Assessing the Value of Research and Exploratory Development Stage of an R&D project under Duopoly and Oligopolistic Competition

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1. Introduction

Among the important issues of a firm engaging in R&D, there is evaluation related to uncertainty regarding the feasibility and profitability of an innovation, the possibility of a protracted development period, the possibility of a rival firm imitating the innovation and appropriating some of the profits in the new market, the possibility of a rival firm innovating first to have either a patent or a significant share of the new market.

However, in contrast with the voluminous array of literature and methods for initial selection or funding of R&D projects, relatively little appears in print regarding evaluating the consequences of R&D. This is rather surprising when one considers the importance of feedback to learning and improvement. The simplest approach to evaluation of R&D results consists of annually tallying discernible outputs of the R&D organization such as patents, publications, reports, etc. The major drawback to this analysis is that tangible indicators are usually indirect measures of R&D success. Patents, publications and so forth are seldom

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ends in themselves.

For solving this drawback, we first divide the stage of an R&D project into three stages by research goal of each stage. Even though a research and development project does not have a clear cut sequence of stages, it might be worthwhile differentiating it into research, exploratory development, development (advanced development and engineering development) before production and marketing begin. Research and exploratory development generally do not generate direct profits. They are used, however, for development which can yield, if successful, substantial monetary returns in the future. After classifying the stage of an R&D project into three stages, the result of each stage can be measured to a monetary value which includes worth of patents, publications and reports. But, the monetary value mentioned here is relative value. Because the value of the intermediate result of an R&D project is not direct one to a firm, we assess the above value in competitive situation. In this competitive situation, inventor who has superior knowledge of each stage has two important decisions.

Two important decisions for the inventor of two intermediate results, such as the outcome of Research and exploratory development, are whether to (or when to) announce the findings publicly. If the inventor decides to announce intermediate findings, he would obtain a recognition. But, the announcement might impair the chance of winning the potentially bigger prize for developing the intermediate results. If he decides not to reveal it, however, there exists a risk that competitor(s) would develop the same knowledge and release them with one's name(s) on them.

The new knowledge derived from an intermediate result may not be revealed, unless the inventor is better off by allowing it to be. If an inventor is able to realize more profits by keeping his invention secret, the outcome will be less contributing to society as it impedes the development of future inventions based on previous ones.

This paper is organized as follows. Review of classification of R&D stages, methods for measuring R&D result are described in section 2. A model for assessing the value of the intermediate results in a competitive R&D project is suggested in section 3. An example is presented in section 4 for identifying the applicability of the model. Finally, section 5 gives the summary and discussion.

2. Literature Review

2.1 Classification of R&D stages

A number of stage classification schemes have been either described or proposed. The classifications are varied and depend on the particular company characteristics or research goal. Thus, some classifications of R&D stages so far are summarized as the following.

Traditionally, R&D stages are classified by a sequence of idea embodiment into *basic research, applied research* and *development.* (1) Pappas and Remer[1] consider five R&D stages for measuring R&D productivity. First stage is *basic research* directed to the search of fundamental knowledge. Second stage is *exploratory research* to determine if some scientific concept might have useful application. Third stage is *applied research* directed to improving the practicality of a specific application. Fourth stage is *development* that is engineering improvement of a particular product or process. Last stage is *product improvement* directed to changes for a product or process that can increase its marketability, reduce its cost, or both. (2) Amrine and Hulley[2] make a classification of applied R&D activities within a manufacturing organization, that is, *product research, materials research, market research, operations research, manufacturing research* and *development* and *product development.* They also defined "applied research" as the systematic search for "unknown" and "uncovered" facts or principles and "development" as the continual searching for the most economically feasible method for applying the facts or principles identified within a particular manufacturing organization. (3) Gibson[3] considers five R&D stages as the following. First stage is *basic research* which is the systemic investigation of natural phenomena in an effort to define more precisely or to extend the principles of nature in a particular scientific area. Second stage is *applied research* which is research carried out in a particular restricted field or within defined parameters for the purpose of laying down a firmer base of knowledge for possible application. Third stage is *exploratory development* which is the organization of existing scientific knowledge to create in concept a new device or process to accomplish a desired societal goal. Fourth stage is *advanced development* which is the extension of the concepts created in exploratory development, along with known technological limitations, to create an operating prototype device or process. Last stage is *engineering development* which is the application of practical constraints such as economic requirements, manufacturability limitations, field maintainability, and the like, to the practical implementation of an objective that is well defined in a conceptual and physical sense. (4) Albala[4] makes a classification of R&D stages in chemical industry as the following. First stage is *exploratory research*. This stage emphasizes "paper studies." Second stage is *applied research*. This stage includes laboratory research directed toward defining the technological characteristics of the new process or product or their improvement. A normal complement of laboratory scale research is bench-scale research to determine quantitative process parameters. Last stage is *development*. This stage includes general development work, such as pilot-scale, detailed marketing and economic studies. (5) Charles and McKean[5] proposed an alternative classification for R&D stages, such as, *research, exploratory development, advanced development, operational systems development* and *management* and *support*.

This classification proposed by several people is not exhaustive, but is representative of available classification.

Therefore, it is possible to observe common approach that each stage is limited by clear boundaries determined by its objectives and scope of work.

From this classification, we note that Gibsons classification is very close to traditional one. It appears that there exists a simple liner progression from basic to applied research and thence to various phases of development, but this progression does not always exists in reality. For example, Edisons approach is best handled by intuitive geniuses, who, although rare, do exist. However, fortunately, as scientific knowledge is broadened and deepened, logical progression seems to become more common. Therefore, Albalas classification is used as basis on classification in R&D stage in the thesis.

2.2 Method for measuring R&D result

Because main purpose of this paper is to construct a model for assessing the value of two intermediate results (i.e., result of research and result of exploratory development) in a competitive R&D project, in this section, we roughly review patent system and measurement method for worth of R&D project result. Firstly, patent system which is related to result of R&D activity (inventive activity) is briefly described. Secondly, because the goal of evaluation methods reviewed in section 2.2 is company by company level evaluation, determination of project continuity (e.g., going or termination) and project selection, measurement method for worth of R&D project result are briefly described below.

One of the purposes of a patent is to get rid of the need for secrecy and to bring new information into the public domain (Scherer [6]). The role of the patent system is the following: that has facilitated the introduction of technology; that has promoted a desire to develop technology; that has guaranteed the recovery of the spending on technological development; that has provided the technological information and business information. The main objectives of past works have been to analyze the trade-off between benefits of patents and social cost due to the monopoly granted through a patent.

The evaluation of the potential worth of the R&D results involves the opportunity concept previously proposed by Gee[7]. A brief review of this basic concept is the following. The primary objective of industrial research should be to create and define business opportunity which can be exploited to provide profits to the firm. Opportunity should be quantitatively and rigorously defined; it should take into account market and competitive factors as well as technical performance factors. If an objective of research is to generate opportunity, research productivity can be measured in terms of the amount of opportunity generated. And further, if an objective of research is to generate opportunity at a minimum cost, research efficiency can be measured in terms of the amount of opportunity generated per dollar of R&D expense. Also opportunity is defined as the size of the market for which the product is both technically and economically adequate.

Mansfield[8] provides an excellent summary of the work that has been performed over the years to develop and apply measurements of R&D impact at the macro level, and specifically addresses the questions of the relationship between R&D and the nation's rate of economic growth and productivity. Taymour[9] develops a methodology for relating the contribution of R&D to a company's sales, and then applies it to historical data from his own firm. Bachman[10] approaches the value problem from a different angle. He relies on the direct relationship between R&D costs and profits as a measure of R&D performance.

Hirshleifer[11] considers the reward to inventive activity by investigating the private and social value of information. His analysis of the value of priority of information necessarily involves both temporality and uncertainty. For convenience, the simplest possible paradigm of choice is employed. However, his intent is to provide an explanation on the distributive aspect of access to superior information, rather than to offer a framework for assessing the value of superior knowledge. Park and Chong[12] propose a framework for assessing the value of superior knowledge in a competitive R&D project. They consider stage of R&D project as basic research and development in assessing the value of intermediate result.

3. An Assessing Model

3.1 Assumptions

A1. A competitive research and development project must have a simple linear progression that is from research to exploratory development and thence to the development (advanced development and engineering development).

A2. We call a result of research and a result of exploratory development "intermediate result I" and "intermediate result II" respectively. The intermediate result I is dependent on the intermediate result II.

A3. Success rates of each stage remain constant throughout the invention process (i.e., distribution of invention process time is exponential).

A4. Overhead cost is estimated by historical data of a company (i.e., multiply direct cost by 0.33).

A5. Potential benefit of the final result of a competitive R&D project is estimated by opportunity concept

A6. We call Round I a state that potential inventors compete for the second stage invention before development stage, and Round II a state that they compete for the third stage invention after completion of first stage invention.

A7. Research expenditure rate in each stage is independent on the time.

3.2 Notations and Definitions

N1. T_{L2} is the random variable that represents the time required for the "leader" to complete the second stage invention (i.e.,exploratory development).

N2. T_{L3} is the random variable that represents the time required for the "leader", equipped with the second stage invention knowledge (i.e., intermediate result II), to complete the third stage invention (i.e., final invention or development).

N3. T_{L1} is the random variable that represents the time required for the "follower" to complete the first stage invention (i.e., research).

N4. T_{L2} is the random variable that represents the time required for the "follower",equipped with the first stage invention knowledge (i.e., intermediate result I), to complete the second stage invention.

N5. T_{L3} is the random variable that represents the time required for the "follower", equipped with the second stage invention knowledge (i.e., intermediate result II), to complete the third stage invention.

N6. $F_{L2}(\ )$, $F_{L3}(\ )$, $F_{F1}(\ )$, $F_{F2}(\ )$ and $F_{F3}(\ )$ are the distribution functions of T_{L2}, T_{L3}, T_{F1}, T_{F2}, and T_{F3}, respectively

N7. $f_{L2}(\ )$, $f_{L3}(\ )$, $f_{F1}(\ )$, $f_{F2}(\ )$ and $f_{F3}(\ )$ are the probability density functions of T_{L2}, T_{L3}, T_{F1}, T_{F2}, and T_{F3}, respectively

N8. P_3 is the monetary reward an inventor receives when he completes the third stage invention first.

N9. P_2 is the reservation price of the second stage invention, in order for the "leader" to be willing to disclose the intermediate result II to the public in exchange for earning P_2.

N10. P_1 is the reservation price of the first stage invention, in order for the "leader" to be willing to disclose the intermediate result I to the public in exchange for earning P_1.

N11. $b_i(t)$ is the research expenditure rate at the ith stage invention time t (in our case $b_i(t)$ is independent on time)

N12. O_i is the overhead cost required to conduct R&D in the ith stage invention.

N13. λ_{F1}, λ_{F2} and λ_{F3} are the success rates at which the first invention, the second and the third invention are ccomplished respectively by the follower.

N14. λ_{L2} and λ_{L3} are the success rates at which the second and the third invention are accomplished respectively by the leader.

3.3 A Model of Duopoly competition

Consider R&D rivalry between two potential inventors. One of the goals of the present study is to determine the appropriate value of and in terms of final recognition, the success rates and the research expenditure. Because of the exponential's memorylessness property, the leader's choice at the time of an invention is reduced to only two options; either disclose the intermediate result

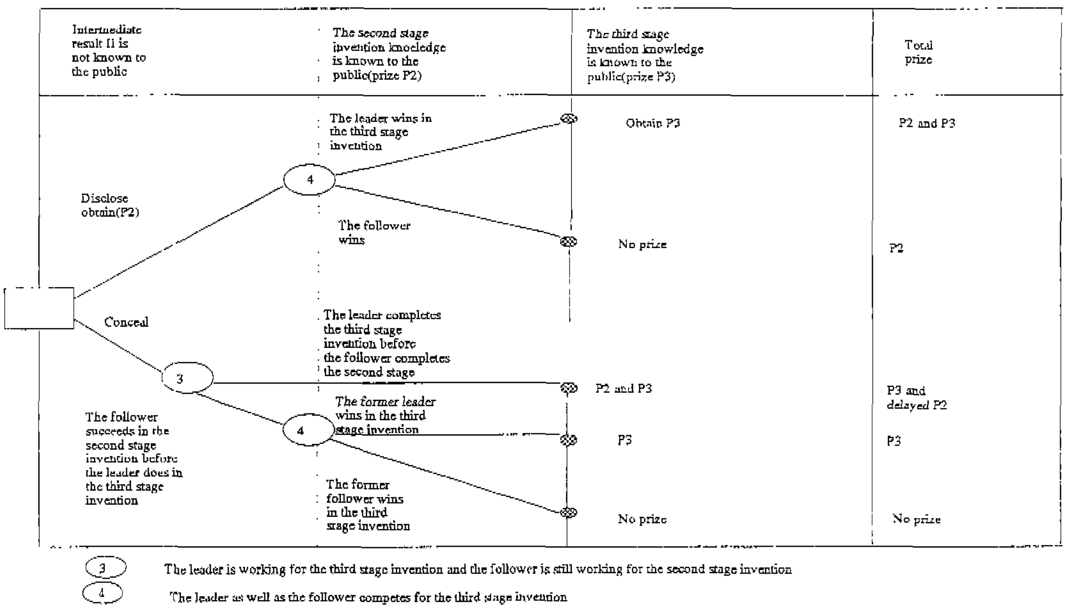

Fig. 1 Decision tree presentation of leader's alternative actions and possible consequences under perfect information about status of competitor in Round II

For computing P_2 in Round II, we have to compare the values of the leader's alternative positions:

immediately or conceal it. We will consider two cases in the following analysis: (1) when competitors know exactly who is at what stage, even if the findings are concealed, and (2) when uncertainty about the status of competitor exists.

3.3.1 Under Perfect Information

We assume that competitors know exactly who is at what stage. That is, even though a competitor conceals his first stage findings or his second stage findings, his opponent will soon be informed that the competitor has completed the first stage or the second stage.

Under Round II, by disclosing the second stage knowledge, the leader can collect immediate prize, P_2 and enable the follower to work for the third stage invention using the second stage invention knowledge which was brought into the public domain by the leader. On the other hand, concealing the second stage knowledge results in only the leader himself conducting the third stage invention while the follower is still working on the second stage invention. Fig. 1 shows the alternative courses of action taken by the leader and their possible consequences. disclosing the second invention knowledge versus concealing it. By disclosing the second stage invention knowledge, the leader certainly obtains an immediate prize P_2. Now both the leader and the follower compete for the third stage invention. The leader is also likely to receive the final prize P_3 with a probability of winning in the third stage invention. The future values of the prize and the cost are converted to be continuously discounted ones according to e^{-rt}, where r is a discount rate. The leader will spend O_3 initially as a lump sum overhead cost, and expend at a rate of b_3 until the third stage invention is completed by the follower or the leader.

Thus P_{D2}(the present value of the leader's position at the time of the second stage invention when the leader decides to disclose his knowledge) can be computed as,

$$P_{D2} = EDR_{D2} - EDE_{D2} - O_3 + P_2,$$

$$EDR_{D2} = \int_0^\infty P_3 e^{-rt}\{1 - F_{F3}(t)\} f_{L3}(t)\, dt$$

$$EDE_{D2} = \int_0^\infty b_3 \left(\int_0^t e^{-rs} ds\right) [\, f_{L3}\{1 - F_{F3}(t)\} + f_{F2}(t)\{1 - F_{L3}(t)\}\,]\, dt.$$

EDR_{D2} represents the expected discounted reward when the leader succeeds in the third stage invention before the follower does. EDE_{D2} represents the expected discounted expenditure until the leader or the follower succeeds in the third stage invention.

P_{C2}(the present value of the leader's position at the time of the second stage invention when the leader decides to conceal his knowledge) can be computed as,

$$P_{C2} = EDR_{C2} - EDE_{C2} + EDR_{C2'} - EDE_{C2'} - O_3$$

$$EDE_{C2} = \int_0^\infty b_3 \left(\int_0^t e^{-rs} ds\right) [\, f_{L3}(t)\{1 - F_{F2}(t)\} + f_{F2}(t)\{1 - F_{L3}(t)\}\,]\; dt$$

$$EDR_{C2} = \int_0^\infty (P_2 + P_3) e^{-rt}\{1 - F_{F2}(t)\} f_{L3}(t)\, dt$$

$$EDR_{C2'} = \int_0^\infty \int_0^\infty P_3 e^{-r(t+s)}\{1 - F_{L3}(t)\} f_{F2}(t)\{1 - F_{F3}(s)\} f_{L3}(s)\, ds dt.$$

$$EDE_{C2'} = \int_0^\infty e^{-rt}\{1 - F_{L3}(t)\} f_{F2}(t) \int_0^\infty b_3 \left(\int_0^s e^{-rm} dm\right).$$

$$[\, f_{L3}(s)\{1 - F_{F3}(s)\} + f_{F3}(s)\{1 - F_{L3}(s)\}\,]\; ds dt.$$

EDR_{C2} represents the expected discounted reward when the leader succeeds again in the third stage invention before the follower finishes the second stage invention. EDE_{C2} represents the expected discounted expenditure until one of the two following events happens: 1) the leader succeeds in the third invention before the follower does in the second, or 2) the follower succeeds in the second invention before the leader does in the third. $EDR_{C2'}$ and $EDE_{C2'}$ reflect the case in which the follower succeeds in the second invention before the leader does in the third (thus the leader loses P_2, and both the leader and the follower work for the third stage invention). $EDR_{C2'}$ is the expected discounted reward, and $EDE_{C2'}$ is the expected discounted expenditure incurred until the third stage invention is completed.

The second reservation price of the knowledge can be obtained by setting $P_{D2} = P_{C2}$, and expressing in terms of other parameters. After simplification, we obtain

$$P_2 = \frac{\lambda_{F3}(P_3 \lambda_{L3} - b_3)}{(r + \lambda_{F3} + \lambda_{L3})(r + \lambda_{F2})} \tag{1}$$

Because Round II is dependent on Round I, leader in Round I is also leader in Round II. Therefore, after obtaining second reservation price (P_2) we can obtain first reservation price (P_1). Then can be obtained by similar way of Round II. That is,

$$P_1 = \frac{\lambda_{F2}(P_2 \lambda_{L2} - b_2)}{(r + \lambda_{F2} + \lambda_{L2})(r + \lambda_{F1})} \tag{2}$$

From (1), for the leader in Round II to have an incentive to disseminate his knowledge to the public, the reward for the intermediate result II must be at least P_2. The second reservation price of an intermediate result II is dependent upon the final prize P_3, the success rates in two stages (λ_{F2}, λ_{F3} and λ_{L3}), expenditure rate of third stage, and a discount rate.

Using the first order derivatives for each parameter, we observe that the second reservation price of an intermediate result II increases when 1) the final prize P_3 increases; 2) completing the third stage invention becomes relatively easier than the second stage invention (i.e., as λ_{L3} increases and/or λ_{F2} decreases); 3) the rival becomes more competitive in the third stage invention (i.e., λ_{F3} increases); 4) the third stage invention becomes less costly; 5) the future value is discounted at a lower rate. An example in section 4.3 shows above observations in detail

3.3.2 Under Uncertainty

In this section, I assume that an inventor does not exactly know his competitor's status exactly, but he has probabilistic information. That is, under Round I, k_1 is the probability that his competitor is in the first stage; and k_2 is the probability that his competitor is in the second stage. Also under Round II, $k_{2'}$ is the probability that his competitor is in the second stage; and k_3 is the probability that his competitor is in the third stage. Therefore, in this situation, it is not clear who the leader is. Of course, k_1 plus k_2, and $k_{2'}$ plus k_3 are one respectively.

In the case of Round II, by disclosing the intermediate result II, the inventor collects an immediate prize P_2, and both competitors work for the third stage invention. On the other hand, concealing the intermediate result II results in different results according to the current status of his competitor. If his competitor is in the stage three (i.e., his competitor is also concealing), both competitors work for the third stage invention for the big prize $P_2 + P_3$. If his competitor is in the second stage, then only the inventor (now he is the leader) himself conducts the third stage invention while the follower is still working on the second stage. If the leader completes the third stage invention before the follower succeeds in the second stage invention, he can collect $P_2 + P_3$. In the event that the follower succeeds in the second stage invention, the follower tends to conceal the knowledge because of the same reason that the leader had concealed it in the first place. Therefore again both competitors will compete to obtain $P_2 + P_3$.

For computing P_2 in Round II, we must compute P_{D2} and P_{C2}. Fortunately, they can be computed by similar way as we did in section 3.3.2.

The second reservation price (P_2) is obtained by setting $P_{D2} = P_{C2}$ as the following

$$P_2=\frac{k_2,\lambda_{L3}P_3(A+\lambda_{F2})-b_3k_2,(A+\lambda_{F2})+k_3B(P_3\lambda_{L3}-b_3)-\lambda_{L3}P_3B+b_3B-b_3k_3B}{AB-k_2,\lambda_{L3}(A+\lambda_{F2})-k_3\lambda_{L3}B}, \tag{3}$$

where $A=r+\lambda_{F3}+\lambda_{L3}$, $B=r+\lambda_{F2}+\lambda_{L3}$.

Also P_1 can be obtained by similar way of Round II. That is,

$$P_1=\frac{k_1\lambda_{L2}P_2(\alpha+\lambda_{F1})-b_2k_1(\alpha+\lambda_{F1})+k_2\beta(P_2\lambda_{L2}-b_2)-\lambda_{L2}P_2\beta+b_2\beta-b_2k_2\beta}{\alpha\beta-k_1\lambda_{L2}(\alpha+\lambda_{F1})-k_2\lambda_{L2}\beta}, \tag{4}$$

where $\alpha=r+\lambda_{F2}+\lambda_{L2}$, $\beta=r+\lambda_F+\lambda_{L2}$.

3.4. A Model of Oligopolistic Competition

In this section, we consider R&D rivalry among n potential inventors when they know exactly who is at what stage. By assuming all these n competitors to be identical, we need only three different success rates. Let λ_1 and λ_2 and λ_3 denote the success rates at which the first and the second and the third inventions are accomplished respectively by an inventor. Let T_i^n be the random variable that represents the time required to finish the ith (i=1,2,3) invention when n potential inventors are competing.

Distribution function and probability density function of T_i^n are given by,

$$F_i^n(t)= \Pr\ [\ \min_{1\le j\le n}(T_{ij})\le t]$$

$$=1-\prod_{j=1}^{n}\Pr\ (T_{ij}^{*}\ge t)$$

$$=1-e^{-n\lambda_i t} \qquad \text{for i=1,2,3}$$

$$f_i^n(t)=\frac{\partial F_i^n(t)}{\partial t}=n\lambda_i,\ \exp\ (-n\lambda_i t) \qquad \text{for i=1,2,3.}$$

Also, in the case of Round II, P_{D2} and P_{C2} are given by,

$$\mathrm{P}_{D2} = \frac{\lambda_3 P_3 - b_3}{r + n\lambda_3} - O_3 + P_2,$$

$$\mathrm{P}_{C2} = \frac{(P_2 + P_3)\lambda_3 - b_3 + \left(\frac{\lambda_3 P_3 - b_3}{r + n\lambda_3}\right)(n-1)\lambda_2}{r + (n-1)\lambda_2 + \lambda_3} - O_3.$$

Therefore the second reservation price (P_2) for the intermediate result II can be computed as

$$P_2 = \frac{(P_3\lambda_3 - b_3)(n-1)\lambda_3}{\{r + (n-1)\lambda_2\}(r + n\lambda_3)}. \tag{5}$$

Also P_1 can be obtained by similar way of Round II. That is,

$$P_1 = \frac{(P_2\lambda_2 - b_2)(n-1)\lambda_2}{\{r + (n-1)\lambda_1\}(r + n\lambda_2)}. \tag{6}$$

4. An Example

4.1 Introduction

In order to verify the model's applicability, we consider three R&D projects to be performed with a linear progression in an anonymous company. Profiles of four projects including duration time and direct cost of each stage are given in table 1. General R&D activities of each stage are described in the following. Research provides fundamental knowledge for the solution of identified military problems. Exploratory development includes efforts directed toward solving specific military application problems from fairly fundamental applied research to sophisticated prototype hardware, study, programming, and planning efforts. Development includes advanced and engineering development

<Table 1> Profiles of Four R&D Projects

name of project	research	exploratory development	development	final recognition(P3)
proj. 1	6 years, 3,594	3 years, 23,391	5 years, 80,969	431,800
proj. 2	6 years, 9,829	2 years, 4,797	7 years, 195,015	838,600
proj. 3	2 years, 1,094	3 years, 15,157	4 years, 16,781	132,100

unit: one million won

For verifying the model's applicability, we apply four projects in Table 1 into a model in the next section 4.2.

4.2 Applying the Assessing Model

For applying four R&D projects into the model and assessing the value of their intermediate result, we should have the estimated values of structural variables about three projects. From Table 1, we can estimate value of structural variables. We apply three projects into the model and obtain assessed value of intermediate result of them for three cases (discount rate γ=0.01, $k_1 = k_2 = k_{2'} = k_3 = 0.5$).

In the case of duopoly competition with perfect information and uncertainty, by (1), (2), (3), (4) and table 1, two reservation prices of each project are given in Table 2.

<Table 2> Two Reservation Price of Each Project in Duopoly Competition with Perfect Information and uncertainty

Reservation	project 1		project 2		project 3	
	certainty	uncertainty	certainty	uncertainty	certainty	uncertainty
Second (P2)	609.1	103.1	525.5	-	257.7	94.1
First (P1)	186.6	-	373.6	-	24.5	-

- : negative value

In the case of oligopolistic competition, we can compute the two reservation prices by (5) and (6) in section 3.4 as the following Table 3.

<Table 3> Reservation Price versus Intensity of Competition in Oligopolistic Competition

Intensity	project 1		project 2		project 3	
	P2	P1	P2	P1	P2	P1
2	609.14	186.63	525.45	373.64	257.66	24.51
3	505.95	165.52	429.69	326.21	211.35	19.04
4	416.73	139.80	353.32	273.21	172.86	15.21
5	351.51	119.44	298.23	232.21	145.16	12.60
6	303.12	103.80	257.48	201.08	124.79	10.74
7	266.13	91.60	226.33	176.99	109.31	9.35

5. Conclusions

This paper provides an analytical framework for assessing the value of intermediate results. Two assessed values of the intermediate result (two reservation prices) were determined on the basis of final prize, the success rates of final invention and intermediate result, research expenditure, and degree of competition.

We believe that the knowledge of intermediate results can be brought into the public domain if an inventor is rewarded at least by the reservation price. An invention can be revealed in exchange for a relatively small amount for incentives compared to its development costs and the potential benefits.

Using the first order derivatives to reservation price, we observe that the first reservation price of an intermediate result I (or the second reservation price of an intermediate result II) increases when i) the second reservation price (or the final prize) increases; ii) completion of the second stage (or the third stage) becomes relatively easier than the first stage (or the second stage) invention; iii) the rival becomes more competitive in the second stage invention (or the third stage invention); iv) the second stage invention (or the third stage invention) becomes less costly; and v) the future value is discounted at a lower rate.

Through the use of exponential invention production functions and an example, we demonstrate how the model can be applied in a competitive R&D situation. This example shows that an inventor wants rather more reward if he and his opponent know exactly who is at what stage than with vague idea of what happens to their opponent.

Even though an applicability of the model is identified through an example in section 4, further empirical research is needed to identify the applicability and validity of this model.

In this paper we assume that expenditure rate in each stage is independent of the time. However, in order to give guideline of R&D project planning to project manager, step, ramp, decay, growth and exponential type may be considered as types of expenditure rate in each stage.

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