice than the social planner, while for $\forall$ $\theta < \theta^*_{\{v(2)=v(1)\}}$, the firms have less incentive for duplication in site choice than the social planner. But, such difference in incentive for duplication between the firms and the social planner may not result in inefficient site choice if the difference in incentive for duplication is not big enough for the firms to change the site choice. Moreover, if compatibility benefit is big enough, then the socially optimal site choice only involves in duplication in site choice as discussed in more detail in the following.

III.4.1.2.1 The case that $V(2) \geq \widetilde{V}(2)_{\{v(2)=v(1)\}}$

When $V(2) \geq \widetilde{V}(2)_{\{v(2)=v(1)\}}$, the slope of $I_{\{12=11\}}(I_{\{12=22\}})$ is greater(smaller than) than 1, which results in no P_{12} as in Figure III.3. Hence, in this case the social optimum involves only duplication in site choice. Now consider the case that $\theta \geq \theta^*_{\{v(2)=v(1)\}}$. In this case, such excessive incentive

[23] Notice that for given $\pi \in (0, 1]$, $\theta^*_{\{v(2)=v(1)\}}(V(2))$ has one-to-one correspondence to $V(2)$ with $V(2) \in [1, \widetilde{V}(2)_{\{v(2)=v(1)\}}]$ where $\widetilde{V}(2)_{\{v(2)=v(1)\}} = \frac{2}{2-\pi}$.

for duplication in site choice doesn't cause any inefficiency because the only efficient site choice is duplication.

But, if $\theta < \theta^*_{\{v(2)=v(1)\}}$, then the under-duplication(or over-differentiation) in site choice may occur when $V(2)$ is not big enough as in the following. For given θ denote by $\overline{V}(2)_{\{v(2)=v(1)\}}(\theta)$ $V(2)$ such that

$$\overline{V}(2)_{\{v(2)=v(1)\}}(\theta) = \frac{1}{1-(1-\theta)\pi}, \tag{III.23}$$

where the slope of $I_{2(1)}$(and $I_{1(2)}$)is exactly 1 as $V(2) = \overline{V}(2)_{\{v(2)=v(1)\}}(\theta)$. Now notice that $\overline{V}(2)_{\{v(2)=v(1)\}}(\theta) \geq \widetilde{V}(2)_{\{v(2)=v(1)\}}$ for $\forall\ \theta \in [0, 1/2]$. Also notice that the slope of $I_{2(1)}$(and $I_{1(2)}$) is increasing(decreasing) in $V(2)$. Then, for given θ if $V(2)$ is greater than $\widetilde{V}(2)_{\{v(2)=v(1)\}}$ but smaller than $\overline{V}(2)_{\{v(2)=v(1)\}}(\theta)$, we have $P_{l(k)} \neq \emptyset$ with $l \neq k$, that is, there exists some set of (p^0_1, p^0_2) for which the firms chooses the different sites in the equilibrium, while the social planner always choose the same sites. But, if $V(2)$ is big enough that $V(2) > \overline{V}(2)_{\{v(2)=v(1)\}}(\theta)$, then the firms' equilibrium site choice is always duplication even when $\theta < \theta^*_{\{v(2)=v(1)\}}$ and there is no inefficiency in site choice in the equilibrium. This efficiency result follows from the fact that the incentive for duplication due to a big $V(2)$ with $V(2) > \overline{V}(2)_{\{v(2)=v(1)\}}(\theta)$ dominates over the incentive for over-differentiation due to low θ with $\theta < \theta^*_{\{v(2)=v(1)\}}$ where duplication in site choice is efficient.[24]

All the discussions hitherto on the equilibrium site choice without production externality when $V(2) \geq \widetilde{V}(2)_{\{v(2)=v(1)\}}$ is summarized in Proposition 11.

Proposition 11 *Suppose that $V(2) \geq \widetilde{V}(2)_{\{v(2)=v(1)\}}$ and there's no production externality. Then, for given θ in the Nash equilibrium of the one period game*
(1) if $V(2) \geq \overline{V}(2)_{\{v(2)=v(1)\}}(\theta)$, the the firms choose the same site, which is efficient ;
(2) if $V(2) \in [\widetilde{V}(2)_{\{v(2)=v(1)\}}, \overline{V}(2)_{\{v(2)=v(1)\}}(\theta)]$, the firms choose the same site for $\forall\ \theta \in [\theta^*_{\{v(2)=v(1)\}}, 1/2)$ which is efficient, while the firms choose different sites for $\forall\ \theta \in [0, \theta^*_{\{v(2)=v(1)\}})$ which is inefficient.

The first result of Proposition 11 implies that with big enough compatibility benefit, the firms find it profitable to duplicate in site choice regardless of how competitive the prospective product market is. Even in the Bertrand case where the reward from R&D success is completely dissipated away in the case of simultaneous discovery, the expected payoff from an exclusive discovery alone

[24] For example, even when $\theta = 0$ that the firms play Bertrand competition in the prospective product market, if $V(2) > \frac{1}{1-\pi} = \overline{V}(2)_{\{v(2)=v(1)\}}(0)$, then $P_{l(k)}$ with $l \neq k$ is empty, implying no inefficiency in site choice in the equilibrium.

is big enough to the the firms for $V(2) > \overline{V}(2)_{\{v(2)=v(1)\}}(0)$ so that the firms choose the same site in the equilibrium.[25]

The second result of Proposition 11 implies that if the magnitude of compatibility benefit is big enough that the social optimum involves only the duplication in site choice, but not big enough that the firms may choose the different site, then whether the equilibrium is efficient depends on the degree of the competitiveness of the prospective product market. Especially the under-duplication for θ with $\theta < \theta^*_{\{v(2)=v(1)\}}$ is the only inefficient site choice which may occur in the equilibrium.

III.4.1.2.2 The case that $1 \leq V(2) < \widetilde{V}(2)_{\{v(2)=v(1)\}}$

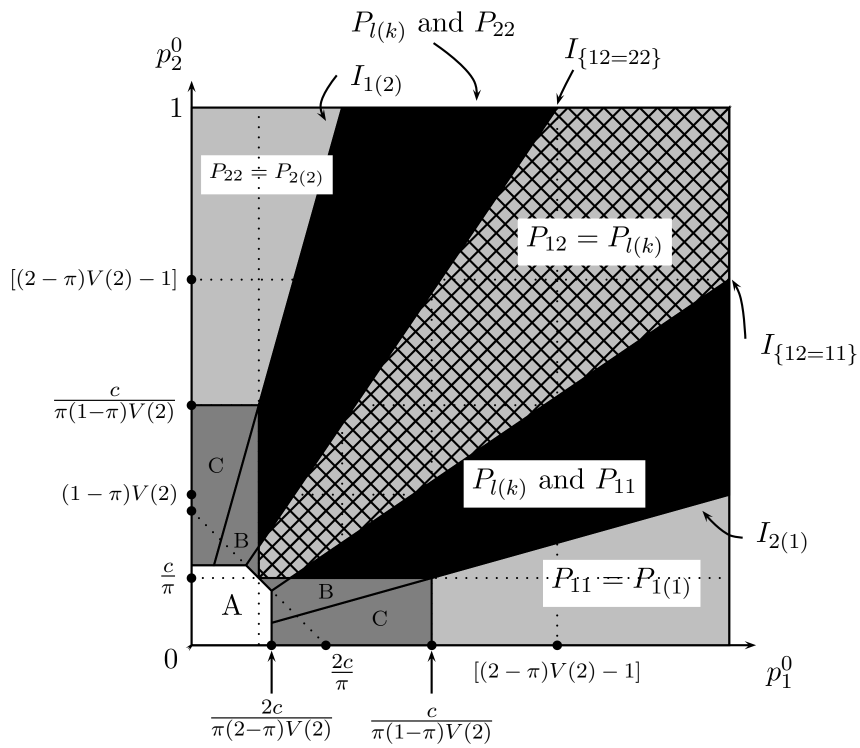

Figure III.11: Over-differentiation in the Nash equilibrium of the one period game without production externality : $\theta = 0$ (Bertrand R&D game)

In this case, we have $P_{12} \neq \emptyset$ so that for some (p_1^0, p_2^0) the social optimum may involve differentiation in site choice, which leaves open the possibility of over-duplication. Notice that unless

[25] This efficient site choice result with the discrepancy in incentive for duplication between the firms and the social planner is similar to the efficient risk choice result with the discrepancy in risk preference between the firms and the social planner in Bhattacharya and Mookherjee (1986). In both results, the incentive space is infinite but the action space is finite. So, small discrepancy in incentive between firms and a social planner isn't problematic where the equilibrium action is a kind of corner solution which is efficient.

$\theta \neq \theta^*_{\{v(2)=v(1)\}}$, $I_{\{12=11\}} \neq I_{2(1)}$ and $I_{\{12=22\}} \neq I_{1(2)}$, which causes inefficiency in the equilibrium for some set of (p_1^0, p_2^0). We examine how such inefficiency arises in the equilibrium for the case of $\theta < \theta^*_{\{v(2)=v(1)\}}$ and for the case of $\theta \geq \theta^*_{\{v(2)=v(1)\}}$ separately.

■ $\theta \in [0, \theta^*_{\{v(2)=v(1)\}})$ If $\theta < \theta^*_{\{v(2)=v(1)\}}$, then the firms have less incentive for duplication in site choice than the social planner, which results in over-differentiation. Recall that the difference in the incentives between the firms and the social planner is visualized by the difference in the slope between $I_{\{12=11\}}(I_{\{12=22\}})$ and $I_{2(1)}(I_{1(2)})$. Especially if $\theta < \theta^*_{\{v(2)=v(1)\}}$ so that the slope of $I_{2(1)}(I_{1(2)})$ is less(greater) than $I_{\{12=11\}}(I_{\{12=22\}})$, then the area for which the $I_{2(1)}(I_{1(2)})$ line lies below(above) $I_{\{12=11\}}(I_{\{12=22\}})$ is nonempty where it represents the set of (p_1^0, p_2^0) for which over-differentiation occurs. In Figure III.11 which is drawn for the case of Bertrand R&D game with $\theta = 0$, the two black areas represent the set of (p_1^0, p_2^0) for which over-differentiation occurs.[26] In the two black areas the socially optimal site choice is duplication but the firms choose different sites in the equilibrium. There are other areas for which the equilibrium site choice is different from the socially optimal site choice.[27] For (p_1^0, p_2^0) in the two dark gray areas named "C", the socially optimal site choice is duplication. Although the firms also prefer duplication to differentiation in site choice, the firms have a negative expected payoff from the R&D activity when they choose the same site. Then, eventually one firm who moves first will stay in business for R&D while the second mover finds it better to opt out of business.[28] For (p_1^0, p_2^0) in the two dark gray areas named "B", the firms prefer differentiation to duplication in site choice, while the socially optimal site choice is duplication. But, the firm which chooses the site later finds it to yield only a negative expected payoff from the R&D activity, leaving only the first mover in the market.[29] For (p_1^0, p_2^0) in the two tiny dark gray areas without any name, the socially optimal site choice is differentiation and the

[26] Figure III.11 is based on the previous numerical example when $\theta = 0$.

[27] Recall that the social planner has a lexicographic preference for both firms' staying in business. So a monopoly which could yield more expected payoff is not social optimal in our main model. However, without such assumption on the social planner's lexicographic preference, the areas of B, C and the tiny dark gray area without name are socially optimal as discussed in the section of Discussion.

[28] Notice that for given θ

$$\begin{aligned} & V_i(S_l, S_l; (p_1^0, p_2^0)) = p_l^0 \pi[1 - (1-\theta)\pi]V(2) - c > 0 \\ \iff \quad & p_l^0 > \frac{c}{\pi[1-(1-\theta)\pi]V(2)} \end{aligned}$$

of which condition is violated in the areas "C".

[29] Notice that for given θ

$$\begin{aligned} & V_i(S_l, S_k; (p_1^0, p_2^0)) = p_l^0 \pi V(1) - c > 0 \\ \iff \quad & p_l^0 > \frac{c}{\pi} \end{aligned}$$

of which condition is violated in the areas "B".

firms also prefer differentiation to duplication in site choice. But, since the reservation condition for differentiation in the footnote 29 is not met for the second mover, only the first mover engages in R&D, while the social planner's reservation condition for differentiation is met so that both firms engage in R&D in the different sites in the social optimum.

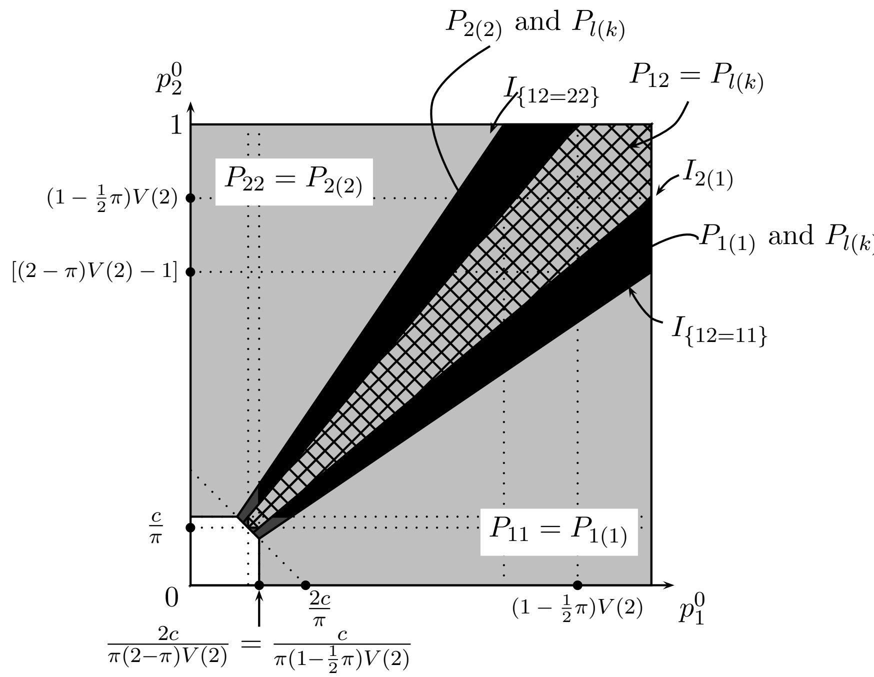

Figure III.12: Over-duplication in the Nash equilibrium of the one period game without production externality : $\theta = \frac{1}{2}$ (Equal sharing R&D game)

■ $\theta \in (\theta^*_{\{v(2)=v(1)\}}, 1/2]$ If $\theta > \theta^*_{\{v(2)=v(1)\}}$, then the firms have more incentive for duplication in site choice than the social planner, which results in over-duplication as shown in the black areas in Figure III.12. Besides the over-duplication, as shown by the dark gray area in the figure, the inefficiency involved in one firm's opting out of business occurs in this case too because of the discrepancy in the reservation condition between the second mover and the social planner.

All the discussions hitherto on the equilibrium site choice without production externality when $V(2) \leq \widetilde{V}(2)_{\{v(2)=v(1)\}}$ is summarized in Proposition 12.

Proposition 12 *Suppose that $V(2) \leq \widetilde{V}(2)_{\{v(2)=v(1)\}}$ and there's no production externality. Then, in the Nash equilibrium of the one period game*

(1) if $\theta < \theta^*_{\{v(2)=v(1)\}}$, as shown in Figure III.11, there exist the set of (p_1^0, p_2^0) for which there occurs over-differentiation, where it occurs for a larger set of (p_1^0, p_2^0) as θ approaches downward to 0. Also there exists the set of (p_1^0, p_2^0) for which monopoly occurs when duopoly is sustainable ;

(2) if $\theta > \theta^*_{\{v(2)=v(1)\}}$, as shown in Figure III.12, there exists the set of (p^0_1, p^0_2) for which there occurs over-duplication, where it occurs for a larger set of (p^0_1, p^0_2) as θ approaches upward to $1/2$ Also there exists the set of (p^0_1, p^0_2) for which monopoly occurs when duopoly is sustainable ;
(3) if $\theta = \theta^*_{\{v(2)=v(1)\}}$, there occurs neither over-differentiation nor over-duplication. But, there exists the set of (p^0_1, p^0_2) for which monopoly occurs when duopoly is sustainable.

Proof. See the Appendix. ■

The result in Proposition 12 shows that how much competitive in the prospective product market is influences the firms' site choice significantly when compatibility benefit is not big enough.

From Proposition 11 and Proposition 12 we can infer the effect of θ on the efficiency of the equilibrium as in the following corollary.

Corollary 4 *Suppose that there's no production externality. Then,*
(1) if $V(2) \geq \widetilde{V}(2)_{\{v(2)=v(1)\}}$, there occurs over-differentiation for a smaller set of θ as π increases ;
(2) if $V(2) < \widetilde{V}(2)_{\{v(2)=v(1)\}}$, there occurs over-duplication(over-differentiation) for a larger(smaller) set of θ as π increases.

Notice that $\theta^*_{\{v(2)=v(1)\}}$ decreases in π where $\theta^*_{\{v(2)=v(1)\}} \equiv \frac{V(2)-1}{\pi V(2)}$. With $\theta \in [0, 1/2]$, as $\theta^*_{\{v(2)=v(1)\}}$ decreases, it's obvious that there occurs over-duplication(over-differentiation) for a larger(smaller) set of θ because the set of $[0, \theta^*_{\{v(2)=v(1)\}}]$ is smaller and the set of $[\theta^*_{\{v(2)=v(1)\}}, 1/2]$ is bigger. Such result is also very intuitive in that it's more efficient for the two firms to choose the different sites when each firm is more likely to succeed in each site with higher π, which is represented by lower $\theta^*_{\{v(2)=v(1)\}}$.

III.4.1.3 Efficiency of equilibrium : when there's production externality ($c = v(2) > v(1)$)

Now we consider the case with production externality in which the duplication in site choice can be used as the firms' reservation choice so that the area of "no R&D" disappears. Recall that in the case without production externality most of the difference between the equilibrium site choice and the socially optimal site choice is visualized with the difference between P_{12} and $P_{l(k)}$ with $l \neq k$ where the difference between P_{12} and $P_{l(k)}$ with $l \neq k$ is determined by the difference between the slope of $I_{\{12=11\}}(I_{\{12=22\}})$ and the slope of $I_{2(1)}(I_{1(2)})$. But with production externality all the indifference lines have strictly positive intercepts where the $I_{\{12=11\}}$ line and $I_{2(1)}$ line (the $I_{\{12=22\}}$ line and the $I_{1(2)}$ line) are shifted up(down) by the value of its corresponding intercepts. But, since the $I_{\{12=11\}}$ line and the $I_{\{12=22\}}$ line have the intercept of $\frac{2c}{\pi}$ while the $I_{l(k)}$ lines with

$l \neq k$ have the intercept of $\frac{c}{\pi}$, the existence of the production externality which isn't internalized fully creates the incentive for under-duplication as shown in the following comparison between the equation of $I_{\{12=11\}}$ and that of $I_{2(1)}$ besides the effect of θ. Recall from the equation (III.4) and the equation (III.18) that the $I_{\{12=11\}}$ line and the $I_{2(1)}$ line respectively are the sets of $(p_1^0, p_2^0) \in \mathcal{P}$ such that

$$\begin{aligned} p_2^0 &= p_1^0[(2-\pi)V(2)-1] + \frac{2v(2)}{\pi} ; \\ p_2^0 &= p_1^0[1-(1-\theta)\pi]V(2) + \frac{v(2)}{\pi}. \end{aligned}$$

From the above equations, it's obvious that due to production externality the $I_{\{12=11\}}$ line and the $I_{2(1)}$ line can't overlap one another unless $v(2) = c = 0$, which implies that there's always discrepancy in incentive for duplication in site choice between the firms and the social planner with production externality. Now denote by $\theta^* \in (0, 1/2]$ such that

$$\begin{aligned} [(2-\pi)V(2)-1] + \frac{2v(2)}{\pi} &= [1-(1-\theta^*)\pi]V(2) + \frac{v(2)}{\pi} \\ \iff \qquad \theta^* &= \frac{\pi[V(2)-1]+v(2)}{\pi^2 V(2)}, \end{aligned} \tag{III.24}$$

where $I_{\{12=11\}}(I_{\{12=22\}})$ and $I_{2(1)}(I_{2(1)})$ intersect at $p_1^0 = 1(p_2^0 = 1)$ as $\theta = \theta^*$. One can see that $\theta^*_{v(2)=v(1)} = \frac{V(2)-1}{\pi V(2)}$ in equation (III.22) is the special case of $\theta^* = \frac{\pi[V(2)-1]+v(2)}{\pi^2 V(2)}$ in equation (III.24) when there is no production externality, i.e. $v(2) = v(1)$. Notice that if $\theta > \theta^*$, then there may exist a set of (p_1^0, p_2^0) for which the $I_{2(1)}(I_{2(1)})$ line lies above(below) $I_{\{12=11\}}(I_{\{12=22\}})$, implying that there may occur over-duplication for the corresponding set of (p_1^0, p_2^0). However, as shown in the analysis on the social optimum, such difference in the incentive for duplication between the firms and the social planner doesn't necessarily result in inefficiency in the equilibrium site choice since it depends on the magnitude of network externality and the degree of competitiveness in the prospective product market, as discussed in the following sections.

III.4.1.3.1 The case that $V(2) \geq \widetilde{V}(2)$

When $V(2) \geq \widetilde{V}(2)$ where $\widetilde{V}(2) \equiv \frac{2(\pi-c)}{\pi(2-\pi)}$, the value of p_2^0 on $I_{\{12=11\}}$ for $p_2^0 = 1$ is greater than 1, resulting in $P_{12} = \emptyset$. Hence, in this case the social optimum involves only duplication in site choice. Then, if $\theta > \theta^*$, the value of p_2^0 on $I_{2(1)}$ for $p_2^0 = 1$ is also greater than 1, resulting in $P_{2(1)} = \emptyset$. Hence the excessive private incentive for duplication in site choice doesn't lead to over-duplication in site choice because differentiation in site choice is never efficient.

But, if $\theta < \theta^*$, it might result in over-differentiation in site choice when $V(2)$ is not big enough.

For given θ denote by $\overline{V}(2)(\theta)$ such that

$$\overline{V}(2)(\theta) = \frac{\pi - v(2)}{\pi[1-(1-\theta)\pi]}, \tag{III.25}$$

where for given θ the value of p_2^0 on $I_{2(1)}$ for $p_1^0 = 1$ is exactly 1 as $V(2) = \overline{V}(2)(\theta)$. One can see that $\overline{V}(2)_{\{v(2)=v(1)\}}(\theta) = \frac{1}{1-(1-\theta)\pi}$ in equation (III.23) is the special case of $\overline{V}(2)(\theta) = \frac{\pi - v(2)}{\pi[1-(1-\theta)\pi]}$ in equation (III.25) when there is no production externality. For given θ, $\overline{V}(2)(\theta)$ can be considered as compatibility benefit in the R&D reward of the magnitude for which the second mover is indifferent between duplication and differentiation in site choice when it's certain that treasures are buried in both sites. So, $\overline{V}(2)(\theta)$ is decreasing in θ, implying that the firms may still prefer duplication in site choice with lower compatibility benefit if θ increases. Now, notice that $\widetilde{V}(2) < \overline{V}(2)(\theta)$ for $\forall\ \theta \in [0,1)$.[30] Then, since the slope of $I_{2(1)}(I_{1(2)})$ is increasing(decreasing) in $V(2)$, it follows that $P_{2(1)}(P_{1(2)}) \neq \emptyset$ if $V(2) \in [\widetilde{V}(2), \overline{V}(2)(\theta))$ for given θ, which implies that there occurs over-differentiation for the corresponding set of (p_1^0, p_2^0). In Figure III.13, the black solid area represents the set of (p_1^0, p_2^0) for which over-differentiation occurs when $\widetilde{V}(2) < V(2) < \overline{V}(2)(\theta)$ and $\theta \leq \theta^*$.

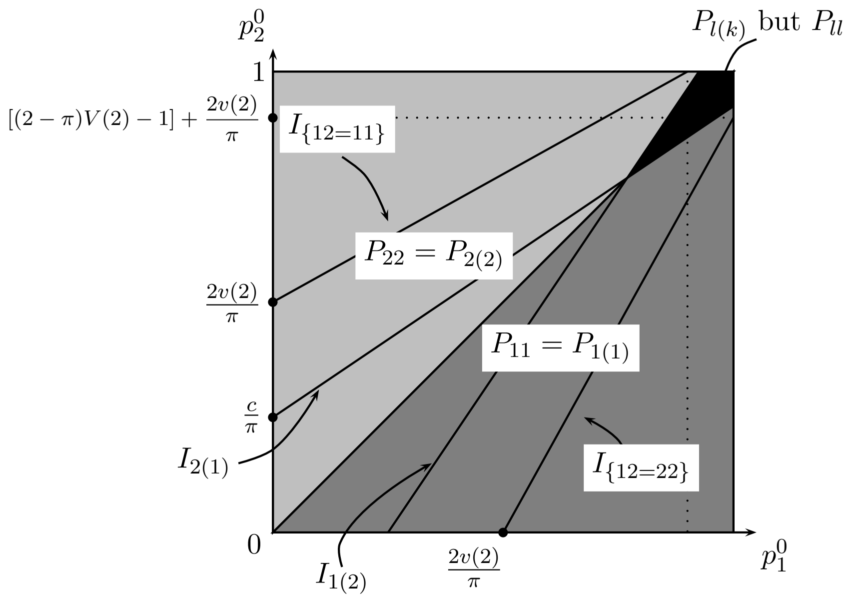

Figure III.13: Over-differentiation in the Nash equilibrium of the one period game with production externality : $\widetilde{V}(2) \leq V(2) < \overline{V}(2)(\theta)$ and $\theta \leq \theta^*$

[30] Notice that

$$\overline{V}(2)(0) \equiv \frac{\pi - v(2)}{\pi(1-\pi)} > \frac{2(\pi - c)}{\pi(2-\pi)} \equiv \widetilde{V}(2) \equiv \frac{\pi - v(2)}{\pi(1-\frac{1}{2}\pi)} = \overline{V}(2)(\frac{1}{2}) \text{ with } v(2) = c.$$

Then, since $\overline{V}(2)(\theta)$ is decreasing in θ, it follows that $\widetilde{V}(2) < \overline{V}(2)(\theta)$ for $\forall\ \theta \in [0, 1/2)$.

All the discussions hitherto on the equilibrium site choice with production externality when $V(2) \geq \widetilde{V}(2)$ is summarized in Proposition 13.

Proposition 13 *Suppose that* $V(2) \geq \widetilde{V}(2)$ *and there exists production externality. Then, for given* θ *in the Nash equilibrium of the one period game*
(1) if $V(2) \geq \overline{V}(2)(\theta)$*, the firms choose the same site, which is efficient ;*
(2) if $V(2) \in [\widetilde{V}(2), \overline{V}(2)(\theta))$*, the firms choose the same site for* $\theta \in [\theta^*, 1/2]$ *which is efficient, while the firms choose different sites for* $\theta \in [0, \theta^*)$ *which is inefficient.*

The result of Proposition 13 is very similar to that of Proposition 11 except that θ^*, the cutoff value with production externality is higher than $\theta^*_{\{v(2)=v(1)\}}$, the cutoff value without production externality by $\frac{v(2)}{\pi^2 V(2)}$. Due to such difference, there occurs over-differentiation in the game with production externality for a larger set of θ than in the game without production externality, which is very intuitive in that the production externality which is beneficial to its rival firm isn't internalized by a firm.

III.4.1.3.2 The case that $V(2) < \widetilde{V}(2)$

In this case, for some (p_1^0, p_2^0) the social optimum may involve differentiation in site choice. Then, the equilibrium may exhibit over-duplication in site choice for some (p_1^0, p_2^0) if θ is high enough, while there always exists the set of (p_1^0, p_2^0) for which over-differentiation in site choice occurs for $\forall\ \theta \in [0, 1/2]$ as in the following.

■ $\theta \in [0, \theta^*)$ Notice that since $\frac{2c}{\pi}$ the intercept of $I_{\{12=11\}}(I_{\{12=22\}})$ lies above(below) $\frac{c}{\pi}$ the intercept of $I_{2(1)}(I_{1(2)})$, if $\theta < \theta^*$, then the $I_{\{12=11\}}(I_{\{12=22\}})$ line always lies above(below) the $I_{2(1)}(I_{1(2)})$, implying that the firms have less incentive for duplication in site choice than the social planner for $\forall\ (p_1^0, p_2^0) \in \mathcal{P}$. Such discrepancy in incentive for duplication may result in inefficiency for some (p_1^0, p_2^0) as shown in Figure III.14 where the area for which differentiation in site choice is efficient is crosshatched.[31] Notice that besides the crosshatched area, the firms choose the different sites also for the black solid areas, which is suboptimal. Since the slope of $I_{2(1)}(I_{1(2)})$ is decreasing(increasing) in θ, the black solid areas reduce in their size as θ approaches to θ^* and enlarge in their size as θ approaches to 0, implying that the firms without the ability to

[31] Figure III.14 depicts the social optimum and the one shot Nash equilibrium for the numerical example that

$$\theta^* = \frac{\pi[V(2)-1]+v(2)}{\pi^2 V(2)} = .375 \text{ and } \widetilde{V}(2) = \frac{2(\pi - c)}{\pi(2-\pi)} \approx 1.4583$$

where $V(2) = 1.25,\ v(2) = c = .1,\ \pi = .8.$

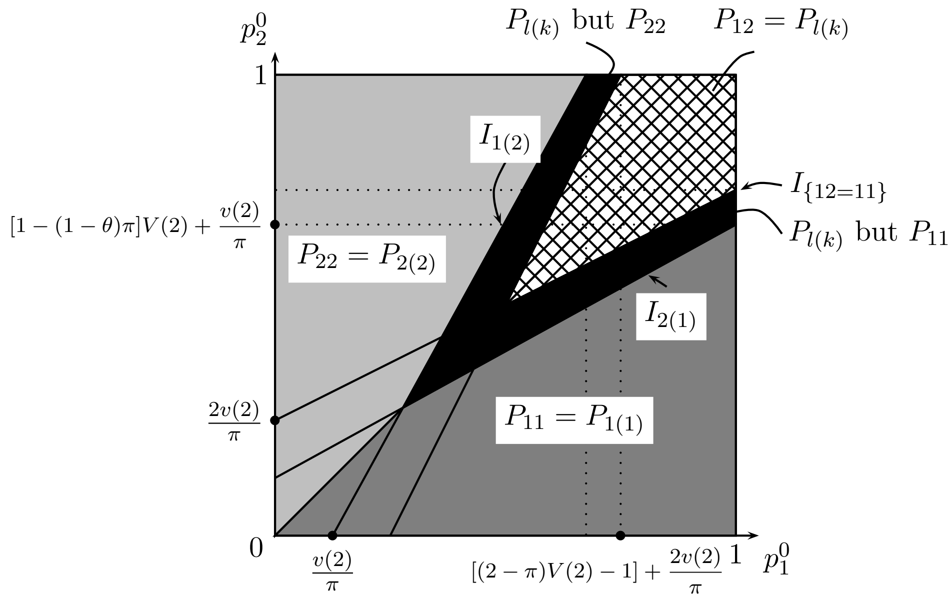

Figure III.14: Over-differentiation in the Nash equilibrium of the one period game with production externality : $\theta < \theta^*$ and $V(2) < \widetilde{V}(2)$

internalize the rival firm's compatibility benefit in the reward from R&D success have less incentive for duplication in site choice than the social planner as θ approaches to 0. Also it's obvious that the increase in production externality increases the distance between the intercept of $I_{\{12=11\}}(I_{\{12=22\}})$ and that of $I_{2(1)}(I_{1(2)})$, which enlarges the area for which over-differentiation occurs. It also occurs due to the firms' inability to internalize the rival firm's compatibility benefit in the production payoff.

■ $\theta \in (\theta^*, 1/2]$ Since the slope of $I_{2(1)}(I_{1(2)})$ is increasing(decreasing) in θ where θ^* solves the equation in (III.24), it's obvious that if $\theta > \theta^*$, then it's nonempty the set of (p_1^0, p_2^0) for which $I_{2(1)}(I_{1(2)})$ is above(below) $I_{\{12=11\}}(I_{\{12=22\}})$, implying there occurs over duplication toward $S_1(S_2)$ for the corresponding set of (p_1^0, p_2^0). Notice that the set of (p_1^0, p_2^0) for which over-differentiation occurs is nonempty when $V(2) < \widetilde{V}(2)$ due to production externality which creates difference in the intercept value between $I_{\{12=11\}}(I_{\{12=22\}})$ and $I_{2(1)}(I_{1(2)})$. Hence, in this case both the set of (p_1^0, p_2^0) for which over-differentiation occurs and the set of (p_1^0, p_2^0) for which over-duplication occurs are nonempty as shown in Figure III.15. In Figure III.15 the black solid area represents the set of (p_1^0, p_2^0) for which over-differentiation occurs and the dark gray solid area represents the set

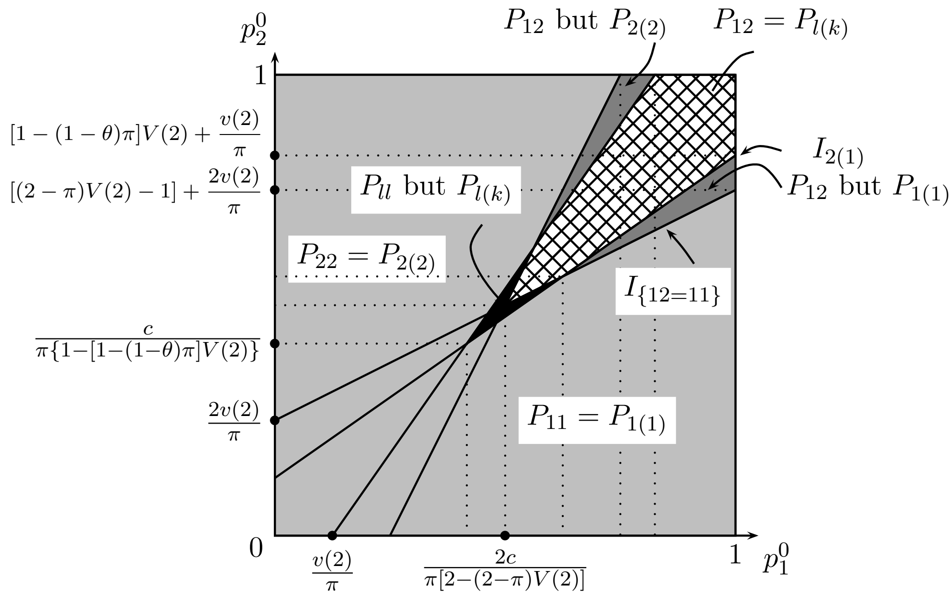

Figure III.15: Over-duplication and over-differentiation in the Nash equilibrium of the one period game with production externality : $\theta > \theta^*$ and $V(2) < \widetilde{V}(2)$

of (p_1^0, p_2^0) for which over-duplication occurs. As $\theta = \theta^*$, there's no gray solid area and only the black solid area exists. But, as $\theta \in (\theta^*, 1/2]$ increases, the black area diminishes and it disappears as $\theta = 1/2$, which implies that there occurs over-duplication for a larger set of (p_1^0, p_2^0) and over-differentiation for a smaller set of (p_1^0, p_2^0) as $\theta \in (\theta^*, 1/2]$ increases. Notice from Figure III.14 that over-differentiation occurs especially when p_1^0 and p_2^0 are almost same in their values, while over-duplication occurs especially when p_1^0 and p_2^0 has much difference in their values and either value is very close to 1.

All the discussions hitherto on the equilibrium site choice with production externality when $V(2) < \widetilde{V}(2)$ is summarized in Proposition 14.

Proposition 14 *Suppose that $V(2) < \widetilde{V}(2)$ and there exists production externality. Then, in the Nash equilibrium of the one period game*

(1) if $\theta < \theta^*$, as shown in Figure III.14, there exists the set of (p_1^0, p_2^0) for which there occurs over-differentiation, while over-duplication doesn't occur for any set of (p_1^0, p_2^0). Over-differentiation occurs for a larger set of (p_1^0, p_2^0) as θ approaches downward to 0 ;

(2) if $\theta > \theta^*$, as shown in Figure III.15, there exist not only the set of (p_1^0, p_2^0) for which over-differentiation occurs but also the set of (p_1^0, p_2^0) for which over-duplication occurs. As θ approaches

upward to 1/2, over-duplication occurs for a larger set of (p_1^0, p_2^0) and over-differentiation occurs for a smaller set of (p_1^0, p_2^0) accordingly so that only over-duplication occurs as $\theta = 1/2$.

When the result of Proposition 14 is compared to that of Proposition 12, one can find that due to the role of production externality as reservation choice, there doesn't exist the set of (p_1^0, p_2^0) for which no R&D activity is efficient when there exists production externality. The second result of Proposition 14 also shows that even when $\theta > \theta^*$, there exists the set of (p_1^0, p_2^0) for which over-differentiation occurs due to the existence of production externality. However, the fact that the sets of beliefs for which different kinds of inefficient site choice occurs coexist provides an implication regarding on the regulation policy on standard regime. If there occurs only one kind of inefficient site(standard) choice, say, over-differentiation, then a regulation agency may choose a single mandatory regime to reduce inefficiency associated with over-differentiation in site(standard) choice. However, if both over-duplication and over-differentiation may occur, then either a single standard regime or a multiple standard regime may end up resulting in a inefficient standard choice unless the regulation agency has accurate information on the set of (p_1^0, p_2^0).

III.4.2 Two period game

In this section we explore the firms' equilibrium site choice in the two period game. As in the section of Social Optimum, we first examine the firms' subsequent equilibrium site choice in each subgame with which we investigate the firms' first period site choice when the expected payoff in the second period is taken into account by the firms.

III.4.2.1 Equilibrium site choice in each subgame

III.4.2.1.1 Subgame following (S_l^s, S_k^s) or (S_l^s, S_l^s)

Since the switching cost is prohibitively high at the beginning of the second period if the R&D in the first period was successful, the firms' equilibrium site choice in the second period is same as in the first period in this subgame. Each firm gets $V(1) + v(1)$ after the history of (S_l^s, S_k^s) and gets $\theta V(2) + v(2)$ for its second period payoff after the history of (S_l^s, S_l^s).

III.4.2.1.2 Subgame following (S_l^f, S_k^f) and (S_l^f, S_l^f)

As shown in the section of Social Optimum, the situation that the firms face at the beginning of the second period in this subgame is same as at the beginning of the second period except that $(p_1(2), p_2(2)) = (p_1^1, p_2^1)$ following (S_l^f, S_k^f) with $l \neq k$ and $(p_l(2), p_k(2)) = (p_l^2, p_k^0)$ following (S_l^f, S_l^f) with $l \neq k$.

Now consider first the subgame following (S_l^f, S_k^f). Suppose that after the history of (S_l^f, S_k^f) the firm A chooses the site S_l first at the beginning of the second period where $p_l^1 \geq p_k^1$. Then, the firm B would choose the site S_k in the second period if (p_1^1, p_2^1) satisfies the condition that

$$p_k^1 \geq p_l^1[1-(1-\theta)\pi]V(2) + \frac{v(2)}{\pi},$$

of which condition expressed in terms of (p_1^0, p_2^0) is

$$p_k^0 \geq \frac{\pi p_l^0(1-\pi)[(1-(1-\theta)\pi)V(2)] + 2v(2)(1-p_l^0\pi)}{\pi\{(1-p_l^0\pi)(1-\pi) + \pi p_l^0(1-\pi)[(1-(1-\theta)\pi)V(2)] + 2v(2)(1-p_l^0\pi)\}}.$$

The equilibrium site choice in the second period after the history of (S_l^f, S_k^f) is summarized in Lemma (9).

Lemma 9 *Suppose $p_l^0 \geq p_k^0$ with $l \neq k$ and the history of search in the first period is (S_l^f, S_k^f). Then, the equilibrium site choice in the second period is*

$$\begin{array}{ll} (S_l, S_k) & \textit{if } p_k^0 \geq \frac{\pi p_l^0(1-\pi)[(1-(1-\theta)\pi)V(2)]+2v(2)(1-p_l^0\pi)}{\pi\{(1-p_l^0\pi)(1-\pi)+\pi p_l^0(1-\pi)[(1-(1-\theta)\pi)V(2)]+2v(2)(1-p_l^0\pi)\}}; \\ (S_l, S_l) & \textit{otherwise.} \end{array} \tag{III.26}$$

Now compare Lemma (9) to Lemma (5) in which the socially optimal site choice after the history of (S_l^f, S_k^f) is discussed. Notice that with $\theta = 0$ the set of (p_1^0, p_2^0) for which the condition (III.11) is satisfied is a subset of the set of (p_1^0, p_2^0) for which the condition (III.26) is satisfied, which implies that if $\theta = 0$ there exists the set of (p_1^0, p_2^0) for which over-differentiation in site choice occurs in the second period after the history of (S_l^f, S_k^f). With $\theta = 1/2$ the set of (p_1^0, p_2^0) for which the condition (III.26) is satisfied is a subset of the set of (p_1^0, p_2^0) for which the condition (III.11) is satisfied, which implies that if $\theta = 1/2$ there exists the set of (p_1^0, p_2^0) for which over-duplication in site choice occurs in the second period after the history of (S_l^f, S_k^f). Notice that the right hand side of the condition (III.26) is continuous in θ. Hence there exists some $\theta' \in (0, 1/2)$ such that the set of (p_1^0, p_2^0) for which the condition (III.11) is satisfied and the set of (p_1^0, p_2^0) for which condition (III.26) is satisfied are identical to each other. Such result on the equilibrium site choice in the subgame following (S_l^f, S_k^f) is summarized in Claim 8.

Claim 8 *Suppose $p_l^0 > p_k^0$ with $l \neq k$ and the history of search in the first period is (S_l^f, S_k^f). Then, there exists some $\theta' \in (0, 1/2)$ such that there occurs over-differentiation for $\forall\ \theta \in [0, \theta')$, while there occurs over-duplication for $\forall\ \theta \in (\theta', 1/2]$ in the equilibrium site choice in the second period.*

Next consider the subgame following (S_l^f, S_l^f). With the firm A's choosing the site first, A will choose S_l if $p_k^0 < p_l^2$ and will choose S_k otherwise. Suppose $p_k^0 < p_l^2$. Then, given the firm A's choosing the site S_l first the the firm B will choose S_l if and only if

$$p_k^0 < p_l^2[1-(1-\theta)\pi]V(2) + \frac{v(2)}{\pi} \text{ for } l \neq k,$$

which is equivalent to the condition that

$$p_k^0 < \frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2 + (1-p_l^0)}[1-(1-\theta)\pi]V(2) + \frac{v(2)}{\pi}. \tag{III.27}$$

Now suppose $p_k^0 > p_l^2$. Then, given the firm A's choosing the site S_k first, the firm B will choose S_k if and only if

$$p_k^0 > \frac{p_l^2\pi - v(2)}{\pi[1-(1-\theta)\pi]V(2)},$$

which is equivalent to

$$p_k^0 > \frac{\frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2+(1-p_l^0)}\pi - v(2)}{\pi[1-(1-\theta)\pi]V(2)}. \tag{III.28}$$

Then, since $p_l^2 = \frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2+(1-p_l^0)}$ for given p_l^0, the results in the above can be summarized as follows.

Lemma 10 *Suppose the history of search in the first period is (S_l^f, S_l^f). Then, for given $\theta \in [0, 1/2]$ the equilibrium site choice in the second period is*

$$\begin{array}{lll} (S_l, S_l) & \text{if } p_k^0 < min\{\frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2+(1-p_l^0)}, \frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2+(1-p_l^0)}[1-(1-\theta)\pi]V(2) + \frac{v(2)}{\pi}\}; \\ (S_k, S_k) & \text{if } p_k^0 > max\{\frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2+(1-p_l^0)}, \frac{\frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2+(1-p_l^0)}\pi - v(2)}{\pi[1-(1-\theta)\pi]V(2)}\}; \\ (S_l, S_k) & \text{otherwise.} \end{array} \tag{III.29}$$

III.4.2.1.3 Subgame following (S_l^s, S_k^f) and (S_l^f, S_k^s)

In this subgame, the firm whose R&D was successful in the first period has an incumbent position in the prospective product market in the second period when the other firm whose R&D was not successful in the first period choose the same site in which the incumbent's R&D was successful. Since the incumbent's R&D was already successful in the first period, the entrant finds that its R&D success leads to at best the situation where both firms have products in the market, resulting in $\theta V(2)$ to each firm for the payoff from R&D success. Now recall that in this subgame $(p_l(2), p_k(2)) = (1, p_k^1)$ following (S_l^s, S_k^f) and $(p_l(2), p_k(2)) = (p_l^1, 1)$ following (S_l^f, S_k^s). Without a loss of generality, suppose that the firm A succeeded in R&D in the site S_l in the first period and the firm B has failed in the site S_k. Then each firm's expected payoff in the second period is as follows.

$$V_A((S_l,\cdot);(1,p_k^1)) = \begin{cases} [(1-\pi)+\pi\theta]V(2)+v(2) & \text{if } B \text{ switches to } S_l \\ V(1)+v(1) & \text{if } B \text{ stays in } S_k \end{cases}$$

$$V_B((S_l,\cdot);(1,p_k^1)) = \begin{cases} \pi\theta V(2)+v(2)-c & \text{if } B \text{ switches to } S_l \\ p_k^1\pi V(1)+v(1)-c & \text{if } B \text{ stays in } S_k \end{cases} \tag{III.30}$$

Since the firm A should continue to choose S_l, the equilibrium site choice in this subgame boils down to the firm B's problem in (III.30). Notice that for given θ, the firm B continues to investigate the site S_k if and only if

$$p_k^1 \geq \theta V(2) + \frac{v(2)}{\pi},$$

which is equivalent to

$$p_k^0 \geq \frac{\pi\theta V(2)+v(2)}{\pi[\pi\theta V(2)+v(2)+1-\pi]}. \tag{III.31}$$

Hence, the equilibrium site choice in the second period after the history of (S_l^s, S_k^f) can be summarized as in Lemma (11).

Lemma 11 *After the history of (S_l^s, S_k^f), the equilibrium site choice in the second period is*

$$\begin{array}{ll} (S_l,S_k) & \textit{if } p_k^0 \geq \frac{\pi\theta V(2)+v(2)}{\pi[\pi\theta V(2)+v(2)+1-\pi]}\ ; \\ (S_l,S_l) & \textit{otherwise.} \end{array} \tag{III.32}$$

Notice that the cutoff condition in (III.31) depends on θ. For example, if $\theta = 0$(the Bertrand game), then the condition in (III.31) boils down to

$$p_k^0 \geq \frac{v(2)}{\pi[(1-\pi)+v(2)]}. \tag{III.33}$$

In the Bertrand R&D game, given the firm A's success in R&D in the first period, the firm B can expect no payoff from R&D activity in the second period when the firm B switches to site S_l. Hence, even though the firm B will still get $v(2)$ from production activity, which will fully recoup the R&D activity cost, the firm B finds it optimal to choose the different site S_k for p_k^0 lower than $\frac{V(2)-V(1)+2v(2)}{\pi[V(2)+2v(2)-\pi]}$ the socially optimal cutoff value in the condition (III.13).[32] Now denote by $\theta^*_{\{(S_l^s,S_k^f)\}}$ θ such that as $\theta = \theta^*_{\{(S_l^s,S_k^f)\}}$, the socially optimal cutoff value in the condition (III.14)

[32] One can see that the condition (III.33) boils down even to $p_k^0 \geq 0$ when there's no production externality.

is identical to the cutoff value in the condition (III.31), where

$$\theta^*_{\{(S_l^s, S_k^f)\}} \equiv \frac{V(2) - V(1) + v(2)}{\pi V(2)}.^{33} \tag{III.34}$$

Since the cutoff value in the condition (III.31) is increasing in θ, it follows that

$$\theta \geq \theta^*_{\{(S_l^s, S_k^f)\}} \text{ iff } \frac{\pi\theta V(2) + v(2)}{\pi[\pi\theta V(2) + v(2) + 1 - \pi]} \geq \frac{V(2) - V(1) + 2v(2)}{\pi[V(2) + 2v(2) - \pi]},$$

where $\frac{\pi\theta V(2)+v(2)}{\pi[\pi\theta V(2)+v(2)+1-\pi]}$ is the equilibrium cutoff value in the condition (III.31) and $\frac{V(2)-V(1)+2v(2)}{\pi[V(2)+2v(2)-\pi]}$ is the socially optimal cutoff value in the condition (III.14). Hence, we have the following result on the efficiency of the equilibrium site choice in the subgame following (S_l^s, S_k^f).

Claim 9 *Suppose the history of search in the first period is* (S_l^s, S_k^f). *Let* $\theta^*_{\{(S_l^s, S_k^f)\}} \equiv \frac{V(2)-V(1)+v(2)}{\pi V(2)}$. *Then, for given* θ *in the equilibrium site choice in the second period*
(1) if $\theta > \theta^*_{\{(S_l^s, S_k^f)\}}$, *there occurs over-duplication in site choice for*
$\forall\ (p_l^0, p_k^0) \in [\frac{V(2)-V(1)+2v(2)}{\pi[V(2)+2v(2)-\pi]}, \frac{\pi\theta V(2)+v(2)}{\pi[\pi\theta V(2)+v(2)+1-\pi]}]$;
(2) if $\theta < \theta^*_{\{(S_l^s, S_k^f)\}}$, *there occurs over-differentiation in site choice for*
$\forall\ (p_l^0, p_k^0) \in [\frac{\pi\theta V(2)+v(2)}{\pi[\pi\theta V(2)+v(2)+1-\pi]}, \frac{V(2)-V(1)+2v(2)}{\pi[V(2)+2v(2)-\pi]}]$.

III.4.2.1.4 Subgame following (S_l^s, S_l^f) and (S_l^f, S_l^s)

In this subgame, the beliefs will be updated to $(p_l(2), p_k(2)) = (1, p_k^0)$. Now suppose the history of search in the first period is (S_l^s, S_l^f) after which the equilibrium site choice problem in the second period boils down to the firm B's site choice problem. Notice that the firm B's expected payoff from each site choice is

$$V_B((S_l, \cdot); (1, p_k^0)) = \begin{cases} \pi\theta V(2) + v(2) - c & \text{if } B \text{ switches to } S_l \\ p_k^0 \pi V(1) + v(1) - c & \text{if } B \text{ stays in } S_k. \end{cases} \tag{III.35}$$

Then, since for given θ the firm B switches to the site S_k if and only if

$$p_k^0 \geq \theta V(2) + \frac{v(2)}{\pi}, \tag{III.36}$$

the equilibrium site choice in the second period after the history of (S_l^s, S_l^f) can be summarized as in Lemma (12).

[33] Notice that $\theta^*_{\{(S_l^s, S_k^f)\}} < \theta^*$ where θ^* is the degree of competitiveness in the prospective product market which makes the social planner's incentive for duplication in site choice to be identical to the firms' incentive for duplicaiton in site choice in the one period game with $\theta^* \equiv \frac{\pi[V(2)-1]+v(2)}{\pi^2 V(2)}$ (See the condition (III.24)). Such inequality implies that with the incumbent's success in R&D in the previous period, a higher degree of competitiveness in the prospective product market will induce the entrant to choose the efficient site choice than the degree of competitiveness needed for the game where neither firm has been successful in R&D. Such result is very intuitive in that after the history of (S_l^s, S_k^f), the second mover finds it more profitable to duplicate on S_l when $p_l = 1$, that is, the uncertainty regarding the site is resovled than when $p_l < 1$, that is, there exists the uncertainty regarding the site.

Lemma 12 *After the history of* (S_l^s, S_l^f)*, the equilibrium site choice in the second period is*

$$\begin{array}{ll} (S_l, S_k) & \text{if } p_k^0 \geq \theta V(2) + \frac{v(2)}{\pi}\ ; \\ (S_l, S_l) & \text{otherwise.} \end{array} \tag{III.37}$$

Now recall the socially optimal cutoff value in the condition (III.14) is $\frac{V(2)-V(1)+v(2)}{\pi}$. Then, it follows that

$$\theta \geq \frac{V(2)-V(1)}{\pi V(2)} \text{ iff } \theta V(2) + \frac{v(2)}{\pi} \geq \frac{V(2)-V(1)+v(2)}{\pi}.$$

Hence, we have the following result on the efficiency of the equilibrium site choice in the subgame following (S_l^s, S_l^f).

Claim 10 *Suppose the history of search in the first period is* (S_l^s, S_l^f)*. Then, for given* θ *in the equilibrium site choice in the second period*
(1) if $\theta > \frac{V(2)-V(1)}{\pi V(2)}$*, there occurs over-duplication in site choice for* $\forall\ (p_l^0, p_k^0) \in [\frac{V(2)-1+2v(2)}{\pi[V(2)+2v(2)-\pi]}, \theta V(2) + \frac{v(2)}{\pi}]$*;*
(2) if $\theta < \frac{V(2)-V(1)}{\pi V(2)}$*, there occurs over-differentiation in site choice for* $\forall\ (p_l^0, p_k^0) \in [\theta V(2) + \frac{v(2)}{\pi}, \frac{V(2)-1+2v(2)}{\pi[V(2)+2v(2)-\pi]}]$*.*

III.4.2.2 Equilibrium site choice in the first period

Now we investigate the equilibrium site choice in the first period when the firms take into account all the subgames in the second period. Recall that the firms move sequentially so that the second mover may observe the first mover's site choice each period. Without a loss of generality, we continue to assume that the firm A moves first and the firm B moves later after observing the firm A's choosing which site to investigate. Given symmetry between firms and symmetry between sites, it suffices to examine the firm B's site choice given the firm A's choice in order to find the equilibrium site choice. For each (p_1^0, p_2^0) and the firm A's choosing the site S_l, the equilibrium site choice is

$$argmax_{\{S_B\}} W_B((S_l, S_k); (p_1^0, p_2^0)), W_B((S_l, S_l); (p_1^0, p_2^0)).$$

III.4.2.2.1 The second mover's total expected payoff from differentiation in site choice

First we examine $W_B((S_l, S_k); (p_1^0, p_2^0))$, the firm B's total expected payoff over two periods when the set of the initial beliefs is (p_1^0, p_2^0) and the firms' site choice in the first period is (S_l, S_k). Since the firm A moves first, the firm A's choosing the site S_l first implies that $p_l^0 \geq p_k^0$. Then, given the payoffs in each game, $W_B((S_l, S_k); (p_1^0, p_2^0))$ can be expressed as

$$\begin{aligned} W_B((S_l, S_k); (p_l^0, p_k^0)) = -c &+ p_l^0 p_k^0 (\pi)^2 \{[V(1) + v(1)] + [V(1) + v(1)]\} \\ &+ p_k^0(\pi)(1 - p_l^0 \pi)\{[V(1) + v(1)] + [V_B^*((\cdot, S_k); (p_l^1, 1))]\} \\ &+ p_l^0 \pi (1 - p_k^0 \pi)\{[0 + v(1)] + [V_B^*((S_l, \cdot); (1, p_k^1))]\} \\ &+ (1 - p_l^0 \pi)(1 - p_k^0 \pi)\{[0 + v(1)] + [V_B^*((\cdot, \cdot); (p_l^1, p_k^1))], \} \end{aligned} \tag{III.38}$$

where each of $V_B^*((S_l, \cdot); (1, p_k^1))$ and $V_B^*((\cdot, S_k); (p_l^1, 1))$ in square brackets represents the firm B's expected payoff from its equilibrium site choice in the second period after the history of search (S_l^s, S_k^f) and (S_l^f, S_k^s) with the updated set of posterior beliefs being $(1, p_k^1)$ and $(p_l^1, 1)$ respectively. Then, the payoff in each curly bracket in (III.38) corresponding each subgame represents the firm B's payoff in each subgame which consists of the sure revenue from the site choice in the first period and the maximized expected payoff from the site choice in the second period. The second period expected payoff depends on the firms' site choice in the second period which in turn depends on $(p_l(2), p_k(2))$. For example, $V_B((S_l, \cdot); (1, p_k^1))$ depends on the firm B's site choice after the history of search (S_l^s, S_k^f) in the first period, which depends on $(1, p_k^1)$. In the subgame following the history of search (S_l^f, S_k^s) in the first period where the firm B continues to choose the site S_k, $V_B((\cdot, S_k); (p_l^1, 1))$ depends on the firm A's site choice, which depends on $(p_l^1, 1)$. In the subgame following the history of search (S_l^f, S_k^f) in the first period, the site choice problem in the second period is same as in the first period except the set of updated posterior beliefs $(p_l(2), p_k(2)) = (p_l^1, p_k^1))$.

III.4.2.2.2 The second mover's total expected payoff from duplication in site choice

Next we examine $W_B((S_l, S_l); (p_l^0, p_k^0))$, the firm B's total expected payoff over two periods when the set of the initial beliefs is (p_1^0, p_2^0) and the firms' site choice in the first period is (S_l, S_l). Notice that both firms choosing the site S_l implies that $p_l^0 \geq p_k^0$. Then, given the payoffs in each game, $W_B((S_l, S_l); (p_1^0, p_2^0))$ can be expressed as

$$\begin{aligned} W_B((S_l, S_l); (p_1^0, p_2^0)) = -c &+ p_l^0 (\pi)^2 \{[\theta V(2) + v(2)] + [\theta V(2) + v(2)]\} \\ &+ p_l^0 \pi (1 - \pi)\{[V(2) + v(2)] + [V_B^*((\cdot, S_l); (1, p_k^0))]\} \\ &+ p_l^0 (1 - \pi)\pi\{[0 + v(2)] + [V_B^*((S_l, \cdot); (1, p_k^0))]\} \\ &+ [p_l^0 (1 - \pi)^2 + (1 - p_l^0)]\{[0 + v(2)] + [V_B^*((\cdot, \cdot); (p_l^2, p_k^0))]\}. \end{aligned} \tag{III.39}$$

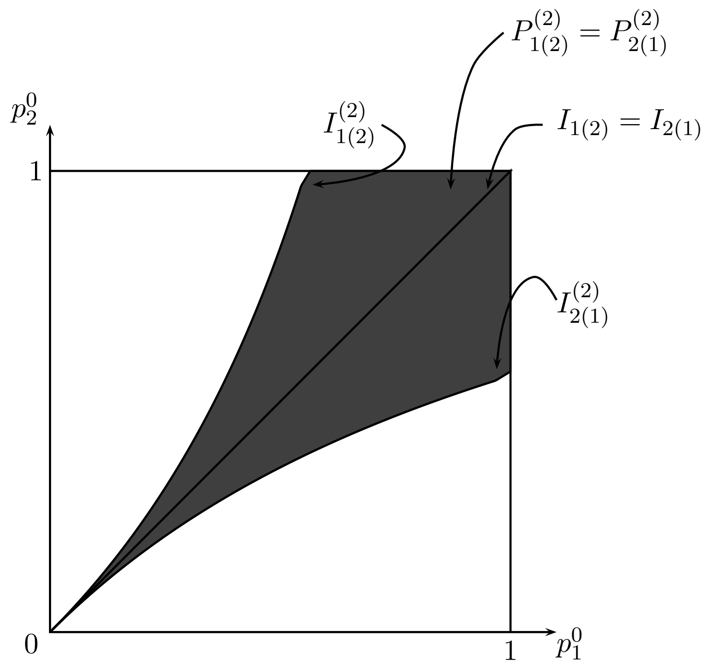

Figure III.16: Non-myopia in the first period equilibrium site choice in the two period Bertrand R&D game without production externality : $V(2) = \overline{V}(2)_{\{v(2)=v(1)\}}(0)$

III.4.2.3 Numerical analysis

Since the closed-form solution of the equilibrium isn't attainable for the same reason as in the analysis of social optimum, we conduct numerical analysis on computation of the first period equilibrium site choice. Especially we focus on the case without production externality for ease of exposition.

III.4.2.3.1 Non-myopia in the equilibrium site choice : More differentiation As with social optimum, the first period equilibrium site choice in the two period game is different from the site choice in the one period game, which implies that in the equilibrium in the two period game the firms are non-myopic. Such non-myopia is very intuitive in that in the subgame perfect Nash equilibrium of a two period game the firms take into account the expected payoffs from the second period in making the first period site choice. Especially the firms would be non-myopic in the equilibrium unless the second period payoff from duplication in site choice happens to be same as that from differentiation in site choice. How different the first period site choice in the two period game is from that in the one period game depends on the magnitude of θ, the magnitude of compatibility benefit in the reward from R&D success and the magnitude of production externality. Figure III.16

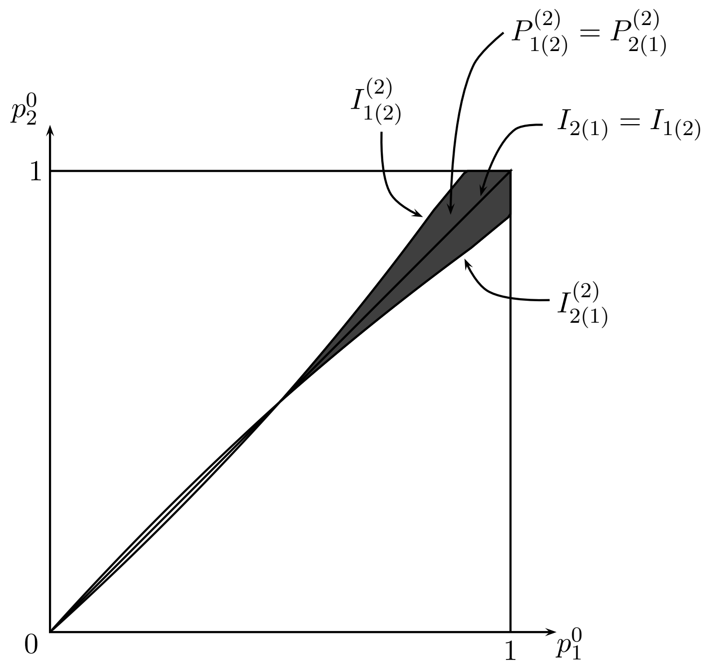

Figure III.17: Non-myopia in the first period equilibrium site choice in the two period equal sharing R&D game without production externality : $V(2) = \overline{V}(2)_{\{v(2)=v(1)\}}(\frac{1}{2})$

shows the case that $\theta = 0$ and $V(2) = \overline{V}(2)_{\{v(2)=v(1)\}}(0)$ without production externality. Notice that both $I_{1(2)}$ and $I_{2(1)}$ coincide to $45^{\diamond}$ line as in the figure when $V(2) = \overline{V}(2)_{\{v(2)=v(1)\}}(0)$, which results in $P_{2(1)} = P_{1(2)} = \emptyset$. But, since $I^{(2)}_{2(1)}$($I^{(2)}_{1(2)}$) is the curve lying above(below) $45^{\diamond}$ for some set of (p^0_1, p^0_2) as in the figure, it follows that $P^{(2)}_{1(2)} = P^{(2)}_{2(1)} \neq \emptyset$ as depicted in the dark gray area in the figure, which implies that in the first period of the two period game the second mover finds it profitable to choose the site different from the one chosen by the first mover even when the compatibility benefit in the reward from R&D success is big enough that the second mover is indifferent between differentiation and duplication in the one period game. Now consider Figure III.17 in the case with $\theta = 1/2$ and $V(2) = \overline{V}(2)^{(2)}_{\{v(2)=v(1)\}}(1/2)$ where $P_{2(1)} = P_{1(2)} = \emptyset$ and $P^{(2)}_{1(2)} = P^{(2)}_{2(1)} \neq \emptyset$ as in Figure III.16 but $P^{(2)}_{1(2)} = P^{(2)}_{2(1)}$ is much smaller in its size than in the case with $\theta = 0$. Now notice that the size of $P^{(2)}_{1(2)} = P^{(2)}_{2(1)}$ is decreasing in $V(2)$. Then, from Figure III.16 and Figure III.17, one can infer that for given $\theta \in [0, \frac{1}{2}]$, $\overline{V}(2)^{(2)}_{\{v(2)=v(1)\}}(\theta) > \overline{V}(2)_{\{v(2)=v(1)\}}(\theta)$ where $\overline{V}(2)^{(2)}_{\{v(2)=v(1)\}}(\theta)$ is the smallest $V(2)$ such that $P^{(2)}_{1(2)} = P^{(2)}_{2(1)} = \emptyset$.

The discussion hitherto about the feature of the firms' non-myopic equilibrium site choice in the first period is summarized in the following result.

Result 5 *Let $\overline{V}(2)^{(2)}_{\{v(2)=v(1)\}}(\theta)$ be the smallest $V(2)$ such that $P^{(2)}_{1(2)} = P^{(2)}_{2(1)} = \emptyset$. Suppose $V(2) =$*

$\overline{V}(2)_{\{v(2)=v(1)\}}(\theta)$ *for given* θ*. Then, in the first period of the two period game,*

(1) $P^{(2)}_{l(k)} \neq \emptyset$*, while* $P_{l(k)} = \emptyset$ *where* $l \neq k$ *and* $l, k \in \{1, 2\}$*.*

(2) For given θ*,* $\overline{V}(2)^{(2)}_{\{v(2)=v(1)\}}(\theta) > \overline{V}(2)_{\{v(2)=v(1)\}}(\theta)$*.*[34]

III.4.2.3.2 Inefficiency in the first period site choice

In the following numerical analysis we focus on exploring how the first period equilibrium site choice may differ from the the first period efficient site choice in the two period game. Especially for given $V(2)$ we focus on the case with $\theta = \theta^*_{\{v(2)=v(1)\}}$ in which $I_{\{12=ll\}} = I_{l(k)}$ with $l, k \in \{1, 2\}$ and $l \neq k$. In such cases, for given $V(2)$, by comparing $I^{(2)}_{\{12=ll\}}$ and $I^{(2)}_{l(k)}$ we can examine whether the first period equilibrium site choice is efficient when the level of competitiveness of prospective product market is just big enough such that the equilibrium site choice is always efficient in the one period game.

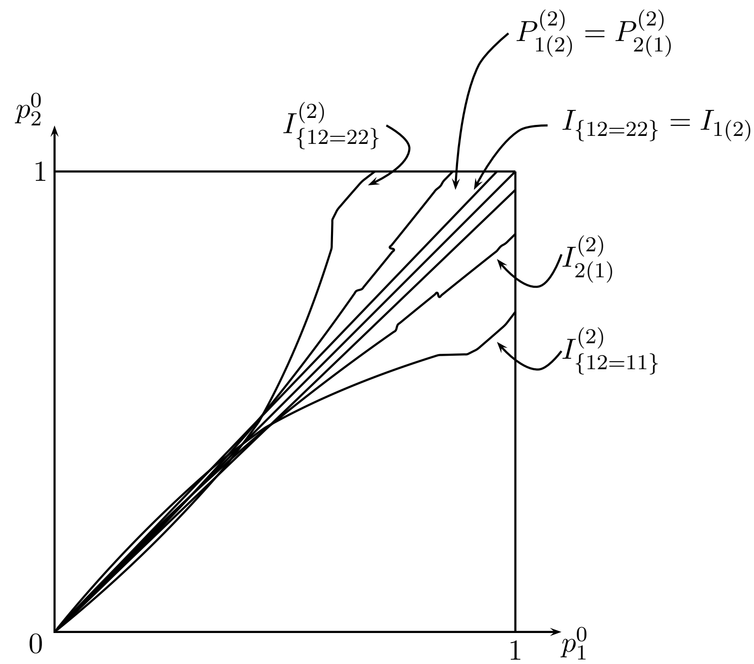

Figure III.18: Over-duplication in the first period equilibrium site choice without production externality : $\theta = \theta^*_{\{v(2)=v(1)\}}$ and $V(2) < \widetilde{V}(2)_{\{v(2)=v(1)\}}$

[34] In the n period game with $n \geq 3$, one can conjecture that for given θ

$$\overline{V}(2)^{(n)}_{\{v(2)=v(1)\}}(\theta) > \overline{V}(2)^{(n-1)}_{\{v(2)=v(1)\}}(\theta), \text{ where } \overline{V}(2)^{(n)}_{\{v(2)=v(1)\}}(\theta) \text{ is similarly defined.}$$

Consider Figure III.18 where $\theta = \theta^*_{\{v(2)=v(1)\}}$ and $V(2) < \widetilde{V}(2)_{\{v(2)=v(1)\}}$.[35] Notice that since $\theta = \theta^*_{\{v(2)=v(1)\}}$, $I_{\{12=ll\}} = I_{l(k)}$ with $l, k \in \{1,2\}$ and $l \neq k$, thereby $P_{12} = P_{1(2)}$ where $P_{12} \neq \emptyset$ because $V(2) < \widetilde{V}(2)_{\{v(2)=v(1)\}}$. But in the figure one can see that $I^{(2)}_{\{12=22\}}(I^{(2)}_{\{12=11\}})$ is further from $45^\diamond$ than $I^{(2)}_{1(2)}(I^{(2)}_{2(1)})$, which implies that there exists the set of (p^0_1, p^0_2) for which over-duplication occurs in the first period equilibrium site choice when $\theta = \theta^*_{\{v(2)=v(1)\}}$.[36] Now recall that all the firms' payoff functions are continuous in θ. Then, it follows that there exists some $\epsilon > 0$ such that for $\theta(\epsilon)$ with $\theta(\epsilon) = \theta^*_{\{v(2)=v(1)\}} - \epsilon$, there occurs over-differentiation in the equilibrium site choice in the one period game, while there occurs over-duplication in the first period equilibrium site choice in the two period game.

The discussion on the inefficiency result of the equilibrium site choice hitherto is summarized in the following result.

Result 6 *Suppose there's no production externality. Then, for given $V(2)$*
(1) for $\theta = \theta^*_{\{v(2)=v(1)\}}$, there occurs over-duplication for some set of (p^0_1, p^0_2) in the first period equilibrium site choice of the two period game, while the equilibrium site choice is always efficient for all (p^0_1, p^0_2) in the one period game;
(2) for $\theta(\epsilon)$ with $\theta(\epsilon) = \theta^*_{\{v(2)=v(1)\}} - \epsilon$ where ϵ is small enough, there occurs over-duplication for some set of (p^0_1, p^0_2) in the first period equilibrium site choice of the two period game, while there occurs over-differentiation for some other set of (p^0_1, p^0_2) in the equilibrium site choice in the one period game.

The result 6 is caused by the firms' inability to internalize all the information benefits from the experimentation through differentiation. Hence, for given compatibility externality the degree of the competitiveness in the prospective product market which is just enough to make the firms' incentive for differentiation to coincide to that of the social planner is too high to make the firms' incentive for differentiation to coincide to that of the social planner in the two period game where there occurs the information benefit from experimentation through differentiation in site choice. Now, regarding the standardization issue, the second part of the result 6 suggests that the single standard regime to fix the possible over-differentiation problem in the short run may turn out to be a wrong choice since in the long run the relevant inefficiency to be fixed would be not over-differentiation

[35] The figure is depicted with the data generated for the case that

$$V(2) = 1.4 \text{ and } \pi = .6 \text{ for which } \theta^*_{\{v(2)=v(1)\}} = 0.4761.$$

[36] Also one can see that the some indifference curves have kinked points, which is caused by the payoff functions' having maximum function.

but over-duplication. Such inversion of inefficiency might create difficulty in implementing the standardization policies especially when how long the relevant technologies survive is not certain.

III.5 Extensions and Concluding remarks

In this paper we investigate the problem on how firms decide on which fundamental technology to choose for their R&D of applied technologies in an environment in which there are two kinds of uncertainties that firms face in their R&D of applied technologies where there exists strict possibility of simultaneous discovery in the presence of network externality within compatible technologies.

We find that the configuration of social optimum depends on the magnitude of compatibility benefit and the equilibrium may involve in too much differentiation or too much duplication, depending on the the magnitude of compatibility benefit and the degree of the competitiveness in the prospective product market both in the one period game and in the two period game. We also find that the social optimum and the equilibrium are non-myopic where they involves in more differentiation in the two period game due to the information benefit from experimentation through differentiation in site choice.

Since we only examine how the equilibrium and the social optimum in the two period game may differ from in the one period game, the natural extension of the analysis is to examine the n period game with $n > 2$ and the game with infinite period. However, since the number of subgames increase as the number of period considered increases, the same problem which restricts us to numerical analysis in the study of the two period game in this paper would cause more complexity to the analysis of the game with more periods. The numerical analysis of the n period game and the game with infinite horizon, however, can be done with some change to the program used for this study. Since the experimentation benefit occurs over more time span as the number of periods of the game increases, we conjecture that the qualitative aspect of our result doesn't change that both the social optimum and the equilibrium involve more specialization in site choice as the number of periods increases.

Another immediate extension is related to endogenization of the uncertainty involved in R&D activity. The one of the easiest way to endogenize it is to relate it to the level of investment in the way that the uncertainty is a decreasing function of investment with a decreasing speed as in Chatterjee and Eveans (2003) and Lee (2003). But, even when the uncertainty can be controlled, the compatibility benefit and the expected competitiveness in the prospective product market still may cause the equilibrium project choice inefficient unless a mechanism with which firms may internalize the relevant externalities can be implemented. Hence the qualitative aspect of the result in the current study with exogenous uncertainty involved in R&D activity would continue to hold for the model with endogenous investment.

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Appendix A

Appendix

A.1 Proofs for Chapter 1

Proof of Claim 1

Proof. Consider Figure A.1 in which $V(2)'' < V(2)^*_{BR} < V(2)'$. Since $c'(\cdot)$ is increasing in π_i, it follows that $\pi_i^{S*}(V(2)'') < \pi_i^{D*} < \pi_i^{S*}(V(2)')$. Since the case shown in Figure A.1 can be generalized for all $V(2)$, it follows that π_i^{S*} is strictly increasing in $V(2)$. Therefore, $V(2) > V(2)^*_{BR}$ if and only if $\pi_i^{S*} > \pi_i^{D*}$. Equivalently, $V(2) < V(2)^*_{BR}$ if and only if $\pi_i^{S*} < \pi_i^{D*}$. ■

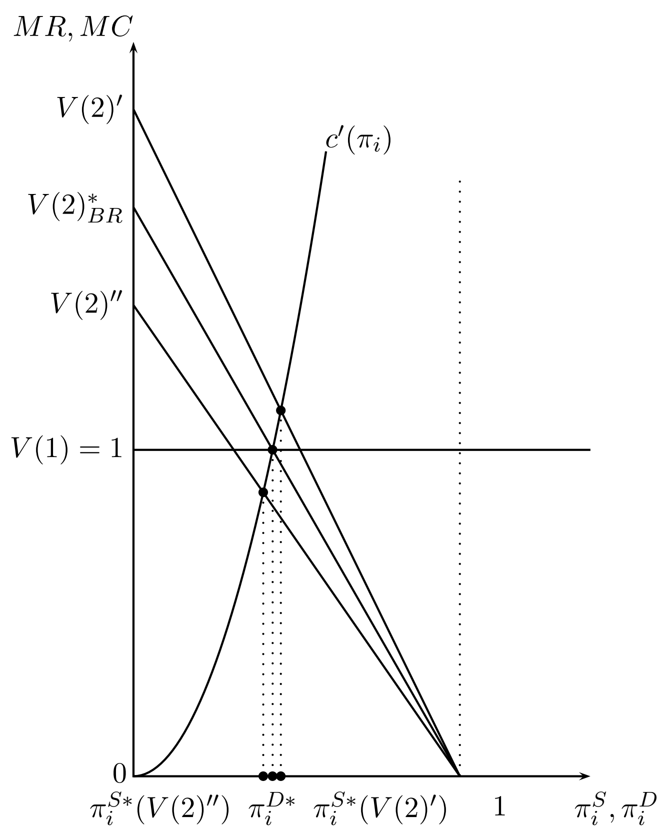

Figure A.1: $\pi_i^{S*}(V(2)'') < \pi_i^{D*} < \pi_i^{S*}(V(2)')$

Proof of Proposition 2

Proof. Suppose the firm A chooses the site S_1 first. Given the firm A's site choice, the firm B receives

$$W_B(S_1, S_1) = \pi_1^{S*}(1 - \pi_1^{S*})V(2) - c(\pi_1^{S*}) \text{ by choosing the same site } S_1$$

$$\text{and } W_B(S_1, S_2) = \pi_2^{D*} - c(\pi_2^{D*}) \text{ by choosing the different site } S_2.$$

Now suppose $V(2) = V(2)^*_{BR}$. Then, since $\pi_1^{S*} = \pi_1^{D*}$ iff $V(2) = V(2)^*_{BR}$,

$$\begin{aligned}
W_B((S_1, S_1); V(2)^*_{BR}) &= \pi_1^{S*}(1 - \pi_1^{S*})V(2) - c(\pi_1^{S*}) \\
&= \pi_1^{S*}(1 - \pi_1^{S*})\frac{1}{1 - \pi_1^{D*}} - c(\pi_1^{S*}) \\
&= \pi_1^{D*}(1 - \pi_1^{D*})\frac{1}{1 - \pi_1^{D*}} - c(\pi_1^{D*}) \\
&= \pi_1^{D*} - c(\pi_1^{D*}) \\
&= \pi_2^{D*} - c(\pi_2^{D*}) \\
&= W_B(S_1, S_2).
\end{aligned}$$

The fifth equality comes from symmetry between sites. Now, recall that $W_i(S_l, S_l)$ with $S_l \in \{S_1, S_2\}$, the firm i's expected payoff conditional on duplication is increasing in $V(2)$, while $W_i(S_l, S_k)$, the firm i's expected payoff conditional on differentiation is independent of $V(2)$. Therefore, the firm B chooses the same site chosen by the firm A for all $V(2)$ with $V(2) > V(2)^*_{BR}$ in the equilibrium. Similarly, the firm B chooses the different site for all $V(2)$ with $V(2) < V(2)^*_{BR}$ in the equilibrium. The proof of the firms' optimal effort level given site choice is provided already in the body text. ■

Proof of Proposition 3

Proof. Note that by construction of $V(2)^{**}$, $W((S_l, S_l), V(2)^{**}) = W(S_1, S_2)$. Since $W((S_l, S_l), V(2))$ is increasing in $V(2)$, duplication is efficient for $\forall$ (2) with $V(2) > V(2)^{**}$, while differentiation is efficient for $\forall\, V(2)$ with $V(2) < V(2)^{**}$.

By definition of π^{D**} and π^{S**}, they should be the optimal effort level given site choice, as shown in the body text. ■

Proof of Lemma 1

Proof. First, we show that $W((S_l, S_l); V(2)^*_{BR}) > W(S_1, S_2)$. Note that

$$\begin{aligned}
W((S_l, S_l); V(2)^*_{BR}) &= \pi^{S**}(2 - \pi^{S**})V(2)^*_{BR} - 2c(\pi^{S**}) \\
&= \pi^{S*}(2 - \pi^{S*})V(2)^*_{BR} - 2c(\pi^{S*}) \\
&= \pi^{D*}(1 - \pi^{D*})V(2)^*_{BR} + \pi^{D*}V(2)^*_{BR} - 2c(\pi^{D*}) \\
&= \pi^{D*} + \pi^{D*}V(2)^*_{BR} - 2c(\pi^{D*}) \\
&= \pi^{D*}[1 + V(2)^*_{BR}] - 2c(\pi^{D*}) \\
&> 2\pi^{D*} - 2c(\pi^{D*}) \\
&= 2\pi^{D**} - 2c(\pi^{D**}) \\
&= W(S_1, S_2).
\end{aligned}$$

The second and the sixth equality follow from Proposition 1 that $\pi^{S**} = \pi^{S*}$ and $\pi^{D**} = \pi^{D*}$ for given $V(2)$. The third equality follows from the fact that $\pi^{S*} = \pi^{D*}$ iff $V(2) = V(2)^*_{BR}$. The fourth equality follows from the fact that $(1 - \pi^{D*})V(2)^*_{BR} = (1 - \pi^{D*})\frac{1}{(1 - \pi^{D*})} = 1$.

Then, since $W((S_l, S_l), V(2))$ is increasing and continuous in $V(2)$, there exists $V(2)^{**}_{BR}$ such that $W((S_l, S_l), V(2)^{**}_{BR}) = W(S_1, S_2)$ and $V(2)^{**}_{BR} < V(2)^*_{BR}$. Since $V(2)^{**}$ is unique given the strictly convex cost function, it follows that $V(2)^{**}_{BR} = V(2)^{**}$, which completes the proof. ■

Proof of Proposition 4

Proof. According to Lemma 1, $[V(2)^{**}, V(2)^*_{BR}] \neq \emptyset$. Then, for $\forall\, V(2) \in [V(2)^{**}, V(2)^*_{BR}]$, $W((S_l, S_l), V(2)) > W(S_1, S_2)$, so the firms should duplicate site choice in the social optimum. But $W_i((S_l, S_l), V(2)) > W_i(S_1, S_2)$ for $\forall\ V(2) \in [V(2)^{**}, V(2)^*_{BR}]$. Therefore, the equilibrium site choice exhibits excess differentiation for $\forall\ V(2) \in [V(2)^{**}, V(2)^*_{BR}]$. ■

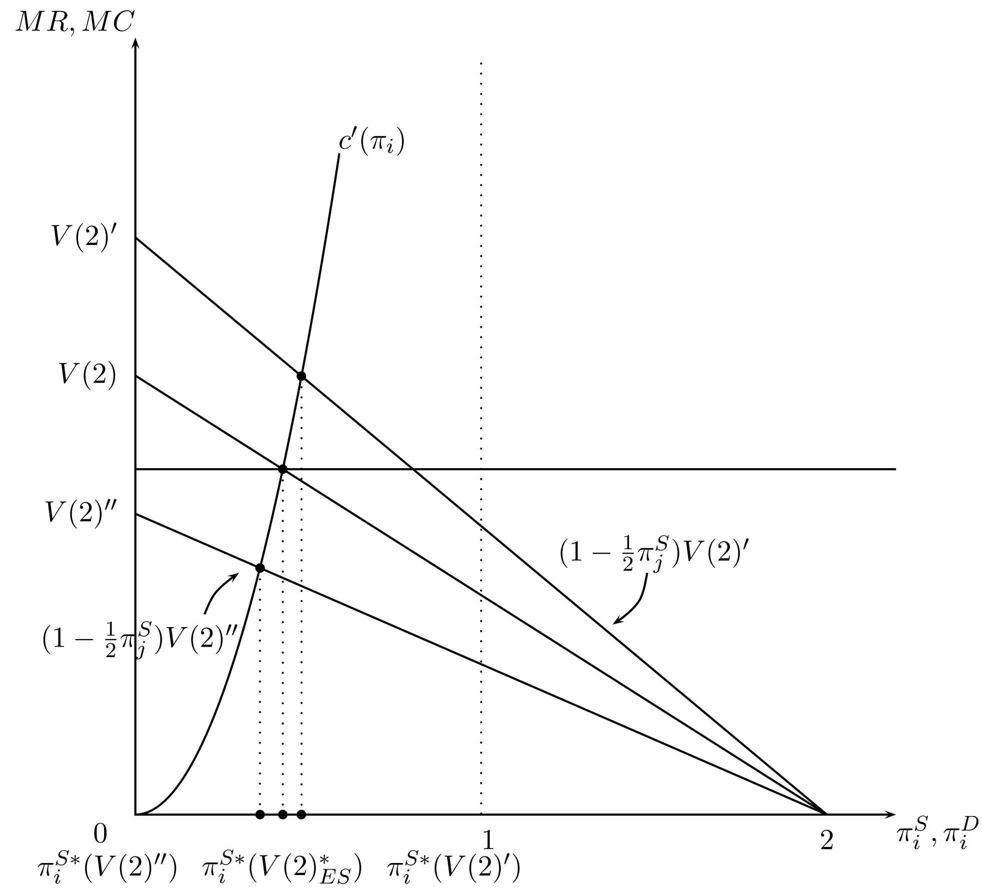

Figure A.2: $\pi_i^{S*}(V(2)'') < \pi_i^{S*}(V(2)^*_{ES}) < \pi_i^{S*}(V(2)')$

Proof of Claim 2

Proof. Consider Figure A.2 in which $V(2)'' < V(2)^*_{ES} < V(2)'$. Since $c'(\cdot)$ is increasing in π_i, it follows that $\pi_i^{S*}(V(2)'') < \pi_i^{D*} = \pi_i^{S*}(V(2)^*_{ES}) < \pi_i^{S*}(V(2)')$. Since the case shown in the Figure can be generalized for all $V(2)$, it follows that π_i^{S*} is strictly increasing in $V(2)$. Therefore, $V(2) > V(2)^*_{ES}$ if and only if $\pi_i^{S*} > \pi_i^{D*}$. Equivalently, $V(2) < V(2)^*_{ES}$ if and only if $\pi_i^{S*} < \pi_i^{D*}$. ■

Proof of Proposition 6

Proof. Suppose the firm A chooses the site S_1 first. Given the firm A's site choice, the firm B receives

$$W_B(S_1, S_1) = \frac{1}{2}\pi_1^{S*}(2 - \pi_1^{S*})V(2) - c(\pi_1^{S*}) \text{ by choosing the same site } S_1$$

$$\text{and } W_B(S_1, S_2) = \pi_2^{D*} - c(\pi_2^{D*}) \text{ by choosing the different site } S_2.$$

Now suppose $V(2) = V(2)^*_{ES}$. Then, since $\pi_1^{S*} = \pi_1^{D*}$ iff $V(2) = V(2)^*_{ES}$ in the equal sharing R&D game,

$$\begin{aligned} W_B((S_1,S_1),V(2)^*_{ES}) &= \frac{1}{2}\pi_1^{S*}(2-\pi_1^{S*})V(2)^*_{ES}) - c(\pi_1^{S*}) \\ &= \frac{1}{2}\pi_1^{S*}(2-\pi_1^{S*})\frac{1}{1-\frac{1}{2}\pi_1^{D*}} - c(\pi_1^{S*}) \\ &= \pi_1^{D*}(1-\frac{1}{2}\pi_1^{D*})\frac{1}{1-\frac{1}{2}\pi_1^{D*}} - c(\pi_1^{D*}) \\ &= \pi_1^{D*} - c(\pi_1^{D*}) \\ &= \pi_2^{D*} - c(\pi_2^{D*}) \\ &= W_B(S_1,S_2). \end{aligned}$$

Hence, by the same logic we used in the proof of Proposition 2, one can see that the firm B chooses the same site chosen by the firm A for all $V(2)$ with $V(2) > V(2)^*_{ES}$ in the equilibrium. Similarly, the firm B chooses the different site for all $V(2)$ with $V(2) < V(2)^*_{ES}$ in the equilibrium. The proof of the result on firms' optimal effort level given site choice is provided in the proof of Claim 1. ■

Proof of Lemma 2

Proof. By the definition of $V(2)^*_{ES}$, we have $\pi^{S*} = \pi^{D*}$ when $V(2) = V(2)^*_{ES}$. Then, we have

$$\begin{aligned} W_A((S_l,S_l);V(2)^*_{ES}) + W_B((S_l,S_l);V(2)^*_{ES}) &= [\pi_{ES}^{S*}(1-\pi_{ES}^{S*}) + \frac{1}{2}\pi_{ES}^{S*}\pi_{ES}^{S*}]V(2)^*_{ES} - c(\pi_{ES}^{S*}) \\ &+ [\pi_{ES}^{S*}(1-\pi_{ES}^{S*}) + \frac{1}{2}\pi_{ES}^{S*}\pi_{ES}^{S*}]V(2)^*_{ES} - c(\pi_{ES}^{S*}) \\ &= 2\pi_{ES}^{S*}(1-\frac{1}{2}\pi_{ES}^{S*})V(2)^*_{ES} - 2c(\pi_{ES}^{S*}) \\ &= 2\pi_{ES}^{S*}(1-\frac{1}{2}\pi_{ES}^{S*})\frac{1}{1-\frac{1}{2}\pi^{D*}} - 2c(\pi_{ES}^{S*}) \\ &= 2\pi^{D*} - 2c(\pi^{D*}) \\ &= 2\pi^{D**} - 2c(\pi^{D**}) \\ &= W(S_1,S_2) \\ &= W((S_l,S_l),V(2)^{**}) \\ &= \pi^{S**}(2-\pi^{S**})V(2)^{**} - 2c(\pi^{S**}). \end{aligned}$$

The third equality and the fourth equality follow from Claimn 2. The fifth equality follows from Proposition 1. The seventh equality follows from the definition of $V(2)^{**}$. The last equality follows from the definition of $W((S_l,S_l),V(2)^{**})$. Now denote by $\pi_{ES}^{S*}(V(2))$ the equilibrium effort level in the equal sharing game when the compatibility benefit is $V(2)$. Also denote by $\pi^{S**}(V(2))$ the efficient effort level when the the compatibility benefit is $V(2)$. Then, from the result of the equation above, we have $\pi_{ES}^{S*}(V(2)^*_{ES}) = \pi^{S**}(V(2)^{**})$ Now recall from Proposition 5 that for given $V(2)$ we have $\pi_{ES}^{S*}(V(2)) > \pi^{S**}(V(2))$. Therefore it follows that $\pi^{S**}(V(2)^*_{ES}) < \pi^{S**}(V(2)^{**})$. Given the monotone relation between $\pi^{S**}(\cdot)$ and $V(2)$, it follows that $V(2)^*_{ES} < V(2)^{**}$, which completes the proof. ■

Proof of Proposition 7

Proof. According to Lemma 2, $[V(2)^*_{ES}, V(2)^{**}] \neq \emptyset$.
(1) For $\forall$ $V(2)$ with $V(2) > V(2)^{**}, W((S_l,S_l),V(2)) > W(S_1,S_2)$, so duplication in site choice in the equilibrium is efficient. But, the equilibrium effort conditional on duplication is inefficiently high according to Proposition 5, so the equilibrium effort level given duplication is higher than in the social optimum although firms' site choice of duplication in the equilibrium is efficient.

(2) Then, for $\forall$ $V(2) \in [V(2)^*_{ES}, V(2)^{**}], W((S_l,S_l),V(2)) < W(S_1,S_2)$, so the firms should differentiate site choice in the social optimum. But $W_i((S_l,S_l),V(2)) > W_i(S_1,S_2)$ for $\forall$ $V(2) \in [V(2)^*_{ES}, V(2)^{**}]$.

Therefore, the equilibrium site choice exhibits excess duplication for $\forall\ V(2) \in [V(2)^*_{ES}, V(2)^{**}]$. Moreover, again the equilibrium effort level conditional on duplication is inefficiently high according to Proposition 5. Therefore for $\forall\ V(2) \in [V(2)^*_{ES}, V(2)^{**}]$, the equilibrium exhibits both excess duplication and excess effort choice. ■

A.2 Proofs for Chapter 2

Proof of Lemma 3

Proof. We prove that $V(2)^{**} < V(2)^*_{BR}$ and $V(2)^*_{RA} < V(2)^{**}$ separately.

First, we show that $V(2)^{**} < V(2)^*_{BR}$. We begin the proof of the first part by showing $W((S_l, S_l); V(2)^*_{BR}) > W(S_1, S_2)$. Notice that

$$\begin{aligned}
W((S_l, S_l); V(2)^*_{BR}) &= \pi^{S**}(2 - \pi^{S**})V(2)^*_{BR} - 2c(\pi^{S**}) \\
&= \pi^{S*}(2 - \pi^{S*})V(2)^*_{BR} - 2c(\pi^{S*}) \\
&= \pi^{D*}(1 - \pi^{D*})V(2)^*_{BR} + \pi^{D*}V(2)^*_{BR} - 2c(\pi^{D*}) \\
&= \pi^{D*} + \pi^{D*}V(2)^*_{BR} - 2c(\pi^{D*}) \\
&= \pi^{D*}[1 + V(2)^*_{BR}] - 2c(\pi^{D*}) \\
&> 2\pi^{D*} - 2c(\pi^{D*}) \\
&= 2\pi^{D**} - 2c(\pi^{D**}) \\
&= W(S_1, S_2).
\end{aligned}$$

The second and the sixth equality follow from Proposition 1 that $\pi^{S**} = \pi^{S*}$ and $\pi^{D**} = \pi^{D*}$ for given $V(2)$. The third equality follows from the fact that $\pi^{S*} = \pi^{D*}$ iff $V(2) = V(2)^*_{BR}$. The fourth equality follows from the fact that $(1-\pi^{D*})V(2)^*_{BR} = (1-\pi^{D*})\frac{1}{(1-\pi^{D*})} = 1$. Then, since $W((S_l, S_l), V(2))$ is increasing and continuous in $V(2)$, there exists $V(2)^{**}_{BR}$ such that $W((S_l, S_l), V(2)^{**}_{BR}) = W(S_1, S_2)$ and $V(2)^{**}_{BR} < V(2)^*_{BR}$. Since $V(2)^{**}$ is unique given the strictly convex cost function, it follows that $V(2)^{**}_{BR} = V(2)^{**}$, which completes the first part of the proof.

Now we show that $V(2)^*_{RA} < V(2)^{**}$. Recall that

$$W_i((S_l, S_l); V(2), \lambda = 0) = [\pi_i^{S*}(1 - \pi_j^{S*}) + \frac{1}{2}\pi_i^{S*}\pi_j^{S*}] + \frac{1}{2}[\pi_i^{S*}(1 - \pi_j^{S*}) + \pi_j^{S*}][V(2) - 1] - c(\pi_i^{S*}).$$

We begin the proof of the second part by showing that $W((S_l, S_l), V(2)^*_{RA}) < W(S_l, S_k)$. Note that

$$\begin{aligned}
W((S_l, S_k)) &= W_1((S_l, S_l); V(2)^*_{RA}, \lambda = 0) + W_2((S_l, S_l); V(2)^*_{RA}, \lambda = 0) \\
&= [\pi_1^{S*}(1 - \pi_2^{S*}) + \frac{1}{2}\pi_1^{S*}\pi_2^{S*}] + \frac{1}{2}[\pi_1^{S*}(1 - \pi_2^{S*}) + \pi_2^{S*}][V(2)^*_{RA} - 1] - c(\pi_1^{S*}) \\
&+ [\pi_2^{S*}(1 - \pi_1^{S*}) + \frac{1}{2}\pi_2^{S*}\pi_1^{S*}] + \frac{1}{2}[\pi_2^{S*}(1 - \pi_1^{S*}) + \pi_1^{S*}][V(2)^*_{RA} - 1] - c(\pi_2^{S*}) \\
&> [\pi^{S**}(1 - \pi^{S**}) + \frac{1}{2}(\pi^{S**})^2] + \frac{1}{2}[\pi^{S**}(1 - \pi^{S**}) + \pi^{S**}][V(2)^*_{RA} - 1] - c(\pi^{S**}) \\
&+ [\pi^{S**}(1 - \pi^{S**}) + \frac{1}{2}(\pi^{S**})^2] + \frac{1}{2}[\pi^{S**}(1 - \pi^{S**}) + \pi^{S**}][V(2)^*_{RA} - 1] - c(\pi^{S**}) \\
&= \pi^{S**}(2 - \pi^{S**})V(2)^*_{RA} - 2c(\pi^{S**}) \\
&= W((S_l, S_l), V(2)^*_{RA}).
\end{aligned}$$

The first inequality in the fourth line follows from the fact that π^{S*}_{RA} maximizes the firms' expected payoffs within the research alliance and $\pi^{S*}_{RA} \neq \pi^{S**}$ according to Claim 3. Now recall that $W((S_l, S_k)) = W((S_l, S_l); V(2)^{**})$ by the definition of $V(2)^{**}$. Then, since $W((S_l, S_k)) > W((S_l, S_l), V(2)^*_{RA})$, it follows that

$$W((S_l, S_l), V(2)^{**}) > W((S_l, S_l), V(2)^*_{RA}).$$

Then, the monotonicity of $W((S_l, S_l), V(2))$ in $V(2)$ shows that $V(2)^{**} > V(2)^*_{RA}$, which completes the second part of the proof. ■

Proof of Proposition 8

Proof. (1) Suppose $V(2) > V(2)^*_{BR}$.

First, we prove $\pi^{S*}_B < \pi^{S**}$ for $\forall\ \lambda \in [0,1]$. Denote by $\pi^{S*}_i(\lambda)$ the firm i's equilibrium effort choice for given $V(2)$ and λ. According to Claim 3, if $V(2) > V(2)^*_{BR}$, then $\pi^{S*}_i(0) < \pi^{S**}$ for given $V(2)$ with $i \in \{A,B\}$. Since $\pi^{S*}_B(\lambda)$ is decreasing in λ, we have $\pi^{S*}_B(\lambda) < \pi^{S**}$ for $\forall\ \lambda \in [0,1]$ given $V(2)$ with $V(2) > V(2)^*_{BR}$.

Second, we prove $\pi^{S*}_A(\lambda)$ may be higher or lower than π^{S**}, depending on λ for given $V(2)$ with $V(2) > V(2)^*_{BR}$. For the case with $\lambda = 0$, we have $\pi^{S*}_A(0) < \pi^{S**}$ according to Claim 3. Now, consider the case with $\lambda = 1$, where the firm A's marginal effort revenue is $(1 - \frac{1}{2}\pi^{S*}_B(1)) + \frac{1+\lambda}{2}(1 - \pi^{S*}_B(1))[V(2) - 1]$ which boils down to $(1 - \pi^{S*}_B(1))V(2) + \frac{1}{2}\pi^{S*}_B(1)$. Then, since $\pi^{S*}_B(1) < \pi^{S**}$, the firm A's marginal revenue from increase in π^S_A is greater than $(1 - \pi^{S**})V(2)$, the social planner's marginal revenue from increase in π^S_A, thereby we have $\pi^{S*}_A(1) > \pi^{S**}$. Hence, we have $\pi^{S*}_A(0) < \pi^{S**}$ and $\pi^{S*}_A(1) > \pi^{S**}$. Then, given that $(1 - \frac{1}{2}\pi^{S*}_B) + \frac{1+\lambda}{2}(1 - \pi^{S*}_B)[V(2) - 1]$ is continuously increasing in λ, there exists some $\lambda' \in (0,1)$ for given $V(2)$ with $V(2) > V(2)^*_{BR}$ such that $\pi^{S*}_A(\lambda') = \pi^{S**}$. Therefore, for given $V(2)$ with $V(2) > V(2)^*_{BR}$, we have $\pi^{S*}_A(\lambda) \geq \pi^{S**}$ if and only if $\lambda \geq \lambda'$, which completes the proof.

(2) First consider $\pi^{S*}_A(\lambda)$. According to Claim 3, $\pi^{S*}_A(0) > \pi^{S**}$ if $V(2) \in [V(2)^*_{RA}, V(2)^*_{BR})$. Moreover, the firm A's marginal revenue from increase in π_A is increasing in λ, so we have $\pi^{S*}_A(\lambda) > \pi^{S**}$ for $\forall\ \lambda \in [0,1]$.

Next, consider $\pi^{S*}_B(\lambda)$. If $\lambda = 0$, then we have $\pi^{S*}_B(0) > \pi^{S**}$ for $V(2) \in [V(2)^*_{RA}, V(2)^*_{BR})$ according to Claim 3. Since the firm B's marginal revenue from increase in π_B is continuously decreasing in λ, it follows that $\pi^{S*}_B(\lambda) > \pi^{S**}$ for λ close to 0 when $V(2) \in [V(2)^*_{RA}, V(2)^*_{BR})$. Now recall that $\pi^{S*}_B(0) = \pi^{S**}$ when $V(2) = V(2)^*_{BR}$. Then, since the firm B's marginal revenue from increase in π_B is continuously decreasing in λ, it follows that $\pi^{S*}_B(\lambda) < \pi^{S**}$ for $\lambda > 0$. Since the firm B's marginal revenue from increase in π_B is continuous in $V(2)$, so it still holds that $\pi^{S*}_B(\lambda) < \pi^{S**}$ for big enough λ even when $V(2) < V(2)^*_{BR}$. Therefore, $\pi^{S*}_B(\lambda)$ can be lower or higher than π^{S**} depending on λ and $V(2)$, which completes the proof. ■

Proof of Lemma 4

Proof. First we prove for necessity. Suppose by negation that firms choose the same site in the equilibrium where $W_B(S_l, S_l; V(2), \lambda = 0) < W_B(S_l, S_k)$. But, given that $W_B(S_l, S_l; V(2), \lambda = 0) < W_B(S_l, S_k)$ and the firm A can't offer λ strictly smaller than 0, the firm B finds it strictly better to choose a different site rather than accepting the firm A's offer of $\lambda = 0$. Therefore, if firms choose the same site in the equilibrium, then it should be that

$$W_B(S_l, S_l; V(2), \lambda = 0) \geq W_B(S_l, S_k) \text{ in the equilibrium.}$$

Next, we prove for sufficiency. Since

$$W_A(S_l, S_l; V(2), \lambda = 0) = W_B(S_l, S_l; V(2), \lambda = 0) \text{ and } W_A(S_l, S_k) = W_B(S_l, S_k),$$

$$\text{we have } W_A(S_l, S_l; V(2), \lambda = 0) \geq W_A(S_l, S_k),$$

$$\text{whenever } W_B(S_l, S_l; V(2), \lambda = 0) \geq W_B(S_l, S_k).$$

By the assumption, firms choose the same site $W_i(S_l, S_l; V(2), \lambda = 0) = W_i(S_l, S_k), i \in \{A,B\}$. Now, consider the case that $W_B(S_l, S_l; V(2), \lambda = 0) > W_B(S_l, S_k)$. Since $W_i(S_l, S_l; V(2), \lambda)$ with $i \in \{A,B\}$ is continuous in λ for given $V(2)$, there exists some $\lambda'' \in (0,1]$ such that $W_A(S_l, S_l; V(2), \lambda'') > W_A(S_l, S_k)$ and $W_B(S_l, S_l; V(2), \lambda'') > W_B(S_l, S_k)$ for given $V(2)$ so that the firm A can offer the firm B λ'' which the firm B better accepts. Hence it follows that if $W_B(S_l, S_l; V(2), \lambda = 0) > W_B(S_l, S_k)$, then two firms choose the same site, which completes the proof. ■

Proof of Claim 3

Proof. Let $\lambda = 0$. Then, the expected payoff of the firm i with $i \in \{A,B\}$ from forming a research alliance is

$$W_i(S_l, S_l; V(2), \lambda = 0) = [\pi_i(1 - \pi^{S*}_j) + \frac{1}{2}\pi_i\pi^{S*}_j] + \frac{1}{2}[\pi^{S*}_j + (1 - \pi^{S*}_j)\pi_i][V(2) - 1] - c(\pi_i).$$

Then, the first order condition with respect to π_i boils down to

$$\frac{1}{2}[(1-\pi_j^{S*})V(2)+1]=c'(\pi_i).$$

Now compare the firm i's marginal revenue from increase in the effort(the left hand side of the first order condition) to that of the social planner which is $(1-\pi_j^{S**})V(2)$. Recall that both the social marginal revenue and the private marginal revenue are monotonic in $V(2)$, so the equilibrium effort levels also are monotonic in $V(2)$. Now let $V(2)=V(2)^*_{BR}=\frac{1}{1-\pi_j^{D*}}$. Then, the social marginal revenue from increase in the firm i's effort becomes 1 which is the firms' marginal revenue conditional on differentiation. The firms' private marginal revenue also becomes $\frac{1}{2}[(1-\pi_j^{S*})\frac{1}{1-\pi_j^{D*}}+1]$ which is strictly greater than 1 if and only if $\pi_j^{D*}>\pi_j^{S*}$. But, if $\pi_j^{D*}>\pi_j^{S*}$ so that the firms' marginal revenue conditional on forming a research alliance is greater than that conditional on differentiation, it should follow that $\pi_j^{D*}<\pi_j^{S*}$ which is contradiction to the supposition. By the same reason, it can't be strictly smaller than 1. So it follows that when $V(2)=V(2)^*_{BR}$, the firms' marginal revenue conditional on forming a research alliance should be exactly 1, which is the same as that of the social planner. Now note that the firms' marginal revenue is increasing in $V(2)$ at the rate of $\frac{1}{2}(1-\pi_j^{S*})$, while that of the social planner is increasing in $V(2)$ at the rate of $(1-\pi_j^{S*})$. Then, since $\pi_i^{S*}=\pi_i^{S**}$ as $V(2)=V(2)^*_{BR}$, so it follows that $\pi_i^{S*}>\pi_i^{S**}$ for all $V(2)$ with $V(2)^*_{RA}<V(2)<V(2)^*_{BR}$. Similarly, $\pi_i^{S*}<\pi_i^{S**}$ for all $V(2)$ with $V(2)>V(2)^*_{BR}$. ■

Proof of Proposition 9

Proof. Since $W_i(S_l,S_l);V(2),\lambda=0)$ is increasing in $V(2)$, $W_i(S_l,S_l);V(2),\lambda=0)\geq W_i((S_l,S_l);V(2)^*_{RA}\lambda=0)$ for all $V(2)$ with $V(2)\geq V(2)^*_{RA}$ by the definition of $V(2)^*_{RA}$. Hence, according to Lemma 3, both firms prefer to form a research alliance if and only if $V(2)\geq V(2)^*_{RA}$. The proof of firms equilibrium effort choice is provided in the proof of Proposition 8. ■

Proof of Proposition 10

Proof. The firms choose the same site for all $V(2)$ with $V(2)\geq V(2)^*_{RA}$ according to Proposition 9. But, according to Lemma 3, $[V(2)^*_{RA},V(2)^{**}]$ is nonempty. Then, since differentiation in site choice is efficient for all $V(2)$ with $V(2)>V(2)^{**}$, firms' choosing the same site is inefficient. For $V(2)$ with $V(2)>V(2)^*_{RA}$, firms incentive to choose a same site coincides to that of the social planner, so firms' choosing the same site is efficient. The inefficiency result in the firms' effort choice and corresponding efficient investment choice is given in Proposition 9 and Corollary 2. ■

A.3 Proofs for Chapter 3

Proof of Footnote III.2.1.1.2

Proof. Consider the following two probability distributions regarding treasures being buried in the site S_l : Under the first probability distribution, treasures are buried in the site with the probability ϕ_H, while there's no treasure buried in the site with the probability $1-\phi_H$. Under the second probability distribution, treasures are buried in the site with the probability ϕ_L, while there's no treasure buried in the site with the probability $1-\phi_L$. Without a loss of generality, assume that $\phi_L<\phi_H$. Denote by p_l^0 the initial belief that $(\phi_H,1-\phi_H)$ is the true probability distribution. Then, by $1-p_l^0$ the initial belief that $(\phi_L,1-\phi_L)$ is the true probability distribution. Then, p_l^1, the updated posterior belief that treasures are buried in the site conditional on one R&D experiment in the current period ending up with a failure is

$$\frac{p_l^0[\phi_H(1-\pi)+(1-\phi_H)]}{p_l^0[\phi_H(1-\pi)+(1-\phi_H)]+(1-p_l^0)[\phi_L(1-\pi)+(1-\phi_L)]}.$$

But, note that treasures should be either buried ($\phi_H=1$) or not ($\phi_L=0$). Hence, such nature of the problem reduces the above expression to

$$\frac{p_l^0(1-\pi)}{p_l^0(1-\pi)+(1-p_l^0)}=\frac{p_l^0(1-\pi)}{1-\pi p_l^0}.$$

Similarly, p_l^2, the updated posterior belief that treasures are buried in the site S_l conditional on two R&D experiments in the current period ending up with a failure is

$$p_l^2 = \frac{p_l^1(1-\pi)}{p_l^1(1-\pi)+(1-p_l^1)} = \frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2+(1-p_l^0)}.$$

■

Proof of Claim 4

Proof. In Figure III.1 it's obvious that P_{12} gets smaller in its size as $V(2)$ is greater, which completes the proof of the first part of Claim 4. Especially, when $V(2) = \widetilde{V}(2)$, the line of $I_{\{12=11\}}$ intersects the line of $I_{\{12=22\}}$ at $p_1^0 = p_2^0 = 1$, implying $P_{12} = \{(1,1)\}$. Then, according to the first part of Claim 4, for $V(2)$ with $V(2) > \widetilde{V}(2)$, $P_{12} = \emptyset$, which completes the proof of the second part of Claim 4(See Figure **??**). Also, since the intercept of both $I_{\{12=11\}}$ and $I_{\{12=22\}}$ is increasing in $v(2)$, it's obvious that P_{12} gets smaller in its size as c is greater, which completes the proof of the third part of Claim 4. ■

Proof of Claim 5

Proof. (1) It's obvious that if (p_1^0, p_2^0) belongs to the "no R&D activity area" for which the condition (III.8) and the condition (III.9) are satisfied, neither $V((S_1, S_2))$ nor $V((S_l, S_l))$ with $l \in \{1,2\}$ is positive, which completes the proof.
(2) Notice that the set of (p_1^0, p_2^0) satisfying the condition that

$$\begin{aligned} (p_1^0 + p_2^0)\pi V(1) - 2c &\leq 0 \\ \iff \qquad p_2^0 &\leq \frac{2c}{\pi} - p_1^0 \end{aligned}$$

is depicted as the triangle with the height and the base of $\frac{2c}{\pi}$ in the left bottom of Figure III.3 and Figure III.4. Also notice that the set of (p_1^0, p_2^0) satisfying the condition that

$$\begin{aligned} p_l^0\pi(2-\pi)V(2) - 2c &\leq 0 \text{ for } l \in \{1,2\} \\ \iff \qquad p_l^0 &\leq \frac{2c}{\pi(2-\pi)V(2)} \end{aligned}$$

is depicted as the square with the length of $\frac{2c}{\pi(2-\pi)V(2)}$ in the left bottom of Figure III.3 and Figure III.4. Notice that the social planner's payoff is negative only for the intersection of the two sets, which is depicted as the white polygon in the in the left bottom of Figure III.3 and Figure III.4. Then, since $2c$, the numerator of $\frac{2c}{\pi(2-\pi)V(2)}$ and $\frac{2c}{\pi}$ is actually $2c - 2v(2)$ with production externality where $2c - 2v(2) = 2c$ without production externality, it's obvious that the polygon shrinks as $v(2)$ grows and disappears as $v(2) = c$, which completes the proof. ■

Proof of Lemma 6

Proof. Notice that

$$V((S_l, S_l); (p_l^2, p_k^0)) \geq V((S_k, S_k); (p_l^2, p_k^0)) \text{ iff } p_l^2 \geq p_k^0 \text{ with } l \neq k.$$

Then, when $p_l^2 \geq p_k^0$ with $l \neq k$ then the socially optimal site choice in the second period after the history of (S_l^f, S_l^f) is (S_l, S_l) if the updated beliefs on treasures being buried in each site satisfies the condition that

$$p_k^0 \leq p_l^2[(2-\pi)V(2) - 1] + \frac{2c}{\pi} \text{ for } l \neq k,$$

which is equivalent to the condition that

$$p_k^0 \leq \frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2 + (1-p_l^0)}[(2-\pi)V(2) - 1] + \frac{2c}{\pi}.$$

Now recall that $p_k^0 > p_l^2$ is equivalent to

$$p_k^0 > \frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2 + (1-p_l^0)}.$$

Then, since (S_l, S_l) is socially optimal if and only if both conditions in the above are satisfied, it follows that (S_l, S_l) is socially optimal if and only if

$$p_k^0 < min\{\frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2 + (1-p_l^0)}, \frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2 + (1-p_l^0)}[(2-\pi)V(2)-1] + \frac{2v(2)}{\pi}\},$$

which completes the first part of the proof.

When $p_l^2 < p_k^0$ with $l \neq k$, then the socially optimal site choice in the second period after the history of (S_l^f, S_l^f) is (S_k, S_k) if the updated beliefs on treasures being buried in each site satisfies the condition that

$$p_k^0 > \frac{p_l^2\pi - 2v(2)}{\pi[(2-\pi)V(2)-1]},$$

which is equivalent to the condition that

$$p_k^0 > \frac{\frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2+(1-p_l^0)}\pi - 2v(2)}{\pi[(2-\pi)V(2)-1]}.$$ [1]

Then, since (S_k, S_k) is socially optimal if and only if both conditions in the above are satisfied, it follows that (S_k, S_k) is socially optimal if and only if

$$p_k^0 > max\{\frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2 + (1-p_l^0)}, \frac{\frac{p_l^0(1-\pi)^2}{p_l^0(1-\pi)^2+(1-p_l^0)}\pi - 2v(2)}{\pi[(2-\pi)V(2)-1]}\},$$

which completes the second part of the proof.

It's obvious that if (p_1^0, p_2^0) belongs neither the case mentioned above, then the socially optimal site choice in the second period after the history of (S_l^f, S_l^f) is (S_l, S_k), which completes the last part of the proof. ∎

Proof of Lemma 7

Proof. Since

$$p_l^1 = \frac{p_l^0(1-\pi)}{1-p_l^0\pi} \text{ for } l \in \{1,2\},$$

we can compute the set of (p_1^0, p_2^0) for which

$$max\{V(2)+v(2), V(1)+p_k^1\pi - c\} = V(1) + p_k^1\pi - c \text{ with } l \neq k \text{ following } (S_l^s, S_k^f).$$

Notice that it boils down to

$$V(1) + p_k^1\pi - c > V(2) + v(2) \text{ iff } p_k^0 > \frac{V(2)-V(1)+2v(2)}{\pi[V(2)+2v(2)-\pi]},$$

which completes the proof. ∎

[1] Recall that $p_2^0 > \frac{p_1^0\pi - 2v(2)}{\pi[(2-\pi)V(2)-1]}$ is the equation for $I_{\{12=22\}}$ in the one period game.

Proof of Claim 7

Proof. From the equation (III.18) (and the equation (III.19)), it's obvious that the configuration of each set of $P_{l(k)}$ with $l, k \in \{1, 2\}$ depends on the slopes and the intercepts of $I_{1(2)}$ and $I_{2(1)}$ where the slopes depend on $V(2)$, the R&D payoff with compatibility externality and the intercepts depend on $v(2)$, the production payoff with production externality. Especially the slope of $I_{2(1)}$(and $I_{1(2)}$) is increasing(decreasing) in $V(2)$ and the intercept of $I_{2(1)}$(and $I_{1(2)}$) is increasing(increasing) in $v(2)$. Hence it's obvious that $P_{1(2)}$ gets smaller in its size as $V(2)$ or/and $v(2)$ is greater, which completes the proof of the first part and the proof of the third part of Claim 7. Especially, when $V(2) \equiv \overline{V}(2)$, the line of $I_{1(2)}$ intersects the line of $I_{2(1)}$ at $p_1^0 = p_2^0 = 1$, implying $P_{1(2)} = P_{2(1)} = (1, 1)$. Then, according to the first part of Claim 7, for $V(2)$ with $V(2) > \overline{V}(2)$, $P_{1(2)} = P_{2(1)} = \emptyset$, which completes the proof of the second part of Claim 7. ■

Proof of Proposition 12

Proof. Most of the proof is already provided in the explanations of Figure III.12. Hence we prove that the set of (p_1^0, p_2^0) for which equilibrium site choice is inefficient gets larger as θ approached either to 0 or to $\frac{1}{2}$. But it also is obvious since with the slope of $I_{2(1)}(I_{2(1)})$ increasing(decreasing) in θ, decrease in θ results in a larger set of (p_1^0, p_2^0) for which over-differentiation occurs when $\theta < \theta^*$. Similarly, increase in θ results in a larger set of (p_1^0, p_2^0) for which over-duplication occurs when $\theta > \theta^*$. ■

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