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THE COST OF INNOVATION

Abstract

We have constructed a simple model to estimate the private and social cost of an innovation in the context of an innovation race among N firms. We get that the private cost for any firm is decreasing in the discount rate, increasing in the reward, and decreasing in the cost of human capital under certain regularity conditions. We also find that it is decreasing in the government's investment in R&D. Another interesting finding is that the private cost for any firm is decreasing with competition, but the social cost of the innovation is increasing with competition. We also make an empirical for some projects. We find that the main component of the private cost is the investment in human capital. There are, however, some other inputs that are also important, like training and advice, scholarships, etc.

Resumen

En este documento se construye un modelo para estimar el costo privado y social de una innovación en el contexto de una carrera de innovación entre N empresas. Los resultados muestran que el costo privado de cada empresa es decreciente en la tasa de descuento, creciente en la recompensa y decreciente en el costo del capital humano bajo ciertas condiciones de regularidad. También se encuentra que es decreciente en el monto de inversión pública realizada por el gobierno. Otro resultado interesante nos dice que el costo privado para cualquier empresa es decreciente con el grado de competencia, mientras que el costo social de la innovación es creciente. Finalmente, se realiza un análisis empírico para una base de datos sobre algunos proyectos de investigación. Aquí, se encuentra que el principal componente del costo privado es la inversión que se hace en capital humano. Sin embargo, se tienen otros insumos que son también importantes, tales como cursos y asesorías, becas, etc.

Introduction

There is an increasing concern in the literature to construct an index to measure the cost of innovation. This is particularly important for Mexico where the government does almost all the investment in research and development (R&D). The private sector invests only a tiny fraction in R&D. There are only a few firms in the manufacturing sector that invest in R&D. One of the main problems is that firms count money in R&D as an expense and not as an investment. They should treat this as an investment which return is going to arrive in a future date. By constructing such an index, we could identify the main components of the investment. Then, government could design a policy to incentive private investment in R&D. We know that there is a positive effect of the government investment in research and development on the private investment (Carreón Rodríguez, 1999). Therefore, this effect combined with a strategic government policy would have a bigger positive impact on the investment made by the private sector. Finally, having this index, we also could compare the cost of an innovation in another country, by using the prices each country is facing in its home market.

We should also distinguish among the different targets of these private investments. There is investment to reduce cost of production, to improve quality, to get new products, to improve packing, etc. Each one of these has different characteristics, which imply different patterns of allocation of resources among the different inputs used in the innovation process.

It is also important to find out the inputs that are used by the firms in the innovation process. These are human capital, raw materials, equipment, scholarships, bibliography, training, advise, etc. Now we will analyze each one of this. First, one of the main inputs is human capital. We can think of this as the personnel involved in the innovation. It can be divided in two, scientific personnel and administrative personnel. The firs one is crucial, but also the second one is important because they make easier the job of the first. Second, the raw materials and the equipment that are utilized in the process are also important. For equipment we have two possibilities: either the firm buys or rents the needed equipment. Third, training and advice are related to the special needs corresponding to the project under study. Finally, even though scholarships are not widely used, they represent an important proportion of the total cost of innovation for those projects that give scholarship to some students.

Based on the discussion presented above, in this paper we construct a simple model to compute the cost of innovation. We present the theoretical model and then we apply it to the case of some innovation projects realized in a Mexican firm. In these projects we have some process innovations and some product innovations.

Basic Model

Let us start by constructing our theoretical model. We take the case of product innovation in which the innovation is assumed to be made by the producer of the good. This is done in the context of a competition in innovation. We construct this model assuming the number of firms fixed. An important point in this model is the date at which the innovation will be ready to be introduced into the market. That date is given by a probability distribution induced by the amount of money committed to R&D[1] and the amount of human capital hired by the firm. It also depends on the past investments in these two inputs. Finally it is also affected by the investments in research and development made by the government. The first firm that comes up with the innovation gets a perpetual flow of rewards. The firm that makes the innovation in first place is the only one that gets this reward; all the remaining firms make a loss given by the sum of their investments in R&D and in human capital.[2] Thus, if there are two firms that make the same investments, only one of them gets the reward and the other makes a loss. Even in the case in which both of them get the innovation at the same time, only one of them gets the reward (say, one of them is randomly selected).

We are thinking of an innovation as a new product that generates expected nonnegative profits to the firm that introduces it into the market. However, *ex post* all firms except one end up having negative profits. An innovation should be distinguished from an invention. When an invention is introduced commercially as a new or improved product or process, it becomes an innovation. For example, the automobile was invented in the late nineteenth century. However, Henry Ford made both a product and a process innovation in this industry when he started the massive production of automobiles in the early twentieth century.

An important point to distinguish at this time is the private cost of the innovation and the social cost of the innovation[3]. The private cost is the sum of the investments of the winning firm. The social cost is the sum of the costs of all the firms engaged in the competition of innovation. Therefore, it can be the case that an innovation is worthy for the winning firm although it can be too costly for the society.

We develop our model in the following context. Think of an industry with N identical firms engaged in a game of innovation for certain number of periods. Each firm, denoted by i, invests resources in R&D and in human capital in each period. Firm i invests $r_t x_{it}$ in R&D and $w_t h_{it}$ in human capital in period t, where, r_t is the

[1] We think of R&D as the money allocated to the innovation process to buy different inputs other than human capital.

[2] This creates social losses because there will be a "duplication of efforts" in terms of R&D and in terms of human capital.

[3] It is important to note that what I am naming "cost of innovation" is only the sum of the investments made in buying the different inputs used in producing the innovation. That is, it is the total investment made by that particular firm or by all the firms in that particular race.

cost of R&D, x_{it} is the money allocated to R&D, w_t is the cost of human capital, and h_{it} is the amount of human capital hired (number of scientific workers, for example). Therefore, the present value of the firm i's cost of participating in the innovation race is given by

$$c_i(x,h;r,w,\rho)=\sum_{t=1}^{T_i}\rho^{t-1}(r_t x_{it}+w_t h_{it})$$

where ρ is the discount rate, assumed the same for all firms. The final time T_i[4] can be thought as the time in which the winning firm introduces the new product into the market or the time at which the losing firm quits the innovation race. In this model this final period is uncertain, we only have a given probability of getting the new product. For simplicity, we assume that $w_t = w$ and $r_t = r = 1$ for all t.

We assume that these costs are binding, so that at the end of the game every firm has committed $c_i(x,h;1,w,\rho)=\sum_{t=1}^{T_i}\rho^{t-1}(x_{it}+w_t h_{it})$ to the innovation race. We can think of this amount as the bet that firm i's make to participate in the innovation race. This firm also specifics the money it would put it at each period. Moreover, these costs are assumed to be independent of any development that could occur in the future and are known to the firm at the beginning of the innovative race. That is, we ask firms to make an investment plan for the complete horizon and do not allow them to change their decisions when they get more information (they make a contingent plant at time t_1). With its investment, the ith firm buys a random variable each period, denoted by $\tau_t(x_{it},h_{it};x_i^t,h_i^t)$, induced by x_{it} and h_{it}, that gives the probability that the project will be successfully completed at period s, where $x_i^t=(x_{i1},x_{i2},\cdots,x_{it-1})$ and $h_i^t=(h_{i1},h_{i2},\cdots,h_{it-1})$ are the histories of past investments in R&D and human capital, respectively, made by the ith firm. That is, it gives the uncertain date at which the innovation will be introduced into the market.[5] This random variable gives the *technological uncertainty* that the ith firm is facing in this setting. We assume that these past values do not influence the

[4] For example, in the Pharmaceutical Industry, it takes an average of 15 years to develop a new drug at a cost around 500 million dollars. We also could think of this as the time when the innovating firm sells the patent to another company to commercialize the product. This is the case in this industry. In the last years, the biotechnology firms are the ones that make the innovation and then sell the product to the big pharmaceutical firms.

[5] I am assuming that when the innovation is done it is successfully introduced in the market. However, it is not the case in the real world where just two out of ten innovations are successfully introduced into the market and just 17% of the new products introduced into the market in 1991 were successful (Garud, Nayyar, and Shapira, 1997).

current or future decisions of the firm. They only shift the probability distribution. That is, for higher values of x_i^t and/or h_i^t we have a greater probability of getting the new product before certain date s.

The environment faced by the ith firm is also affected by the government's investments in this industry. Let the government invest resources z to produce basic knowledge $f(z)$.[6] This knowledge affects the technology uncertainty faced by all the firms in the industry. Assume that $f(z)$ is nondecreasing and concave with $f(0)=0$ and $\lim_{z\to\infty} f_z(z)=0$. The very first firm that comes up with the innovation gets a constant perpetual flow of rewards V, which is assumed to be known by all the firms in the industry. Think of V resulting from the production of the new good in a monopolistic situation or from the sales of the technology rights to other firms.

For simplicity, we assume that the distribution function governing the behavior of the uncertain date of introduction, $\tau_t(x_{it},h_{it};x_i^t,h_i^t)$, is given by the exponential function:

$$pr\{\tau_t(x_{it},h_{it};x_i^t,h_i^t)\le s\}=1-e^{-f(z)g(x_{it},h_{it};x_i^t,h_i^t)s}$$

where the function $g(\cdot)$ is like a production function for the innovation using two inputs. It is increasing in x_{it} and h_{it}. In this case, $pr\{\tau_t(x_{it},h_{it};x_i^t,h_i^t)\le s\}$ denotes the probability that firm i will introduce the innovation before certain date s.

For the exponential distribution function, we know that

$$E[\tau_t(x_{it},h_{it};x_i^t,h_i^t)] = \frac{1}{f(z)g(x_{it},h_{it};x_i^t,h_i^t)}$$

which gives the expected time of introduction of the innovation by the ith firm.

We assume that all firms know the exact set up of the model. Moreover, they know the behavior of each other. So, firm i knows that any rival firm may introduce the innovation before it with a positive probability. To formalize this, let $\bar{\tau}_{it}$ be the random variable at period t representing the unknown date at which any rival may be able to introduce the innovation. This random variable represents firm i's *market uncertainty*. Since firms' expectations are rational, we can express $\bar{\tau}_{it}$ as follows:

[6] The government is assumed to invest resources in basic research. Any product that comes up from this research is distributed as a public good.

$$\bar{\tau}_{it} = \min_{1 \le j \ne i \le N} \{\tau_t(x_{jt}, h_{jt}; x_j^t, h_j^t)\}$$

This expression gives the unknown date at which any rival firm will introduce the innovation before firm i finishes its project.

We also assume that there are no private externalities in the innovative process so that the random variables $\tau_t(x_{it}, h_{it}; x_i^t, h_i^t)$ may be taken as independent.[7] This assumption makes our analysis closer to the property rights approach, which emphasizes the importance of patent protection. This is a very strong assumption in this model. However, it allows any firm to fully appropriate the returns from its investments, namely V, by introducing the new product before any other firm.

Therefore, we have that the probability, at period t, of the innovation being introduced by any firm, other than i, before certain date s is given by

$$pr\{\bar{\tau}_{it} \le s\} = 1 - e^{-f(z)a_{it}s}$$

where

$$a_{it} = \sum_{j \ne i} g(x_{jt}, h_{jt}; x_j^t, h_j^t)$$

is the degree of rivalry faced by the ith firm. The ith firm takes a_{it} as a constant.

For any time $s \ge 0$, the ith firm will get the revenue flow V only if it is the first firm to come up with the innovation. This will happen if it is the case that

$$\tau_t(x_{it}; h_{it}; x_i^t, h_i^t) \le \min\{\bar{\tau}_{it}, s\}$$

Integrating the joint density of $(\tau_t(x_{it}, h_{it}; x_i^t, h_i^t), \bar{\tau}_{it})$ over the relevant region, we have

$$pr\{\tau_t(x_{it}; h_{it}; x_i^t, h_i^t) \le \min\{\bar{\tau}_{it}, s\}\} =$$

$$\frac{g(x_{it}, h_{it}; x_i^t, h_i^t)}{a_{it} + g(x_{it}, h_{it}; x_i^t, h_i^t)}[1 - \exp\{-f(z)(g(x_{it}, h_{it}; x_i^t, h_i^t) + a_{it})s\}]$$

By assuming that these firms are profit-maximizers, the ith firm chooses x_{it} and h_{it}, given a_{it}, x_i^t, h_i^t, z, w, ρ, and V to maximize its expected discounted profits. So, each period t, it solves the following problem:

[7] We should note that we are using both assumptions in this model since the government's innovations are public while the firms' innovations are private.

$$\max_{x_{it},h_{it}} \Pi(x_{it},h_{it};x_i^t,h_i^t,fa_i,z,w,\rho,V) =$$

$$\max_{x_{it},h_{it}}\left\{\frac{Vf(z)g(x_{it},h_{it};x_i^t,h_i^t)}{\rho\left(f(z)a_{it}+\rho+f(z)g(x_{it},h_{it};x_i^t,h_i^t)\right)}-x_{it}-wh_{it}\right\}$$

If $\Pi(x_{it},h_{it};x_i^t,h_i^t,fa_i,z,w,\rho,V)\geq 0$ for some (x_{it},h_{it}), then we know that a global maximum exists.

Suppose that $\Pi(x_{it},h_{it};x_i^t,h_i^t,fa_i,z,w,\rho,V)\geq 0$ for some (x_{it},h_{it}) when $N=1$ (that is, in case of no rivalry, so that $a_{it}=0$).[8]

If there is an interior solution, it must satisfy the following first-order conditions (where we omit the arguments x_i^t, h_i^t, and z for simplicity) for each period:

$$\frac{(fa_{it}+\rho)fg_x(x_{it},h_{it})}{[fa_{it}+\rho+fg(x_{it},h_{it})]^2}-\frac{\rho}{V}=0 \tag{1}$$

$$\frac{(fa_{it}+\rho)fg_h(x_{it},h_{it})}{[fa_{it}+\rho+fg(x_{it},h_{it})]^2}-\frac{w\rho}{V}=0 \tag{2}$$

The second-order conditions require the following matrix to be negative definite

$$|M|=\begin{vmatrix}(fa+\rho+fg)g_{xx}-2fg_x^2 & (fa+\rho+fg)g_{xh}-2fg_xg_h\\ (fa+\rho+fg)g_{xh}-2fg_xg_h & (fa+\rho+fg)g_{hh}-2fg_h^2\end{vmatrix} \tag{3}$$

Equations (1) and (2) define implicitly $x_{it}^*=x_{it}^*(x_i^t,h_i^t,fa_t,z,w,\rho,V)$ and $h_{it}^*=h_{it}^*(x_i^t,h_i^t,fa_t,z,w,\rho,V)$. For a firm that assumes that the instantaneous probability of rival introduction at period t is induced by a_i, x_{it}^* is the expected profit maximizing investment in R&D and h_{it}^* is the expected profit maximizing investment in human capital.

From this solution, we get the expected effects of ρ, V, and w on x_{it}^* and h_{it}^*.

[8] This Assumption is needed in order to get an interesting problem for the case in which there is just one firm in the industry. Otherwise, we would have no problem at all since this monopoly would not have any incentive to innovate.

Proposition 1: The investments in R&D and in human capital, in each period, are decreasing in the discount rate, ρ. They are increasing in the reward, V. Finally, both investments are decreasing in the cost of human capital, w, if $g_{xh} \geq 0$ and $\frac{fa+\rho+fg}{2f} \geq \frac{g_x g_h}{g_{xh}}$. However, if $g_{xh} \leq 0$, then h^* is decreasing in its own cost but x^* is increasing in that cost.

From this proposition, we get the following result

Proposition 2: The cost of innovation per firm, $c_i(x,h;1,w,\rho) = \sum_{t=1}^{T_i} \rho^{t-1}(x_{it} + w_t h_{it})$ is decreasing in the discount rate, increasing in the reward, decreasing in w, if $g_{xh} \geq 0$ and $\frac{fa+\rho+fg}{2f} \geq \frac{g_x g_h}{g_{xh}}$.

An interesting result is the effect of the government investments on the firm's behavior. This result is stated in the following proposition.

Proposition 3: The private investments in human capital and in R&D are increasing in the past government's investment and decreasing in the current investment in research and development. Then, the cost of innovation for any firm is decreasing in the government's investment in research and development.

Therefore, there is a positive effect from the increasing knowledge produced by the government's investment in basic research, which is available to all the firms in the industry. By having more knowledge available for free, all firms have a greater probability of making the innovation and, as a consequence, each single firm can make the innovation sooner. Thus, they have incentives to invest more resources in human capital and in R&D. That is, all firms are free loaders on the government's investment. Since all firms are free loaders, their private cost of innovation is lower in presence of the government investment.

Now, we are interested in knowing how the private cost of innovation is affected by the degree of rivalry in the context of partial equilibrium. In order to do that, we need to impose some restriction on the function $g(x,h)$.

Assumption 1: The function $g(x,h)$ satisfies the following restriction whenever $g_{xh} \geq 0$

$$\frac{fa+\rho+fg}{2f} \geq \frac{g_x g_h}{g_{xh}} \qquad (4)$$

Proposition 4: Suppose Assumption 1 holds. Suppose $fa_{it} + \rho \geq fg$ for all t. Then investments in R&D, x_{it}^{*}, and investment in human capital, h_{it}^{*}, are decreasing in the degree of rivalry, a_{it}. Therefore, the cost of innovation per firm is lower if $fa_{it} + \rho \geq fg$ and Assumption 1 holds for all t if that firm faces higher degree of rivalry.

The response of the ith firm to changes in the degree of rivalry, a_{it}, depends on the expectations it holds about the sign of $fa_t + \rho - fg$. If this firm thinks that $fa_t + \rho \geq fg$ (that is, the increase in rivalry implies that the probability of introduction by any rival is bigger than the probability of introduction by firm i at period t), then it decreases its investments in R&D and in human capital when there is an increase in the degree of rivalry. However, if this firm thinks that $fa_t + \rho < fg$ (and Assumption 1 still holds), then an increase in a_{it} induces this firm to increase its investments in R&D and human capital. As a consequence of this behavior, the private cost of innovation is lower when the firm thinks that $fa_t + \rho \geq fg$.

Now, we turn to the general equilibrium analysis. Given that the firms are identical, we have that $x_{it} = x_t^{*}$ and $h_{it} = h_t^{*}$ for all $i = 1,...,N$ for each period. Since firms' expectations are rational, we have that $a_{it} = a_t = (N-1)g(x_t^{*}, h_t^{*})$. Thus, we have that $fa_t + \rho \geq fg$ for all $N \geq 2$. Therefore, from Proposition 4 we conclude that the investments in R&D and in human capital are always decreasing in the degree of rivalry, a_{it} and, therefore, the private cost of innovation is always decreasing in the degree of rivalry.[9]

Given the optimal value $a_t = (N-1)g(x_t^{*}, h_t^{*})$, equations (1) and (2) define implicitly

$$x_t^N = x_t^{*}((N-1)f(z)g(x_t^N, h_t^N; x^t, h^t), x^t, h^t, z, w, \rho,, V) \tag{5}$$

$$h_t^N = h_t^{*}((N-1)f(z)g(x_t^N, h_t^N; x^t, h^t), x^t, h^t, z, w, \rho,, V) \tag{6}$$

Thus, x_t^N and h_t^N are the Cournot-Nash equilibrium levels of R&D and human capital, respectively, chosen by firms for each period t. We should note that these optimal values depend on the number of firms in the industry. Therefore, the private cost of innovation for firm i is given by

[9] Notice that we are not saying anything about the firm's preferences for risk.

$$c_i(x^N, h^N; 1, w, \rho) = \sum_{t=1}^{T_i} \rho^{t-1}(x_t^N + wh_t^N)$$

Now, we want to know how the number of firms, N, affects this equilibrium.

Proposition 5: The optimal investments in R&D, x_t^N, and in human capital, h_t^N, are decreasing in the number of firms in the industry. Therefore, the cost of innovation for any firm is decreasing in the number of firms in the industry.

Therefore, we expect to see lower investment per firm in research and development and in human capital in those industries where more firms are engaged in the innovative race. Hence, increasing competition reduces the investments in R&D and in human capital. That is, higher investments per firm are associated to higher concentration. As a consequence of this the cost of innovation for any firm is lower when there are more firms competing for the new product. So, it is more costly for any firm to get the new product in more concentrated industries. It could also be the case that the cost is so high that no firm will get into the innovation race.

From Proposition 5 we get a reduction in investments and in the cost of innovation per firm if there is an increase in the number of firms in the industry. This raises an interesting question. What happens to the total investment in the industry and to the social cost of innovation?

Let us analyze this question. Define $X_t = Nx_t^N$ and $H_t = Nh_t^N$ as the total industry investments in R&D and in human capital, respectively, in period t. Define the social cost of the innovation as

$$\sum_{i=1}^{N} c_i(x^N, h^N; 1, w, \rho) = \sum_{t=1}^{T_i} \rho^{t-1}(X_t + wH_t)$$

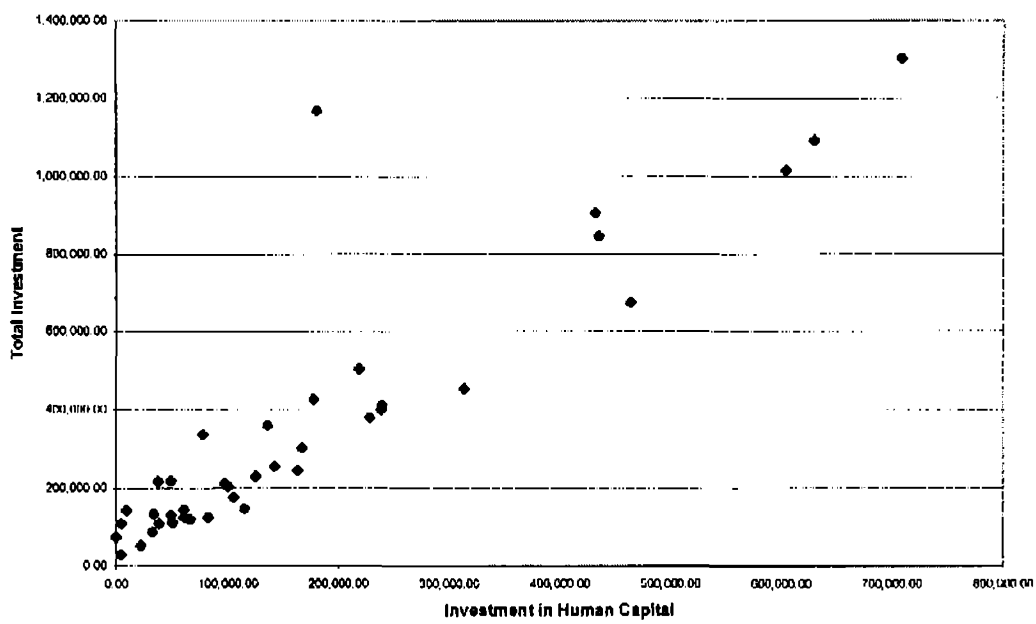
Proposition 6: Suppose that $\frac{x_t^N}{N} \geq -\frac{dx_t^N}{dN}$ and $\frac{h_t^N}{N} \geq -\frac{dh_t^N}{dN}$ (that is, the elasticity is smaller than one at any period). Then total industry investment in R&D, X_t, and total industry investment in human capital, H_t, are increasing in the number of firms in the industry. Therefore, the social cost of the innovation is increasing in the number of firms in the industry.

Therefore, if the elasticities are smaller than one, we conclude that the total investments in R&D and in human capital are larger in industries with more firms than in more concentrated industries. As a consequence, the social cost of the innovations is greater in more competitive industries.

Empirical Evidence

Now we present a descriptive analysis of the data for some projects of innovation. The total investment in a project is divided in various inputs. First, we have the investment in human capital. It is measured by the salaries paid to the scientific that are looking for a new product or a new process. Figure 1 shows the relationship between the total investment and the investment in human capital

Figure 1. Total investment and investment in human capital



From this Figure we see that an investment in human capital is an important input in the innovation process. There is a positive relationship between total investment and investment in human capital (measured by the salaries paid to the scientific workers).

In Figure 2 we present the relationship between the total investment cost and investment in raw materials. In this case, 40% of the projects present zero investment in raw materials. This can be because these projects are for getting new products and they still do not make the tests in production.

Figure 2. Total investment and investment in raw materials

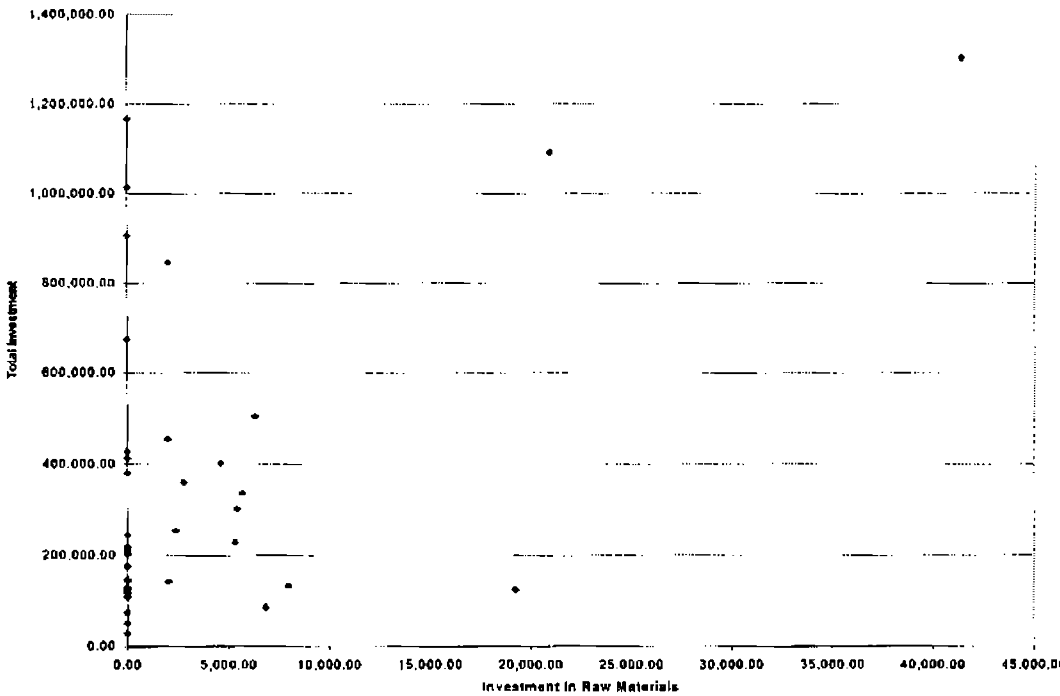
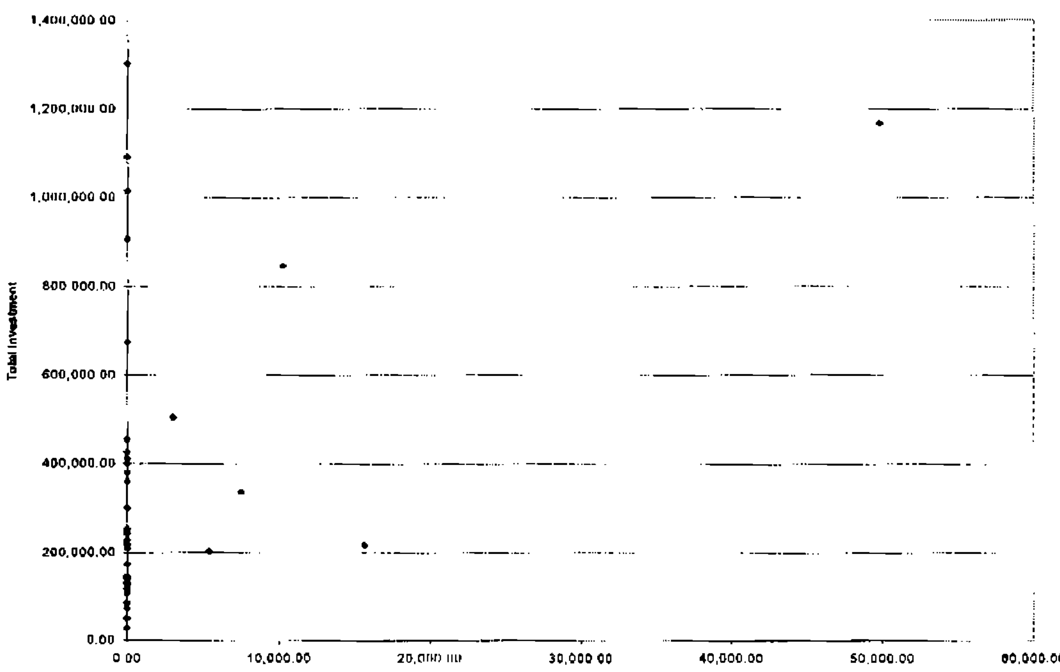


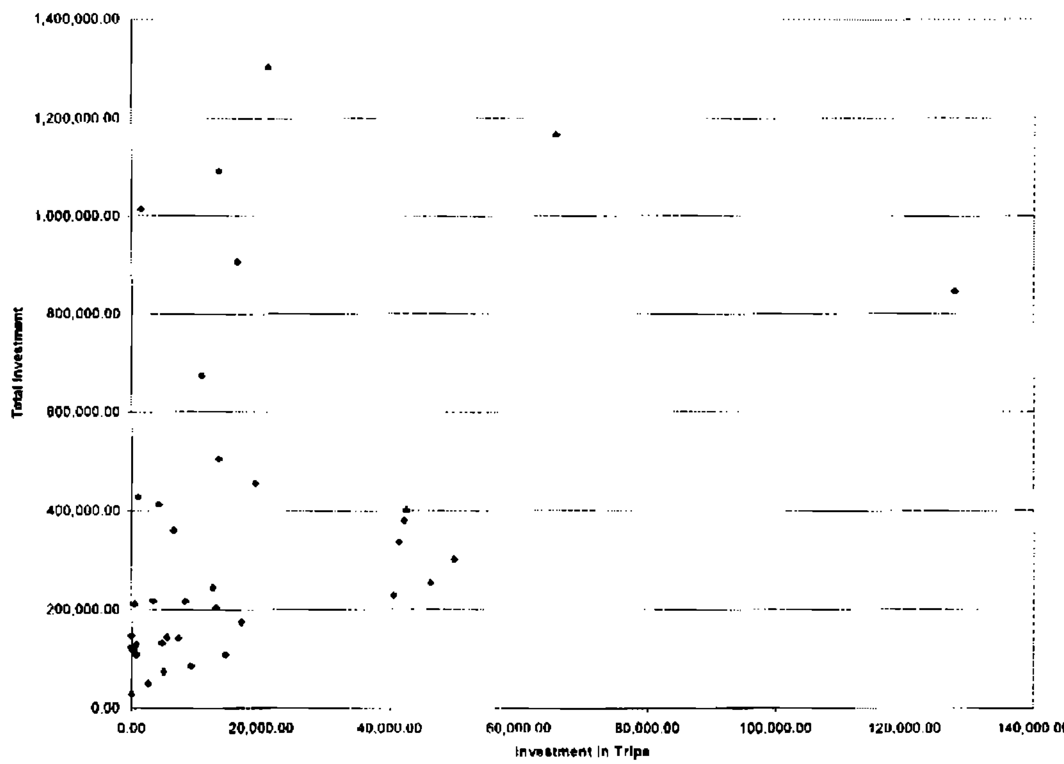
Figure 3. Total investment and investment in training and advice



In Figure 3, we have training and advice. We see that almost all the projects did not invested in these two inputs. There are two possible explanations for this. First, there was no need for that; that is, the scientific workers were good enough to get the innovation successfully by themselves. Second, it was to expensive to pay for it and firms preferred not to have training.

In Figure 4, we analyze the money allocated to business trips that are need for getting information from other places. Maybe they should trip to see some other plants to get the innovation done.

Figure 4. Total investment and investment in business trips



Therefore, from these Figures we can see some possible relationships. First, the positive relationship between total investment and investment in human capital. By using OLS we get

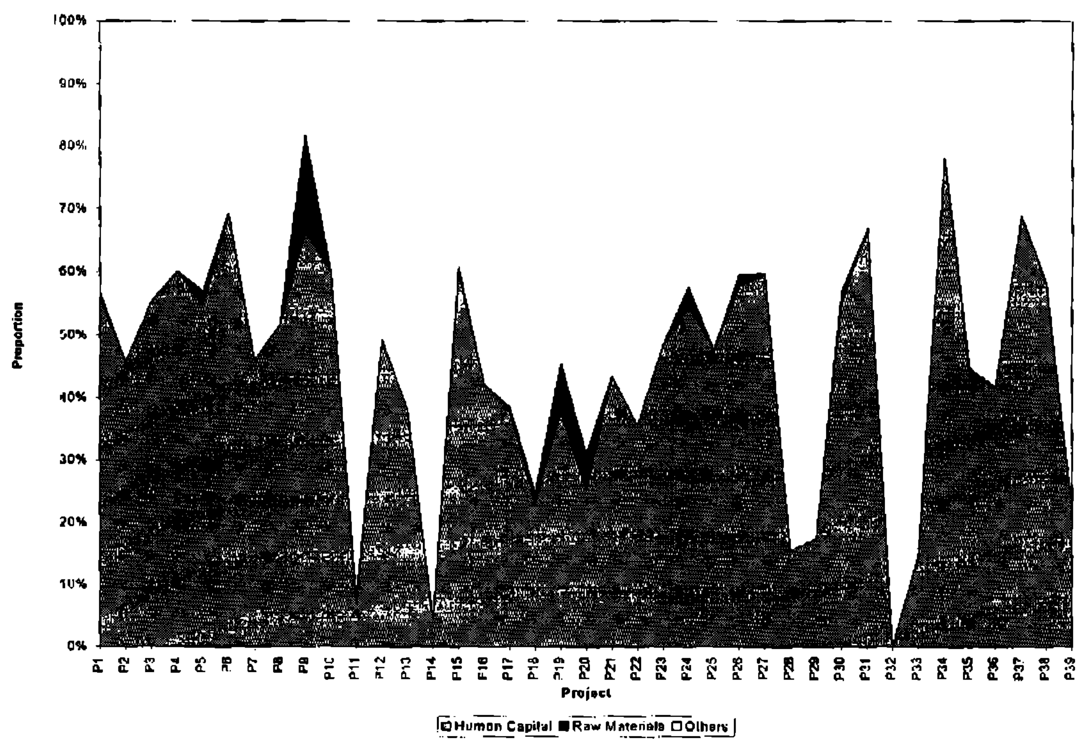
$$Total\ \ Investment = 73867 + 1.6552 * (Investment\ \ in\ \ human\ \ capital)$$

with $R^2 = 0.8085$. The best fit is given by the following equation estimated by OLS.

	Unstandardized Coefficients B	Std. Error	*Standardized Coefficients* Beta	*t*
(Constant)	-231.328	8627.610		-.027
Human Capital	.881	.072	.423	12.281
Scholarships	2.944	.515	.065	5.718
Direct costs	2.793	.207	.517	13.485

Finally, from this information, we see that the main input in the innovation process is human capital. It accounts for some 50% of the total cost. See Figure 5.

Figure 5. Proportions in the Total Investment



Conclusions

We have constructed a simple model to estimate the private and social cost of an innovation in the context of an innovation race among N firms. We get that the private cost for any firm is decreasing in the discount rate, increasing in the reward, and decreasing in the cost of human capital under certain regularity conditions. We also find that it is decreasing in the government's investment in R&D. Another interesting finding is that the private cost for any firm is decreasing with competition, but the social cost of the innovation is increasing with competition.

On the other hand, there are some clear extensions for further work. Fist, we should allow free entry in this industry to see the effect on the cost when there are no entry barriers and any firm can participate in the innovation race. Second, and more important, we can perform an empirical estimation for some innovation in a given industry and compare that cost with the cost that would have been incurred in other country for the same innovation. Finally, in doing this, we could try to get a cost index for innovation.

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