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Choosing between traditional and innovative technologies: the case of scientific uncertainty

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Giovanni Immordino*

Abstract

We study the choice between a traditional technology characterized by known risks and an innovative technology (a geological storages for nuclear wastes, a genetically modified organism or a new treatment in medical science) subject to scientific uncertainty. We assume that the two technologies differ in first period implementation costs, second period risk, and degree of irreversibility, and we study the effect of foreseen scientific progress on the present choice between the two. If the first-period choice is restricted to be 'all or nothing', scientific progress promotes the traditional technology; with constant absolute risk aversion, scientific progress increases the optimal level of the technology with the higher implementation cost.

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1. Introduction

When a new product or a cost saving production process is invented, policymakers have to decide whether to allow it or not. In taking this decision they try to evaluate expected costs and benefits, but the possible effects of innovations on the environment or on consumers' health are generally imperfectly known. Consider for example the storage of nuclear wastes. Up to now the standard technology has been (for highly radioactive wastes) to treat and store them in a non-permanent site, a technology which has the advantages of being reversible and with low present cost. A possible alternative currently under study is to store them once for all in a geological storage 500 to 1000 meters deep. This alternative imposes a higher initial cost and is characterized by higher irreversibility (in the event of a leakage of radioactivity in the environment, it is very costly or even impossible to recoup the wastes), but has lower risk.

In this context imperfect scientific knowledge is an important source of uncertainty. There are ongoing studies about how to reduce the radioactivity of wastes (a technique known as "separation and transmutation"[1]). If these studies succeed in discovering a new process for treating and recycling wastes, decision makers would prefer ex-post to have used the reversible technology, as this would allow them to recoup the wastes and treat them with the new technique.

These considerations raise the following questions: which storing technology should

[1] The separation-and-transmutation technique consists in separating long living particles from short living ones and in transmuting the latter into short living via a complex process, thus making a lengthy storage of wastes unnecessary.

we adopt today if we expect more progress in scientific research?

The purpose of this paper is to study the choice between a traditional technology characterized by known risks and an innovative technology subject to scientific uncertainty. A common feature of all the examples is that uncertainty is resolved at least partially over time. We will therefore deal with a dynamic model insisting on the fact that decisions are sensitive to available information. The way we model it, scientific uncertainty differs from risk as regards the possibility of diminishing over time.

A health economics example is the choice between surgery (an intervention once and for all) and a new treatment to prevent an illness from spreading. In many situations surgery is considered more costly (more traumatic) and irreversible but less risky (for instance surgery is considered a more efficient preventive technology for many types of cancer). In this case we ask: how does the choice of preventive technologies vary if we expect more or less progress in medical science? One of the most fashionable example of scientific uncertainty is the current controversy on genetically modified organisms (GMO). There is still no agreement about the risks of the adoption of GMO. The risks most frequently evoked concern human health (toxicity, possibility of allergies) and the environment (genetic mutations in animals fed with GMO, transfer of the gene to different cultures). Should we choose biological productions (more costly) or GMO cultures (riskier and more irreversible) if we expect better information in the future?

We compare two technologies differing in the three dimensions we have seen emerging in the examples: first period implementation costs, second period risk, and degree of irreversibility. We study the effect of foreseen scientific progress (better information) on the present choice between one or the other. We find that scientific progress alone is not enough to push towards one technology or the other. We find that: i) if the first period choice is restricted to be 'all or nothing', like in the health economics example, scientific progress promotes the traditional technology. This is as in Epstein (1980); ii) otherwise for different discrete or continuous technology choices expected scientific progress alone is not enough to push towards one technology or the other and the result depends on the specific assumptions about: costs, risk and preferences; iii) if for example absolute risk aversion is constant (CARA), scientific progress increases the optimal level of the technology with the higher implementation cost.

In standard irreversibility theory (Arrow and Fisher (1974), Henry (1974), Epstein (1980), Freixas and Laffont (1984), Jones and Ostroy (1984)) the decision maker chooses a level of today's decision variable. This choice results from an intertemporal trade-off between raising today's utility and constraining tomorrow's choices. In this paper the first period decision is more complex because choosing one technology not only restrict tomorrow's possibility set but also implies different present and future payoffs.

We contribute to this strand of the literature showing that Epstein's result does not generalize to the case of two technologies unless the choice is restricted to be all or nothing, and that the result depends on specific assumptions about costs, risk and preferences.

The paper is organized as follows. In section 2 we present the model and we clarify the role of risk and scientific uncertainty. In section 3 we study the comparative statics of a better information structure: i) when the choice between the two technologies is restricted to be binary; ii) when the choice is continuous. Some concluding comments are provided in the last section.

2. The Model

For expositional purposes we refer to the example of nuclear wastes and we present the model by assuming that the innovative technology is more costly and less risky than the traditional technology. We discuss the opposite case in subsection 2.1.

We propose a model with two dates i=1,2. There is a decision maker who maximizes the sum of the expected utility of the generations living at dates 1 and 2. Let w_i be the wealth in period i, i=1,2. At time 1 the decision maker chooses the proportion β of nuclear wastes (normalized to one) to store with a traditional reversible technology (T) in a non-permanent site, and the proportion $(1-\beta)$ to store with an innovative irreversible technology (I) in a geological storage. Define c^I the cost of storing the wastes with the innovative technology and c^T the cost of storing them with the traditional technology. Assume $c^I > c^T$: it is more expensive to store the wastes with the innovative than with the traditional technology. In the second period the decision maker chooses the fraction $k \in [0, \beta]$ of wastes stored with the traditional storage that must be moved to the innovative one. We assume that it is impossible or too costly to switch from the innovative to the traditional technology. The unit cost of moving them is C (a measure of the irreversibility of the reversible technology). This cost must be traded-off against the extra risk that is borne if they are left in the traditional storage. Nuclear wastes left in the traditional storage induce a random damage $\tilde{x}^T$. Random variable $\tilde{x}^I$ is the cost to society of the nuclear wastes stored with the innovative technology. We assume $\tilde{x}^T$ riskier than $\tilde{x}^I$.[2]

Differing from risk for the possibility of diminishing over time, when we study the way uncertainty is resolved over time, we must consider the related information structure, i.e. a set of possible signals characterized by a statistical relation with the events we are interested in. The observation of this signal may change beliefs in the events. The change in beliefs in turn has an impact on decision-making. Assume $\tilde{x}^I$ discrete with n atoms $\left(x_1^I, x_2^I, ..., x_n^I\right)$. The decision maker has some prior beliefs about the distribution of $\tilde{x}^I$. At t=1 it is known that some information $\tilde{y}$ on the distribution of $\tilde{x}^I$ will be available before t=2[3]. This information will allow the decision maker to revise the distribution of $\tilde{x}^I$ according to Bayes' rule. The expected change in beliefs in turn has an impact on the initial choice of β. We assume time separability of preferences. Utility functions u and v are assumed to be twice differentiable, with $u^{'} > 0, u^{"} < 0, v^{'} > 0, v^{"} < 0$. The decision problem is thus the following:

$$\begin{aligned} & \max_{0\leq\beta\leq1} u\left(w_1 - c^T\beta - c^I\left(1-\beta\right)\right) + \\ & E_{\tilde{y}} \max_{0\leq k\leq\beta} E_{\tilde{x}^I/\tilde{y}} E_{\tilde{x}^T} v\left(w_2 + \left(\beta - k\right)\tilde{x}^T + \left(1-\beta+k\right)\tilde{x}^I - kC\right). \end{aligned} \tag{2.1}$$

In this model the decision maker is then facing a trade off between lower (deterministic)

[2]It looks reasonable that if an accident occurs on the surface damage is greater than if it occurs in a geological storage 1000 meters deep.

[3]For the nuclear wastes example the information may concern a possible leakage of radioactivity in the environment, the discovery of a new treatment to reduce the radioactivity of wastes, and so on.

costs today and higher (random) risk tomorrow.

2.1. Preliminaries

Besides the nuclear wastes example our purpose is to compare two technologies differing in first period implementation costs, $c^T \lesseqgtr c^I$; second period risk. It immediately follows that if $c^T = c^I$ the decision maker will choose $\beta = 0$ or $\beta = 1$ depending on whether the traditional or the innovative technology is less risky; If $\tilde{x}^T = \tilde{x}^I$ the cost C of switching from the traditional to the innovative technology does not matter because $k = 0$ and therefore the optimal initial choice is the one that offers the highest first period return (the lowest first period cost); Those cases where a technology is characterized both by an higher first period cost and second period risk are also trivial; If the position is perfectly reversible, $C = 0$ and if $c^T < c^I$, the optimal initial choice is to select technology T. The straightforward intuition being that if in the second period one can switch to technology I at no cost, then it is better to save on the initial cost and opt for technology T, at least until t=2. Remark that when C decreases it becomes easier to switch from one technology to the other. This leads to a higher optimal β.

Following the previous analysis we are left with two relevant scenarios:

A) $\left\{c^T < c^I, \tilde{x}^T \text{ riskier than } \tilde{x}^I, C \in (0, \infty)\right\}$,

B) $\left\{c^T > c^I, \tilde{x}^I \text{ riskier than } \tilde{x}^T, C \in [0, \infty)\right\}$,

where the problem is more complex and scientific uncertainty plays a role. Case A includes for example our nuclear wastes story or the treatment (technology T) versus surgery (technology I) story. An example of Case B is biological production (technology

T) versus GMO culture (technology I). In the next section we will study the comparative statics of a better information structure on the first period optimal mix of technologies.

3. Comparative Statics on Information Structures

We denote $\pi_y\left(x^I\right)$ the probability of $\tilde{x}^I = x^I$ conditional on the reception of message y, $\pi_y = \left(\pi_y\left(x_1^I\right), \pi_y\left(x_2^I\right), ..., \pi_y\left(x_n^I\right)\right)$, and $S = \left\{\pi_y \in R_+^n \left| \sum_{i=1}^n \pi_y\left(x_i^I\right) = 1\right.\right\}$ the set of potential conditional distributions on $\tilde{x}^I$. Let also denote

$$E_{\tilde{x}^T} v\left(w_2 + (\beta - k)\,\tilde{x}^T + (1-\beta+k)\,\tilde{x}^I - kC\right) = V\left(w_2 + (\beta - k)\,x^T + (1-\beta+k)\,\tilde{x}^I - kC\right)$$

and

$$J(\beta, \pi_y) = \max_{0 \leq k \leq \beta} E_{\tilde{x}/\tilde{y}} V\left(w_2 + (\beta - k)\,x^T + (1-\beta+k)\,\tilde{x}^I - kC\right),$$

as the value function for the second period problem.

Following Blackwell (1951) and Marschak and Miyasawa (1968) we say that a signal $\tilde{y}$ is more informative than a signal $\tilde{y}^{'}$ if and only if:

$$for\ any\ \rho\ convex\ on\ S : E_{\tilde{y}}\rho(\pi_y) \geq E_{\tilde{y}'}\rho\left(\pi_{y'}\right). \tag{3.1}$$

As in Epstein (1980) and Gollier, Jullien and Treich (2000), our main purpose is to determine the comparative statics of a better information structure. In our model, this means determining how a signal $\tilde{y}$ more informative than signal $\tilde{y}^{'}$ affects the efficient level β. From now on when we refer to two economies satisfying condition (3.1), we will talk of "a better information structure". As shown by Marschak and Miyasawa (1968), condition (3.1) is equivalent to the fact that all expected utility maximizers observing $\tilde{y}$ are at least as well off as when observing $\tilde{y}^{'}$. That is to say:

$$E_{\tilde{y}} J\left(\beta, \pi_y\right) \geq E_{\tilde{y}'} J\left(\beta, \pi_{y'}\right). \tag{3.2}$$

We thus have two equivalent definitions of a better information structure, (3.1) and (3.2). We can now rewrite problem 2.1 as:

$$\max_{0 \leq \beta \leq 1} u\left(w_1 - c^T \beta - c^I (1-\beta)\right) + E_{\tilde{y}} J\left(\beta, \pi_y\right).$$

We assume $J\left(\beta, \pi_y\right)$ to be concave and differentiable with respect to β[4]. Then the objective function is concave in β, and we obtain the following result:

Proposition 1. *A better information structure increases the optimal investment in the technology with the higher implementation cost if and only if $J_\beta\left(\beta, \pi_y\right)$ is concave in π_y.*

Proof. If A (B) $\left(c^I - c^T\right)$is positive (negative). Writing first order conditions both for $\tilde{y}$ and $\tilde{y}^{'}$ it is immediate that a better information structure increases (decreases) the optimal investment in the innovative technology if and only if $E_{\tilde{y}} J_\beta\left(\beta, \pi_y\right) \geq E_{\tilde{y}'} J_\beta\left(\beta, \pi_{y'}\right)$. Then definition (3.1) of better information structure gives the result. ■

A potential intuition of this result is as follows: more information in the future implies the optimal exposure to risk to be more sensitive to signals. More extreme signals push to switch decision more often in the second period. This yields an increase in risk ex ante. Therefore, while for a given information structure the optimal β is chosen comparing

[4] $J\left(\beta, \pi_y\right)$is concave in β if $v\left(.\right)$ is concave in β, k and the choice set for k is convex.

today's costs with tomorrow's risk. With more information tomorrow's risk is higher and in the decision less weight is given to the costs. While the hypothesis about the first period cost can be verified, it is often difficult to verify concavity or convexity with respect to the vector of the conditional probability of the value function's derivative. Next we consider some special cases where it is possible to sign the effect of a better information structure.

3.1. The Binary Choice Problem

We consider a simple special case of our problem. Suppose for the moment that the decision maker is forced to choose only one technology, i.e. β can take only values zero or one. In other words, the decision maker is forced to store all the wastes in one of the two technologies because of the fixed costs related to each investment. The problem then becomes:

$$\max_{\beta\in\{0,1\}} u\left(w_1 - c^T\beta - c^I(1-\beta)\right) +$$
$$E_{\tilde{y}} \max_{k\in\{0,\beta\}} E_{\tilde{x}^I/\tilde{y}} V\left(w_2 + (\beta - k)\, x^T + (1-\beta+k)\,\tilde{x}^I - kC\right).$$

That is, opting for the innovative technology completely constrains the second period decision. Therefore there is no longer choice k. Common wisdom suggests that more information should make the traditional technology more attractive. We would expect that if the traditional technology is chosen in an economy with a given information $\left(i^-\right)$, it would also be chosen in an economy with more information $\left(i^+\right)$. This is true as shown in the following Proposition:

Proposition 2. *Assume $\beta \in \{0,1\}$. Then: If the traditional technology is preferred in a given economy, it is also preferred in an economy with a better information structure: $\beta^{i^-} = 1 \Rightarrow \beta^{i^+} = 1$.*

Proof. If we choose $\beta = 0$ the information is useless and the expected utility is the same in the two economies:

$$U^{i^-}(\beta = 0) = U^{i^+}(\beta = 0) = u\left(w_0 - c^I\right) + Ev\left(w_1 - \tilde{x}^I\right)$$

Because the information has a value when $\beta = 1$ we have that given:

$$U^{i^+} = u\left(w_1 - c^T\right) + E_{\tilde{y}} \max_{k \in \{0,1\}} E_{\tilde{x}^I/\tilde{y}} V\left(w_1 + (1-k)\,x^T + k\tilde{x}^I - kC\right)$$

and

$$U^{i^-} = u\left(w_1 - c^T\right) + E_{\tilde{y}'} \max_{k \in \{0,1\}} E_{\tilde{x}^I/\tilde{y}'} V\left(w_1 + (1-k)\,x^T + k\tilde{x}^I - kC\right)$$

$U^{i^+}(\beta = 1) \geq U^{i^-}(\beta = 1)$ is ensured by the Marschak and Miyasawa (1968) result, that all expected utility maximizers are at least as well off observing $\tilde{y}$ rather than $\tilde{y}'$. So if it is optimal to adopt the traditional technology in the economy with less information i.e. $U^{i^-}(\beta = 1) > U^{i^-}(\beta = 0)$, then combining the previous inequalities we get:

$$U^{i^+}(\beta = 1) \geq U^{i^-}(\beta = 1) > U^{i^-}(\beta = 0) = U^{i^+}(\beta = 0)$$

which concludes the proof. ■

The intuition of the above result is the following. Setting $\beta = 0$ leaves no choice to make in t=2: information is useless because there is no choice left to make. Now, the cost of constraining the second period choice is somehow higher when time 2's decision could have made use of more information. So if the traditional technology is optimal when one expects information $\left(i^{-}\right)$, it must also be optimal when one expects more information. We get the same result as Epstein (1980).

For any binary choice $\beta \in \{\beta_L, \beta_H\}$ with $\beta_L + \beta_H = 1$ and $\beta_L \neq 0$ information is always useful and $U^{i^+}(\beta_L) \geq U^{i^-}(\beta_L)$. Therefore the proof does not go through anymore and the result depends on the parameters.

The discrete case, though extreme, lends itself to describe some real situations. One example is the choice between surgery (an intervention once and for all) and a treatment to avoid the illness to expand. Our prediction is that the expectation of progress in medical science (more information) should induce patients to postpone surgery while undergoing a treatment.

3.2. The Continuous Choice Problem

In the previous subsection we showed that the standard result that better information decreases the optimal level of the innovative irreversible technology still holds for the case of multiple technologies if the first period choice is restricted to be all or nothing. Let us now analyze the continuous choice problem.

To analyze the case of a continuous first period choice we first solve the second period constrained maximization problem. The solution to this problem will be a function of the first period choice and of information structure: $k(\beta, \pi_y)$.

The Lagrangian is written as:

$$L = E_{\tilde{x}^I/\tilde{y}} V\left(w_2 + (\beta - k)\, x^T + (1 - \beta + k)\, \tilde{x}^I - kC\right) + \lambda(\beta - k) + \mu k,$$

the first order condition is:

$$E_{\tilde{x}^I/\tilde{y}} V'\left(w_2 + (\beta - k)\, x^T + (1 - \beta + k)\, \tilde{x}^I - kC\right)\left(\tilde{x}^I - x^T - C\right) - \lambda + \mu = 0.$$

This give rise to three possible cases:

$$\begin{cases} If\ k = 0; \mu \geq 0, \lambda = 0 \\ If\ k = \beta; \mu = 0, \lambda \geq 0 \\ If\ k \in (0, \beta)\,; \mu = \lambda = 0 \end{cases}$$

By the Envelope Theorem: $J_\beta(\beta, \pi_y) =$

$$\begin{cases} -E_{\tilde{x}^I/\tilde{y}} V'\left(w_2 + (\beta - k)\, x^T + (1 - \beta + k)\, \tilde{x}^I - kC\right)\left(\tilde{x}^I - x^T\right)\ if\ k(\beta, \pi_y) < \beta \\ -E_{\tilde{x}^I/\tilde{y}} V'\left(w_2 + \tilde{x}^I - \beta C\right) C\ If\ k(\beta, \pi_y) = \beta \end{cases}$$

$$J_\beta(\beta, \pi_y) = \max \begin{pmatrix} -E_{\tilde{x}^I/\tilde{y}} V'\left(w_2 + (\beta - k)\, x^T + (1 - \beta + k)\, \tilde{x}^I - kC\right)\left(\tilde{x}^I - x^T\right) \\ -E_{\tilde{x}^I/\tilde{y}} V'\left(w_2 + \tilde{x}^I - \beta C\right) C \end{pmatrix} \tag{3.3}$$

By restricting the set of utility functions we can state:

Proposition 3. *Suppose CARA. Then a better information structure increases the optimal level of the technology with the higher implementation cost.*

Proof. Given that $E_{\tilde{x}^I/\tilde{y}} V'\left(w_2 + \tilde{x}^I - \beta C\right) C$ is linear in $\pi_{\tilde{y}}$, $J_\beta(\beta, \pi_y)$ will be convex if

$$-E_{\tilde{x}^I/\tilde{y}} V'\left(w_2 + (\beta - k)\, x^T + (1 - \beta + k)\, \tilde{x}^I - kC\right)\left(\tilde{x}^I - x^T\right) \tag{3.4}$$

is convex or linear in π_y.

If $k(\beta, \pi_y) = 0$ the above equation is linear.

If $k(\beta, \pi_y) \in (0, \beta)$then:

the first order condition of the Lagrangian implies:

$-E_{\tilde{x}^I/\tilde{y}} V'\left(w_2 + (\beta - k) x^T + (1 - \beta + k) \tilde{x}^I - kC\right) \left(\tilde{x}^I - x^T\right) =$

$-E_{\tilde{x}^I/\tilde{y}} V'\left(w_2 + (\beta - k) x^T + (1 - \beta + k) \tilde{x}^I - kC\right) C$

Under CARA $-v'$ is proportional to v, this implies that the right hand side of the above equality is proportional to $J(\beta, \pi_y)$. Being (3.4) equal to the left hand side of the equality, we have that (3.4) is proportional to $J(\beta, \pi_y)$. Then definition (3.2) and (3.1) of a better information structure say that (3.4) is convex. Therefore $J_\beta(\beta, \pi_y)$ is convex and Proposition 1 gives the result. ■

We have shown another special case where we are able to sign the effect of a better information structure on today's technology choice. For more general preferences the result is ambiguous: if absolute risk aversion is not constant we have one better information structure pushing toward technology I while another favoring technology T. This is in fact true as proven by the following example. Suppose $v(z) = \ln(z)$, then the effect of a better information structure is ambiguous in the following sense: given an information structure $\tilde{y}$ a better information structure $\tilde{y}'$ increases the optimal level of T and a better information structure $\tilde{y}''$ increases I. We assume $\beta \in \{.5, .8, 1\}$and we show that:

$U(\beta = .8) > U(\beta = .5)$

$U^i_{\tilde{y}}(\beta = .5) > U^i_{\tilde{y}}(\beta = .8)\, but$

$U^i_{\tilde{y}'}(\beta = 1) > U^i_{\tilde{y}'}(\beta = .8)$

Let us consider the following numerical example:

$$
\begin{cases}
u(z) = v(z) = \ln(z) \\
w_1 = w_2 = 10 \\
c_1 = 1 \text{ and } c_2 = 2 \\
\tilde{x}_1 = h\tilde{x} \text{ and } \tilde{x}_2 = \tilde{x} \\
C = 1 \text{ and } h = 1.5
\end{cases}
$$

The prior distribution of lottery $\tilde{x}$ is $(-1, .99; -6, .01)$. A first information structure has two possible signals with equal probability, the posterior updated probabilities are $\tilde{x}/y_1 =_d (-1, .99; -6, .01)$ and $\tilde{x}/y_2 =_d (-1, .01; -6, .99)$. A second information structure always has two possible signals the first with probability .9 and the second with probability .1. The posterior updated probabilities are $\tilde{x}/y_1' =_d (-1, .999; -6, .001)$ and $\tilde{x}/y_2' =_d (-1, .001; -6, .999)$.

After some lengthy calculations we obtain:

$U(\beta = .8) = 4.3097 > 4.2966 = U(\beta = .5)$

$U^i_{\tilde{y}}(\beta = .5) = 3.8491 > 3.8284 = U^i_{\tilde{y}}(\beta = .8)\, but$

$U^i_{\tilde{y}'}(\beta = 1) = 4.2313 > 4.2262 = U^i_{\tilde{y}'}(\beta = .8)$ as we were looking for.

Therefore the standard result that a better information structure decreases the optimal level of irreversibility generalize to the case of multiple technologies only if the choice is restricted to be all or nothing, but fails in general.

4. Conclusion

The emergence of new technologies: geological storages for nuclear wastes, GMO or a new treatment in medical science; urge an analytical study of how the policymaker should choose between traditional technologies characterized by well known risks and innovative technologies subject to scientific uncertainty. The purpose of this paper has been to study the effect of foreseen scientific progress on the present optimal mix. We compare two technologies differing in the three dimensions we have seen emerging in many examples: first period implementation costs, second period risk, and degree of irreversibility. We find that the effect of information is in general ambiguous. We also find the following: if the first period choice is restricted to be all or nothing, scientific progress promotes the traditional technology and this result generalizes the standard result obtained when only one technology is available; with constant absolute risk aversion scientific progress increases the optimal level of the technology with the higher implementation cost.

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