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Economic Quantitative Methods for the Evaluation of the Impact of R&D Programmes

A State-of-the-Art

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Economic Quantitative Methods for the Evaluation of the Impact of R&D Programmes

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Executive Summary

1. The Findings

The bases on which a nation can acquire competitive advantages in order to increase its material welfare are manifold and depend on its endowment with resources, its stock of total capital and its institutional infrastructure. The stock of total capital is composed of physical capital, knowledge capital and human capital. For a long time, knowledge capital and human capital have been treated by governments, at most, as second-hand targets in the economic policy formation. Physical investment and labor were the focus targets around which it was thought an efficient economic policy could be designed. In the late seventies, the flagrant inefficiency of economic policies showed policy makers that knowledge and human capital were really the active sources of economic growth and competitiveness. This led them to review their conception of science and technology policy as well as education and training policy and to adapt their institutional system accordingly. In the search for a higher efficiency of the science and technology policy, public managers increasingly view science and technology assessment as an integral component of policy management. At the roots of the present science and technology policies, there is the objective to stimulate innovative activities as a means of fostering economic growth and strengthening competitiveness. Therefore, the ultimate question of the policy evaluation process should be : what are the economic impacts of the science and technology policy ? This questioning then leads them to try and find how to measure these economic impacts and, in a further stage, when searching the toolbox of policy makers, these wonder whether using econometric methods and models might be advisable.

Econometric methods are extensively used as an economic policy evaluation tool. Nevertheless, its credibility and usefulness in the field of science and technology policy is, to a large extent, subject to controversy. Main arguments against them are the identification problem of the causal relationship between technological performance and economic development, the time lag between knowledge investment and its economic impact, the variability of results, the complexity and uncertain nature of innovation. Besides, lots of evaluation studies point out that the evaluation processes are mainly focused on technological aspects and neglect economic impacts. When economic impacts are covered by the evaluation process, the methods used are essentially case studies and surveys. The drawback of these methods is that results obtained from case studies cannot be easily generalized and that surveys may provide biased results. So, these methods have their advantages and disadvantages. The modalities of their use are varied. They should be simultaneously used in some cases in order to improve the reliability of observations and, when the results are divergent, to reinforce the evaluation process by learning about sources of divergence. Besides, they could be separately used depending on specific objectives. Yet, some criticisms against econometric methods are grounded. Hence, the problems econometric techniques of impact evaluation are faced with are threefold : the methodological drawbacks, the measurement issue and data availability.

The methodological drawbacks essentially follow from the treatment of technical change in economic analysis. Indeed, technical change is conceived as an intrinsically exogenous process in economic theory and, consequently, in economic models. It is exogenous because assumed to depend exclusively on technical constraints. The empirical consequence is that it is rudimentarily measured through a time trend. It is intrinsically exogenous because any attempts to grasp how it operates, as is the case for the inducement and embodiment hypotheses, have not removed the exogeneity, and hence the time dependence. Yet, in the past thirty years, a great amount of research has been devoted to relaxing this hypothesis by introducing research and development (R & D) in production functions. As long as R & D investment is only integrated as a production factor without being itself, at least partially explained, by economic mechanisms, we have only identified but not endogenized one of the sources of technical change. Nevertheless, we may agree that it is a first important step towards endogenization.

Despite its limitations, the production function approach is presently the only operational way of assessing the economic impact of R & D. This impact is measured by estimating the relationship between R & D and productivity. The main attempts to measure the impact of R & D on economic growth rely on the Cobb-Douglas production function and make use of two alternative theoretical frameworks. The first one is based on the estimation of the R & D capital elasticity with respect to the output and the second one on the estimation of the rate of return on R & D investment. It is worth noting that the interpretation of the estimated coefficients will differ depending on the level of data aggregation. Indeed, empirical analyses can be performed at three levels : micro (i.e. on firm data), meso (i.e. on industry data), macro (i.e. on nationwide data). At the micro level, both coefficients only deal with the private effect of R & D. At the meso level, both coefficients can be assumed to measure the intra-industry social effect of R & D. At the macro level, both coefficients should provide an estimate of the nationwide social effect of R & D. Furthermore, regression analyses can be alternatively performed on time-series data, cross-section data or both. The high variability observed in the estimates can, to a large extent, be explained by data characteristics. When firm sales are used as output measure the mean value of R & D elasticity is .05 for time-series data against .10 for cross-sections and the mean value of the rate of return is 15 percent. The use of value added as output measure provides weaker estimates which often turn to be non-significant. The estimates are higher when data are corrected for double counting and expensing and in scientific sectors. At the industry level, the mean value of the rate of return is 22 percent and amounts to 35 percent when the fall observed in the rates of return during the sixties is taken into account. At the nationwide level, the R & D elasticity noticeably differs from one country to the other. The mean value is about .40. In recent years, dynamic disequilibrium models have been applied to measure the contribution of R & D to the changes in output. These adjustment cost models consider R & D as a quasi-fixed factor which does not adjust instantaneously to its optimal level and which is endogenously determined by demand, input prices and inputs. At the nationwide level, the estimates short-run elasticity of R & D for the manufacturing sector is about .15 and the net internal rate of return on R & D investment is about 13 percent. There is no major contradiction between these estimates and the latter are strikingly compatible with results obtained from case studies. So, these studies undoubtedly put forward the influence of R & D activity on productivity. Nevertheless, this contribution varies from one sector to an other. In the scientific sector, the R & D elasticity is higher than in other sectors, its mean value being .13 for time-series against .18 for cross-sections. Regarding its rate of return, it is 10 percent higher than in other sectors. Furthermore, as shown by case studies, its impact changes over time and occurs with a variable lag depending on the orientation of research. Finally, econometric studies are faced with two categories of problems : conceptual fuzziness and methodological drawbacks. The former principally concerns the interpretation of estimates and data to be used and the latter, econometric techniques implemented and data measurement.

There is a general agreement that the social return to R & D is higher than the private return because the effects of R & D go beyond the firm, the industry and the country which perform the investment. Indeed, the returns to R & D may not be completely appropriable because knowledge produced by R & D investment performed in a firm is a public good which allows other firms to develop new innovations with less R & D efforts than otherwise. This spillover effect is a positive externality which causes the social rate of return on R & D to be generally higher than the private rate of return, an observation largely confirmed by empirical studies. The literature reports several methods dealing with the measure of spillovers. A first method is to take into account the proximity between industries by giving weights to R & D stocks according to how close to each other industries are. The different proximity measures which have been suggested are successively : weights proportional to the flows of intermediate input purchases, to the flows of patents or innovations or again to the firm's position in a technology space. A second approach is to consider the outside pool of R & D stock globally. A last method is to enter separately into the production function the R & D stock of each potential source of spillover. According to the inter-industry technology flow approaches, the rate of return on external R & D should be around 50 percent. Yet, the relationship between external R & D and productivity varies across industry and over time. The use of intermediate input purchases, patents or innovations in order to identify technology flows is not free from criticisms. If intermediate input purchases may be assumed to be a good proxy of embodied R & D, it is not necessarily a good measure of technological opportunities. On the other hand, when patents or innovations are used, they are assumed to be equally important, which is far from being right. When technological proximity is measured by characterizing the firm's position in the technological space, patents are made use of to distribute firms according to their research interests across technological areas. The results obtained from this approach show that firms in R & D intensive areas have, on average, relatively more patents and a higher return to R & D though low R & D intensity firms have lower return if their neighbors are R & D intensive. Further, firms adjust their technological positions in response to technological opportunities. In the approach considering the unweighted outside pool of R & D knowledge, the spillover effects are measured by estimating a cost function which includes intraindustry and interindustry spillover variables. The empirical evidence based on this approach is very limited. The findings suggest that interindustry spillovers cause unit costs to decline substantially more than intra-industry spillovers. However, the contribution of the interindustry spillover to the social rate of return appears to be lower than the intraindustry spillover effect. The latter contributes of about 10 percent against 2 percent for the former. Not only is there a substantial difference between the social and private rates of return but the spillover effects, to a large extent, differ across sectors. The latter approach, which separately enters the R & D stock of each potential source of spillover into the cost function empirically demonstrates that tracing the sources and beneficiaries of spillovers is econometrically feasible. However, only main spillover sources can be significantly identified because of multicollinearity. Each producer is treated as a distinct spillover source and the direction and magnitude of the interindustry spillovers can vary across receiving industries so that the spillover network of senders and receivers can be traced. The results obtained for the few empirical investigations show that all industries are influenced by spillovers but not all are sender industries. All industries are characterized by very high private rates of return, which, on average, amount to 25 percent. Besides, the social rate of return greatly varies across industries and can be three to four times as big as the private rate of return, as seems to be the case in the sectors of scientific instruments, nonelectrical machinery and chemical products. R & D spillovers do not only affect production characteristics but both output supply and input demand decisions. Moreover, spillovers are intertemporal externalities because they result from present and past decisions about R & D investment process. Such features can be taken into account by considering simultaneously cost and product demand functions in which R & D stocks are defined as quasi-fixed factors of production which, because of adjustment costs, do not adjust instantaneously. A last point is that it would be useful to extend the input-output by treating R & D activities as an independent activity in the input-output structure. As R & D investment is a strategic policy variable which increases the future production potential and not principally the current production, it should be regarded as a final demand component. Then, an R & D input-output matrix should be constructed in order to have a disaggregation of R & D final demand between consumer sectors and producer sectors.

Most efforts in the econometrics of R & D have been devoted to measuring the impact of industrial R & D. Econometric methods are only marginally used as policy evaluation tool in the field of science and technology. Yet, assessing economic impacts of policy intervention is not an easy task because a variety of effects and causes may contribute to specific outcomes. So far, only a few empirical pinpoint studies have endeavoured to estimate the economic impact of R & D policy. They principally make use of two direct approaches. In the first one, the productivity approach, the respective effects of privately-funded and publicly-funded R & D expenditures on productivity are measured. These studies provide evidence of the output elasticity of public R & D or of its rate of return. The second one, the investment approach, evaluates to what extent publicly-funded R & D crowds out, complements or stimulates private R & D. Besides these two conceptual approaches, probabilistic models which deal with qualitative data, and a supply approach, which is an alternative indirect method to the productivity approach, are also used. Studies dealing with the impact on productivity of government-funded R & D often fail to find evidence that public support to R & D is productive. Yet, some studies show that the relationship between government R & D and productivity is more subtle than the link between private R & D and productivity growth. The objectives of public support, the rules that govern the allocation of public funds and the character of use of government R & D are all elements which might strongly influence the effectiveness of public R & D investments. So, defense-oriented R & D is not directly aimed at furthering economic growth, basic research certainly sustains more long-term economic growth than short-term objectives and the effectiveness of public support to new economic products and processes produced by business enterprises strongly depends on the recipient private enterprise's own economic effectiveness. Studies taking into account some of these characteristics provide evidence that public support has a positive and significant influence on productivity and also show that this productivity effect cannot be generalized to the whole public R & D. Turning now to the impact of public support on private R & D, studies, to a large extent, emphasize a marginally stimulating effect of publicly-funded R & D on privately-funded R & D. Yet, here too, the effectiveness of public support depends on the characteristics of public intervention. Furthermore, the impact largely differs from one country to the other. Unfortunately, like the productivity approach, most of the evidence comes from the United States and shows that the relationship between government-financed and company-financed R & D is more subtle than suggested by global approaches. Although results are highly variable, the studies support the complementary hypothesis. In other words, government R & D allocations to industry should not substitute for privately-financed R & D. This observation is confirmed by other approaches. All these approaches suffer from the same drawbacks than studies on the impact of R & D on productivity. Moreover, a striking feature of these studies is their lack of grounded theoretical framework. So, what are the theoretical links between the productivity and investment approaches ? What is the behavior of the firm regarding public support ? How to explain the apparent divergence of results obtained from alternative approaches ? Why should the impact of public support on productivity be less effective than private R & D ? If the accumulated empirical evidence proves that econometric methods can be usefully used for policy evaluation, the theoretical background of models should be improved and any analysis should be grounded on a reliable specification of both causal relationships and the economic environment.

A fundamental distinction between science and technology policy and a large part of other economic policies is that the former is largely motivated by strategic issues and is designed to deal with a highly competitive technological environment. While, in recent years, there has been an important literature dealing with both technological rivalry and public R & D-incentive policies, in the present state-of-the-art, it has not led to clear-cut recommendations on how to implement an efficient R & D policy. When a potential strategic public policy is being designed, the endogenous characteristics of each industry must be taken into account to use the most appropriate instruments. An effective policy in an industry might be totally ineffective in another. So, it should be fruitful to learn about how different industries might react to different instruments. The public policy should also take into account the fact that its effectiveness is to a large extent conditioned by the existence of critical mass. Technological opportunities, cumulativeness and the degree of appropriability are characteristics which underlie sectoral and national technological performances and may lead R & D to agglomerate. This phenomenon is also an important component for the policy design. Coming back to a more general viewpoint, it is worth emphasizing that R & D public policy is increasingly viewed as a strategic activity implemented as a response to external challenges. R & D is a major determinant of non-price competition and a primary means of gaining market shares. So, besides the productivity approach, a demand approach might be suggested to study how successful R & D is in generating greater demand and to what extent rivals are able to annihilate this demand increase through R & D efforts.

In oligopolistic situations, firms are thought to react to rivals' decisions in order to preserve and increase their market shares. Therefore, on the one hand, market share models are well-suited to capture the interdependence among firms and, on the other hand, reaction functions are able to provide evidence on how firms move in response to strategic actions undertaken by rivals. This approach could give information on the magnitude of asymmetries firms are faced with and on the extent of submissive multiple reactions which underlie the firm's behavior. Furthermore, public policy considerations might be integrated into the model to measure how R & D subsidies influence firms' reactions and market shares and how strategic partnership affects economic performance. While such a model still has to be developed, its advantage in comparison with the preceding ones is to introduce the strategic component into the model and to evaluate how both firms' and governments' strategic behaviors are effective to increase market share.

2. The Appraisal

1. The economic quantitative methods, particularly econometric models, should be viewed as an ex post quantitative evaluation tool of the economic impacts of science and technology policy. They have their shortcomings and limits. They are an instrument in the toolbox of policy evaluation which can be used for structured quantitative analyses of the economic impact of R & D policy.

2. The economic analysis of technological change remains a fallow field impounded by the neo-classical paradigm of exogenous technical change. Over the last thirty years, empirical evidence has been accumulated on the economic impact of technical change and recently new promising avenues have been opened for future research.

3. The applied economics of R & D has emphasized the link between R & D and productivity. The experiments cover the micro-, meso- and macro-levels and the estimates bear on the R & D elasticity with respect to output and the rate of return on R & D. A large part of divergences observed in results can be explained by data characteristics. Nevertheless, this approach is still faced with measurement problems and conceptual inaccuracies.

4. The spillovers of R & D investment are very high due to the inability of firms to appropriate all the benefits of their own R & D. Several alternatives have been applied to the measure of spillover effects. Besides the approaches based on proximity measures, some recent econometric works have put forward that tracing sources and

receivers of spillovers was feasible and that the social rate of return on R & D greatly varies across industries.

5. The economic impact of government-financed R & D might be evaluated by using simultaneously existing pinpoint methods and extended macroeconometric models. While existing pinpoint methods are numerous, the most commonly used ones are the productivity and the investment approaches. Extended macroeconometric models might be conceived by adapting present macromodels or developing adequate modules.

6. Public R & D policy is designed in a competitive environment so that the strategic grounding of science and technology policy needs to view the evaluation process of the economic impacts of R & D programmes as a strategic activity. To deal with this issue, competitive interaction models could be fruitfully used as a complement to the preceding approaches.

7. Econometric methods are suitable for policy evaluation but several techniques can be used. The choice of a measurement method depends on four criteria : the objective of the evaluation, the data availability, the time devoted to the evaluation and the implementation cost.

8. The evaluation of the economic impact of R & D programmes provides an ultimate objective judgment of the science and technology policy and, to some extent, of the complex, subjective and interactive technology assessment process. Its results should serve as a discussion basis to improve policy design.

Introduction

The economic turbulences of the seventies have disrupted the technological trajectories on which the industrialized countries had built their prosperity. The traditional instruments of economic policy have proved to be ineffective to overcome the slackness which Western economies are faced with. The process of creative destruction which goes together with it reminds the industrial countries that investment and employment are not the only sources of growth. Indeed, they observe that any policy aiming at promoting either of these variables only gives paltry results if it is not mixed with technological mastery. The latter will be the real motor of growth. So, although investment and employment are conducive to growth, they are themselves boosted by technological change. But technological change is not manna from heavens and requires some types of investment, namely, investment in research and development but also investment in education and on-the-job training, which are the main factors through which economic growth can be restored.

The sudden awareness of the central role played by technological change has led governments to review their conception of science and technological policy and pay particular attention to its interconnexion with economic policy. Yet, in lots of countries, science and technology policies are implemented in a context of budgetary austerity which obliges them to define priorities to look out for the efficiency of the system set up. Since its resources are strongly limited, the Commission of European Communities is faced with the same problem. In view of the lack of resources to finance R & D activities on the one hand, and of the increasing importance of these activities, on the other hand, a great number of countries have become aware of the necessity of implementing procedures in order to improve the efficiency of their science and technology system. To do that, public authorities are incorporating evaluation into their research programmes. If the practice of evaluation is not a new issue, its generalization is certainly a recent phenomenon.

Among the problems the evaluation must deal with, there is that of the economic impacts of R & D programmes. The evaluation of these impacts raises the issue of their measurement, i.e. their quantification. So, the questions at stake are : What can quantitative methods, and particularly econometric techniques, bring to the evaluation of the economic impacts of R & D programmes ? What are their strengths and weaknesses ? In what context and to what end could they be used ? Through this research, we have tried to shed light on these questions.

Research on the state-of-the-art of economic quantitative methods for the assessment of the impact of R & D programmes can be conducted in two ways. The first one is to write a synthesis on quantitative methods and to think about their potential use in a field such as the evaluation of science and technology policy. The second one is to review how quantitative methods, particularly econometrics, are used to evaluate the economic impact of R & D and to show what their results are. It is this alternative approach which has been adopted here because, to a large extent, these methods speak by themselves and the reader can easily deduce their advantages and disadvantages as well as the limits for their use.

In their analytical synthesis on evaluation methods in use at the Commission of European Communities, Bobe and Viala (1990) point out that substantial progress in methodologies and instruments necessary for the evaluation of the socio-economic impacts of R & D programmes should be made during the nineties. Despite the efforts undertaken in the past forty years to highlight the mechanisms which underlie the relations between economic growth and technical change, the relative weakness of the accumulated knowledge in this field will lead anyone to consider such an agenda as an impossible challenge. Credibility and usefulness of economic quantitative methods in the field of technology assessment is often questioned. Yet, the use of econometric techniques in economic policy formation has become common place. Policy decisions in the field of macroeconomic policy are now largely checked against a macroeconometric model. While models are only an imperfect representation of economic reality, it is generally admitted that it is more rational to test a potential policy decision by experimenting through a model rather than to subject the real economy to the experience, which may turn out to be a crash. Besides, the pervasive handling of the economic process by public authorities and the questioning about its results have enhanced the need for a systematic evaluation of their interventions. So, econometric methods are extensively used as a policy evaluation tool for economic matters. To the extent that science and technology policy deals with economic matters, technical expertise based on econometric modelling may be considered to be a helpful guide in science and technology policy formation. For example, econometric techniques are the only way to give information on the global economic effects of a science and technology policy. They may also be used as a complement or an alternative to other methods when economic issues are under scrutiny.

The first chapter gives an overview of the main technology assessment methods presently used. Its object is to emphasize that all these methods have their advantages and their drawbacks and to position econometric methods in the tool box of evaluation techniques. Lots of methods are directly concerned with scientific and technological matters. The issue of the economic impacts of R & D policy often remains uncovered by evaluation exercises because of methodological drawbacks and limits of economic quantitative methods. As evaluation is a trial and error process, any method has its own deficiencies and each of them contributes something to the evaluation process.

The economic analysis of technical change is the focus of the second chapter. After defining main concepts and notions, we describe how technical change is taken into account in production functions. In economic textbooks, technical change is regarded as a black box in which no component except output is faced with economic rules. But even the way in which this output is appraised, i.e. time, is ridiculously rudimentary when compared with the high sophistication of economic theory and models.

Yet, over the past thirty years, experiments have been performed in order to substitute a better candidate as a proxy for technological change. Given the methodological difficulties to define a clear output variable of the science and technology process, researchers turned to an input variable to measure technological change, i.e. research and development investment. The latter has then been introduced in models aiming at explaining productivity growth. It is to a review of this literature that chapter three has been devoted.

While the R & D investment performed by a firm, an industry or a country will firstly benefit to its originator, the new knowledge so created may not be fully secured by the innovator but spills over in the economy through improved equipment and new products. In recent years, there have been substantial efforts to measure these spillover effects. As these effects are not uniformly distributed among industries, some methods have been developed to trace technology flows among industries. In chapter four, we summarize the main attempts to measure these spillovers at the aggregate level as well as when receiving industries are separately identified.

The issue of the quantitative measure of the economic impact of government financing is dealt with in chapter five. Only studies dealing with direct public intervention in the field of R & D are reviewed. More indirect subsidy instruments like tax deduction and loans for R & D investment are not covered in this survey. Besides studies which have introduced R & D investment into productivity growth models through sources of financing (private versus public), an alternative approach has been developed which aims at estimating what is the stimulus-response effect of public financing on private financing. Although the main amount of research has been devoted to these two approaches, alternative methods have also been implemented in order to analyze some specific effects.

Some strategic considerations are discussed in the last chapter. Contrary to the traditional economic policy, the design of an efficient science and technology policy is directly conceived to help firms to adapt to technological competition. In the past few years, several normative models of technological competitive behavior have been developed. After a rapid glance at these models regarding their possible empirical implementation, some empirical studies grappling with some strategic aspects are discussed. Finally, a multiple competitive reaction model is considered. This approach, although exploratory, might serve as an analytical framework to analyze the nature of technological competition when both enterprises and governments are regarded as strategic oligopolists.

Chapter 1. Technology Assessment : An Overview

In a world in which capital, work, and technology determine the national production limits, advanced economies resolutely attempt to organize the research process in order to gain competitive edge, especially on the NIC's. Technological knowledge proves to be the ultimate constraint of growth.

As research and development expenditures in the industrialized countries are substantial, as both the European Community and the member States are implementing research and development programmes, which mobilize considerable resources, the time is ripe for assessing their impact on the economy so as to justify the investments, direct later choices, and define the productive potential of a technology. This is why a quantitative analysis is useful.

Besides, the positive and negative effects of research on society and the environment have raised questions about how they can be anticipated. Besides, too budgetary restrictions due to the crisis have required the definition of primary objectives and projects. The staggeringly fast development of scientific and technical activities also accounts for the interest taken in technology assessment methods.

As we have pointed out already, research finds its justification in the advantages expected for the community. This same economic justification is required to buttress projects and programmes.

Actually, the question is what the economic performance would have been, if there had not been any technological change. And in this respect, besides the research and development expenditures made by enterprises, and the patenting costs, one should not forget the importance of the transfer of technological know-how between enterprises and industries through the market mechanisms or industrial liaisons.

An assessment is crucial because, through its diagnosis of the implemented policies and the technological choices it implies, it conditions the satisfaction of individual and collective needs. In fact, research and development investments affect all aspects of economic and social life. Productivity, commercial performance, employment, investments, income distribution, quality of goods, economic growth, inflation, environment, safety, industrial structure of the economy, ... to name just a few, are variables influenced by technical progress. Obviously, it is at the diffusion stage that those impacts are materialized. That is why, regarding that particular stage, numerous assessing methods have been developed.

1.1. How Can One Assess ?

The idea of assessing technology first came up in the United States to comply with the will to guide choices regarding R & D programmes. Value systems, technical and economic approaches were to be taken into account.

How can the profit actually derived from R & D investments be measured ? How can the degree of accuracy of the measurement be defined if one cannot define the object to be measured (some even speak of measurement of the intangible) ? How can one experiment in this field ? Which model should be chosen ? How abstract is it realistic to be ? Is a "closed" system relevant to represent an "open" system ? These are a few questions that arise when one analyzes the techniques and methods of technological assessment.

A major feature of R & D investments is that, compared with traditional investments, they are mainly made up-stream. Although R & D expenditures are preeminently creative investments, since they are aimed at generating products, technical procedures, and new services, or at improving those already existing on the market, yet, they also mean considerably lenghtening the production process. The average ripening time of an R & D investment, even though it varies from one sector to another, is about one to three years and even more in some industries (e.g. drugs and medecine) and some research fields (e.g. basic research)[1]. So, in some cases, the decision to invest must therefore often be taken some 10 years earlier, which does not always allow for letting oneself be suitably guided by market reactions. Hence, the forecasts are long-term ones. The low success rate of R & D projects, and the risk involved in them account for the fact that a part of the R & D investments are financed with public funds. However, even though the risk is high, this type of investment remains a strategic weapon in the competitive climate that reigns between enterprises and countries.

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[1] The R & D gestation lag would be about 2 years [Pakes and Schankerman (1984a) Ravenscraft and Scherer (1982)]. Mansfield (1991) reports an average time lag of 7 years between an academic research finding and its first commercial exploitation. It is also well-known that the lag between the discovery of a new potential product and its launching out to the market can reach fifteen years in the pharmaceutical industry.

As a concept, research assessment may mean quite different things : it may be a simple observation, a systematic analysis, or a global examination of the extent to which results meet earlier defined objectives, or even an assessment of the impacts of research on the economic and social world. According to Gibbons (1984), the term "assessment" should be reserved to the measurement of the extent to which activities have been modified following the adoption of a measure or a policy.

However this may be, several levels of assessment can be envisaged :

- assessment of individual projects;
- assessment of programmes;
- assessment of the national research and of its efficiency, which is, of course, the highest aggregation level. It is the macroeconomic level;
- assessment of research sectors such as university research or industrial research;
- assessment of individual researchers;
- assessment of research institutions.

The last two points are beyond the scope of this analysis and will not further be dealt with.

Finally, the evaluation process can also cover the different stages of research. Generally, the three following phases are distinguished :

- ex ante evaluation : before launching the project;
- on going evaluation : during the research process;
- ex post evaluation : when the project has been completed;

The ex ante evaluation (done during the planning period) is closely linked to the selection and implementation of the orientations of the research, and proves useful to define the research priorities, and, in some cases, alternatives (except at university level). It can also allow to set standards for resources and outputs, and determine how resources will be allocated. So, it proves necessary to assess and select innovation strategies.

The on going evaluation allows a permanent assessment of the situation which may lead to re-calibrate the project or programme under way.

The ex post evaluation consists in analyzing to what extent the obtained results meet the objectives initially set. It can prove useful to implement further programmes. It gives an account of the outputs and of the resources used for them to be compared with the standards estimated during the planning period. So, the performance is assessed, which enables to take corrective actions, and to appreciate the impacts of technical progress on the economic variables.

As Luukkonen-Gronow (1987) points out, the United States has mainly developed the ex-ante approach, while Great-Britain and the EEC have favoured the ex-post one[1].

R. Cordero (1990) suggests a systematic model to measure the performance of the firms' R & D investments. The firms are to define exactly what they want to measure (outputs or inputs) as well as at which organizational level measuring is to take place (global, technical (in the case of fundamental research) or commercial performance). Measuring outputs allows to assess how effective R & D investments are, i.e. to what extent they can meet objectives, while input evaluation is more particularly aimed at assessing how efficient they are, i.e. whether minimum quantities of inputs are used.

The evaluation procedures are quite different from each other depending on the field covered, the objective to be attained, and the criteria applied. As the social function of science and the structure of the national research system have to be taken into account, it seems a priori little feasible or irrelevant to draw lessons from experiments made in other countries in order to sift out "the best technique". According to Luukkonen-Gronow again, the choice of a method for a particular purpose or circumstance cannot be guided with assurance.

Indeed, when assessing the effects of research, one is faced with several difficulties :

1) The positive effects of research are uncertain and cannot always be measured (this mainly hampers ex ante evaluation, but also ex post evaluation (especially with regard to the consequences on society and on the environment).

2) The time-lags for effects to appear are often long.

3) For research to have positive effects on the economy, it has to result in innovations. Yet, implementing the knowledge derived from research for product innovation purposes is a complex process. So, if a scenario of this process is not integrated into the input-output models, and one simply attempts to define the correlation between research

[1] For a review of methods being used in several countries, cf. Aubert (1989) as well as the special issue of Research Policy in 1989 (vol. 18, n°4) devoted to this subject.

investment levels and other macro-economic results, the results obtained are unlikely to be convincing [Gibbons and Georghiou (1987)].

Hence, economic effects can not easily be spotted effectively, which is why resorting to evaluation by the user has to be considered.

For some years, the EEC has been trying to work out a strategy for the important research fields. An ex-post evaluation by peers, carried out over a 6- to 8- month period, is made about the technical and scientific results, the economic and social contribution of actions whose costs are shared, i.e. undertaken by national or private laboratories and substantially funded by the EEC. When the EEC's financial participation is smaller, a simple evaluation on the basis of a three-day interview is made.

Let us again draw the attention to how important it is for an evaluation that the scientific and socio-economic objectives of the programmes should be clearly defined beforehand. It is the evaluation of the socio-economic incidence that raises the biggest methodological problems. With a view to remedying them, and in order to define the incidence of R & D on the national variables, the EEC has ensured the collaboration of users and specialists of the cost - effectiveness analysis to the evaluation groups. Although this cannot but improve the quality of the assessment, one may wonder whether this move can meet the requirements of quantification.

The issues are :

- determining the amount of funds to be devoted to R & D investment.
- choosing between the different R & D programmes.
- forecasting technological evolution. In this respect, two types of methods are usually distinguished :
  * the exploratory method, which is ill-adapted because it consists in an extrapolation of the past trend, which implies some continuity, while technical progress is in essence discontinuous.
  * the normative methods which consist in setting a future objective to be attained at a given term, and in finding the "critical path" to attain it.
- the impact of research and development expenditures on the economy. The aim is in fact to evaluate to what extent the invested means meet the objectives defined, and thereby justify public funding.

Consequently, a systematic evaluation is a key element of an effective, common research policy. It is a retroaction circuit for the decisions regarding future management policies [Bobe and Viala, (1990)].

The methods developed hereunder are more particularly, or, sometimes, more adequately suitable for one of these issues. This review of the literature is the obvious thing to do in so far as a judicious combination of qualitative and quantitative methods would allow to achieve an optimum quantitative evaluation. So, for instance, exogeneous modifications of the parameters in a quantitative method could be introduced on the basis of results provided by qualitative analyses.

Further in this chapter we will give a synthetic overview of the different techniques for evaluating research activities, their advantages and drawbacks, as well as the fields in which they can be applied.

Let us first notice that qualitative and quantitative methods can be more or less accurately distinguished. The former are often aimed at selecting and sorting out the different projects but prove to be little useful to evaluate the economic impact of investments in research and development. The latter, fairly heterogeneous, are aimed at developing quantitative analyses and measurements of evaluation. Their degree of quantification varies. Most of these studies deal with the evaluation of R & D in terms of economic profits. They are mainly indicators. Subjective evaluation methods have indeed been developed to supplement the quantitative ones because, among other reasons, technical progress being discontinuous, the quantitative methods did not seem suitable for making reliable technological forecasts[1], which makes them less interesting for a long-term perspective. Yet, the "subjective" methods do not seem to be more reliable for long-term evaluation. But qualitative methods are above all used for more pragmatic objectives, particularly, operational and strategic management of research. Both methods, qualitative and quantitative, have their own advantages and drawbacks and are more complementary than substitutable.

Figure 1 classifies the different types of studies which can be made. Let us specify right away that socio-historical, technical, and theoretical economic studies are not covered in this work. Yet, as it is difficult to remove all theoretical substratum from any approach made in terms of applied economics, some incursions into the theoretical economic foundations will prove necessary for a critical analysis of some methods. Among the

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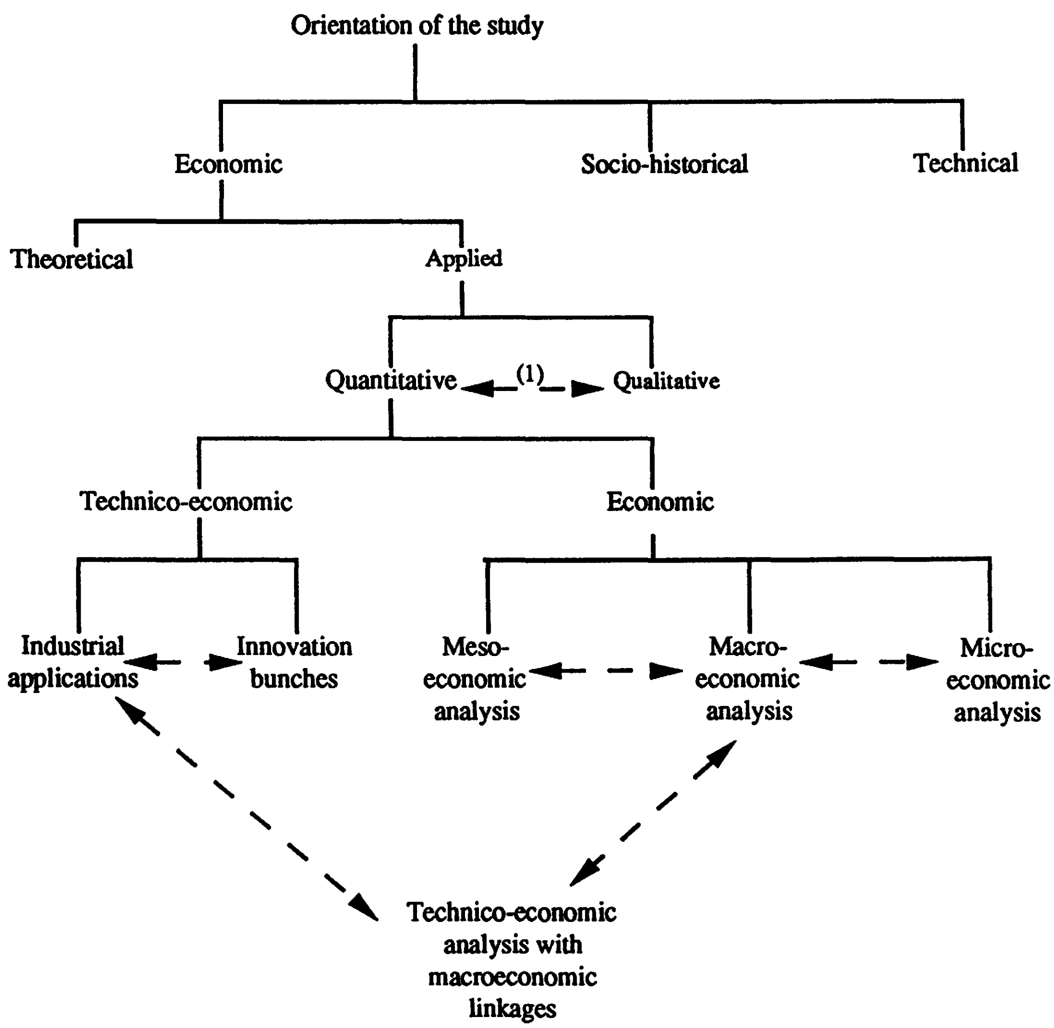
[1] In this respect, let us, however, note that technical progress is unlikely to show sudden ruptures. Besides, to what extent don't the observed discontinuities partly result from economic fluctuations ?

applied quantitative studies, a distinction can be made between the economic approach, mainly centred on the intrinsically economic relations and the technico-economic approach in which technological structures (e.g. identification of innovation clusters and development of industrial applications) are assigned a predominant part. The economic approach itself can be decomposed on the basis of the analytical levels considered :

- micro-economic analysis if one considers studying the phenomena of industrial organisation;
- meso-economic analysis if the formalisation of the inter-industrial links is of major importance for the envisaged research;
- macro-economic analysis which allows to build a complete scale model of the economic circuit.

Obviously, there are interconnections between the three approaches and technico-economic information can turn out to be quite useful to achieve a macro-economic loop.

Figure I - The Analysis of Technical Change



(1) Sometimes, studies are a mixture of both approaches.

1.2. Overview of Methods

The literature reports plentiful methods of research evaluation but only a very small part of them are really in use. This overview of the main methods does not deal with the technical aspects of methods but with their more prominent characteristics in order to emphasize their strengths and weaknesses and, hence, show that econometrics, rarely referred as a research evaluation tool - and when, it is treated with suspicion - is certainly no less credible than other methods. There is now an extensive literature reviewing and surveying research evaluation methods to which we refer the interested reader[1].

1.2.1. Assessment by Peers, Questionnaires, Interviews

a. Direct Assessment by Peers - This is an evaluation made by one or more specialists of the same discipline to appreciate in particular the scientific value of the research [Gibbons and Georghiou (1987)]. The drawbacks of this method are the following :

- the subjectivity of the experts and of their diagnoses. This can be put down to :
  * (intellectual or scientific) fashions which can be found both in the answers and in the questions and prove difficult to get rid of. The solution to this problem is to repeat the assessment operation periodically. (Besides, the fashion bias can be evaluated). However, there still is a risk that the experts may take the political and socio-political objectives of the moment as forecasts;
  * the experts being insufficiently trained to reason in the prospective mode;
  * a lack of rigour;
  * the fact that the maturation times required by some ideas are not sufficiently taken into account;
  * the desire to conform which impels into self-censorship;
  * the experts not being independent, which makes it necessary to have recourse to an anonymous questionnaire;
  * the fact that researchers are involved in the evaluation which entails the risk that their willingness to participate may be linked to the benefits they can derive from it. That is why some precautions have to be taken regarding the choice of experts, which is a decisive criterion for the method to be valid. So, for instance, too close

[1] Among others, see Saint-Paul and Tenière-Buchot (1974) and Vinck (1991) for a description of techniques and Luukkonen-Gronow (1987), Gibbons and Georghiou (1987) and Danila (1989) for a critical review of methods.

cooperative or polemical relations should be avoided, and experts should be chosen that are as open-minded as possible with regard to their schools of thought and their orientations.

- The partial character of the forecasts. Using cross-impact matrices somewhat allows to remedy this problem.

- When the evaluation criteria bear upon the socio-economic impacts, non-scientific members have to be included into the group of experts (for instance, clients or potential users of the research, industrialists, economists, public authorities). This working method, used by the EEC, is what is called assessment modified by peers.

- Assessing the social and economic effects of research activities is a challenge for expert appraisements because their assessments are based on science-oriented criteria, which are not appropriate to make an assessment of this kind.

- This method does not provide a sufficiently reliable basis to determine the global economic impact of R & D expenditures.

b. Direct Assessment Modified by Peers - This is a direct assessment but whose object is not only the scientific value of the research. So, other criteria, such as the economic and social influence are taken into account. This type of evaluation requires completing the group of experts for it to cover domains in which scientific competence is not sufficient. Apart from this improvement, the advantages and drawbacks of this approach are the same as for the preceding method.

c. Questionnaire Method and Interviews - This is a kind of assessment by peers but more systematic, based on standardized questionnaires. This method allows to work out quantitative indices provided the questions are phrased so that the answers can be marked.

This method has the drawbacks of its advantages, i.e. :

- a reduced quantity of information since the prephrased questions limit the number of possible answers, which can result in trivial information.
- The necessity of making up structured questionnaires in which the questions have to be independent, accurate and quantifiable. Those who devise them have to combine their technical expertise with a thorough knowledge of the subject, which requires using complementary methods.

d. Direct-Systematic-Assessment-by-Peers Method - It consists in sending a closed questionnaire to a number of experts. A median opinion with an error margin and quartiles is deduced from the answers. This result is returned to the specialists who are to confirm or invalidate their estimates. After a number of iterations, the convergence gets clearer, the objective being to reduce the interquartile interval while making the median clearer [Schméder, (1988)]. This method is often used to make technological forecasts and select projects. The Delphi method has so far been one of the most used methods. Among the methods based on consensus, we also find the Ringi method, used by the Japanese decision-makers, and the Rule of Thumb method, with which managers are to assess and estimate the risks and advantages of projects [Danila, (1989)].

The indirect-assessment-by-peers method is often used as well. It adds to the direct assessment by peers a quantitative dimension and rests on the analysis of indicators. Besides, it is a further systematization of the assessment-by-peers method.

The drawbacks of the method are the following :

- the method is not valid for comprehensive domains for it provides partial and incorrect results.
- The results are sensitive to radical changes.
- The Delphi method gives quite a satisfactory answer to the occurrence question, but quite an unsatisfactory one to those bearing upon relevance (desirability for the enterprise or for the users), impact, and feasibility. The Probe and Soon techniques are an attempt to improve on this method.
- All the drawbacks mentioned earlier with regard to direct assessment by peers hold in this case as well.

1.2.2. Scoring methods

a. Matrix Approaches - There can be two kinds :

a.1. Analysis Matrices - They are applied for selecting and decision making. This approach is closer to economic analysis. They help put into shape "research-research" and "research-industry" matrices similar to the input-output tables of interindustrial relations per branch or sector.

Several stages can be distinguished, each of them leading to a matrix :

- evaluation of the economic impact of the researches on the other researches (research-research matrix);
- evaluation of the economic impact of the researches on the industrial sectors (research-industry matrix);
- multiplication of these two matrices, the product of which will give the impact of research decisions on the rise of industries. Let us notice that by reversing this matrix, one can determine which researches should be chosen to maximise industrial development.

The main drawback of this method is that it is difficult, if not impossible, to collect the data required to make a matrix of the interdependences between researches.

The BIPE (Bureau d'Information et de Prévision Economique), specialized in technological "filières", has oriented its researches towards isolating the motor vectors in order to determine and quantify the consequences of technological innovations on the different industrial branches. It has thus developed channels comparable to relevance trees whose different levels are the following : different research centres --> innovation --> functional sub-set --> basic technologies --> interested production enterprises. This method can be supplemented with a preliminary qualitative analysis.

Among other methods, let us mention the Quest method, which is half-way between analysis and decision-making matrices as it combines both subjectivity and matrix calculation through the following stages :

- evaluating how much the technologies have contributed to achieving previously fixed objectives by means of ordinal scales. Multiplying these scales by the weighted values of the missions involved provides a value index of the technologies.
- evaluating, by means of a similar process, how much the various scientific researches made upstream (fundamental and applied) have contributed to the technologies. Questar (Quantitative Utility Evaluation Suggesting Targets for the Allocation of Resources) allows for instance to determine how much the R & D project has contributed to the commercial value of the product.

An extension of this method which incorporates the notion of budget constraint has been suggested, the Macro-R & D method. So, the research lump sum can be determined, and the obtained selection can be justified.

a.2. Decision-Making Matrices - This method enables to arrange projects in order of importance. It is closer to technological evaluation techniques. It is made up of multicriteria appraisal grids (for instance, the Profile method[1]). The stages of the method are :

- determining criteria and sub-criteria;
- marking the projects in function of those criteria;
- evaluating the correlation between the experts' answers with Spearman's formula and showing off the experts whose answers diverge from the "standard ones".

Its advantages are that it systematizes decision making, rationalizes and simplifies choosing. In this category let us also mention the Seer method (besides Profile) and the Trimatrix method (which combines Macro-Quest and Profile) which considers the socio-political, technological, and economic viewpoints).

Its drawbacks are that it is subjective, lacks flexibility, and uses a substantial number of statistical information.

b. Multicriteria Analysis - This method consists in ranking and selecting the projects according to several criteria weighted against each other. So, it can be used to select projects under financial constraints.

The different stages of the method are the following :

- listing the criteria;
- formalizing the criteria : so, at each stage, the qualitative goals and the quantified objectives are inquired about;
- the different criteria are weighted.

Some methods allow to perform tests about the sensitiveness to one criterion or another, or to iterate the procedure according to how far advanced the project is. This is, for instance, the case of the Marsan-Electre method whose drawbacks are, on the one hand, the necessity to have recourse to a specialized coordination and execution group, and, on the other hand, the subjectivity involved in choosing the criteria and weighting them. Its application field is mainly sorting out and selecting projects. When the projects are characterized by a high dependence degree, the Electre-Oreste method proves more appropriate.

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[1] The Profile method (Programmed Functional Indices for Laboratory Evaluation) is an example which attempts to structure the selection of R & D projects and to help manage them.

c. Relevance Trees - This is a combination of the decision theory and of the operational research techniques. The aim of the method is not so much selecting projects, but rather emphasizing the links between the different research projects, technology, and the economy in order to determine to what extent the project is relevant. The drawbacks of this method are that it is very empirical, that working out a good tree is not an easy matter, the fact that it is heavy, and that it is difficult to assign relative quantitative values to how important it is to carry out those R & D projects. The advantage of this method is basically that it provides lots of information to those who manage to implement it.[1]

1.2.3. Systemic Approaches

a. Systemic Analyses - They combine the advantages of the multicriteria analysis and of the relevance trees, and are the most advanced form of the methods providing aid to decision making. The resulting information is very rich.

Regarding this type of analysis, two complementary methods can be mentioned :

1. the factor analysis whose purpose is to identify which elements form a system, and, hence, select criteria to evaluate and select research programs;

2. the structural analysis whose aim is to define the schedule and the control of the research process.

System dynamics, which, among other things, studies the stability of systems, could, according to some, be regarded as belonging to this category. Yet, because of its specific characteristics, it has been classified separately.

b. Dynamic Modelling - According to Allen (1986), economics better agrees with a concept of evolution than with one of equilibrium. Given the complexity and the permanent evolution of the system in which we are living, innovation creation, acceptation, diffusion cannot, according to him, be envisaged in purely economic terms without taking elements into account such as history, culture, social and environmental structures. Economic decisions as a whole must therefore be made within a broader framework. Any action will have effects on different elements and feedback phenomenona will develop as well. That is how a complex chain of actions and reactions is formed which little fits in with a simple and intuitive assessment. Hence,

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[1] The methods Pattern (Planning Assistance Through Technical Evaluation of Relevance) and CPE (Centre de Prospective et d'Evaluation) are examples of implementation.

understanding technical change can only come from a better knowledge of the problem as a whole.

The system theory is based on the idea that big aggregates evolve towards a state of desequilibrium, phenomenon which alters the structures and induces qualitative changes. Yet, with a view to discussing the concepts of a system, a classification and an aggregation on that basis prove necessary in order to reduce its complexity. Allen also shows that evolution does not necessarily lead to an optimal behaviour. Enterprises are thought to be prompted to make new discoveries only because their present production planning is imperfect. Besides, competition between firms will lead to pro-active and retro-active moves on their part in reply to technical and organizational changes. Obviously, this constant evolution advantages individuals or firms that can easily adapt and understand new situations.

The advantage of this approach is that the whole process is taken into account. Although the method may at first seem very interesting because it considers all the aspects of a system, the practical applications, however, are much less obvious. These works are along the lines of the analysis of evolution processes [Prygogine and Stengers (1979)] and of the dynamics of systems [Forrester (1973)]. The evolutionist approach with regard to technical progress has been developed by Nelson and Winter (1982). Its object is to identify and formalize the links between the elements which make up a dynamic system in order to study its stability properties.

1.2.4. Financial Methods

This general name encompasses lots of methods worked out to define and quantify the social and economic consequences of projects and their financial return as well as their profitability and net social profit.

a. The Cost Benefit - Cost Effectiveness Analysis - It deals with the study of the advantages and drawbacks of a project. This method provides, besides the net present value, an estimate of the impact of the investment made on the annual profit of the companies which have made it. Any modification while the project is under way is taken into account in the form of sensitivity factors. The method usually consists in calculating the ratio between the expected profit and the cost. With regard to the economic index, the calculation of the profit includes the probability of obtaining one, and the cost sometimes includes the capital; the most commonly used financial indices are the NPV (Net Present

Value) and the ROI (Return on Investment). The relative performance is evaluated on the basis of the past industrial research and development expenditure and sales. This measurement, R. Cordero (1990) reminds us, is not that of a profit for it does not include the resources used by the commercial units. Besides, it does not link the sales to the present research and development expenses but to those of the past year. In this respect, it is rather surprising, though that, usually, only the most recent information should be used, while the maturation times are longer. Let us note as well that "average delays" are usually worked with; as investments in development usually involve more substantial amounts of money than those in fundamental research, the average delay in question turns out to be shorter. To determine the relative force of the "commercializable" outputs, one can simply use market shares. Other measurements which allow to compare the output to industrial means, to past outputs or to those of another firm are the number of new products developed in the past few years in the percentage of current sales, the number of significant innovations during that period, the innovation output weighted by its importance as well as the success rate of a new product.

Besides this, there are the methods of return on investment which are suitable for the selection of projects. A return index has to be determined, i.e. an interest rate so that the actualized value of the monetary incomings should be equal to the outgoings (in terms of mathematical expectation). One deduces thus the interest rate by equalizing the incoming and outgoing flows. If it is higher than the interest rate of the market, the project in question is carried out.

Many methods of maximising the present net value of projects (internal profitability rate, actualized self-financing) have been proposed in the literature (e.g. Disman, Hess, Dean-Segupta, Daudé methods). The advantage of these methods is that they take expenses and receipts into account as they occur. Yet, their drawbacks are :

- the substantial number of statistical data required;
- the fact that strategical conditions are ignored;
- the fact that technical constraints are not analyzed;
- the fact that competition is not analyzed;
- evaluation difficulties similar to those encountered with the ratio method.

From a theoretical point of view, according to Gibbons and Georghiou (1987), the method is valid. Other drawbacks usually mentioned are the cost and the difficulty of gathering the required information as well as of choosing a realistic actualization rate. This method does not allow either to clearly determine the external effects of research works (not taken into account in the prices). Indeed, some effects or factors cannot be measured and evaluated in financial terms. This difficulty mainly arises as far as outputs are concerned. One can of course consider giving them an arbitrary value, but, in this case, the method is not more relevant than any qualitative evaluation.

This problem affects almost all quantitative methods in so far as they require making hypotheses, since some data on the research activities are not available. As for the recovering time method, inspired by similar concerns as those previously set out, it consists in taking into account a compensation for the profits expected from research and development and its costs, as well as those of production, commercialization, and capital. Hence, an actualization rate, a success probability as well as the firm's level of experience in the field have to be determined.

b. The Ratio Method - It deals with the evaluation of the value of the investment compared to other items. The objective is not only to determine the financial lump sum to be devoted to R & D investment but also to measure the ex-post profitability of the programmes. The numerous ratios considered usually establish the link between profit (savings, incomes, profits, cash flow) and cost of R & D.

The drawbacks of this method are the following :

- the time-lag between the research and development expenditures and their economic results is difficult to quantify (the econometric method could help clarify this problem);
- it is not clear how many periods have to be taken into account;
- the results can be quite different depending on the periods considered;
- the result can be extremely hazardous.

The most obvious advantage is the simplicity of the instruments used.

The ratios have been generalized, using a technical or commercial criterion which evaluates how likely the project is to be successful. These are the score or desirability indexes. The most commonly used indices are the Olsen, Pacifico, Teal, and Texas Instruments ones. This method has its own limits as well, among which :

- subjectivity when determining how likely success is : it is in fact a simple reduction coefficient and not a probability;
- the fact that the estimating error is unknown;
- sujectivity in the choice of criteria (simplistic and mechanistic aggregation);
- the traditional financial aspect of the mehod (at the expense of the technical or commercial aspect or of the study of the economic impact as a whole).

Besides, the ratio method provides us with purely descriptive information. The economic impact it describes is only expressed in financial terms and is an evaluation criterion inside the firm or sector only. Neither the impact on the economic variables, nor the indirect effects, nor the spillover effects, nor the relations between firms are taken into account. The ratio for a firm may be very good in spite of an eviction effect on the other firms, which cancels the positive effect at sectorial level.

The method can prove useful, though, since it provides a valuable analysis tool at firm level, and could, provided a few modifications are made, be integrated with the range of management tools for public projects.

c. The Hazard Profiles - It is a process by which projects are selected on the basis of the investor's aversion to risk. They simultaneously take into account the hazards linked to carrying out a project and the expected profitability.

d. Programming Models - These models maximise, for the whole set of evaluated projects, the expected gross value in order to distribute the budget optimally between the different projects selected. Others deal with the selection of R & D projects and the allocation of manpower.

e. Portfolio Selection Models - Very developed in the financial world, they are based on the definition of the usefulness of a project and on the expected value of the same project as well as on estimates regarding occurrence probabilities.

1.2.5. Technological Forecasting Methods

a. Scenario Method - It is both a qualitative and quantitative analysis of heavy trends, which consists in building coherent and complete scenarios. Compared to the Delphi method, this method allows to reverse the "innovation-technology" causality chain and takes social changes into account. It also allows to show how the different research fields fit into one another. The drawbacks mentioned with regard to expert committees hold here as well.

b. Cross-Impact Matrices (or interdependence matrices) - After events and/or trends regarded as important have been identified, they are aimed at emphasizing the interactions, i.e. the reciprocal influences between them, and at classifying them

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according to their degree of influence. This method can be used in forecasting. It is again an improvement on the Delphi method to make up for the bias resulting from the potential links between the questions asked. So, it has the advantage of explicitly analyzing the relations which may exist between the events to be forecast.

This method integrates both the a priori probabilities and the Monte Carlo methods, and leads to real quantified scenarios. It then consists in transforming the a priori probabilities into a posteriori probabilities thanks to a simulation of the stochastic type. One can also measure how sensitive the result is to a modification of the a priori probabilities. Although it remedies some of the subjectivity, the method does not altogether ward it off.

c. Morphological Analysis - This method of technological forecasting combines technological assessment methods and creativity techniques. Its discontinuous character makes it different from the other methods. Its objective is no longer tracing the evolution of situations or systems in time or forecasting an event but rather imagining what the as yet still unknown event will be. With this procedure forecasting verges on inventing. It is an inductive method.

1.2.6. Quantitative Indicators

a. Science and Technology Indicators - They have been developed for the ex-post evaluation. Their aim is to evaluate R & D activities and technological change, and to measure the effectiveness of the national R & D input at macroeconomic level. They rest upon the theories about invention, innovation, technological change and international competitiveness, and have recourse to measurements of the R & D investments of innovations, of patents, of the balance of technological payments, of the technological intensity of exchanges, and of the productivity growth. They also use bibliometrical indicators. The indicators worked out are used to determine the direct technical, economic, social, and environmental consequences at an aggregate level.

Their drawbacks are the following :

- the fact that the indirect effects, which are often noticeably bigger than the direct ones, are not taken into account;
- the indicators are difficult to interpret;
- statistics may not be available or comparable;

- these indicators infer macroeconomic relations while they are based on data which describe technological change at microeconomic level.

b. Bibliometrics - It allows to construct quantitative indicators of the outputs of scientific, mainly fundamental, research. It derives useful information from the analysis of scientific periodicals. At the level of fundamental research this method can be justified in three ways :

- The results of scientific research are often presented in articles.
- How frequently an article is referred to is a more or less reliable indicator of its quality.
- One gets accurate data about the activities described in the articles.

It is an ex-post method which is less suitable for evaluating the experimental development. The main drawback of this method is that the indicator it provides is a partial one given the wide range of ways in which results can be diffused (such as oral, personal communications and memos) and the secret which, for strategic reasons, may surround some breakthroughs. Besides, there is a time-lag between the moment when results are obtained, the moment when they are published, and the moment when they are quoted, which reduces the effectiveness of the bibliometric method.

1.2.7. Econometric Method

It is the only global method that is available to answer the question regarding how much R & D contributes to growth and to globally measure the direct and indirect effects of R & D programmes on the macroeconomic aggregates. Indeed, if the financial methods seem easy to implement, they do not allow to take the indirect effects into account. Yet, although the econometric approach seems able to estimate the main impact parameters, there are many reasons for doubting the value of the results, among which :

- theoretical and methodological problems;
- measuring problems and the availability of statistics;
- is having recourse to the past relevant to analyze the present and make forecasts ? It can only be a useful tool if production and technical progress keep on evolving as in the past;
- the aggregation bias;
- some variables are omitted.

In a study about the evaluation of the economic effects of the Community's research programmes, Toulemonde (1990) stresses that the econometric quantitative method could be a valid instrument only if the statistical adjustments suppose a causal relationship but they do not prove it. He adds that reverse causal relationships can be imagined so that the (productivity) performances affect the level of research and development expenditures by increasing the resources available for all items, including research. This view seems somewhat severe, though, as it ignores phenomena which are well-known in econometrics, namely the delay effects, the retroaction phenomena and the analysis of simultaneous causality. He further rightly adds that the production functions systematically ignore non-measurable factors (which can have a substantial influence on productivity) such as the technology exchanges between firms or countries, sociological resistances to change, and the organization of the innovation process. With regard to taking technology exchanges between firms or countries into account, a study based on the input-output matrices could prove quite useful. As for sociological resistances to change and the organization of the innovation process, one can consider combining econometric methods with more subjective methods as well as making use of the firm organization and management theory.

Case studies can prove useful to study the links existing between research and its economic and social effects. The drawbacks of the method are that it concentrates on specific fields, which biases the measurement of global impact, how much such studies cost and how long they take. Supposing that making such a study has been opted for, methodology has to be paid special attention to. This approach emphasizes how difficult it is to economically justify fundamental and strategic research works, which leads to pass a critical judgement on economic and other quantitative models. In the following chapters we describe the advantages and drawbacks of these methods.

In a conference held at the EEC in 1982, Davignon insisted on clearly defining the objectives, clearly evaluating the way in which the objectives are achieved, no matter which instrument may be chosen to this end[1]. So, the issue is indeed evaluating the programme in function of the objective defined at the start. But here is the whole problem of ex ante defining a specific research objective given the degree of uncertainty linked to the programme itself.

Three levels of research evaluation can be distinguished, namely :

- the scientific quality of the results;

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[1] Statement reported by Bob and Viala (1990).

- the programme management rules;
- the socio-economic impact.

Although the first two points can be dealt with in a fairly adequate way thanks to the peer review system and to qualitative measurements, it is largely admitted just as the critical analysis by Bobe and Viala (1990) of ten years' technological evaluation of the Community's R & D programmes, that those methods are not appropriate to tackle the economic impact issue. It is from this point of view that an econometric quantitative study can prove useful. So, the research productivity indicators must be improved and the objectives of the European Community's research and development programmes must be quantitatively defined in a more accurate way.

The synthesis presented in table 1.1 clearly shows that both the qualitative and quantitative approaches are imperfect. Yet, some answer a particular question better than others. Some quantitative measurements are complex and costly, and none encompasses all outputs and inputs. Combining them remedies this shortcoming but that only increases the cost. Besides, some characteristics are "non-quantifiable" even though they are critically important (consequences on society, on the environment, product quality). That is why qualitative measurements are often used to palliate problems encountered when quantitative measuring instruments are used, but, as we have seen, these measurements are sometimes lacking in objectivity, and prove less appropriate to measure output or economic impact.

A study by Booz and Allen [Rockwell and Particelli, (1982)] shows that in a sample of 700 US manufacturing enterprises, 65% use formal measures to evaluate the performance of new products. Schainblatt (1982), on his part, emphasizes that out of 34 enterprises, 20 use qualitative measures, the others quantitative ones. From an empirical investigation of the French industry, Danila (1985) observes that only 20 % of 80 listed methods are really used by firms.

The most commonly studied aspects are : the technical output quality and the extent to which the objective has been attained. As no measurement is perfect, managers use several of them simultaneously. Besides, as they are not accurate, they use them as flexible planning or control tools in order to reduce uncertainty. As these measurements are costly, using them only makes sense if the benefits derived from them make up for the costs. For instance, when the quantities of resources used are less substantial and there is uncertainty as to the outputs, which is the case of fundamental research, qualitative methods are preferred. In this case, planning and control will be less emphasized.

Conversely, when plenty of resources are used and there is more certainty as to the outputs, the measurements used are more quantitative and complex and blanning and control will be laid more emphasis on as well. Quantitative methods, and more particularly econometric ones, used together with techniques such as the Delphi method, relevance trees, decision-making analysis, can provide a useful evaluation tool.

Introducing technical change into econometric models through incorporating R & D expenditures into production functions has so far given rise to much controversy. To Saint-Paul and Tenière-Buchot (1974), the production function approach results in a stalemate. This statement seems, however, somewhat forced and ungrounded, as recent works in this field have shown. Indeed, the econometric approach is the only one that allows an actual interaction between economic variables and the economic impacts of technological evolutions. Examining the evaluation reports of the European Community's various programmes shows that the main problem is how to evaluate the impacts on the economic variables, or, simply, the modifications in the economic performance that are due to research and development expenditures.

Table 1.1. Synthesis of Evaluation Methods - Relevance and Drawbacks

Method	Relevance	Drawbacks	Field of application
a. Assessment by peers, questionnaires and interviews.	- Screens of projects and research orientations.	- Subjectivity of experts. - Partial forecasts. - Lack of independence of experts. - Does not allow to measure the global economic impact.	- Selection and technical evaluation. - Technological forecasting.
b. Matrix approaches : - Analysis matrices.	- Rich information.	- Difficult, even impossible to collect the required information.	- Evaluation of the industrial impact of R & D expenditure.
- Decision-making matrices	- Decision-making process. - Rationalise and simplify choices.	- Subjectivity. - Lack of flexibility. - The number of statistics required is substantial.	- Multicriteria interpretation.
- Multicriteria analysis	- Profiles projects and R & D planning.	- Requires constituting a specialized group. - Subjective choice of criteria and weightings.	- Project selection.
- Relevance trees	- Provide lots of information.	- Strongly empirical. - Arborescence. - Subjectivity in the allocation of quantitative values.	- Emphasizing the links between the different research projects, technology and the economy.
c. Systemic approaches : - Systemic analysis.	- Can be used to implement an evaluation. - R & D strategies. - Appropriate to select projects.	- Not really suitable for evaluating as such.	- Selection and control.
- Dynamic modelling.	- Takes the evolutionary character of the economy into account. - Includes social, historical and ecological structures. - Takes feedback phenomena into account.	- Very difficult to implement.	- Analysis of the evolution of a system and of its adaptability.

d. Financial methods :			
- Cost-benefit / cost-effectiveness analyses.	- Measure marketable outputs and commercial resources.	- Difficult to collect the information. - Some factors cannot be measured or financially assessed. - The actualisation rate is difficult to choose. - Do not allow to take R & D externalities into account.	- *Financial* evaluation of a project.
- Ratios methods.	- Simple instruments.	- Difficult to estimate time-lag between research and development. - Number of periods to take into account.	- Measurement of the ex-post return. *Financial* evaluation. - Project selection.
- Risk profiles.		- Highly variable results.	- Determining the financial lump sum to invest in R & D.
- Programming models.		- Subjectivity in the choice of the success probability and of criteria.	
- Portfolio models.		- Purely financial aspects.	
e. Technological forecasting methods			
- Scenario method.	- Allows to reverse the causality chain. - Takes social transformations into account.	- See a.	- Selection and technical evaluation. - Technological forecasting.
- Cross-impact matrices.	- Overcome the problem of interdependences between questions.	- Subjectivity always present. - See a.	- Selection and technical evaluation. - Technological forecasting.
- Morphological analysis.	- Discontinuous character.		- Forecasting.
f. Quantitative indicators			
- Science and technology indicators.	- Easy measurement. - Measure technical resources.	- Purely descriptive. - Does not take the indirect effects into account. - Micro-macro cross-cutting.	- Measuring how efficient the R & D input is at the macro level.
- Bibliometrics	- Builds up fundamental research indicators.	- Not well suited for evaluating development. - Partial indicators.	- Analysis of the evolution of a system and of its adaptability.
g. Econometrics.	- The only general quantitative method available for evaluating the economic impact of R & D expenditure.	- Theoretical and methodological background. - Availability of statistical material. - Aggregation bias. - Not well-suited for forecasting.	- Evaluation of the impact of R & D expenditure upon the economy.

Chapter 2. The Economic Analysis of Technological Change

Before moving on to the analysis of the interdependences between technical progress and macroeconomic dimensions, i.e. in particular to the evaluation of the impact of R & D expenditure on the macroeconomic variables (i.e. production, growth, employment), it is useful to define basic concepts such as technological change, technical progress and to see to what extent R & D expenses integrate into a general pattern. Such an exercise will clarify the subject of the study and will delineate some of the limits of the present formalization of the links between macroeconomics and R & D.

For a long time, economic theory has had some difficulty in dealing with technological change. The traditional growth theory emphasized the role of capital accumulation rather than technological change as the major driving force of economic growth. In this view, technological change, to a large extent, failed to fit into any formalized theoretical framework because it essentially followed from the technical system and, therefore, depended on technical compatibilities. Like manna from heavens, technical change exogenously boosted economic growth at a constant growth rate. With the exception of a few theoretical major contributions, it was essentially on the side of applied economics that evidence accumulated showing that technological change was really a major source of growth and was driven by economic forces. In the last ten years, a radical theoretical breakthrough has been made with the development of a theory of growth which views innovation activities as an endogenous process. What is now known as the new growth theory legitimates, if need be, on the theoretical ground, forty years of forerunner works on the applied economics of technological change. While important and certainly a fruitful ferment for future econometric works, this approach is not tackled here because its empirical fallouts remain limited.

Another major contribution to the economic theory of technological change is the development of the evolutionary theory. More radical than but complementary to the new growth theory, the evolutionary approach views technological change as the main source of economic growth and as, at the same time, an interactive, cumulative, institutional and disequilibrating process. It departs from the neoclassical theory in the sense that producers adopt a satisficing behavior rather than an optimizing one due to bounded rationality. Yet, this behavioral approach has not so far prompted on a new generation of econometric studies.

2.1. Technological Change and R & D

To begin with, a difference has to be made between change of techniques and change of technology. The distinction between these two notions usually proves to be ambiguous and inaccurate, which is why authors often indifferently use either one or the other.

The notion of technological change encompasses that of change of techniques. The technological change concept is thus more comprehensive, more analytical as well. Somehow it consists in penetrating the whole logic of the technical processes. It also implies the necessity of taking into account all the socio-economic structures which accompany the change of techniques.

According to Mansfield (1968), technology is the whole set of (technical or managerial) knowledge which enables to launch new products or processes. Technique differs from technology in so far as the former is a production method at a given time which is defined by the equipments and management methods used while the latter encompasses the whole set of knowledge used in the production. The term "technique" can be reserved for productive equipments and the work organisation they involve. Technology is a more comprehensive concept which incorporates other functions such as management and control which are grafted on to the technique. To Stoneman (1983), technical progress is a process through which economies evolve in time as a function of the produced goods and of the means to produce them.

Technological change is usually considered to count three stages :

Invention - It is the starting point of a new product, process or system which can lead to a patent. So, Freeman (1982) defines it as "an idea, a sketch or model for a new improved device, product process or system. Such inventions may often (not always) be patented but they do not necessarily lead to technical innovation". It is somehow a potential innovation or a batch of potential innovations. Only when it practically opens on an innovation does the invention become economically meaningful. So, as Stoneman (1983) suggests, invention can be regarded either as a given ex-post resource, or as a resource expected for the innovation process.

To Kennedy and Thirwall(1972), inventing is actually imagining new ways of attaining the same objective. Hence, the inventing activity encompasses not only the creation (thanks to the use of existent and "new" knowledge) of previously non-existent products, processes and systems but also an original exploitation of elements that have always existed (such as penicillin, for instance). Further, one may wonder whether invention is autonomous or whether it is induced by the economic environment. In this respect, it seems right to believe that it is a major factor in the economic activity and that it is, to some extent, subject to the supply and demand forces. So, an invention market is thought to exist. Yet, the researches carried out in this field are mainly directed towards theoretical microeconomic developments and, so far, have not easily lent themselves to a macroeconomic globalisation.

Innovation - It is the commercial stage of invention. Schumpeter distinguishes five main types of innovation :

1. product innovation : this is research and development expenditure aimed at improving on or creating new products;
2. process innovation : this is research and development expenditure directed towards perfecting the methods or obtaining new processes;
3. new markets and marketing methods;
4. legislation changes;
5. innovations with regard to organisation.

Referring again to Freeman (1982), "an innovation, in the economic sense, is accomplished only with the first commercial transaction involving the new product, process, system or device although the word is used also to describe the whole process".

Diffusion - It is the process through which innovation spreads out to the market. The notion of appropriation of the scientific discovery follows from here. Unless one is in a monopolistic situation, appropriation is never perfect, even if there is a patent or a licence. The interest of the innovator, who wants to protect his right to exploit the innovation, clashes with the general interest which requires a more intensive and competitive exploitation of the innovations for these to be able to pass on to the whole economic structure as effectively as possible. So, it is through the diffusion process that innovations have an impact on the economy as a whole.

Innovation diffusion is not instantaneous over time and uniform across space. The timing and the magnitude of the diffusion process depend on the features of the new technologies, the behavior of economic agents, the characteristics of the environment and the economic incentives. The diffusion process is a learning process which takes place among users and producers and involves a reallocation of resources in favour of new products and processes. After its introduction upon the market, the innovation can receive incremental improvements which affect the pace of adoption. Its diffusion is also often at the source of other successive innovations and leads to imitation. To a large extent, diffusion is at the core of the process through which technical change boosts up the economy as a whole.

Frascati's manual [OCDE (1976)] defines experimental research and development as a creative work undertaken systematically in order to increase the knowledge stock and the use of it so as to achieve new applications. Research and development expenditure is usually classified into three main categories :

Fundamental research which consists in experimental or theoretical works mainly undertaken in order to acquire further knowledge of the foundations of observable phenomena and facts, without considering any particular application or utilisation. The expected result is mainly discovery.

Applied research which, like fundamental research, also consists in experimental works aimed at acquiring further knowledge but it departs from it in so far as it is directed towards an objective or towards particular goals. So, it includes research into applications. The expected result is often invention.

Fundamental and applied researches only have economic implications if they have a cost or if, in the short or long term, they allow a commercial exploitation.

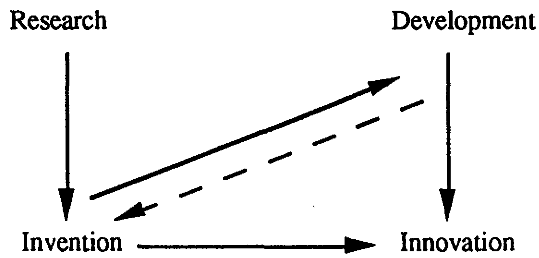
Development which refers to systematic works based on existent knowledge obtained through research and/or through practical experience, with a view to launching the manufacture of new materials, products or devices, establishing new processes, systems or services, or improving those that already exist. The expected result is information and innovation through investment and experience.

It should, however, be noticed that the separation between the different stages of technological change and of the R & D process is not as clear-cut as it may look at first sight. Besides, in spite of the OECD's prescriptions, concepts are used so heterogeneously in international statistics that comparisons are rather hazardous.

Another distinction can be made between the research and development expenditure funded privately or publicly, and between those made by enterprises or by other organisations (e.g. universities and research institutes). This is a distinction we are particularly interested in since the community R & D expenditure can be assimilated to public funding.

After analyzing the different stages of technological change and the different components of the research and development concept, it seems relevant to show how these two concepts can overlap. Investments in research and development can be assimilated to activities and the different stages of technological change to results or products of those investments.

In this respect, as emphasized by Kennedy and Thirwall (1972), research and development are an input to invention; invention and development are inputs to innovation; invention is an input to development. Hence, we have the following diagram with a retroaction effect between invention and development.



As we have pointed out already, the innovation will only occur after it has been decided to commercialise the invention. The innovating firm then makes the investments required to produce the new product, which goes together with a learning process materialised in the steady improvement of the performances, the result of a greater command of the innovation.

Simultaneously, other potential users of the innovation get to know it and the diffusion process engages. As the innovation is spreading around on the market, its economic impacts are gradually being felt.

2.2. The Measurement of Technical Progress

The difficulty economists have in calculating to what extent technical progress contributes to production growth has led them to construct what is called growth accounting, i.e. to evaluate the contribution of technical progress by means of the balance. The method has gone through considerable developments brought about by the identification of the effects of the intermediary inputs as education, R & D and infrastructure.[1]

The contribution of technical progress to growth would thus be the part of productivity growth rate that is not explained by the other factors, in other words, the residual factor, whose measure is nothing but the measure of our ignorance. In fact, first works gave a residual of more than 80 percent, a challenging measure of our misunderstanding of the real sources of growth. As Abramovitz (1956) pointed out "the indicated importance of this element may be taken as some measure of our ignorance about the causes of economic growth in the United States and some sort of indication of where we need to concentrate our attention".

To allow an accurate and significant evaluation, this method implies from the outset two major hypotheses :

1. all the other factors have to be exhaustively taken into account in the relation;
2. the contribution of those factors has to be calculated without any mistake.

Admittedly, meeting these two conditions is difficult.

Because formalising technical progress is difficult, the assumption has been made that its growth rate was constant so that it has been represented by time. This approach is not satisfactory in so far as technical progress is not a godsend [Kennedy and Thirwall (1972)]. It results from actions directed towards creating new processes or products, and for which substantial financial resources have been engaged. The growth rate of technical progress is only constant in the process of time in so far as the technological innovations are constant too.

Hence, to measure technical progress in a production function, it would better be represented as being the technological innovations actually achieved in the economy. Yet, as chronological series on innovations are hard to come by (indeed, how can innovations be accounted since they do not necessarily have the same value ?), one will somehow work one's way up to the innovation so as to obtain indicators capable of representing it.

If one goes about it that way, one has to go back to the invention process since it leads to innovation. In quantitative models one usually envisages two different ways of grasping this process :

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[1] See the works of Maddison (1987), Denison (1984) and Kendrick (1976).

- through its inputs - i.e. the investments in research and development or the personnel allocated to R & D;
- through its output - i.e. the number of patents taken out.

First of all, let us note that while the latter are outputs for invention, they are inputs for innovation.

In view of the criticism voiced about these measurement instruments, it might be more useful to regard them as complementary and non-substitutable sources of information. Yet, in this case, causality and multicollinearity problems will arise.

The measurement of technical progress in terms of output is subject to much criticism. Indeed :

- the quality of the patents can vary a great deal;
- a patent is not taken out for all inventions;
- the legislations regarding patents can vary a lot from one country to another and can be modified regularly;
- patents do not always have a commercial value;
- enterprises have different tendencies to take out patents, which evolve in the course of time, and differentiated protection strategies for their innovations.

However this may be, as emphasized by the OECD [OCDE (1986)], the data about them can help assess the position of the different economies as technology producers. Besides, the fact that there are international patent systems and patents taken out by foreign companies in the national systems already provide indicators as to the place of the different economies within the process of international diffusion of the techniques.

In practice, even if a stream aimed at promoting studies based on patent statistics is developing[1], input measures such as R & D expenditure or the personnel allocated to R & D (as production factor of invention) are more frequently used. This measure is incomplete and imperfect as well, though. Indeed, if what is considered is the invention activity, the research and development expenditures exceed those made for invention since they cover part of the innovating activity. On the contrary, if what is considered is the innovation activity (and, hence, technical progress), the research and development expenditures are readily found to cover only part of innovation and technical progress (presumably not

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[1] Cf., for example, the state-of-the-art written by Griliches (1990).

even half of it [Griliches (1979)]). Indeed, isolated inventors and accidental progress have to be taken into account. In this respect, let us note that R & D is increasingly a structured organisational process, which implies that gradually this issue can be investigated more and more accurately. Besides, it is obvious that there is an important theoretical shift in moving from technical progress to growth induced by research and development expenditures since the concepts of improvement of the educational level and of organisational progress (i.e. infrastructure) are made light of. The technology transfer should also be taken into account. Its features can be direct investments from abroad, the purchase of foreign licences and patents or the importation of fixed high technology capital. Technical progress is therefore not only a function of the nationwide R & D, but also of the worldwide R & D, of accidental technical progress, of training and of infrastructure.

Boyer and Magrange (1989) have listed the various hypotheses made in the literature about the factors which can determine the innovation potential. The major factors innovation potential originates from are successively :

- ***pressure on the profit rate*** between the innovation dynamism (measured by the number of patents) and the evolution of profitability [Mensch (1979)]

$$INNO_t = l\,(\pi_{t-i} \ldots) \qquad \frac{\partial\, l}{\partial\, \pi_{t-i}} < 0$$

where i is the average time lag
INNO is the innovation

This hypothesis, which was verified in several empirical studies, contrasts with the Shumpeterian theses which argue that high transaction costs and market power incite firms to finance innovative efforts internally depending on how profitable their activities are.

- ***growth of the markets corresponding to innovations*** [Schmookler (1966), Mansfield (1972)]

$$INNO_t = n\,(Q_t, Q_{t-1} \ldots) \qquad \frac{\partial\, n}{\partial\, Q_t} > 0$$

where Q is the output

This demand-pull hypothesis originally emphasized by Schmookler is challenged by the technology-push hypothesis. According to this alternative view, a reverse causality is equally plausible. But these hypotheses might not be mutually exclusive, demand and innovation might actually be mutually dependent.

- ***public and private research and development expenditures*** (among others, Terleckyj (1980a), Griliches (1986), Scott (1984) and Mansfield (1984)).

As pointed out earlier, innovations are seldom the fruits of chance; they are more often engendered by a deliberate research process implying investments in know-how and equipments in the field of R & D.

$$INNO_t = h\ (R\&Dg_{t-i}, R\&Dp_{t-i}, ...) \qquad 0 < \frac{\partial h}{\partial RDg_{t-i}} < \frac{\partial h}{\partial RDp_{t-i}}$$

where R&Dg are the public R & D expenditures
R&Dp are the private R & D expenditures.

Government increasingly plays a central role in the innovation system by directly investing or indirectly stimulating R & D. The effectiveness of government intervention in the R & D process has been questioned and under scruting for a long time. However this may be, privately-financed R & D and publicly-financed R & D are thought to exert a differentiated impact on the innovation system.

- ***investment and learning.*** Innovation can be endogenised by comparison with the volume of the production of equipment goods [Kaldor (1957)]. Alternatively, the effects of training manpower are normally correlated with the total production volume [Arrow (1962)] :

$$INNO_t = m\ (SE_t\ , SQ_t\ , \ldots) \qquad \frac{\partial\ m}{\partial\ SE_t}\ , \frac{\partial\ m}{\partial\ SQ_t} > 0$$

$$\text{where } SE_t = \int_0^t EQUIP\ (\tau)\ d\ \tau$$

$$SQ_t = \int_0^t Q\ (\tau)\ d\ \tau$$

In the Kaldorian thesis, technological progress is assumed to be infused into the economic system through the creation of new equipment. In this case, technological change might be endogenized through the volume of investment goods produced. On the other hand, Arrow (1962) suggests that invention and innovation might be spurred by learning by doing. As this form of skills is acquired by producing, this factor may be measured by the cumulated past production.

- *infrastructure and Training* [Freeman, Clark and Soete (1982)]

The development and diffusion of the innovations to the whole productive system can only be envisaged through a minimum infrastructure conducive to the development of the innovating action and through the educational system (particularly the technical and scientific training).

$$INNO_t = f(I_t, E_t, \ldots) \qquad \frac{\partial f}{\partial I}, \frac{\partial f}{\partial E} > 0$$

As further factors we can add :

- components of R & D by character of use [Evenson (1984)] :

$$INNO_t = p((B_{t-i}, A_{t-i}, D_{t-i} \ldots) \qquad \frac{\partial p}{\partial D_{t-i}} > \frac{\partial p}{\partial A_{t-i}} > \frac{\partial p}{\partial B_{t-i}} > 0$$

where B = basic research investment
A = applied research investment
D = development investment

All the categories of R & D investment are not identically conducive to innovation. They do not have the same properties while they ultimately improve the knowledge state. Basic research serves as an essential input in applied research and applied research in development. Although all three categories of research evolve in close interaction, their innovation productivity is not the same, and the allocation of research resources will therefore affect the performance of the innovation system.

- science-push and technological substitutability [Wyatt (1986) and Mowery and Rosenberg (1979)] :

$$INNO_{jt} = z((TQ_t, SB_t) \qquad \frac{\partial z}{\partial TQ} < 0 \quad \frac{\partial z}{\partial SB} > 0$$

where j = activity sector
TQ = total output excluding sector j
SB = technological base

Mowery and Rosenberg (1979) disagree that market demand alone could influence the innovative process, innovative activity also depends on the underlying science and technology base on which the potential innovator can draw to develop new products and processes.

This idea was implemented by Wyatt (1986) in a re-examination of Schmookler's analysis. He also suggests that, if the technological base is sufficiently wide and flexible, it can be used to create improvements in whatever area is desired and, therefore, there should be high substitutability on the supply side between invention outputs in different fields. While Wyatt only considers the interaction between sectoral patents, the technological base might include technology transfers as a potential source of innovation.

Further, endogenising the volume of research and development expenditures could be considered as well supposing the results are fairly homogeneous in terms of productivity, demand, employment depending on the countries. In this case, the factors to be taken into account would be :

- the profit rate :
  * favourable effect : funding or access to credit means,
  * unfavourable effect : firms innovate only when they are under pressure, under threat of going bankrupt in a negative conjuncture;
- the estimate of the expected return;
- the past and anticipated growth rythms;
- the taxation methods governing this type of expenditures.

Several remarks can be made about this possibility of endogenising the research and development expenditures : first of all, estimating such a complete equation is not an easy task; besides, research and development expenditures are concentrated in a small number of sectors, which can make the merely macroeconomic determinants insufficient. Yet, in a complete model, this type of formalisation would have the advantage of partially endogenising innovation and of examining what differentiates this formalisation from a purely exogenous treatment of technical change.

Figure 2.1. summarizes the sequence of interactions between the components of technological change. This diagram is an extension of a scheme originally suggested by Rosegger (1980) and emphasizes the main factors which influence the innovation process. Essentially, technological change is a dynamic process in which stocks of knowledge accumulated by R & D activities are inputs in the generation of new techniques and products which displace old techniques and products through adoption by utility-maximizing economic agents. As technological change is a dynamic process of

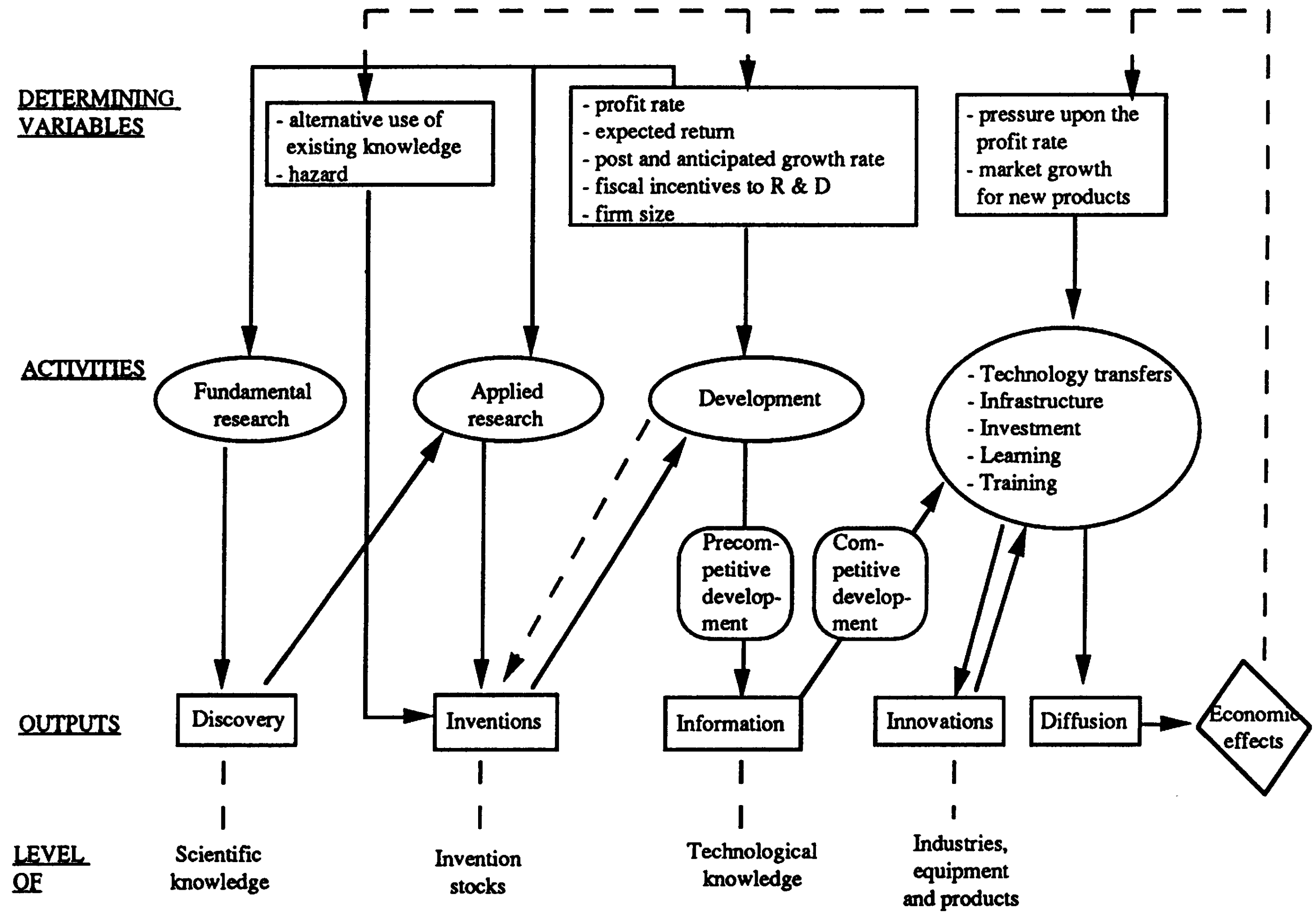

Figure 2.1. - The Process of Technological Change

creative destruction, there are feedback effects due to the competitive strengths which permanently stimulate the search for new techniques and products.

2.3. The Applied Economics of Technical Change

2.3.1. The Exogenous Disembodied Technical Change

The traditional neoclassical specification of technical change considers an aggregate production function (Q) whose production factors are labor (L) and capital (K) and where time (t) is a proxy variable representing the state of technology :

$$Q = F(K, L, t)$$

From the analytical viewpoint, a less general but more functional form which considers how technical change can affect the efficiency of production factors is largely used in the literature. Indeed, it allows to categorize technical change with respect to the way it alters the relative demands for inputs. Its formulation is :

$$Q = F(A_t K, B_t L)$$

where A_t and B_t are measures of efficiency gains resulting from technical improvements in the utilization of both factors, capital and labor. On the basis of this equation, a well-known set of results has been obtained about the different types of technical progress. A worthwhile question is to know if inventions are labour-saving, capital-saving or neutral. However, there is not a single definition of what is a neutral technical progress. The three most popular types of neutrality are respectively :

- Hicks-neutrality when the marginal rate of substitution is left unchanged at a constant capital-labor ratio ($A_t = B_t$);
- Harrod-neutrality when the capital-output ratio is left unchanged at a constant rate of return to capital ($A_t = 1$);
- Solow-neutrality when the labour-output ratio is left unchanged at a constant wage rate ($B_t = 1$);

Any deviations from these particular kinds of neutrality are classified as technical biases as shown in table 2.1. The analysis of the "biasedness" of technical change gives indications about the directions of the bias, these directions being specific for each factor.

Table 2.1. Classification of Technical Change

Hicks-neutral technical progress = product-augmenting technical progress $Q = A_t F(K, L) \Rightarrow K/L$ constant $\frac{\partial (F_K K) / (F_L L)}{\partial t}\Big|_{K/L} \gtreqless 0 \Rightarrow$ Hicks $\begin{cases} \text{labor-saving} \\ \text{neutral} \\ \text{capital-saving} \end{cases}$
Harrod-neutral technical progress = labor-augmenting technical progress $Q = F(K, B_t, L) \Rightarrow K/Q$ constant $\frac{\partial (F_K K) / (F_L L)}{\partial t}\Big|_{K/Q} \gtreqless 0 \Rightarrow$ Harrod $\begin{cases} \text{labor-saving} \\ \text{neutral} \\ \text{capital-saving} \end{cases}$
Solow-neutral technical progress = capital-augmenting technical progress $Q = F(A_t K, L) \Rightarrow L/Q$ constant $\frac{\partial (F_K K) / (F_L L)}{\partial t}\Big|_{L/Q} \gtreqless 0 \Rightarrow$ Solow $\begin{cases} \text{labor-saving} \\ \text{neutral} \\ \text{capital-saving} \end{cases}$

While these definitions give a useful theoretical reference point, the empirical measurement of technical change and of its characteristics is like an inextricable puzzle due to the difficulty of identifying parameters.

The most used empirical production functions are defined by the following implicit relationship :

$$Q_t = F(q_{1t}, \ldots, q_{nt}, t; \gamma, g_0, g_1, \ldots, g_n, \delta_1, \ldots, \delta_n, \rho, \mu)$$

where Q_t = output at time t

q_{it} = input i at time t

t = time variable as a proxy for technical change

γ = scale parameter denoting the efficiency of the initially underlying technology

g_0 = impact of technical change upon the efficiency of the initially underlying technology

g_i = impact of technical change upon the efficiency of input i

d_i = intensity degree in the use of factor i ($0 < \delta_i < 1$). Without loss of generality, it can be assumed that $\sum_i \delta_i = 1$

r = substitutability degree between factors ($-1 \leq \rho < \infty$)

m = homogeneity degree of the production function denoting the degree of returns to scale.

Table 2.2. summarizes the main fixed form production functions on the basis of the hypothesis that technical progress grows exponentially over time :

$$x_{it} = e^{(g_0 + g_i)\,t}\, q_{it}$$

where g_0 = growth rate of Hicks-neutral technical change

g_i = growth rate of factor i-augmenting technical change.

In such functions, the polarization of technical progress will depend not only on the value of g_i but also on the value of the elasticity of substitution. According to Solow (1957), the bias in technical change can be defined as :

$$\frac{\partial\,(F_{q_i}\, q_i \,/\, F_{q_j}\, q_j)}{\partial\, t}\bigg|_{q_i/q_j} \doteq (1 - \sigma)\,(g_j - g_i)$$

so that :

if $\sigma = 1$ and/or $g_j = g_i$, technical change is neutral

if $\sigma < 1$ and $g_j > g_i$
$\sigma > 1$ and $g_j < g_i$, } technical change is factor j saving

if $\sigma < 1$ and $g_j < g_i$
$\sigma > 1$ and $g_j > g_i$, } technical change is factor i saving

This Hicksian definition of bias implies that, in the n-factor case, the analysis of the bias for each factor will be measured by (n - 1) variables. Recently, an alternative definition of bias has been suggested. This new definition expressed in terms of factor shares has the advantage that it is a single measure of bias for each factor :

$$B_i = \frac{\partial\, S_i}{\partial\, t} \cdot \frac{1}{S_i}$$

where S_i stands for the i^{th} factor cost share and $\partial\, S_i \,/\, \partial\, t$ refers to the share change while keeping factor combination constant.

Table 2.2. Fixed-Form Production Functions with Immaterial Technical Progress

Types of production functions	Production functions	Elasticity of substitution (q_i, q_j)	Indirect estimation functions $(\mu = 1)$
Perfect substituability	$\gamma (\sum_i \delta_i x_i)^{\mu}$	∞	-
Leontief	$\gamma \delta_i x_i^{\mu} \ \forall i$	0	-
Cobb-Douglas	$\gamma \prod_i x_i^{\delta_i \mu}$	1	-
CES	$\gamma [\sum_i \delta_i x_i^{-\rho}]^{-\mu/\rho}$	$\frac{1}{1+\rho}$	$\frac{q_{it}}{q_{jt}} = A_C (\frac{P_j}{P_i})^{\sigma} e^{(1-\sigma)(g_j - g_i) t}$
NH-CES	$\gamma [\sum_i \delta_i Q^{\varepsilon_i} x_i^{-\rho}]^{-\mu/\rho}$	$\frac{1}{1+\rho}$	$\frac{q_{it}}{q_{jt}} = A_N (\frac{P_j}{P_i})^{\sigma} Q^{\sigma(\varepsilon_i - \varepsilon_j)} e^{(1-\sigma)(\alpha_j - \alpha_i) t}$
Mukerji	$\gamma [\sum_i \delta_i x_i^{-\rho_i}]^{-\mu/\rho}$	$\sum_k G_k / \sum_k \frac{G_k}{1+\rho_k} (1+\rho_i)(1+\rho_j)$ where $G_k = \delta_k \rho_k x_k^{-\rho_k}$	-
Sato	$\gamma \{\sum_c \alpha_c [\sum_{j \varepsilon c} \beta_{cj} x_j^{-\rho_c}]^{-\rho/\rho_c}\}^{-\mu/\rho}$	$\frac{1}{1+\rho_c} \ \forall \ i, j \ \varepsilon \ c$	-
VES	$\gamma [\sum_i \delta_i ((\frac{x_j}{x_i})^m x_i)^{-\rho}]^{-\mu/\rho}$	$\frac{1}{1 + \rho - \frac{m\rho}{S_i}}$	$\frac{Q}{q_i} = A_V (\frac{P_i}{P})^{\sigma} (\frac{q_j}{q_i})^{m(1-\sigma)}$
IES	$\gamma [\sum_i \delta_i (e^{\beta I_{ij}} x_i)^{-\rho}]^{-\mu/\rho}$	$\frac{1}{1+\rho} + \rho \beta I_{ij}$	$\frac{q_i}{q_j} = A_C (\frac{P_j}{P_i})^{\sigma} e^{(1-\sigma)[\beta I_{ij} + (\alpha_j - \alpha_i) t]}$

Note : - A_C, A_N, A_V are constant terms; $I_{ij} = P_j / P_i$.
- g_j is the growth rate of factor-j augmenting technical progress.
- S_j is the part of factor j in the ouput.
- Indirect estimation functions are based upon the hypothesis of perfect competition from which the optimal firm-management principle is deduced. This implies that (at the optimum) the marginal rate of substitution between factors is equal to the ratio of prices.

Abramovitz (1956), Solow (1957) and Fabricant (1954) were the first to develop growth accounting exercices. The formal theoretical framework for this type of analysis was provided by Solow along the line of the neoclassical model. Assuming a neutral technical change, constant returns to scale and a perfect competitive environment, the following expression :

$$Q = A_t F(K, L)$$

can be rewritten by taking proportional changes with respect to time :

$$\frac{\dot{Q}}{Q} = \frac{\dot{A}}{A} + \varepsilon_k \frac{\dot{K}}{K} + \varepsilon_l \frac{\dot{L}}{L}$$

where ε_k and ε_l are respectively the output elasticities of capital and labor. Since under neoclassical assumptions these elasticities are equal to the share of factors in output, we can write :

$$\frac{\dot{Q}}{Q} = \frac{\dot{A}}{A} + s_k \frac{\dot{K}}{K} + s_l \frac{\dot{L}}{L}$$

where s_k and s_l are respectively the share of capital in output and the share of labor in output.

This equation provides the theoretical justification for growth accounting and hence a method of measuring technical progress. The index value of technical change is nothing else that the indice of total-factor-productivity improvements :

$$\frac{\dot{A}}{A} = \frac{\dot{Q}}{Q} - s_k \frac{\dot{K}}{K} - s_l \frac{\dot{L}}{L}$$

An alternative way of measuring total factor productivity is the approach developed by Kendrick (1961) who defines the level of total factor productivity as :

$$A = Q / (s_k K + s_l L)$$

Solow's method,is referred to as the geometric method [1] of measuring technical progress and Kendrick's method as the arithmetic method. These two methods are easily generalized to take into account a higher number of production factors and were

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[1] It is also largely called the Divisia index method. In this case, the total productivity index is defined as :

$$A = Q / (K^{s_k} L^{s_l})$$

extensively used in empirical studies to measure the weight of technical progress in productivity growth at the aggregate level. All the pioneer works in this field confirmed the existence of a residual to growth [1].

In a survey article, Maddison (1987) draws up a list of the numerous variables that, besides technical change, can explain the residual :

- changes in economic structure,
- effects of the process of convergence or "catching-up" of countries,
- volume of foreign trade,
- economies of scale at the national level,
- energy price,
- natural resource discovery,
- use of capacity effects,
- regulation,
- labor hoarding and dishoarding.

Despite efforts to reduce the size of the residual by taking into account additional factors, an important residual remains. Furthermore, this approach has been criticized by Nelson (1981) on grounds that the sources of growth are strongly interdependent so that a growth of one input augments the marginal contribution of others and that if the factors are highly complementary, it makes little sense to try to divide up the credit for growth. In other respects, this decomposition method is based on an accounting caveat which attributes to factor accumulation the causes of economic growth without really identifying the propelling factors of growth. Finally, few of such studies attempted to directly measure the contribution of R & D to economic growth. Using a 30 percent rate of return to R & D, Griliches (1973) and the US Department of Labor (1989) found a contribution of R & D that amounts to 0.2 percent of the productivity growth for various years over the period 1960-1987 in the United States. Applying a higher rate of return to R & D, Kendrick (1981) gives an estimation ranging from 0.60 to 0.85 for various subperiods covering the years 1948-1978. In the last years, there has been a large debate about the role of R & D expenditure in the productivity slowdown observed in the 1970's. How can the apparent paradox of declining productivity growth in a period of accelerated technological change be explained ? From the various attempts made at explaining this

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[1] Among the oldest ones, we refer the reader to Solow (1957), Kendrick (1964) and Schmookler (1966) who estimated an average total factor productivity growth rate of about 1% from 1870 to 1950 in the United States. A similar value was found by Fraumeni and Jorgenson (1980) for the period 1948-1976. As reported by Kennedy and Thirwall (1972), other country studies about Finland, Norway and United Kingdom also emphasized the importance of the residual factor. On the other hand, Gaathon (1961) estimated that the physical capital was the prominent factor in the case of Israel.

slowdown, some of which have been summarized by Wolff (1984), it follows that advances in knowledge cannot be charged with causing the decline in growth.

In the seventies, substantial advances in production theory were made with the development of new functional forms providing a local approximation to any production frontier. These functions are quite flexible in approximating arbitrary production technologies and, as a consequence, are less restrictive in the sense that they include the specific functional forms. These so-called transcendental production functions exploit the duality between prices and quantities in the theory of production. The two most commonly used flexible functional forms are the generalized Leontief and the translog whose main characteristics are given in table 2.3.

All these functions have been largely used to measure the contribution of technological change to economic growth. However, in such models the treatment of technical change is very rudimentary :

- new technologies appear at a constant exponential rate;
- technical change is like a public good;
- technical change identically affects all inputs no matter how old they are;
- technical change is an exogenous phenomenon acting in a totally independent manner upon the economic system.

This hypothesis of exogenous immaterial technical progress has been discussed in Kennedy and Thirwall (1972)'s and Nadiri (1970)'s surveys. What is called technical progress is in fact the combination of several elements, among which :

- the substitution between capital and labour,
- the returns to scale,
- the learning effects,
- the improvements in education and on-the-job training,
- the changes in resources,
- the improvements in organization,
- the efficiency of production.

As the Cobb-Douglas production function has been largely used in analyses, it is useful to have a look at its limits and drawbacks compared with other alternative specifications. The constraints associated with this function are :

Table 2.3. Flexible-Form Production Functions with Immaterial Technical Progress

Generalized Leontief function

1. Linear homogeneous dual functions

$$C = h(Q)\,[\sum_i \alpha_i p_i t + \sum_i \sum_j \beta_{ij} (p_i p_j)^{\frac{1}{2}} + \sum_i \gamma_i p_i t^2]$$

$$Q = \sum_i \alpha_i q_i t + \sum_i \sum_j \beta_{ij} (q_i q_j)^{\frac{1}{2}} + \sum_i \gamma_i q_i t^2$$

2. Constraints $\beta_{ji} = \beta_{ij} \quad \forall\, i, j$

3. Factor-demand functions

$$q_i = \alpha_i t + \sum_j \beta_{ij} (\frac{p_j}{p_i})^{\frac{1}{2}} + \gamma_i t^2 \quad \forall\, i$$

$$p_i = \alpha_i t + \sum_j \beta_{ij} (\frac{q_j}{q_i})^{\frac{1}{2}} + \gamma_i t^2$$

4. Partial elasticity of substitution $\sigma_{ij} = \beta_{ij} \frac{C\,Q}{2\, q_i\, q_j} (p_i p_j)^{\frac{1}{2}}$

Translog function

1. Linear homogeneous dual functions

$$\log C = \log [h(Q) + \alpha_0 + \sum_i \alpha_i \log p_i + \frac{1}{2} \sum_i \sum_j \beta_{ij} \log p_i \log p_j + \gamma t + \sum_i \delta_{it}\, t \log p_i + \frac{1}{2} \delta_{tt} t^2]$$

$$\log Q = \alpha_0 + \sum_i \alpha_i \log q_i + \frac{1}{2} \sum_i \sum_j \beta_{ij} \log q_i \log q_j + g\, t + \sum_i \delta_{it}\, t \log q_i + \frac{1}{2} \delta_{tt} t^2$$

2. Constraints $\sum_i \alpha_i = 1,\ \sum_i \beta_{ij} = 0,\ \sum_j \beta_{ij} = 0,\ \sum_i \delta_{it} = 0 \quad \forall\, i, j$

3. Factor-demand functions

$$S_i = \alpha_i + \sum_j \beta_{ij} \log \rho_j + \delta_{it}\, t = \alpha_i + \sum_j \beta_{ij} \log q_j + \delta_{it}\, t \quad \forall\, i$$

$$V_T = \gamma + \sum_i \delta_{it} \log \rho_i + \delta_{tt}\, t = \gamma + \sum_i \delta_{it} \log q_j + \delta_{tt}\, t$$

4. Partial elasticity of substitution $\sigma_{ij} = [\beta_{ij} + S_i (S_j - \delta_{ij})] / S_i S_j \quad \forall\, i, j$

where δ_{ij} Kronecker delta operator

- neutral technical progress,
- elasticity of substitution equal to unity,
- constant returns to scale,
- disembodied technical progress.

Neutral technical progress - According to Salter (1966), it should be a reasonable hypothesis. Yet, David and van de Klundert (1965) gave clues that technical progress might not be neutral. More striking is the impossibility theorem due to Diamond, McFadden and Rodriguez (1978) demonstrating that it is not possible to identify the nature of technical change without a priori information about the production function. As pointed out by Kennedy and Thirwall (1972), "while very considerable econometric ingenuity has been used in order to distinguish bias in technical progress from factor substitution, it remains doubtful whether the basic identification problem has been entirely overcome. Even if it is possible to identify parameters for the "degree of bias" and for the "elasticity of substitution" it is not clear that these parameters will necessarily correspond to those which from an analytical point of view one would ideally want to obtain".

Constant elasticity of substitution - An elasticity of substitution different from unity can induce a bias in the estimate of technical change if capital and labor grow at different rates. If $\Delta K > \Delta L$ and $\sigma < 1$, there will be an over-estimate of the contribution of capital to growth and an under-estimate of that of technical progress. The smaller the elasticity of substitution, the more difficult it is to achieve increased output simply by increasing one factor because diminishing returns set in strongly [Kennedy and Thirwall (1972)]. There were several attempts to remove the restrictive features of both Cobb-Douglas and CES production functions. This led to the development of the variable elasticity of substitution production function (VES) [Diwan (1970), Tsang and Yeung (1976)], of the multifactor generalized function [Mukerji (1963)], of the nested-CES function [Sato (1967)] and of the "induced"-CES function [Yeung and Roe (1978)]. In order to isolate the effect of technical change from the scale effect, Sato (1977) has suggested a new type of functions, the non-homothetic CES production functions. But all these production functions only bring punctual improvements which impose stringent constraints on production patterns (among which, separability, homotheticity and substitutability). The flexible functional-form production functions which are able to approximate theoretically consistent production functions satisfactorily were a radical theoretical breakthrough. In essence, they allow interaction terms in the independent variables and represent second-order approximation to any arbitrary function. The best known parametric forms are the generalized Leontief functional form originated by Diewert (1971) and the transcendental logarithmic functional form introduced by Christensen, Jorgenson and Lau (1973). They overcome the limitations of the fixed functional forms by using the duality relation between cost minimisation behavior and profit maximisation behavior to characterize the production function by means of demand and supply functions based on prices without imposing arbitrary constraints on production patterns. In other words, it allows to test the validity of some restrictions such as separability, homotheticity, substitutability and biasness of technical change [1]. Yet, White (1980) rightly recalls that such functions have their own limitations. They are only local approximation functions of any production function and, as such, can induce erroneous interpretations due to the inherent restrictions in these functions [2].

Constant return to scale - If there are economies of scale and if the underlying production function is homothetic, the effect of neutral technical change and the effects of economies of scale cannot be detected empirically [3]. If the linear homotheticity constraint is imposed when there are real economies of scale, the growth rate of technical change may be overestimated. Furthermore, a part of the economies of scale can be a result of technical change, and from this standpoint, it is very difficult to disentangle economies of scale due to technical progress from economies of scale resulting from the growth of inputs. Finally, if the returns to scale are not constant, there is no reasons for thinking that the production function is not of the Cobb-Doublas type [Griliches and Ringstad (1971)].

Disembodied technical progress - The disembodiment hypothesis considers that technological change affects all production factors in use identically, whatever their ages. On the other hand, if technical change implies incremental improvements which make new inputs more efficient than the old ones, it will be characterized by the implementation of a more efficient production process for each generation of inputs.

Although the Cobb-Douglas function has its own limits, it is empirically very useful indeed. The choice of other specifications is largely motivated by the objectives pursued. As pointed out by Griliches (1979), the choice of a functional form is not very important unless we are interested in the specific interaction of variables. Furthermore, empirical studies seem to show that the complexity of the formulation rarely improves the

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1 For a survey, see Jorgenson (1986).

2 According to Wales (1977), they are not necessarily representative of a cost minimisation-profit maximisation behavior applying to the full sample. Furthermore, Anderson (1979) challenges the usefulness of these parametric forms for forecasting purposes.

3 See the well-known Solow-Stigler controversy [Solow (1961), Stigler (1961)].

estimates significantly and that the form of the production function is of secondary significance [Nadiri (1970)].

Yet, it must be kept in mind that such a function is only a first-order approximation to any arbitrary function which imposes strong restrictions on the substitution possibilities and consequently, is not adapted for the analysis of interaction phenomena. It is now well-accepted that the criteria that must guide the selection of functional form are [Lau (1986)] :

- the theoretical consistency : the functional form should heed the restrictions imposed by theory;

- the domain of applicability : the extent to which the functional form may be expected to perform satisfactorily should be well-known and satisfy the theoretical requirements;

- the flexibility : the functional form should be able to satisfy the requirements of the analysis;

- the computational facility : the choice of the functional form will be largely conditioned by the following properties : linearity in parameters, explicit representability, uniformity and parsimony;

- the factual conformity : the functional form should be consistent with known empirical facts.

As, in practice, it is not possible to satisfy all these criteria simultaneously, some trade-offs have to be made. According to Lau, the only area in which compromises may be made is the domain of applicability.

2.3.2. The Exogenous Embodied Technical Change

Models with embodied technical change rest upon a distinction between the different generations of investment intervening in the measure of capital stock. This way of looking at technical progress gives a more realistic view of the role of capital in the growth process. The idea underlying such an approach can be summarized as follows : if technological knowledge can only be embodied in new capital goods, the more recent extensions in capital stock must be more subtantially weighted than the preceding ones with, as a consequence, higher sensitivity of growth to the changes in capital stock.

According to Cette and Szpiro (1990), if investment induces productivity gains, that supposes the existence of a technical progress embodied in equipment. Yet, investment will implement production technologies which perform better than the older ones because they embody new technological innovations. As a result, costs will go down and competitiveness of production processes will improve.

So, considering that technical change is embodied implies identifying each vintage of equipment, ∂, each new vintage corresponding to the starting-off of more efficient new machines, operating independently of older vintages. This vintage approach with its concept of embodiment can be formalized by the following production function for any new vintage :

$$Q_{\partial t} = F(K_{\partial t}, L_{\partial t}, \partial)$$

where $Q_{\partial t}$ = output on vintage ∂ at time t
$K_{\partial t}$ = capital stock of vintage ∂ at time t
$L_{\partial t}$ = labour allocated to vintage ∂ at time t.

The global production is then obtained by :

$$Q_t = \int_{-\infty}^{t} Q_{\partial t} \, d\partial$$

The different definitions of neutrality can also be applied to this approach but now they will be established with respect to the different vintages :

- Hicks-neutrality : $Q_{\partial t} = A_{\partial t} F(K_{\partial t}; L_{\partial t})$
- Harrod-neutrality : $Q_{\partial t} = F(K_{\partial t}; B_{\partial t} \; L_{\partial t})$
- Solow-neutrality : $Q_{\partial t} = F(A_{\partial t}; K_{\partial t} \; L_{\partial t})$

A summary of the main theoretical formulations of vintage models is given in table 2.4. These basic models have been largely improved from a methodological point of view as well as to meet the needs. The distinction between the three models rests on the substitutability characteristics of capital vintages and labor before and after the installation of new equipment. Their philosophy is as follows :

Table 2.4. Vintage Models

Models	Putty-putty	Putty-clay	Clay-clay
Ex ante production function $Q_{v,t}$	$\gamma e^{\lambda t} [e^{\xi v + \alpha(v-t)} I_{v,t}]^{\delta} L_{v,t}^{(1-\delta)}$		$\min (\beta_{v,t} K_{v,t}, \delta_{v,t} L_{v,t})$
	Marginal productivity rule	Intertemporal optimization rule	Factors productivity
Derivation rules of the model and hypothesis	$\frac{\partial Q_{v,t}}{\partial L_{v,t}} = \frac{(1-\delta)}{L_{v,t}} Q_{v,t}$	$\frac{\partial Q_{v,t} / \partial L_{v,t}}{\partial Q_{v,t} / \partial I_{v,t}} = \frac{(1-\delta) I_{v,v}}{\delta L_{v,v}} = \frac{w_v (1 - e^{-r\theta_v})}{r p_v}$	$\beta_{v,t} = \beta e^{\xi_1 v + \lambda_1 t}$ $\delta_{v,t} = \delta e^{\xi_2 v + \lambda_2 t}$
Real capital stock J_t	$_{-\infty}\int^t e^{\xi v + \alpha (v-t)} I_v \, dv$	$\int_{S_t} e^{\xi v + \alpha (v-t)} I_v \, dv$	$\int_{S_t} e^{\xi_1 v + \lambda_1 t + \alpha(v-t)} I_v \, dv$
Total employment L_t	$(1-\delta) \frac{p_t}{w_t} Q_t$	$\int_{S_t} \frac{(1-\delta) r p_v I_v}{\delta w_v (1-e^{-r\theta_v})} dv$	$\int_{S_t} \frac{\beta}{\delta} e^{(\xi_1-\xi_2)v+(\lambda_1+\lambda_2))t+\alpha(v-t)} I_v \, dv$
Total production Q_t	$\gamma e^{\lambda t} L_t^{(1-\delta)} J_t^{\delta}$	$\int_{S_t} \gamma e^{\gamma t+\delta(\xi v+\alpha(v-t))}$ $[\frac{(1-\delta) p_v}{\delta w_v (1-e^{-r\theta_v})}]^{1+\delta} I_v \, d_v$	$\int_{S_t} \beta e^{\xi_1 v + \lambda_1 t + \alpha(v-t)} I_v \, dv$
Scrapping rule	Technical obsolescence	Economic obsolescence	$w_t L_{v,t} = p_t Q_{v,t} \Rightarrow$
		$w_t L_v = P_t e^{(\lambda-\delta\alpha)(t-v)} Q_v$	$w_t L_{v,t} = p_t \delta e^{\xi_2 v + \lambda_2 t} L_{v,t}$
Identification of the oldest equipment V_t		$[\log (\frac{w_t}{p_t}) - \log (\frac{L_v}{Q_v})] / (\lambda - \delta\alpha)$	$(\log (\frac{w_t}{p_t}) - \lambda_2 t - \log \delta) / \xi_2$
Equipments		$S_t = (v \mid v = v_t^* > 0)$	

(5)

Definition of symbols

- The putty-putty and putty-clay models are based upon an assumption of a Cobb-Douglas technology, of constant growth rate of technical progress, constant depreciation and constant returns to scale.
- w_t = nominal wage at time t.
- p_t = output price.
- ξ = embodied technical progress.
- α = depreciation rate.
- λ = growth rate of immaterial technical progress.
- J_t = real capital stock.
- S_t = equipment set used at time t.
- $\theta_{v,t}$ = expected life time of the investment.
- ρ_v = investment cost.
- $\beta_{v,t}$, $\gamma_{v,t}$ = respectively capital and labor productivities for an equipment of vintage v at time t.
- v_t = the oldest equipment yet operational.

- Putty-putty vintage model : substitution possibilities between capital and labor exist both ex ante and ex post. Although the equipment of a vintage is fixed after the installation, the entrepreneur can always allocate labor to this equipment according to the rule of equalization of the real labor cost rate to its marginal product. The least realistic characteristic of this model is certainly the hypothesis of ex post substitutability between factors. Furthermore, in this model, capital vintages are only scrapped because of technical obsolescence.

- Putty-clay vintage model : substitution possibilities only exist before the installation of the new vintage, when the equipment has been installed, labor requirements for this vintage are definitively fixed for the whole lifetime of the vintage. The choice of the appropriate capital-labor ratio is made on the basis of the maximization of the expected profits yielded by the equipment during its planned lifetime. A capital vintage will remain in operation as long as its expected quasi-rent is positive.

- Clay-clay vintage model : substitution possibilities are excluded both before and after the installation of the new capital vintage. The equipment of each generation is characterized by a fixed capital-labor ratio that the entrepreneur cannot alter. Given the labor productivity for each capital vintage, capital vintages whose real labor cost rates are not compensated by their productivity will be scrapped. Consequently, the scrapping of old equipment is ruled by both technical and economic obsolescences.

Among the numerous specifications of vintage models reported in the literature, two very simple models have been suggested by Nelson (1964) and Solow (1959). The first one is nothing else but a putty-putty Cobb-Douglas production function with a Solow-neutral exogenous embodied technical change :

$$Q_t = P_t^{'} L_t^{\alpha} J_t^{1-\alpha}$$

where J_t is the number of machines weighted by their quality (the new machines having a more important weight)

$P_t^{'}$ is the disembodied technical change which does not take into account the quality improvements of capital.

If technical development allows an increase in the quality of new machines of 100 λ_K% per year, one can write :

$$J_t = \sum_{0}^{t} K\partial_t \, (1 + \lambda_K)^{\partial}$$

where $K\partial_t$ is the gross amount of capital of vintage ∂ which is still in use at time t.

This equation shows that the growth of the effective capital stock is a function of the growth of the actual capital stock, $\overset{o}{K}_t$, the average rate of its improvement, λ_K and the effect of changes in its average age, which is itself a function of changes in the rate of investment. Consequently, the approximated form to be estimated can be written :

$$\overset{o}{Q}_t = \overset{o}{P}_t + \alpha \, \overset{o}{L}_t + (1 - \alpha) \, \overset{o}{K} + (1 - \alpha) \, \lambda_K - (1 - \alpha) \, \lambda_K \, \Delta \, \bar{a}$$

where $\bar{a}$ is the average age of capital

$\Delta \bar{a}$ is the change in the average age of capital and is assumed to be a rough measure of the change in the gap between the average level of technology and the best practice technology

λ_K is the net growth per year of the average quality of capital.

In fact vintage models are almost exclusively physical capital vintage models which ignore the improvements of labor in the use of the production potential. Why should technical progress be exclusively embodied in physical capital and not in labor ? Therefore, if the heterogeneity of capital stock in taken into account by the embodiment hypothesis, the assumption of labor homogeneity certainly plays an important role in the underestimation of the relationship between technical progress and labor growth. Labor is not more malleable than physical capital. Not only does each physical capital vintage generate a demand for some specific employment but increasingly, the output itself is directly influenced by the level of labor qualification. Consequently, technological progress will not happen if it is not materialized within physical capital and human capital. So far, the vintage model approach has focussed the attention on the importance of qualitative changes in the stock of physical capital in explaining how technological change operates but it has largely neglected the real role of human capital vintages on productivity growth.

An extended version of the Nelson-Solow model integrating quality improvements in labour has been realized by Kennedy and Thirwall (1972) who suggest to rewrite their equation as :

$$Q_t = P''_t (ZL_t)^\alpha J_t^{1-\alpha}$$

where Z represents the quality improvements in labour.

By analogy with the equation only including physical capital improvements, the function adjusted for the change in both the quality of capital and that of labour may be approximated by :

$$\overset{o}{Q}_t = \overset{o}{P}'' + \alpha \overset{o}{L} + (1 - \alpha) \overset{o}{K} + \alpha \lambda_L - (1 - \alpha) \lambda_K - \alpha \lambda_L \Delta \bar{e}$$

where λ_L is the average rate per year of quality improvement in labour

$\Delta \bar{e}$ is the change in the average age of labour.

It is interesting to observe that improvements in, both, physical and human capital increase the output while an increase in the average age of these two categories of factor has a negative impact on the output. However, there is an interaction between the rate of improvements in factors and the average age of factors : the higher the rate of quality improvements in factors, the faster the rate of obsolescence of factors will be and, consequently, the lower the average age of factors will be. Otherwise, improvements in labour quality will increase the efficiency of physical capital and the implementation of new physical capital vintages will not be neutral with regard to the structure of qualification required. Besides, a large part of improvements in labour quality is a result of education which is intrinsically linked to technological progress. By stressing only the role of generations of physical capital stock in the implementation of technical progress, the present vintage models adopt a reductionist view of technological change.

Some authors are, skeptical about the ability of vintage models to capture embodiment effects. So, Fellner (1970) argues that "all progress is necessarily disembodied in the sense that new ideas must always be put into effect with reliance on the initially given resources. This is an essential constraint under which all economies operate. Improved production with the initially given resources then leads to more and better capital goods ... and it yields more and better consumer goods. But all this represents *forward*, not *backward* embodiment". Besides, he asks the following fundamental question : " Why should the possibilities with a period's capital goods - a given vintage - become exhausted during a specific period for which a specific level of technological knowledge is defined ?". Denison (1984) also sets out that "the gain in the average quality of the capital stock that vintage models imagine to be derived from additional new investment is not realized because the change in average age automatically is largely offset by a reduction in the average amount of quality improvement incorporated in new capital".

2.3.3. The Induced Technical Change

Models of induced technical change suggest that factor prices, goods prices and market expansion are sources of technical change. This inducement hypothesis implies that technical change is endogenous to the economic system and is a result of the interplay of economic forces. Hence, the rate and direction of technical change would be determined essentially by economic variables. According to Binswanger (1978) the term induced innovation can be used "for all theories that are concerned with explaining rate and biais of technical change as endogenous to the economic system".

Yet, at the basis of the inducement hypothesis, there is not necessarily a direct functional relationship but the idea that changes in factor prices induce biases which save the more expensive factor. Nevertheless, in some models, the biases of technical change are endognized and depend on relative factors. This theory is very controversial. According to Salter (1966), it must be rejected because "the enterpreneur is interested in reducing costs in total, not particular costs such as labor costs or capital costs ... There is no reason to assume that attention should be concentrated on labor-saving techniques, unless, because of some inherent characteristic of technology, labor-saving knowledge is easier to acquire than capital-saving knowledge". Nordhaus (1973) also shows himself skeptical about this theory because it lacks a microeconomic background and he considers that it must be at best considered to be a special case of how technical change takes place.

From the standpoint of the theoretical background of this model, Ahmad (1966) has developed a model of price-induced technical change. He uses the concept of innovation possibility curve which is nothing else than the envelope of all isoquants of the potential innovations which the producer may develop. Hence, each potential innovation is characterized by an isoquant whose elasticity of substitution is relatively small and requires the use of a given quantity of labor and capital. He works by analogy with the production theory to show that if the shift of the innovation possibility curve is neutral over time, factor price movements will induce biased technical change.

The most direct test of this theory was run by Yeung and Roe (1978) in an analysis of the development of Japanese agriculture from 1880 to 1940. They formulate a factor-augmenting CES production function[1] in which the inputs are land and labor. As they rightly point out about the classical CES production function, " because the source of innovation is not specified, we cannot know whether a given technical change is induced or autonomous". They, therefore, postulate that "the innovation is induced by relative input price changes that reflect changes in relative input scarcities". In their production functions, the factor-augmenting terms are a function of time and of ther relative factor prices. Their estimates suggest that, during that period, technical change was biased in the direction of saving labor and using land despite the fact that the price of labor declined compared to the price of land. These results do not prove consistent with the Hicks-Ahmad model of induced innovation.

Contrary to this direct approach, the measure of the bias of technical change is often obtained as a residual from the estimation of a production function. Alternatively, time is introduced into the production function to represent the level of technology. This variable, specifically assigned to each input, measures the bias of productivity growth, i.e. its coefficient indicates the effect of change in technology on the use of the concerned input. This approach was adopted by Jorgenson (1984) in his analysis of the effect of technological change on the US economy for the period 1958-1979. His production model includes five inputs : capital, labor, electricity, non electrical energy and materials. His analysis of 35 industrial sectors shows that the pattern of bias of technical change that occurs most frequently is capital-using, labor-using, electricity-using, nonelectrical energy-using and materials-saving technical change. Technical change proves to be labor-saving for only 9 of the 35 industries and materials-saving for 27 industries. For all other inputs, technical change is predominantly input-using.

These two illustrative studies provide evidence against the hypothesis of a labor-saving technical change as suggested by models of induced innovation. If there is some plausibility in the inducement theory, it is only an explanatory element of the innovation dynamic which underlies technical change. This approach may certainly partly shed light on some technological bias in the development of process innovation but it is not well-suited to deal with product innovation. Hence, it may explain the development of energy-saving technologies after the oil shocks but it cannot explain why countries with low labor costs invest in capital-intensive techniques.

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1 This production function is reproduced in table 2.1.

2.3.4. The Endogenous Technical Change

To some extent, the preceding approach already assumes that technical change is endogenous to the economic process. Yet, it remains silent about the process according to which the innovation production shifts over time depending on the resources allocated to the search for new and improved techniques and products. The main characteristic of the innovation production is to create new knowledge which increases stocks of basic and applied knowledge. The latter are themselves inputs in the generation of production processes.

These stocks of basic and applied knowledge do not accumulate exogenously to the economic system. The accumulation process of knowledge is ruled by economic forces and conditioned by technical contingencies. As we have seen, the most widespread conception is based upon the postulate that technical change belongs to an autonomous sphere with its own rationality and advancing independently of the social and economic environment. If we have a look at this thesis, a contradiction immediately appears when one looks into the problem of the effectiveness of a new technical system. Indeed, one realizes that this apparaisal can only be made in economic terms, the price system playing the role of comparison unit. Moreover, technological innovation costs money, requires material supports and, therefore, consumes resources that could otherwise be used for other purposes. Consequently, technical change is endogenous, it is directed within the economic system in accordance with the principle that economic agents behave rationally.

Technical change is the outcome of investment in knowledge, i.e. R & D expenditures. These investments are a main source of improvements in the efficiency of production structures, i.e. a main source of productivity growth. To measure the impact of the stock of knowledge on productivity growth, it is treated as a production factor and is introduced in production functions besides other traditional inputs. Hence, the production function approach to the study of the relationship between knowledge accumulation and productivity gains proves to be a logical way of proceeding. A major conceptual issue is what is really the stock of knowledge ? The process of knowledge accumulation may take several different forms including organized research, non-organized research, education and on-the-job training. Another major issue is the measurement problem. The stock of knowledge as a whole cannot be calculated accurately, it can only be approximately valued through research activities. The two main candidate variables are patenting activities, as output measure of the knowledge production process, and R & D investment as input measure of the innovation process. Yet, both measures have their advantages and drawbacks. Not all innovations are patented and they are not all equally valuable. Besides patent regulations are not time invariant and are difficult to compare at international level. Regarding R & D investment, besides the fact that it is only an input measure there are the problems of gestation lag, of effectiveness and efficiency. Not all new prices of knowledge are exclusively the results of organized research. Despite the shortcomings of patent and R & D data, they are extensively used as a measure of the stock of knowledge. From a production function viewpoint, the use of R & D expenditures has the advantage of reflection both imitation and innovation activity while patenting activity only reflects the innovation process.

Although there is a large agreement on the use of R & D data to study the relationship between technological knowledge and productivity, this input factor in production functions has some characteristics on its own which distinguish it from other inputs. Contrary to other forms of capital accumulation, it is not subject to physical obsolescence. Yet, as "its earning capacity erodes over time, both because better products and processes become available and because its own knowledge begins to lose its specificity" it is thought to be faced with a high rate of obsolescence [Griliches (1979)]. In contradiction with that, it may be argued that R & D does not depreciate at all as a source of productivity. Another characteristic is the substantial uncertainty that R & D investment materializes by the creation or the improvement of new or existing products and processes. As already mentioned, there is also a gestation lag in R & D investment. A last prominent characteristic is that it is subject to large external economies. Notwithstanding these difficulties, large efforts have been devoted to measure the impact of R & D investment on productivity.

At most, this approach must be considered as a first step towards the endogenization of technological change. A further step is to explain how economic mechanisms affect R & D investment behavior to really endogenize technological change in economic analysis. Hence, R & D investment must be viewed as constrained by the profit maximisation criterion just like other investments. Profit opportunities for R & D investment are directed by market demand, factor prices and competitive strengths. There is a long-standing research tradition stressing the role of supply-side factors, market structure and technological opportunity on R & D along the lines initially traced by Schumpeter. This industrial organization approach has been extensively reviewed by Cohen and Levin (1988). Another approach, which is more in the line of the macroeconomic thought, emphasizes the role of the demand side factors. The underlying hypothesis of this approach is that R & D is an input in the production process and therefore is a decision variable for the producer who is assumed to select the R & D investment that minimizes costs given factor prices and output demand. In the past few years, short-run disequilibrium dynamic models of R & D investment demand incorporating spillover effects have been developed, which represent an important contribution for the endogenization of technological change in economic model.

Chapter 3. The Applied Economics of R & D

Over the past thirty years, evidence has been accumulated on the productivity effects of R & D investment. As total factor productivity growth is considered to be the prime consequence of technological change, it is quite logical to investigate the impact of R & D investment on productivity growth. Furthermore, since R & D expenditures are investments aiming at the improvement of techniques and products, their most direct effects should be on total factor productivity growth. This approach can be regarded as the first step towards the endogenisation of technological change in economic modelling. Most econometric studies dealing with this first issue rely on the Cobb-Douglas production function and generally treat R & D expenditure as a whole without looking at how the shifts in the composition of R & D expenditures affect productivity growth.

In addition to this productivity approach, some recent researches have been devoted to R & D demand functions. The underlying hypothesis of this demand approach is that R & D, like investment in plant and equipment and labor, is an input in the production process and therefore is a decision variable for the producer. In these models, changes in output, input prices and production factors are shown to influence R & D decisions. Besides, the demand for the other inputs is also affected by R & D investments. While the preceding approach assumes that all the inputs are given and measures the contribution of R & D to productivity growth, this approach investigates what are the determinants of R & D investment. Besides, a more financial approach suggests that resources devoted to R & D are faced with restrictions due to cash flow limitations and the potential alternative use of funds. The R & D investments are submitted to the constraints of the budgeting decision process of the firm and therefore, financial variables, like liquidity and profitability, also determine the magnitude and pattern of R & D expenditures. This second issue is a further step towards endogenisation of R & D investment. While we are here only concerned with these two issues, it is worth drawing attention to two other important issues.

A third issue, largely examined in empirical works on industrial organisations bears on the relationship between market structures and innovative activity. This literature is focused on Schumpeter's hint that firm size and concentration influence the magnitude and the appropriability of innovative efforts. So far, the empirical tests performed to verify these hypotheses are at best inconclusive.

A last important issue, which has raised an abundant amount of research, concerns the effects of technological development on trade performance. The theoretical bases of empirical research in this field are technology gap and product life cycle theories which show that innovation tends to lead to trade advantages. Overall, empirical studies emphasize the important role of technological activities on trade performance.

3.1. The Economics of R & D

The endogenisation of technical progress is very recent and is generally limited to the search of some economic relationships without any attempt to integrate them into a global macroeconomic model.

Griliches (1979) has suggested a general version of production functions including R & D expenditure :

$$Y = F(K, L, C, u)$$

where K and L are the traditional inputs, capital and labour
Y, the output
C, the current state of technological knowledge
and u, the error term

The R & D expenditure is a component of knowledge stock which is an input in the production process. The current state of knowledge is a result of the present and past R & D expenditure. So, there is a relationship between C and W(B)R :

$$C = G\,[W(B)\,R, v]$$

where W(B) is a polynomial function describing the contribution of present and past R & D expenditure to the current state of technological knowledge C, B being the lag operator and v the non-measured influences of the accumulated knowledge level.

So that we can write :

$$\begin{aligned} W(B)\,R_t &= (w_0 + w_1 B + w_2 B^2 + \dots)\,R_t \\ &= w_0 R_t + w_1 R_{t-1} + w_2 R_{t-2} + \dots \\ &= \sum_i w_i R_{t-i} \end{aligned}$$

The arguments which underlie such a specification are :

- the existence of a lag between the realisation of R & D investments made and the inventions or innovations which result from them;
- the existence of a lag between product and process innovations and the development of new products and their diffusion across the market;
- the depreciation of the knowledge stock currently used due to external factors and to the development of new techniques and products.

However, this specification does raise problems :

- R & D investment is only a component of technical progress;
- in production functions, the traditional inputs and the R & D investment are assumed to take the separability hypothesis into account;
- the linear relationship for the measure of the R & D capital stock implies the absence of diminishing returns or rising costs at the annual R & D level [1];
- on the one hand, R & D data are often only available for a short period and on the other hand, there is a more or less important lag between the investment and its impact on output, which makes any macroeconomic estimation difficult;
- such an approach remains silent about the diffusion process;
- technical change not only has an impact on productivity but also on other macroeconomic aggregates, particularly employment.

Concerning the explicit form of the production function, many studies are based on the Cobb-Douglas type :

$$Y_t = AC^{\alpha} L^{\beta} K^{\gamma} e^{\lambda t+u}$$

The issue of the functional form is not very crucial except if a specific interaction between the factors is suspected [Griliches (1979)]. In a study of the US telecommunications and computer industries, Levy and Terleckyj (1989) test both Cobb-Douglas and CES production functions and conclude that the hypothesis of a unitary elasticity of substitution cannot be rejected.

In this function, we have the choice of assuming constant returns to scale or not, λ is the rate of disembodied technical change and α, β and γ are the elasticities of output with respect to each of the inputs.

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[1] According to Berndt and Christensen (1973), this hypothesis cannot really be tested.

An alternative approach to this model has been suggested by Griliches (1973) and Terleckyj (1974). Instead of estimating the R & D elasticity, we can directly estimate the rate of return to R & D. To do that, the initial equation need to be expressed in terms of growth rate :

$$\dot{Y}_t = \lambda + \alpha \dot{C} + \beta \dot{L} + \gamma \dot{K}$$

In this equation, we have :

$$\gamma \dot{K} = \frac{\partial Y}{\partial K} \cdot \frac{K}{Y} \cdot \frac{\Delta K}{K}$$

so that we can write :

$$\gamma \dot{K} = \rho \frac{\Delta K}{Y}$$

where ρ is the rate of return of R & D capital.

If we assume that the rate of depreciation of R & D capital is zero or close to it, one may write :

$$\frac{\Delta K_t}{Y_t} = \frac{R_t - \delta K_{t-1}}{Y_t} \simeq \frac{R_t}{Y_t}$$

This assumption is often considered a reasonable one because new knowledge resulting from R & D investment builds on and adds to old knowledge. Unlike physical investment, which faces technical and economic obsolescence, knowledge investment is incremental and cumulative, new knowledge upgrading the existing knowledge stock. If such an argument is right at the level of the general stock of knowledge, it is less right when one considers the appropriable revenues of knowledge. At the firm level, the marketable knowledge ensuing from its R & D investment decreases over time because upgraded products and processes reduce its market valuation and because the privately acquired knowledge leaks out to competitors. Quoting Pakes and Schankerman (1984), the rate of obsolescence of R & D capital is higher than that of physical capital as new knowledge diffuses. From patent renewal data, Bosworth (1978) has estimated that the rate of obsolescence of knowledge capital is about 10% in the United Kingdom. Pakes and Schankerman (1984) have provided clues that allow us to say that the decay rate in appropriable revenues from knowledge activities should be 25%. His patent renewal model was based on data for France, the United Kingdom, the Netherlands and Switzerland. In the case of the United States, Griliches (1980a) puts forward an estimate of 0.31. In a study on the effect of R & D on productivity growth in Japanese manufacturing industries, Goto and Suzuki (1989) have measured the rate of obsolescence of R & D capital by taking the reverse of the average life span of patents. Their estimates range from 6% for low-technology industries to 25% for high-technology industries. Schankerman and Pakes (1986) and Schankerman (1991) have provided further evidence that the rate of decay in the returns from patents differ across countries and sectors. So, the rates are estimated to be 0.17 for the United Kingdom, 0.11 for Germany and 0.10 for France in the 70's and there is statistical evidence that between the 50's and the 70's they declined. At the industrial level, the estimates obtained for patents granted in France were 3% for the pharmaceutical industry, 4% in the chemical industry, 10% for the mechanical industry and 15% in the electronics. Yet, there are other ways of appropriating the benefits of R & D and it is very hazardous to assimilate the patent protection decay to the R & D obsolescence rate. Several authors have tried to estimate the R & D capital stock by means of sensitivity analyses for different depreciation rates. So, Griliches and Mairesse (1984) have made an experiment based on the measure of the output elasticity of R & D. They have unsuccessfully experimented alternative R & D capital stock measures without rejecting the hypothesis of no depreciation of R & D. As quoted by Mairesse (1991), the estimates of the R & D elasticity are rather robust regarding the rate of obsolescence. Indeed, the use of R & D investment instead of R & D capital can be expected to affect the measure of elasticity only slightly. To demonstrate this statement, one can consider that the R & D capital stock is evaluated by using the perpetual inventory method :

$$C_t = R_t + (1 - \delta) C_{t-1}$$

Supposing that the R & D investment grows at a constant rate g, one can write :

$$C_t = \sum_{i=0}^{\infty} \left(\frac{1 - \delta}{1 + g}\right)^i R_t$$

so that :

$$C_t = \left(\frac{1 + g}{g + \delta}\right) R_t$$

This relationship indicates that, ceteris paribus, the use of R & D capital stock and R & D investment will give a similar measure of the elasticity. In the logarithmic model, the constant will slip out of the expression to the constant term of the regression and in the growth rate model, it will disappear.

Griliches and Lichtenberg (1984) have experimented alternative depreciation schemes for the measure of the rate of return which have also led to accept the hypothesis of no depreciation of R & D in terms of its effects on productivity at the industry level. Conversely, Goto and Suzuki (1989)'s study emphasizes the distinction between gross R & D investment (R & D expenditure) and net R & D investment (R & D capital) when one measures the rate of return to R & D. By contrast with the elasticity approach, the rate-of-return approach is characterized by the lack of robustness. In such a model, the hypothesis about the rate of obsolescence of R & D is very important. To show that, let us consider the numerator of the R & D capital intensity :

$$C_t - C_{t-1} = R_t - \delta\, C_{t-1}$$

Assuming that the R & D investment grows at constant rate g, one can write :

$$C_t - C_{t-1} = R_t \left(\frac{g}{g + \delta}\right)$$

So, according to this relationship, using R & D investment instead of R & D capital leads to an underestimate of the return. The higher the rate of obsolescence, the higher the underestimate will be. Furthermore, if g is negative, the rate of return will be negative if $\delta > |g|$. Ceteris paribus, an overestimate will be obtained when $g < 0$ and $\delta < |g|$.

Although one can indifferently use the growth rate of R & D capital or the R & D intensity to estimate the effects of R & D on productivity growth, each of these specifications implies some hypotheses. So, when the output elasticity of R & D capital is viewed as the parameter, it does not vary over time. As this elasticity is equal to the product of the marginal productivity of R & D capital by the R & D capital intensity, this means that if the R & D capital intensity increases, the marginal product of R & D will decrease. On the other hand, if the marginal productivity of R & D capital is the parameter, this means that the rate of return on R & D capital is invariable across observations. Yet, quoting Nelson (1988), in dynamic equilibrium, the rate of technological progress is insensitive to R & D intensity for any firm or industry. Firms in the same line of business will experience the same rate of technical progress, regardless of their R & D intensity. However, the levels of productivity should differ among firms reflecting differences in R & D intensity. Such an argument, casts doubts on the advisability of strictly interpreting the estimated cross sectional coefficient of R & D intensity as measuring the private or social rate of return on R & D.

Another problem raised by this alternative model concerns the interpretation of the coefficient ρ. First, both labour and physical capital data often already include respectively R & D labour and R & D physical capital, so that these data are counted twice since they are also the basic components of R & D capital stock. This double counting causes downward biases in the measure of both the rate of return on R & D and the R & D elasticity. Schankerman (1981) and Cuneo and Mairesse (1984) have shown that the resulting biases could be very large. Consequently, when data are not corrected with respect to the R & D double counting, ρ is interpreted as being the excess rate of return to R & D investment.

Consider that L_K and C_K are respectively the labour and physical capital components included in the measure of the R & D capital. An approximation of the rate of return on R & D can be obtained by calculating a corrected value of ρ, ρ_K. Assuming that the variables are defined in value units, the time regression can be specified to measure directly the rate of return of each production factor :

$$\dot{Y} = \lambda + \rho_C \frac{\Delta C}{Y} + \rho_L \frac{\Delta L}{Y} + \rho_K \frac{\Delta K}{Y}$$

The estimated equation is :

$$\dot{Y} = \lambda + \rho_C \frac{\Delta C + \Delta C_K}{Y} + \rho_L \frac{\Delta L + \Delta L_K}{Y} + \rho \frac{\Delta K}{Y}$$

This adapted interpretation has been forcefully argued as being conceptually incorrect by Schankerman (1981). He also points out the bias from R & D expensing out when a value added measure is used for output. Material consumption components of R & D investment are intermediate inputs and, consequently, are not accounted in the measure of value added.

Taking the difference between these two equations, we obtain :

$$\rho_K = \rho + \rho_C \frac{\Delta C_K}{\Delta K} + \rho_L \frac{\Delta L_K}{\Delta K}$$

where ρ_K, the rate of return on R & D capital is equal to the rate of return on R & D capital in excess of the normal remuneration of its labour and physical capital components plus the sum of the rates of return on labour and physical capital weighted by the contribution of these factors to the net R & D investment.

Alternatively, as many studies combine the measure of the elasticities of labour and physical capital with a measure of the excess rate of return on R & D physical capital, we can adapt the preceding correction by combining these estimates :

$$\rho_K = \rho + \alpha \frac{\Delta C_K}{\Delta K} \frac{Q}{C} + \beta \frac{\Delta L_K}{\Delta K} \frac{Q}{L}$$

A third correction can also be given for the measurement of R & D elasticity :

$$\gamma_K = \gamma + \alpha \frac{\Delta C_K}{\Delta K} \frac{K}{C} + \beta \frac{\Delta L_K}{\Delta K} \frac{K}{L}$$

(6)

Besides these theoretical correction formulas, one cannot ignore that returns on investment and elasticities are the result of estimates and that, consequently, the correction will be more or less important as the variation of the relative components is less or more stable across observations. The effects of double counting cannot be expected to be identical whatever the level of the data analysis may be, i.e., a firm cross-section analysis, an industry cross-section analysis or a time series analysis.

In a study on French data at the firm level, Cuneo and Mairesse (1984) have shown that the overall biases in the estimates caused by double counting and expensing could be quite sizeable. Their results emphasize biases in the estimates of the R & D elasticity going from 25% to 50%.

Be X and X_K, the disaggregation of a variable between its R & D and "output" components. Its growth rate is equal to :

$$(X_t + X_{K_t}) / (X_{t-1} + X_{K_{t-1}}) = (X_t / X_{t-1}) \cdot [1 + (X_{K_t} / X_t)] / [1 + (X_{K_{t-1}} / X_{t-1})]$$

If the relative part (X_{K_t} / X_t) does not vary very much over time compared to (X_t / X_{t-1}), its impact on the measure of the elasticity should be small.

A second problem is raised by the interpretation of the rate of return on R & D. By investing in R & D, entrepreneurs will earn a return through net appropriable revenues from the business utilization of created new knowledge. The internal private rate of return to R & D depends on the present value of the revenues accruing to this activity. Under competitive assumptions, the marginal product of R & D represents the rate of return on R & D so that the internal private rate of return on R & D during the life span of a unit investment in R & D is :

$$1 = \int_0^{\infty} \rho \, e^{-(r+\delta)t} \, d\, t = \frac{\rho}{r + \delta}$$

which gives :

$$r = \rho - \delta$$

where r is the implicit discount rate or the net internal private rate of return. In this equation, one supposes that there is no gestation lag of R & D investment.

This equation shows that ρ is defined as the gross internal private rate of return and that, if one wants to compare the return of alternative forms of investment, particularly the returns to R & D and physical capital, one cannot escape the measure of the rate of obsolescence of R & D capital. This interpretation is valid as long as the data analysed are about firms. At the industry and the nationwide level, the coefficient ρ can no longer be assimilated to a private rate of return because of the spillover effects of a firm's private R & D investment within and outside the industry. Before discussing this new issue, it seems important to clarify the real need of taking into account the rate of obsolescence of R & D investment in the analysis of its impact on productivity.

In order to clarify the issue of depreciation of R & D, Terleckyj (1984) has suggested to draw sharp distinctions between the different economic effects of R & D among which :

1) R & D as private capital asset : as a source of profit, R & D depreciates very rapidly due to the intensity of domestic and foreign competition regardless of its impact on productivity;
2) R & D as determinant of the level of productivity : as a source of productivity, R & D does not depreciate at all because the level of productivity reached in an economy as a result of technological improvements based on past R & D can be maintained indefinitely by replacing factors of the same kind without need for any additional R & D conducted to maintain it;
3) R & D as social capital asset determining the rate of growth : as a source of growth in income and output, the social R & D capital does depreciate but less rapidly than the private R & D capital because it is affected only by foreign competition.

This distinction emphasizes three important items which certainly call for further investigations. It is particularly worth pointing out that the empirical analysis of the relation between R & D and competition is still at an early stage of development. However this may be, the R & D investment only depreciates as a consequence of the alteration of its competitive impact while the productivity gains resulting from this investment remain acquired. An important logical conclusion of this reasoning is that equations leaving out the term $- \delta K / Q$ in the rate of return approach are not misspecified and do not underestimate the rate of return of R & D investment.

A third cause for concern is the interpretation of the rate of return regarding the level of data aggregation for the regression analysis. The level of productivity achieved by one firm or industry or nationwide depends on its own R & D investment and on the set of knowledge capital available.

For a given firm i, the model taking into account the within-industry spillover effect is given by :

$$Y_i = A\, C_i^{\alpha} L_i^{\beta} K_i^{\gamma} K_I^{\delta} e^{\lambda t}$$

where K_i is the specific knowledge capital of the firm i

K_I is the aggregate knowledge capital of the industry in which the firm i carries on its activity

and where γ is the own R & D elasticity while δ is the within-industry R & D elasticity or the within-firm spillover elasticity.

If, with Griliches (1979), we assume that the within-industry aggregate knowledge capital is the sum of all firm R & D capital levels and resources are allocated optimally and all firms face the same relative factor prices we can write :

$$\frac{K_i}{C_i} = \frac{\alpha}{\gamma} \cdot \frac{P_C}{P_K} = r$$

$$\frac{K_i}{L_i} = \frac{\alpha}{\gamma} \cdot \frac{P_L}{P_K} = l$$

where P_C, P_L and P_K are the prices of C, L and K respectively. Assuming constant returns to scale ($\alpha + \beta + \gamma = 1$) the individual production functions can be aggregated :

$$\sum_i Y_i = \sum_i A \left(\frac{C_i}{K_i}\right)^{\alpha} \left(\frac{L_i}{K_i}\right)^{\beta} K_i K_I^{\delta}$$

$$= A \left(\frac{1}{r}\right)^{\alpha} \left(\frac{1}{e}\right)^{\beta} K_I^{\delta} \sum_i K_i$$

Since the ratios $\frac{K_i}{C_i}$ and $\frac{K_i}{L_i}$ are equal to r and l respectively, so also are $\sum_i K_i$ / $\sum_i C_i$ and $\sum_i K_i / \sum_i L_i$, we can write :

$$Y = A \left(\frac{\sum_i C_i}{\sum_i K_i}\right)^{\alpha} \left(\frac{\sum_i L_i}{\sum_i K_i}\right)^{\beta} K_I^{\delta} K_I$$

$$= A\, C^{\alpha} L^{\beta} K_I^{\delta+\gamma}$$

The industry production function has a higher elasticity of aggregate knowledge capital ($\delta + \gamma$) than at the micro level (γ). The coefficient δ cannot be estimated when we are looking at a firm panel within a specific industry and could only be evaluated from an industry sample. By extension to the preceding development, we can write :

$$\dot{Y}_i = \lambda + \alpha \dot{C}_i + \beta \dot{L}_i + \rho \frac{\Delta K_i}{Q}$$

$$\dot{Y} = \lambda + \alpha \dot{C} + \beta \dot{L} + \rho_I \frac{\Delta K_I}{Q}$$

where ρ measures the private rate of return to R & D while ρ_I represents the social (including private) rate of return. Compared to the elasticity approach which assumes a common elasticity of output with respect to R & D stock when the relationship is estimated across industries, which is not very likely given the large divergences in R & D intensity, this alternative approach turns out to be more consistent with the optimal R & D choice behavior [1]. Given that R & D inputs are often already included into the conventional factors, under the hypothesis that the discrepancy between social and private returns is distributed randomly across industries, one can argue that the estimated coefficient will be a consistent estimate of the average excess of social over private returns [Griliches and Lichtenberg (1984)]. Generally, the estimated rates of return are a mixture of private and social rates of return. For data at the firm level, there is no doubt that a variable like own R & D investment can only explore the magnitude of private returns. At the industry level, only the private and within industry returns can be seized, and hence only a part of the social rate of return. A complete measure of the social rate of return on R & D conducted in a firm must cover the private rate of return, the social rate of return on the within industry productivity and the social rate of return on the outside industry productivity [2]. The latter category of spillover effects is much more complicated to evaluate. The extent to which an industry gains from the available pool of knowledge of other industries depends on the economic and technological proximity of these industries. In other words, for each industry, the spillover will be a weighted sum of the R & D capital stocks of the other industries.

From a practical viewpoint, it is difficult to separate private and social return. The extent of the gap between the social and the private rate of return on R & D is highly dependent on the competitive environment, the orientation of the research and the nature of the results. If the innovator is in a monopoly or oligopoly position, he will be able to appropriate a proportion of the social benefits. When the competitive forces are stringent the innovator will be in a less secure position to collect the social benefits. The degree of appropriability will also differ according to whether the innovation deals with new

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[1] If the inputs are used at their competitive equilibrium levels, industries are unlikely to have the same output elasticities. The production technology being specific for each industry, industries will use different factor shares. A consequence of this is that a total productivity approach will be more relevant.

[2] Conversely, for a firm the social rate of return on R & D will be equal to the private (or internal) rate of return (on own R & D) plus the external rate of return from the R & D conducted by other firms within both its own industry and other industries. It is worth noting that the external effects are not limited in space (e.g. a country) since a firm also profits by the R & D conducted outside the country.

products or processes. Product innovations are likely to be under more intense competitive pressures than process innovations. So, the discrepancy between social and private returns could be larger for products than for processes. A last characteristic of the discrepancy between social and private returns rests on the distinction between generic and derived innovations. A radical innovation is more likely to be imitated quickly than incremental innovations and, consequently, it will be very difficult for the originator of a radical innovation to keep the benefits of his technological breakthrough.

On the other hand, when a new innovation comes onto the market place, numerous economic variables come into action, which raises the issue of the measurement of the social return on R & D and its distinction from private return. As Griliches (1980a) points out : "Assuming that, on average, the outside world pays for [new processes and] products what they are worth to it, using sales or value added as our dependent variable does in fact capture the private returns to such research endeavors. However, the observed private returns may underestimate the social returns because, given the competitive structure of the particular industry, the market price of the new product or process will be significantly below what consumers might have been willing to pay for it. On the other hand, part of the increase in sales of an individual firm may come at the expense of other firms and not as the result of the expansion of the market as a whole. Also, some of the increase in prices paid for a particular new product may come from changes in the market power of a particular firm induced by the success of the research program. Moreover, some of the gains in productivity or in the sales of new products may be based on the research results of other firms in the same or some other industry. Such factors could result in the observed private returns overestimating the social returns significantly. We cannot say much about the net impact of such forces on the basis of [firm data]. It requires a detailed comparison of the individual firm results with estimates based on industry and economy-wide returns to research [...]. But since expected private returns are presumably a determinant of private investment flows into this activity, the estimates presented [on the basis of firm data] may be of some interest even if they cannot answer the social-returns question unequivocally".

A last issue is which output variable should be introduced in the production function : value added, sales or total factor productivity based on gross output or net output. Conceptually, these alternative solutions rest on different hypotheses regarding the production process and the optimality conditions. Their main impact on the measurement of the rate of return, which is alternatively estimated by comparison with net output or gross output, is that the latter provides higher estimates. This apparent overestimate is understandable since the marginal product of R & D in terms of gross output is logically higher than the marginal product of R & D in terms of net output. On the other hand, the use of a value-added measure of output instead of sales will not result in biased estimates. Yet, any measure based on gross output will be mispecified as long as intermediate inputs are not taken into account besides primary inputs while any net output measure must be connected with primary inputs only [1].

3.2. Econometric Studies in Retrospect

After discussing the main issues concerning the measurement of the impact of R & D on productivity, we turn to the most significant studies investigating the relationship between R & D and productivity. The literature in this field can be classified according to the level of data aggregation. So, we can consider successively :

- studies at the micro level which are based on firm data (also called panal data) whose main advantage is that they substantially increase the degrees of freedom. Furthermore, they provide evidence on the private rate of return on R & D investment;

- studies at the meso level which use industry data and whose estimates can be associated with the social rate of return on R & D. Yet, estimates will give at best a partial measure of this social rate of return, i.e. an evaluation of the intra-industry return;

- studies at the macro level which analyze economy-wide time series data in order to measure the social rate of return on R & D. While such an approach can give an idea of the domestic social return, we must keep in mind that, incomplete appropriability property of R & D returns, which causes the social return to differ from the private return, is not restricted by the existence of frontiers.

Besides, econometric analyses can also be classified according to :

- the dimensional extent : findings can be grounded on cross-sectorial or time-series data or both;

- the econometric specification : the measure of the impact of R & D can be expressed in terms of R & D elasticity or rate of return on R & D;

[1] All variables having been beforehand corrected for double counting and expensing out.

- the data measurement issue : sales, value-added or partial or total productivity can be referred to as the explained variable, data can be corrected or not for R & D double counting and expensing or R & D intensity can be defined with respect to sales or value added.

This review is based on the classification of studies according to the level of data aggregation and their econometric specification.

3.2.1. Micro Level Studies

Table 3.1. summarizes the main estimates of the R & D elasticity from firm panel data. These estimates are performed within the framework of the Cobb-Douglas production function except for Jaffe (1986)'s results which arise from the adjustment of a profit function.

One of the first studies to use firm data to estimate R & D elasticity was that by Minasian (1969) performed on a small sample of chemical US firms. With the average growth rate of value added as a dependent variable he experimented without firm dummies and with firm dummies. These alternative approaches are respectively called total regressions and within regressions. The latter can also be obtained by using the deviations of variables from the individual firm means or by performing on growth rates. Minasian finds R & D to have a positive and significant effect in the first case, an observation which is not confirmed by his second estimate. This result shows that biased estimates can be obtained if not all firm-specific variables are included, which effect can be picked up with firm dummies.

It is in the 1980's that the analyses at the firm level multiply. The first study of a large number of firms was realized by Griliches (1980a) who investigated 883 large US manufacturing companies accounting for more than 90 % of all industrial R & D. Working on both cross-section and time series, he obtains similar results for the two types of regressions. Yet, estimates by industry give very different values ranging from 0.03 in aircraft to 0.14 in motor vehicles.

As already pointed out, Schankerman (1981) has forcefully argued that the measured contribution of R & D to productivity improvements is often largely biased downwards by failing to correct traditional inputs (labor and physical capital) for double counting as well as net output for R & D expensing (subtracted from value added as an

Tableau 3.1. Estimates of R & D Elasticity at the Firm Level

Studies	Estimation method	Sample	Specification and estimation procedure	Elasticity of R & D
Minasian (1969)	Cross-section	United States, Chemistry, 17 firms, 1948-1957.	Total regression.	0.26 (0.03)
	Time-series	United States, Chemistry, 17 firms, 1948-1957.	Within regression.	0.08 (0.07)
Griliches (1980a)	Cross-section	United States, 883 firms, 1963.	Industry dummies.	0.07 (0.01)
	Time-series	United States, 883 firms, 1957-1963.	Average growth rate, industry dummies.	0.08 (0.01)
Schankerman (1981)	Cross-section	United States, 110 firms, Chemistry and Petroleum, 1963.	Data corrected for double counting in R & D.	0.16 (0.04)
	Cross-section	United States, 110 firms, Chemistry and Petroleum, 1963.		0.10 (0.04)
		United States, 101 firms, Electric Equipment, 1963.		0.03 (0.02)
		United States, 101 firms, Electric Equipment, 1963.	Data corrected for double counting in R & D.	0.23 (0.03)
		United States, 187 firms, Metals and Machinery, 1963.		0.02 (0.02)
		United States, 187 firms, Metals and Machinery, 1963.	Data corrected for double counting in R & D.	0.10 (0.02)
		United States, 34 firms, Motor Vehicles, 1963.		0.07 (0.05)
		United States, 34 firms, Motor Vehicles, 1963.	Data corrected for double counting in R & D.	0.09 (0.05)

		United States, 31 firms, Aircraft, 1963.		0.03 (0.03)
		United States, 31 firms, Aircraft, 1963.	Data corrected for double counting in R & D.	0.29 (0.05)
		United States, 419 firms, Miscellaneous, 1963.		0.04 (0.01)
		United States, 419 firms, Miscellaneous, 1963.	Data corrected for double counting in R & D.	0.07 (0.01)
Griliches and Mairesse (1983)	Time-series	United States and France, 343 and 185 firms, 1973-1978.	Average growth rate.	0.02 (0.03)
Griliches and Mairesse (1984)	Cross-section	United States, 133 firms, 1966-1977.	Total regression, constant returns to scale.	0.07 (0.01)
			Total regression, free returns to scale.	0.05 (0.01)
	Cross-section	United States, 77 scientific firms, 1966-1977.	Total regression, constant returns to scale.	0.22 (0.01)
			Total regression, free returns to scale.	0.18 (0.01)
	Time-series	United States, 133 firms, 1966-1977.	Free returns to scale, within regression.	0.09 (0.02)
			Constant returns to scale, within regression.	0.16 (0.02)
Cunéo and Mairesse (1984)	Cross-section	France, 182 firms, 1972-1977.	Total regression, data corrected for R & D double counting.	0.20 (0.01)
	Cross-section	France, 98 firms, scientific sectors, 1972-1977.	Total regression, data corrected for R & D double counting.	0.21 (0.01)
			Total regression.	0.11 (0.01)

	Time-series	France, 182 firms, 1972-1977.	Within regression, free returns to scale, data corrected for R & D double counting.	0.05 (0.04)
			Within regression, constant returns to scale, data corrected for R & D double counting.	0.11 (0.04)
Mairesse and Cunéo (1985)	Cross-section	France, 296 firms, scientific sectors, average year 1974 and 1979.	Without industry dummies, data corrected for R & D double counting, between-firm regression.	0.16 (0.02)
			Industry dummies, variable for labour qualification, corrected data, between-firm regression.	0.10 (0.02)
	Time-series	France, 390 firms, 1974 and 1979.	Growth rate between extreme years.	0.02 (0.10)
Griliches (1986)	Cross-section	United States, 491 firms, 1972.	Industry dummies, employment corrected.	0.11 (0.02)
	Cross-section	United States, 491 firms, 1977.	Industry dummies, employment corrected.	0.09 (0.02)
	Time-series	United States, 652 firms, 1966-1977.	Average growth rate, industry dummies, constrained elasticity of labour.	0.12 (0.02)
Jaffe (1986)	Cross-section	United States, 432 firms, 1973 and 1979.	Profit, total regression, labour non included.	0.20 (0.05)
	Time-series	United States, 432 firms, 1973 and 1979.	Profit, growth rate between extreme years.	0.10 (0.30)
Sassenou (1988)	Cross-section	Japan, 394 firms, 1976.		0.10 (0.01)
	Time-series	Japan, 394 firms, 1973-1981.	Within regression, constant return to scale.	-0.01 (0.01)
			Within regression, free return to scale.	-0.02 (0.01)
			Annual growth rate, constant return to scale.	0.02 (0.02)

			Annual growth rate, free return to scale.	-0.02 (0.02)
			Average growth rate, constant return to scale.	0.04 (0.04)
			Average growth rate, free return to scale.	0.04 (0.04)
	Cross-section	Japan, 112 firms, Scientific sectors, 1976.		0.16 (0.03)
			Variable of externality of R & D	0.08 (0.03)
			Industry dummies	0.07 (0.02)

Note : Estimated standard errors in parentheses.
Source : Adapted and extended from Mairesse and Sassenou (1991).

intermediate input). His estimates show that the downward bias varies from 50 percent for chemicals and petroleum and motor vehicles to 800 percent for electric equipment and aircraft. It is worth noting that the downward biases are largest in the two industries that are most R & D intensive and most reliant on government funding, i.e. electrical equipment and aircraft.

Cunéo and Mairesse (1984) arrive at a similar observation in their analysis of French data. For scientific sectors, the downward bias amounts to 50 %. From their study it also appears that the hypothesis of constant returns to scale is not without consequences on the estimates. When this assumption is relaxed, estimates of R & D elasticities are lower and returns to scale appear to be decreasing. Large divergences are also observed between estimates from total regressions and within regressions. The within estimate under the hypothesis of free returns to scale gives a non-significant R & D elasticity (except for scientific sectors). The order of magnitude of coefficients obtained in this analysis is quite comparable to that reported by Griliches and Mairesse (1984) for the United States. Yet, in this study, within regressions give higher coefficients than total regressions (except for the scientific sector). In a simultaneous analysis of both American and French data, Griliches and Mairesse (1983) fail to find any significant relationships between output growth rate and R & D investment.

In fact, we observe that time-series estimates of R & D elasticity provide more controversial results than cross-section ones. In a large number of time series studies, the estimated coefficient appears non-significant. But it is not the case for Griliches (1980b, 1986)'s studies in which the estimated coefficients are close for the two types of estimates. In the second study, a partial correction of data gives a higher estimate of R & D coefficient while two additional variables about the share of R & D investment devoted to basic research and privately financed research are introduced into the model, the latter showing a high premium effect for these categories of research. The results obtained by Jaffe (1986) from a profit equation are congruent with the observations made by Griliches. A similar conclusion emerges from the estimates reported by Sassenou (1988) for Japan. On the one hand, his coefficients are significant for the cross-section analysis, but, on the other hand, these results are not confirmed by the time series analysis.

According to Mairesse and Sassenou (1991) the high disparities between estimates arising from the cross-section and the time-series analyses are likely to be due to various causes. High collinearity of R & D capital with time, random measurement errors in variables, inadequate specification of lags in the effects of R & D capital, omission of variables reflecting short-term adjustments and the simultaneity of the decision process regarding employment and production are all phenomena which may explain why time-series estimates give poorer results than cross-sectional ones.

Models estimating the rate of return on R & D have been developed as an alternative method to the hypothesis of a constant R & D elasticiy. In this approach, the marginal productivity of R & D capital, in other words, the rate of return on R & D, is assumed to be constant. This hypothesis of a same rate of return on R & D for all firms and industries is compatible with the competitive equilibrium conjecture all the more as the measure bears on the private return and not on the social return. Although estimates based on firm data are generally seen as measuring the private return, the results may also, to some extent, represent the social return depending on the analytical context. So, it is the case when industry dummies are not included into the regression. Other practical problems raised by this approach will be discussed throughout the review of the most prominent studies whose results are gathered in table 3.2.

In their respective studies, Minasian (1962) and Mansfield (1980) provide some clues to a very high rate of return on R & D in the chemical industry for the United States. This result is not confirmed by Link (1981) for the shorter period covering the beginning of the 70's. Yet, the rate of return for the chemical industry is significant which is not the case for other industries, particularly those related to mechanical manufacturing and transport equipment. An estimate based on a sample of 302 firms for the end of the 70's no longer provides any strong evidence of the rate of return on R & D [Link (1983)].

As opposed to these disappointing experiments, Griliches and Mairesse (1983) produce estimates of a significant rate of return in the United States and France with a larger return for the latter. The use of industry dummies appreciably reduces the order of magnitude of the estimated return. So, more attention should be paid to the construction of variables in the measurement of the rate of return. The relationship between changes in productivity and levels of R & D intensity can be evaluated by using alternatively sales or value added as reference output. Generally, the measurements of the productivity variable and the R & D intensity indicator are consistent with each other. Nevertheless, one needs to be careful when comparing the returns on R & D provided by different studies because estimates may sensitively diverge depending upon whether R & D intensity is measured with respect to value added or sales. Consequently, the estimates obtained by Minasian (1962), Mansfield (1980) and Link (1981) are not directly comparable to those reported by Link (1983) and Griliches and Mairesse (1983), the former being based on value added and the latter on sales. As the amount of sales is

Table 3.2. Estimates of the Rate of Return at the Firm Level

Study	Sample	Specification	Rate of return	
			Without industry dummies	With industry dummies
Minasian (1962)	United States, 18 firms, Chemistry, 1947-1957.	Total factor productivity, value added.	0.25 (0.04)	-
Mansfield (1980)	United States, 16 firms, Chemistry and Petroleum, 1960-1976.	Total factor productivity, value added.	0.27 (0.07)	-
Link (1981a)	United States, 1971-1976, 174 firms.	Total factor productivity, value added.	0.00 (0.03)	-
	United States, 1971-1976, 33 firms, Chemistry.		0.07 (0.03)	-
	United States, 1971-1976, 34 firms, Mechanical.		0.05 (0.07)	-
	United States, 1971-1976, 19 firms, Transportation equipment.		0.15 (0.21)	-
Link (1983)	United States, 302 firms, 1975-1979.	Total factor productivity, sales.	0.06 (0.04)	-
Griliches and Mairesse (1983)	United States and France, 343 and 185 firms, 1973-1978.	Sales.	0.28 (0.06)	0.12 (0.06)
	United States, 343 firms, 1973-1978.	Sales.	0.19 (0.11)	-
	France, 185 firms, 1973-1978.	Sales.	0.31 (0.07)	-

Odagiri (1983)	Japan, 370 firms, 1969-1981, Scientific sectors.	Total factor productivity, sales.	0.26 (0.10)	-
	Japan, 370 firms, Other sectors, 1969-1981.	Total factor productivity, sales.	-0.47 (0.29)	-
Clark and Griliches (1984)	United States, 924 production units, 1971-1980.	Sales.	0.18 (0.05)	0.18 (0.05)
	United States, 924 production units, 1971-1980.	Total factor productivity, sales.	0.20 (0.05)	0.20 (0.05)
Griliches (1986)	United States, 386 firms, 1966-1977.	Sales.	0.24 (0.07)	-
Odagiri and Iwata (1986)	Japan, 135 firms, 1966-1973.	Total factor productivity, value added.	0.20 (0.11)	0.17 (0.13)
	Japan, 168 firms, 1974-1982.	Total factor productivity, value added.	0.17 (0.06)	0.11 (0.06)
Sassenou (1988)	Japan, 394 firms, 1973-1981.	Sales.	0.69 (0.19)	-
		Value added.	0.22 (0.11)	-0.02 (0.07)
		Value added, free returns to scale.	-	-0.04 (0.07)
Goto and Suzuki (1989)	Japan, 13 firms, Drugs and medecines, 1976-1984.	Total factor productivity, value added.	0.42 (0.12)	-
		Total factor productivity, R & D capital.	0.23 (0.13)	-
	Japan, 5 firms, Electrical industrial machinery, 1976-1984.	Total factor productivity, R & D capital.	0.53 (0.18)	-

		Total factor productivity, value added.	0.22 (0.09)	-
	Japan, 5 firms, Industrial inorganic chemicals, 1976-1984.	Total factor productivity, value added.	0.32 (0.25)	-
		Total factor productivity, R & D capital.	0.45 (0.21)	-
	Japan, 5 firms, Industrial organic chemicals, 1976-1984.	Total factor productivity, value added.	0.56 (0.15)	-
		Total factor productivity, R & D capital.	0.81 (0.21)	-
	Japan, 4 firms, Glass, 1976-1984.	Total factor productivity, value added.	0.25 (0.34)	-
		Total factor productivity, R & D capital.	0.19 (0.48)	-
	Japan, 5 firms, Parts for electronic appliances and communications equipment, 1976-1984.	Total factor productivity, value added.	0.22 (0.14)	-
		Total factor productivity, R & D capital.	0.22 (0.21)	-
	Japan, 3 firms, Motor vehicles, 1976-1984.	Total factor productivity, value added.	0.33 (0.14)	-
		Total factor productivity, R & D capital.	0.32 (0.16)	-
Fecher (1990)	Belgium, 292 firms, 1981-1983.	Total factor productivity, sales.	-	0.04 (0.04)
Griliches and Mairesse (1990)	United States, 525 firms, 1973-1980.	Sales.	0.41 (0.09)	0.27 (0.10)

(7)

		Sales, free returns to scale.	-	0.25 (0.10)
	Japan, 406 firms, 1973-1980.	Sales.	0.56 (0.23)	0.30 (0.21)
		Sales, free returns to scale.	-	0.20 (0.21)
Lichtenberg and Siegel (1991)	United States, 5240 firms, 1972-1985.	Total factor productivity, sales.	-	0.13 (0.02)
Klette (1991)	Norway, 1396 plants, 1977-1988	Total factor productivity, gross output	-	0.11 (0.03)

Note : Estimated standard errors in parentheses.
Source : Adapted and extended from Mairesse (1991).

largely higher than the value added, the ratio of R & D to sales is expected to give higher estimates than the R & D-value added ratio. The ratio of sales to value added being superior to two, the estimates of Minasian and Mansfield appear very high when compared to those obtained by Griliches and Mairesse.

The results reported by Clark and Griliches (1984) and Griliches (1986) are roughly comparable to those obtained by Griliches and Mairesse. It is worth noting that the introduction of industry dummies in their sample does not modify the estimates obtained by Clark and Griliches and that the authors estimate a product-process mix effect. Their mix coefficient indicates that the rate of productivity growth is lower when the increase in R & D is product-oriented than when it is process-oriented. This is explained by the fact that new products tend to be disruptive to established production processes because their introduction involves a start-up and debugging phase. Moreover, when new products are an important aspect of competition, businesses may sacrifice a part of productivity to gain flexibility to avoid too rigid equipments and processes which reduce the possibilities of adaptation.

If we turn to other estimates, we see that some studies show negative results. So, Odagiri (1983) reports a positive and statistically significant return coefficient for the scientific sector in Japan, but for other sectors, the coefficient is negative. This finding is not isolated in the sense that detailed results published by other authors, like Link (1981) for the United States and Fecher (1989) for Belgium, also yield negative estimates. Yet, these astonishing findings are often only at most marginally significant.

Other studies of Japanese data by Odagiri and Iwata (1986), Sassenou (1988) and Goto and Suzuki (1989) give more credible estimates. The estimates reported by Sassenou (1988) show how different the return can be depending on whether the R & D intensity is measured with respect to sales or value added as well as how the introduction of industry dummies can affect the coefficients. The originality of Goto and Suzuki (1989)'s study mainly lies in the fact that they emphasize the implications of disregarding R & D depreciation in the measurement of R & D intensity. In some sectors, such as pharmaceuticals, machinery, and chemicals, the corrected intensity measures give noticeably different estimates compared to those obtained with the uncorrected measure.

As pointed out by Mairesse and Sassenou (1991), the interpretation of discrepancies between the estimates from corrected and uncorrected measures in terms of a net rate of return versus a gross rate of return does not hold. What has to be underlined from the estimates reported by Griliches and Mairesse (1990) is the fall in estimates when both industry effects and free returns to scale are taken into account in the regressions.

Finally, Lichtenberg and Siegel (1989) and Klette (1991) carried out very large-scale experiments for the United States and Norway respectively and their estimates of the rate of return on R & D are astonishingly very close.

3.2.2. Meso Level Studies

Besides these estimates obtained at the firm level, there are several studies which have measured the rate of return on R & D at the industry level. The interpretation of the rate of return estimated through such studies is different from that given for coefficients estimated on the basis of panel data. What is measured through such an approach is the excess gross social rate of return on R & D. It is an "excess" measure because data are rarely corrected for double counting and expensing. The "gross" adjective results from the fact that the R & D intensity measure used is based on gross R & D investment and not net R & D investment. These two restrictions are not specific to industry level analyses, they are also used in panel data analyses. The social characteristic of this rate of return arises from the aggregation across firms of R & D expenditures which causes the coefficient to represent the return on industry R & D for the industry as a whole. Yet, it does not give a full estimate of the social return because it is restricted to the R & D performed inside the concerned industry. In other words, it is an internal rate of return or a rate of return internal to the industry. Consequently, the meaning of the return at the industry level is not clearer than at the firm level[1]. Table 3.3 presents a synthesis of the main estimates of the rate of return at the industry level. As in the case of firm level analyses, the R & D intensity indicator is alternatively measured with respect to sales or value added. Anticipating the following chapter, we have also summarized in this table the studies measuring both the internal and the external rates of return. This external rate of return measures what are for a given industry the external effects of the R & D realized in the other industries.

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[1]For recall, Griliches and Lichtenberg (1984) define it as the average excess of the social gross rate of return. There is no reason to expect the social return to be equalized across industries but under the hypothesis that the discrepancy between social and private returns is distributed randomly across industries, the coefficient will give a consistent estimate of the average excess of social over private returns. It is a social return because it is based on output in constant prices rather than profit calculations. It is gross because it also includes a possible allowance for depreciation. And it is excess because R & D expenditures are already included in conventional inputs at normal factor prices.

Table 3.3. Estimates of the Rate of Return at the Industry Level

Study	Sample	Data and weighting matrix	Rate of return	
			Internal	External
Terleckyj (1974)	United States 20 industries 1948-1966	Total factor productivity Value added	0.37 (0.11)	-
		Transaction flow and capital flow matrices	0.29 (0.08)	0.78 (0.21)
Terleckyj (1980a)	United States 20 industries 1948-1966	Total factor productivity Value added Transaction flow and capital flow matrices	0.20 (0.31)	1.83 (0.72)
Scherer (1982)[1]	United States 87 industries 1964-1969	Labor productivity Sales Patent flow matrix	0.13 (0.13)	0.64 (0.35)
	1973-1978		0.29 (0.14)	0.74 (0.39)
Griliches-Mairesse (1983)	France 15 industries 1964-1968, 1969-1973	Total factor productivity Sales	0.33 (0.14)	-
	United States 15 industries 1964-1968, 1969-1973		0.23 (0.12)	-
Griliches-Lichtenberg (1984a)	United States 27 industries 1959-1968	Total factor productivity Sales	0.09 (0.05)	-
	1964-1973		0.20 (0.06)	-
	1969-1976		0.34 (0.08)	-
Griliches-Lichtenberg (1984b)[1]	United States 193 industries 1964-1969	Total factor productivity Interindustry transactions Sales	0.15 (0.08)	0.74 (0.19)
	1973-1978	Sales	0.28 (0.11)	0.50 (0.25)
	1964-1969	Value added	0.08 (0.05)	0.40 (0.10)
	1973-1978	Value added	0.16 (0.06)	0.26 (0.14)
Goto-Suzuki (1989)	Japan 50 industries 1978-1983	Total factor productivity Value added Transaction flow and capital flow matrices	0.26 (0.14)	0.80 (0.42)
Leonard (1971)	United States 16 industries 1957-1968	Sales	0.09 (0.04)	-
Griliches (1973)	United States 85 industries 1958-1963	Total factor productivity Value added	0.32 (0.10)	-

Note : Estimated standard errors in parentheses.

1. In these studies, the analyses are not based on a distinction between own and purchased R & D but between own product R & D and own process and embodied R & D.

A first estimate made by Leonard (1971) gives a very weak rate of return on R & D in the US industry. This result strongly contrasts with that obtained by Griliches (1973) and is all the more disappointing as the first author makes use of sales and the second one of value added. The estimates by Terleckyj (1974,1980a) are of the same order of magnitude as the value reported by Griliches. The two types of results presented by Terleckyj are based on alternative measurement methods of total factor productivity. While the first measurement is derived from net output and net input, the second one uses gross values and accounts for quality characteristics of inputs. This explains why in the second case, the estimate of the rate of return on R & D is lower and non significant.

Except for the first subperiod studied, Scherer (1982)'s results are comparable to those obtained by Terleckyj. It is the same for results reported by Griliches and Mairesse (1983) who provide evidence of a higher rate of return in France. Griliches and Lichtenberg (1984a, 1984b) show how different the estimates may be depending on the reference period and the R & D intensity indicator. The rate of return on R & D appears to have increased over time. The estimates obtained by Goto and Suzuki (1989) are comparable to those reported for the United States.

3.2.3. Macro Level Studies

Finally, let us close this review by having a glance at some studies estimating the elasticity of R & D at the economy-wide level except for Capron (1990,1992b) who uses total R & D expenditure. These studies only consider industrial R & D expenditure. All the results gathered in table 3.4. show that there also exists a relationship between productivity and R & D at the aggregate level.

The estimated elasticities are noticeably higher than the elasticities resulting from panel experiments. Except for Italy, the private industrial R & D elasticity is lower than the total industrial R & D elasticity. In the equations with total industrial R & D, the elasticity of each type of R & D (private versus public) is equal to the estimated elasticity weighted by the relative part of the corresponding type of R & D in total R & D. Consequently, the lower level of private industrial R & D elasticities indicates that public industrial R & D expenditure contributes to productivity growth. This finding is particularly obvious for the United States, France and the United Kingdom where the public contribution to industrial R & D expenditure is very high. It is worth noting that a large part of this public intervention is not directed towards civil projects but is part of defense objectives. By running the regression for two subperiods, Patel and Soete

(1988) tested whether the coefficients were significantly different in the two periods. They find evidence that there was a break in the relationship between productivity and R & D in the mid seventies in Canada, the UK, Sweden and Japan. While the impact of R & D decreased in Canada and Sweden, it increased in the UK and Japan.

Table 3.4. Estimates of the Elasticity of R & D at the Aggregate Level

Study	Sample	Data characteristics	Total R & D	Private R & D	Public R & D
Levy-Terleckyj (1983)	United States 1949-1981	Sales No depreciation rate	-	0.27 (0.07)	0.05 (0.03)
Suzuki (1985)	Japan 1965-1982	Value added Depreciation rate (0.10) imported technology included	0.12 (0.05)	-	-
Patel-Soete (1988)	United States 1967-1985	Total factor productivity Depreciation rate (0.15)	0.61 (0.01)	0.34 (0.02)	-
	Canada 1967-1985		0.26 (0.03)	0.25 (0.03)	-
	Japan 1967-1985		0.41 (0.03)	0.41 (0.03)	-
	Germany 1967-1985		0.38 (0.01)	0.38 (0.01)	-
	United Kingdom 1967-1985		0.82 (0.06)	0.62 (0.07)	-
	France 1967-1985		0.43 (0.01)	0.37 (0.01)	-
	Italy 1967-1985		0.56 (0.04)	0.61 (0.04)	-
	Sweden 1967-1985		0.40 (0.04)	0.31 (0.03)	-
Capron (1990)	Belgium 1965-1985	Value added Depreciation rate (0.15)	0.76 (0.12)	-	-
Capron (1992b)	Belgium 1965-1985	Value added Depreciation rate (0.15)	-	0.58 (0.12)	0.24 (0.04)

Note : Estimated standard errors in parentheses.

3.3. An Assessment of Econometric Studies

What can we conclude from this survey of econometric studies ? Like Mairesse and Sassenou (1991), we think that the real issue is whether or not econometric studies can characterise the relationship between productivity and R & D in a satisfactory and useful manner. Studies are rarely comparable with each other and there are large disparities between parameters. The differences between estimates may be due to data peculiarities : periods, industries, countries, data transformation and quality, estimation methods and specification of models may, to some extent, explain the large range of estimates reported in the literature. With a view to completing this qualitative evaluation, a regression analysis has been conducted on the coefficients gathered in the preceding tables. The objective of this regression analysis is to evaluate to what extent the main data and regression characteristics play a prominent role in the explanation of the observed disparities in estimates. The characteristics taken into account are the number of enterprises covered by the sample, the periods considered, the industry sectors, reference countries, regression methods and the nature of the output.

The regression analyses have been performed on the estimated coefficients gathered in tables 3.1., 3.2. and 3.3. so that the samples of experiments are respectively :

- the estimates of the output elasticity of R & D capital at the firm level : the regressions are run on the total sample of 46 coefficients and alternatively on a subsample of 32 coefficients which does not include the estimates obtained for each industry separately (i.e. by excluding Minasian's and Schankerman's studies).

- the estimates of the rate of return on R & D at the firm level : the number of observations in this sample is of 47 coefficients in which the "abnormally" negative coefficient reported by Odagiri as well as the result of Klette's study are not included. Alternative results are also presented for a subsample of 28 coefficients which does not include the estimates obtained for each industry separately (i.e. by excluding Minasian's, Mansfield's, Link's and Goto and Suzuki's studies).

- the estimates of the internal rate of return on R & D at the industry level whose sample is composed of 17 observations.

Two alternative estimation methods have been applied on these three samples of coefficients. First, the explanatory power of data and regression characteristics have been evaluated by running the ordinary least square method. Yet, this method is not appropriate to obtain an unbiased estimate of the mean value of coefficients. The quality of adjustment varies considerably from one experiment to the other and the ability to measure the impact of R & D on productivity for each experiment is monitored by the standard deviation of estimates. Consequently, an unbiased estimate of the mean value of coefficients will be obtained by running a weighted least square regression on the distribution of coefficients whose weights are the inverted variance of the estimated coefficients. However, as the number of observations used in the studies may also have something to do with the estimated coefficients, a second weighted least square regression has been performed by using the number of firms or industries taken into account in each experiment. By doing so, we give a higher weight to coefficients based on a large sample whilst in the first weighted least square, it is the quality of adjustment which sets the weight given to the coefficients.

The data and regression characteristics from which the explanatory variables have been constructed are :

- the inverse of the number of observations taken into account in each experiment (number of firms or industries) (IOBS);

- the average period of estimation defined as the average year covered by the sample (mean year less 1950) (PER);

- a dummy variable taking the value one for the within industries estimation in cross-section analyses and zero otherwise (Industry dummies);

- a dummy variable taking the value one for data corrected for double counting and expensing and zero otherwise (corrected);

- a dummy variable taking the value one for cross-section analyses and zero otherwise (cross-section);

- a dummy variable taking the value one for analyses based on sales as output variable and zero otherwise (Sales);

- a dummy variable taking the value one for analyses bringing on Japanese data and zero otherwise (Japan dummy);

- a dummy variable taking the value one for analyses bringing on scientific sectors and zero otherwise (Scientific sector);

- a dummy variable taking the value one for studies bringing on the profit equation and zero otherwise (π);

- a dummy variable taking the value one for studies bringing on the total factor productivity measured from sales and zero otherwise (TFPs);

- a dummy variable taking the value one for studies bringing on the total factor productivity measured from value added and zero otherwise (TFPav);

- a dummy variable taking the value one for studies bringing on a production function with value added as output measure (AV);

- a dummy variable taking the value one for studies whose the R & D intensity indicator is based upon a measure of the R & D capital stock and zero otherwise (STK);

- a dummy variable taking the value one for studies which measure both internal and external rates of return on R & D and zero otherwise (External).

The regression results are listed in tables 3.5., 3.6. and 3.7. The wideness in the range of estimates is explained for about two third by data and regression characteristics. About one third of disparities in the results is a consequence of data measurement problems. As it could be thought, the output measurement issue is of prime importance. The use of either sales or value added as dependent variable or as a basis for computing productivity has significant effect on the regression results. The lack of corrections for R & D double counting and expensing as well as for depreciation in the measure of R & D intensity significantly affects the final result.

Another crucial issue in the lack of robustness between the estimates obtained from time-series and cross-sections. Time-series estimates are generally very poor and non significant, which is not the case for cross-sectional ones. Differences in the specification of regressions are also at the source of significant deviations in the estimates. So, the introduction of industry dummies reduces the estimated return on R & D (but does not seem to affect the estimated elasticity significantly).

More specifically, the main results can be summarized as follows :

- firstly, regarding the estimates of the output elasticities of R & D

Table 3.5. Regression Analysis of the Estimated Coefficients of the Output Elasticity of R & D Capital at the Company Level

Estimation method	C	Cross-Section	Corrected	Sales	Scientific sector	Π	R^2	N
OLS	0.03 (1.96)	0.06 (3.01)	0.06 (2.73)	0.06 (2.37)	-	-	0.35	47
OLS	0.01 (1.03)	0.03 (1.43)	0.07 (4.20)	0.08 (3.67)	0.07 (4.06)	0.12 (3.27)	0.58	47
WLS (inverted variances)	0.0 (0.29)	0.04 (2.75)	0.08 (4.97)	0.05 (3.72)	0.08 (5.84)	-	0.86	47
WLS (number of companies)	0.01 (1.77)	0.05 (5.57)	0.03 (3.00)	0.08 (7.70)	0.04 (2.10)	0.11 (7.14)	0.85	47
OLS	0.01 (1.26)	0.02 (1.68)	0.07 (4.88)	0.08 (4.74)	0.06 (3.83)	0.12 (4.02)	0.74	47
OLS	0.02 (1.38)	0.04 (1.92)	0.06 (3.27)	0.07 (3.81)	0.05 (2.42)	0.11 (3.46)	0.67	32
WLS (inverted variances)	0.0 (0.32)	0.05 (2.95)	0.10 (5.15)	0.05 (3.23)	0.07 (4.38)	-	0.89	32
WLS (number of companies)	0.01 (1.63)	0.06 (5.32)	0.04 (2.43)	0.08 (6.80)	0.03 (1.20)	0.11 (6.10)	0.86	32

Note : t-statistics in parentheses.
N = number of observations.

Table 3.6. Regression Analysis of the Estimated Coefficients of the Internal Rate of Return to R & D at the Company Level

Estimation method	C	TFP_S	TFP_{AV}	AV	STK	Industry dummies	Japan dummy	Scientific sector	R^2	N
OLS	0.30 (6.83)	-0.15 (1.88)	-0.03 (0.50)	-0.25 (2.36)					0.16	47
OLS	0.30 (7.84)	-0.15 (2.16)	-0.09 (1.73)	-0.25 (2.71)	0.57 (3.84)				0.38	47
OLS	0.42 (8.57)	-0.19 (2.95)	-0.19 (3.49)	-0.25 (3.12)	0.54 (4.00)	-0.17 (3.40)			0.52	47
OLS	0.36 (7.87)	-0.18 (3.17)	-0.26 (5.03)	-0.34 (4.48)	0.40 (3.22)	-0.14 (3.08)	0.13 (3.18)	0.08 (1.77)	0.64	47
WLS (inverted variances)	0.20 (6.36)	-0.07 (2.26)	-0.19 (5.33)	-0.35 (3.64)	-	-	0.14 (2.69)	0.11 (4.50)	0.85	47
WLS (number of companies)	0.32 (13.42)	-0.07 (4.17)	-0.28 (3.35)	-0.36 (6.60)	-	-0.12 (5.59)	0.17 (4.53)	-0.16 (1.88)	0.95	47
OLS	0.35 (8.89)	-0.14 (2.84)	-0.30 (5.58)	-0.37 (5.61)	-	-0.14 (3.73)	0.17 (3.59)	-0.12 (1.08)	0.74	28
WLS (inverted variances)	0.20 (7.13)	-0.07 (2.53)	-0.20 (6.01)	-0.35 (4.05)	-	-	0.14 (2.90)	-	0.91	28
WLS (number of companies)	0.32 (9.74)	-0.07 (3.01)	-0.29 (2.44)	-0.36 (4.81)	-	-0.12 (4.07)	0.18 (3.31)	-0.17 (1.40)	0.93	28

Note : t-statistics in parentheses.
N = number of observations.

Table 3.7. Regression Analysis of the Estimated Coefficients of the Internal Rate of Return to R & D at the Industry Level (N = 17)

Estimated method	C	External	TPF_{AV}	PER	PER^2	BETA	External * BETA	R^2
OLS	0.26 (6.33)	-0.04 (0.84)	-0.03 (0.74)	-	-	-		0.09
OLS	0.50 (8.96)	-0.09 (3.10)	-0.15 (3.98)	-0.04 (5.28)	0.002 (5.48)	-		0.74
OLS	0.46 (13.74)	-0.09 (4.02)	-0.10 (4.26)	-	-	-53.58 (7.17)		0.82
OLS	0.50 (12.34)	-0.15 (3.58)	-0.10 (4.42)	-	-	-67.03 (6.04)	21.38 (1.57)	0.85
WLS (inverted variances)	0.22 (5.72)	0.02 (0.52)	-0.12 (2.89)	-	-	-	-	0.38
WLS (inverted variances)	0.38 (12.66)	-0.02 (1.52)	-0.10 (5.22)	-	-	-45.69 (6.89)		0.87
WLS (inverted variances)	0.49 (11.78)	-0.17 (3.51)	-0.09 (5.39)	-	-	-76.53 (6.85)	39.56 (3.11)	0.93
WLS (number of industries)	0.36 (4.97)	-0.15 (2.11)	-0.08 (2.54)	-	-	-	-	0.79
WLS (number of industries)	0.45 (16.46)	-0.13 (5.37)	-0.09 (7.62)	-	-	-37.81 (9.86)		0.98
WLS (number of industries)	0.56 (9.71)	-0.24 (4.24)	-0.09 (8.67)	-	-	-84.44 (3.71)	47.69 (2.08)	0.98

Note : t-statistics in parentheses.
N = number of observations.
$BETA = (\frac{PER}{50})^2 (1 - \frac{PER}{50})^{10}$.

- all things being otherwise equal, the mean value of output elasticity of R & D is about .08 for sales and zero for value added when data have not been corrected for double-counting and expensing;

- cross-section analyses show a measure of elasticity superior to .05 to that obtained from time-series analyses;

- corrections for double-counting and expensing give a positive differential of elasticity which amounts to .08;

- scientific sectors have a higher elasticity than other sectors, the differential being of .07;

- estimates obtained from the profit equation give mitigated results (there is a positive differential from OLS which becomes non significant when variances-based WLS is used);

- the number of observations, the average period of estimation, the hypothesis of free return to scale, the reference country and the industry dummies do not significantly influence the estimated elasticity of R & D;

- secondly, turning to the estimates of the rate of return on R & D at the firm level :

  - all things being otherwise equal, the mean value of the gross excess rate of return on R & D is 0.20 when the return is measured with respect to sales and 0.13 when the total factor productivity with respect to sales is used as dependent variable. Yet, when the dependent variable is value added or total factor productivity with respect to value added, the estimated return is not significantly different from zero;

  - the use of R & D capital stock instead of R & D expenditure in the measure of R & D intensity does not provide a significantly different return from that obtained in the second case. The extra relative return of 40 percent emphasized by OLS results is not confirmed by WLS. This apparent discrepancy in the results may be explained by the lack of statistical representativity of this approach in our sample. Consequently, the approach calls for further investigations;

  - the introduction of industry dummies significantly affects the estimates of the rate of return (in opposition to the output elasticity of R & D) but without giving better estimates of the rate of return as it seems to be suggested by the non significance of this variable in the WLS with respect to variances;

- there is a significant premium to the Japanese R & D which amounts to 0.14;

- scientific sectors benefit by a significant premium on R & D of 0.11 (the non significant result obtained for the subsample is explained by the fact that these sectors are to a large extent excluded);

- the number of observations, the average period of estimation and the hypothesis of free return to scale do not significantly influence the estimated rate of return on R & D;

- thirdly, concerning the estimates of the rate of return on R & D at the industry level :

  - all things being otherwise equal, the mean value of the gross excess internal rate of return on R & D is 0.22 when it is estimated with respect to sales and it is 0.10 when estimates are run on the basis of value added, but these estimates are downward biased due to the fall in the rates of return during the sixties.

  - when this phenomenon is taken into account the mean values go up to 0.38 and 0.28 respectively. To grasp the decrease in the rate of return during the sixties, we introduced as an explanatory variable into the model a quadratic function of the average period of estimation (represented in the results by PER and PER^2). Yet, as such a function has infinite values at its extremes, we alternatively adjusted a Beta distribution whose optimal values of the exponents were estimated by a search procedure. According to these two approaches, the lowest rate of return was attained in 1959-1960 with values equal to 0.18 and 0.08 respectively. The mean values referred above are hit at the beginning of the seventies;

  - taking value added instead of sales to measure R & D intensity shows a decrease in the estimated rate of return of about 10 percent;

  - the joint estimation of both internal and external rates of return decreases the estimate of the internal rate of about 10 percent. Yet, as shown by the combined variable External *BETA, this effect is less pronounced when the internal rate of return is weak.

In a nutshell, the econometric evaluation of the impact of R & D on economic growth allows to conclude that R & D investment is a significantly important source of productivity gains. A large part of discrepancies between the coefficients estimated may be explained by data and regression characteristics. To some extent, the discrepancies explained by our regression analysis show that econometric studies of R & D are not so imprecise and unreliable as it might be thought at first glance. Yet, plentiful methodological and conceptual problems remain. In the last years, some very significant improvements have been brought to the modelling of R & D and its spillover effects.

3.4. Adjustment Cost Models

So far, we have only considered static equilibrium models in which production factors are always at their expected long-term level. These models can be made dynamic in two ways :

- first, by considering that all or some factors only adjust partially to their short-run equilibrium level;
- second, by envisaging a cost of adjustment model with a short-run disequilibrium situation whose dynamic perspective presupposes the realisation of a long-term equilibrium.

The adjustment cost models are based upon the hypothesis that firms face a technology which uses variable factors (e.g., labor, energy and intermediary inputs) and quasi-fixed factors (like physical capital and R & D capital). Some of the quasi-fixed factors cannot vary at short-term with respect to the equilibrium level and any change in the level of these factors implies costs of adjustment.

Mohnen and Nadiri (1985) developed cost of adjustment models including R & D investments. They are assimilated to a production factor because they are at the origin of new products and/or processes generating new sales and/or a reduction of production costs. Both physical capital and R & D stock face costs of adjustment when their level changes. These costs are caused by the instalment of new machines, the reorganisation of production tasks and the familiarization with new working circumstances in the case of capital; they also result from the difficulty in implementing and working out a research project, and in marketing new products and processes. In this model, labor and intermediary inputs are variable factors.

The objective of the firm is to select both physical and R & D profiles that minimize the discounted value of costs at given prices :

$$\underset{\substack{K_{t+\rho} \\ R_{t+\rho}}}{\text{Min}} \sum_{\rho=0}^{\infty} \{[C_{t+\rho} + P_{R_t} I_{R_{t+\rho}}] (1 - u_t) + p_{K_t} I_{K_{t+\rho}}\} (1 + r)^{-\rho}$$

with $C_{t+\rho} = c\ (p_{L_t}, K_{t+\rho-1}, R_{t+\rho-1}, \Delta K_{t+\rho}, \Delta R_{t+\rho}, Q_t)$

$I_{K_{t+\rho}} = K_{t+\rho} - (1 - \delta_K) K_{t+\rho-1}$

$I_{R_{t+\rho}} = R_{t+\rho} - (1 - \delta_R) R_{t+\rho-1}$

under the production constraint

$$Q_t = F\ (M_t, L_t, K_{t-1}, R_{t-1}, \Delta K_t, \Delta R_t, t)$$

where $p_{R_t}, p_{K_t}, p_{L_t}$ are respectively the acquisition price of R & D and physical capital and the real wage rate

u_t is the corporate tax rate

δ_K, δ_R are respectively the depreciation rate of capital and R & D

$\Delta K_t = K_t - K_{t-1}$

$\Delta R_t = R_t - R_{t-1}$

t is a proxy for exogenous technical change

r is a constant actualisation rate.

C, the cost variable has been normalized with respect to the price of materials. From the following functional form of the normalized restricted cost function :

$$\begin{aligned} C_t = {} & Q_t [\alpha_0 + \alpha_1 p_{L_t} + \tfrac{1}{2} \alpha_2 P_{L_t}^2] + \alpha_3 K_{t-1} + \alpha_4 R_{t-1} + \tfrac{1}{2} \alpha_5 K_{t-1}^2 / Q_t \\ & + \tfrac{1}{2} \alpha_6 R_{t-1}^2 / Q_t + \alpha_7 K_{t-1} R_{t-1} / Q_t + \tfrac{1}{2} \alpha_8 \Delta K_t^2 / a_t + \tfrac{1}{2} \alpha_9 \Delta R_t^2 / a_t \\ & + \alpha_{10} P_{L_t} K_{t-1} + \alpha_{11} P_{L_t} R_{t-1} \end{aligned}$$

for which restrictions on parameters are imposed [1] so that the marginal adjustment costs are zero in the steady state. The resolution of the optimization problem yields :

$$K_t - K_{t-1} = \beta_1 Q_t + \beta_2 p_{L_t} Q_t + \beta_3 p_{K_t} Q_t + \beta_4 p_{R_t} Q_t + \beta_5 K_{t-1} + \beta_6 R_{t-1}$$

$$R_t - R_{t-1} = \gamma_1 Q_t + \gamma_2 p_{L_t} Q_t + \gamma_3 p_{K_t} Q_t + \gamma_4 p_{R_t} Q_t + \gamma_5 K_{t-1} + \beta_6 R_{t-1}$$

$$L_t = [\alpha_1 + \alpha_2 p_{L_t}] Q_t + \alpha_{10} K_{t-1} + \alpha_{11} R_{t-1}$$

$$M_t = C_t - p_{L_t} L_t$$

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[1] i.e. $\alpha_8 = \alpha_9 = 0$.

(8)

in which the β_i and γ_i coefficients are linked to the α_i by different constraints [1].

It is a similar model which was successfully estimated by Cardini and Mohnen (1984), Mohnen and Nadiri (1985) and Mohnen, Nadiri and Prucha (1986) for the Italian, American, Japanese, German and French cases. They observed that the adjustment lags of R & D are noticeably more important than for physical capital[2]. While the adjustment speed of capital is relatively identical among countries, the adjustment speed of R & D is faster in the United States. Furthermore, the internal rate of return appears higher for R & D than for physical capital. The main results are summarized in table 3.8.

Table 3.8. Impact of R & D in the Manufacturing Sector (1965-1978)

Dependent variable	Parameter	US	Japan	Germany	France	Italy
Gross output	Adjustment speed in first period	.17	.11	.09	.02	-
	Short-run elasticity	.16	.23	.20	.13	-
	Internal rate of return	.11	.15	.13	-	-
	Contribution to labor productivity	.03	.03	.02	.04	-
Value added	Adjustment speed in first period	.15	.26	.26	.07	.13
	Short-run elasticity	.18	.36	.35	.16	.18
	Internal rate of return	-	-	-	.11	.12

Sources : Cardani and Mohnen (1984),Mohnen and Nadiri (1985) and Mohnen, Nadiri and Prucha (1986).

While the labor factor is still considered in a traditional way in this model, the incorporation of R & D expenditure as a quasi-fixed factor submitted to adjustment costs makes this model an important step towards the endogenisation of technical change. It could easily be extended to take into account human capital by distinguishing the skill levels some of which are not readily malleable in the short run and face adjustment costs resulting from the learning process inherent in the acquiring skills.

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[1]For more details, cf. Mohnen and Nadiri (1985) and Mohnen, Nadiri and Prucha (1986) whose studies have inspired the simplified model developed here.

[2] The mean lag for physical capital is about 3 years against five years and more for R & D capital.

This dual formulation based on the producer theory, which represents the technology of production by means of the cost function, is an important methodological step in modelling producer behavior. The measurement of the rate of return on R & D in models noticeably differs from the method used in Cobb-Douglas functions.

In the framework of the adjustment-cost model, it is assumed that the firm minimizes the present value of expected production costs. This problem can be written as :

$$\min_{I_K, I_R} \int_0^{\infty} e^{-\rho t} \left[c(\rho_L, K, R, I_K, I_R, Q) + \rho_K(\rho + \delta_K) K + \rho_R (\rho + \delta_R) R\right] dt$$

where the prices $\rho_i (\rho + \delta_i)$ are the relative rental rates of the capital stocks, δ_i, the rate of depreciation and ρ, the real discount rate.

The internal gross rate of return on R & D is equal to :

$$(\rho + \delta_K) = \left(- \frac{\partial C}{\partial R} + \frac{\partial \dot{C}}{\partial I_R}\right) / P_R$$

This equation shows that the internal net rate of return on R & D is nothing else that the diminution of the production cost due to a marginal increase of R & D stock, net of marginal adjustment cost and net of depreciation.

If the producer can immediately adapt his inputs to his level of production, the cost minimisation problem amounts to minimizing the costs at each period :

$$\min_{I_K, I_R} \left[c(\rho_L, K, R, Q) + \rho_K(\rho + \delta_K) K + \rho_R (\rho + \delta_R) R\right]$$

so that in the static case, the internal gross rate of return on R & D is given by :

$$(\rho + \delta_R) = - \frac{\partial C}{\partial R} / P_R$$

from which, compared to the dynamic case, the marginal adjustment cost has disappeared. So, the existence of costs of adjustment affects the rate of return on R & D.

Chapter 4. The Spillovers from R & D Investment

The effects of R & D go beyong the firm, the industry and the country that perform the R & D. The main feature of such an investment is that firms which do it cannot exclude others from obtaining a part of the benefits free in charge. In other words, spillovers arise because the returns of R & D are not entirely appropriable. Only a perfectly discriminant monopolist can appropriate quasi-rents from technical change and so escape the diffusion of technological know-how to other enterprises. Von Hippel (1982) indicated that, in the case where there is no monopoles and even if there exists a patent or licence, there will not be perfect appropriability of the scientific discovery. There is to some extent a contradiction between the social interest which suggests that the diffusion of innovations should rapidly spread out throughout the economy and so boost the economic growth and the private interest which checks the diffusion process in order to maximise the private rent. Coming back to the seminal contribution of Arrow (1962), technology is equivalent to information and as such characterized by indivisibilities. It can be transmitted and rented without cost. Once produced, a new technology is like a public good because it is available to everybody free of charge. At the two extremities of the spectrum of appropriability opportunities, there is on one side the perfect monopolist who can grab all the benefits from an innovation, and, on the other side, the producer facing a perfect competititve market is not in a position to grab the welfare benefits from the innovation. Along the spectrum, there are lots of situations which depend on the market structures. This appropriability phenomenon corresponds to a first kind of spillovers emphasized by Griliches (1979). There are characterized by R & D intensive inputs purchased from other industries at less than their full quality price. Their productivity effects are not fully measured by official prices indexes because all quality improvements are not totally appropriated by the senders and are rarely incorporated into official statistics. The second kind of spillovers deals with the real knowledge transmission. They result from discoveries and innovations in an industry whose some ideas of which can be fruitfully borrowed in other industries to generate technological improvements of products and processes in these industries. All these industries need not buy from each other to benefit from this new knowledge and consequently, such spillovers cannot adequately be trailed through the conventional interindustry relationships such as input-output matrices.

So, these "knowledge" spillovers are more difficult to trace than the "economic" spillovers because we do not have any grounded a priori information about the potential beneficiaries of these researches. At the very most, it seems reasonable to assume that for a given firm the major knowledge spillovers come from inside its own industry. For the knowledge spillovers coming from outside its own industry, it is the concept of technological proximity which must guide the search of source industries. The confusion in the literature between these two kinds of spillovers is due to the fact that, in empirical analyses, it is not an easy task to measure their effects separately. Regarding the methods, the measure of any type of spillovers will be conveniently approximated but one should bear in mind that, to some extent, the measure will also represent the effects of the second type of spillovers.

While case studies are less general than econometric studies, they enable a more acute measure of the real performance of specific innovations. However, their results cannot be generalized and these studies often focus on successful innovations. They usefully supplement the more aggregated approaches which deal with the full research system at firm, industry or economy wide level. In order to have a larger view of the extent of inter-industry spillovers, several approaches have been investigated in the literature. A first method is to take into account the proximity between industries by giving weights to R & D stocks according to how close to each other industries are. The question here is to know what proximity measure to use to construct the weights. The different proximity measures reported in the literature are successively : weights proportional to the flows of intermediate input purchases by using the input-output coefficients, to the flows of patents or innovations by constructing a technology flow matrix or to the firm's position in a technology space as measured by the uncentered correlation of the patent distribution across technological areas. A second approach is to consider the outside pool of R & D knowledge globally by adding up the R & D stocks of other firms or industries. A strong assumption at the basis of this method is that the R & D knowledge of other firms or industries is equally useful for the studied industry whatever its characteristics. A last method is to enter separately into the production function the R & D stock of each potential source of R & D spillover which constitutes an extension of the preceding one.

4.1. About some Case Studies

In a case-study of 17 industrial innovations, Mansfield and al. (1977) calculated both the private and the social rates of return from the investments in these innovations. Their results indicate that the private rates have been much lower than the social ones. The medium social rate of return was about 56 percent against a median private rate of about 25 percent. Yet, there are very high variations in the private rates of return : six innovations had a return inferior to 10 percent and five innovations a return superior to 40 percent. In this study, private benefits are measured by the net profits from the innovator to the innovation. Social benefits are obtained by adding to the private benefits the benefits derived by households and other firms from price reducing and imitation and substracting the private costs, the unsuccessful R & D costs incurred by other firms and environmental costs. Information was obtained from interviews with the relevant firms and from published reports. The median values are consistent with the main estimates obtained from econometric studies. Yet, this case-study shows that there can be very wide differences between private and social rates of return, a result also consistent with new econometric studies.

In a study of the spillovers from advances in general purpose computers to the financial services, Bresnahan (1986) showed that the demand for high-speed computers implied a very large social gain. The welfare gain that he measured is the reduction in the price-performance ratio of computers not taken into account in real output indexes. The basic idea is that, if an innovation only lowers the price of a consumption good, the area under its demand curve measures the sum of the increased producer's surplus in the downstream sectors plus the consumer's surplus of final demanders. Purchases of computers by the financial services are treated as if this sector acted as an agent for its customers and under this assumption, the welfare gains to the customers from service's derived demand for computers are evaluated. From the calculations covering years 1958 and 1972, it appears that the spillover to adopters of computers and their customers has been large comparatively to expenditures on computers. The size of the downstream welfare gains resulting from the fall in the price-performance ratio of computers in the US was at least five times the size of computer expenditures in 1972.

A method of constructing quality-adjusted price indices capturing the impact of product innovations has been suggested by Trajtenberg (1989). This approach is based on a two-stage estimate. First, discrete choice models are used to model the consumer preference system and to derive the surplus function in order to measure the benefits from innovation. Second, quality-adjusted price indices are constructed by using the estimates of the social surplus function. The author applies the method to the case of Computed Tomography Scanners, a highly sophisticated medical diagnostic technology first introduced in the US in 1973. The evolution of this market was characterized by a fierce competition between firms which brought about a breathtaking pace of technical advance. The pace of innovation in CT scanners subsided in the mid-eighties as the technology matured and new technological developments took over. His main finding is that the quality-adjusted price of this product went down from 10 000 to 7 from 1973 to 1982 (implying an average price reduction of 55 percent per year) while the unadjusted price went up from 10 000 to about 26 000, (i.e. 2.6 times more expensive in 1982). The rate of decline particularly staggered during the first years following the introduction of the innovation. This example illustrates how inadequate conventional economic indicators are to deal with the welfare consequences of technical advance.

4.2. The Inter-Industry Technology Flow Matrix Approaches

The first to propose the construction of an input-output matrix of invention flows was Schmookler (1966) but it was only ten years later than his advice materialized with the first attempt made by Terleckyj (1974). In a first analysis, Terleckyj combined R & D data with conventional input-ouput tables to estimate the R & D borrowed by an industry under the hypothesis that the higher the purchase of intermediate inputs of an industry from an other industry is, the more knowledge the purchasing industry borrows from the sending industry. He then regresses the total factor productivity growth rates of manufacturing industries[1] on R & D performed in the industry and the R & D embodied in inputs purchased from other industries. He also operates a distinction between privately and publicly-financed R & D. The estimated excess rate of return for embodied R & D was almost triple the rate of return on own R & D for private R & D while the indirect effects from federally-financed R & D were not significant. His result as well as the main ones of studies discussed below are reproduced in table 3.3. of the preceding chapter. In a second study, Terleckyj (1980a) re-examines his results by exploiting new data on total factor productivity growth which attempted to account for quality improvements of inputs. The coefficient for privately-financed purchased R & D was statistically significant and more than twice the estimate obtained with unadjusted data.

Griliches and Lichtenberg (1984b) reexamined this relationship between productivity growth and R & D intensity using detailed data for US manufacturing industries over various subperiods and breaking down R & D into own and purchased product- and process-improvement-oriented components. According to them, the productivity growth rate of an industry is affected by the R & D performance of industries which supply it with intermediate inputs because of errors in the output deflators of these supplying industries-errors which cause the materials deflators not to accurately reflect changes in the user value of intermediate inputs. They add that the extent of mismeasurement of the growth in a deflator depends on the extent of product-oriented R & D activity in the supplying industry and argue that "since process-oriented R

1 For non-manufacturing industries, only indirect returns are significant with a coefficient of 1.87.

& D does not alter the characteristics of products sold in inter-industry transactions, it should not contribute to errors in the measurement of deflators corresponding to these transactions". In their subsequent empirical analysis, these measurement errors are assumed to be proportional to the product-oriented R & D intensity of supplying industries. Their results are consistent with the assumption that the product-oriented R & D of the origin industry has a lesser effect than own process-oriented and embodied product-oriented R & D. This study is a re-assessment of Scherer (1982)'s study in which the author gave "evidence of substantial returns on used R & D, i.e. from internal process work and the purchase of R & D embodying products, but not ... to the performance of product R & D". In their study, Griliches and Lichtenberg showed that the significance of the combined process and embodied R & D variable was largely due to the process component.

A similar study using an input-output table of transaction flows was realized by Goto and Suzuki (1989) to examine the effects of R & D on the productivity growth of Japanese manufacturing industries. They obtain comparable results to these obtained by preceding analyses : the coefficient of the embodied R & D intensity is much larger than that of own R & D intensity. They complete their study by an attempt to measure the effect of electronics technology upon the productivity growth in industry through the electronics-related embodied R & D and through the diffusion of technological knowledge created by the electronics-related industries. The knowledge spillover variable is a weighted sum of R & D by electronics-related industries where the weights are the uncentered correlation coefficients between the R & D expenditures by product areas realized by each industry and by the electronics-related industries. The results suggest that the impact of electronics technology on the productivity growth of industries is mainly achieved through the diffusion of technological knowledge rather than through the electronics-related embodied R & D. This finding may be explained by the public goods characteristics which permit industries to acquire these technologies through other channels than through the transactions of intermediate or investment goods and exploit them to develop new products and to improve their production processes.

The second way of constructing an inter-industry technology flow matrix, initiated by Scherer (1982), is by classifying patent data according to industry of origin and industries of use. The patent flow matrix is then used to attribute R & D data by industry of origin to the industry of use. Patents with multiple or general uses were flowed out to multiple using industries proportionally to their purchases from the origin industry. In his matrix, row sums measure R & D by industry of origin, column sums R & D by industry of use and the diagonal represents pure process R & D. Then, he uses these new data to analyse the links between R & D and productivity growth by distinguishing between the effects of origin and user industry R & D. Origin industry R & D concerns own product R & D while user industry R & D combines own process and embodied R & D. He finds little positive effect of origin industry R & D and a high positive effect of user R & D and concludes that user R & D is the more appropriate measure. Yet, whereas Scherer's results indicate an increase in both the size and the significance of the coefficient on user R & D from 1964-69 to 1973-78, Griliches and Lichtenberg (1984b) in their re-examination of Scherer's findings on the basis of a more disaggregated and superior data set observe a secular decline in the effect of user R & D on productivity growth. In contrast to Scherer, they also find own-product of R & D to be a significant determinant of productivity growth except for the period from 1964-68 to 1969-73.

A more extensive similar study was realized by Englander, Evenson and Hanazaki (1988) by pooling country data for the period 1970-1983. Their country sample includes France, the United-States, the United-Kingdom, Germany, Japan, Canada and Italy. To construct the user industry R & D stocks, their use the Canadian patent-based technology flow matrix by assuming that the proximity between industries is the same for all the countries. Then, they separately regress total factor productivity levels on user industry R & D intensities and on origin industry R & D intensities for both manufacturing and non-manufacturing industries. From their estimates, they conclude that productivity levels are linked to user industry R & D, even more so in manufacturing than in non-manufacturing, and that the extent of these links varies a lot across industries. The effects are higher in the R & D intensive industries and the equation using user industry R & D stocks instead of origin industry R & D stocks gives better results. In order to see if the R & D potential had really changed over the period, alternative regressions were realized in which the influence of R & D could modify after the period 1970-1973. Their results give evidence that the R & D seems to be becoming less productive after this period in a lot of industries. However, such an observation may be discussed because of the weak significance of the estimated coefficients. It will also be noted that only seven coefficients are significant and have the right sign in their analysis, four coefficients are non-significant, the remaining ones are generally significantly negative. The authors do not offer clear explanation for such divergences in results. The omission of important explanatory variables for the non-manufacturing industries, the low user industry R & D stocks for some industries and the distortions in the measure of the explanatory variable may be at the origin of the mitigated results obtained.

On the one hand, the transaction approach assumes that the user industries of R & D output originated in another industry are distributed proportionally to the purchases of

Table 4.1. Inter-Industry Proximity and Spillovers

1. Intermediate input flows

Flow of technology embodied in intermediate goods from origin industry i to user industry j :

$$T^1_{ij} = a_{ij} R_i :$$

where a_{ij} = share of the output of industry i sold to industry j as intermediate goods
R_i = R & D expenditure or stock of industry i

Flow of technology embodied in the investment goods purchased by user industry j to origin industry i :

$$T^2_{ij} = c_{ij} R_i :$$

where c_{ij} = share of the output of industry i sold to industry j as investment goods
Total in flow of technology from industry i to industry j :

$$T_{ij} = T^1_{ij} + T^2_{ij}$$

Total in flow of technology to industry j :

$$T_j = \sum_i T_{ij} = \sum_i (a_{ij} + c_{ij}) R_i$$

$$\frac{\overset{\circ}{P}_j}{P_j} = \alpha + \beta \frac{R_j}{Q_j} + \gamma \frac{T_j}{Q_j}$$

2. Proximity in the technology space

Proximity between the firms i and j :

$$P_{ij} = (f_i f_j') [(f_i f_i') (f_j f_j')]^{-1/2}$$

where f_k = technological position vector of firm i measured by the fraction of the firm's research effort devoted to the N diverse technological areas $[f_k = (f_{k1} \ldots\ldots f_{kn})]$

R & D potential spillover pool to firm i :

$$s_i = \sum_{j \neq i} P_{ij} R_j$$

Firms are clustered into groups according to their technological position to partition the total pool into the part coming from inside the cluster for a firm belonging to a cluster (S^c) and a part coming from outside the cluster (S^o).

$$\frac{\overset{\circ}{P}_j}{P_j} = \alpha + \beta \frac{R_j}{Q_j} + \gamma \frac{\overset{\circ}{S}{}^c}{S^c} + \gamma\lambda \left(\frac{\overset{\circ}{S}{}^o}{S^c}\right)$$

intermediate inputs and capital goods to this industry and, on the other hand, the patent approach assumes that each industry has a same propensity to patent, all patents have a same value inside an industry and patent data are representative of the innovative activity. Each of these approaches has its own advantages and drawbacks. To overcome some limits of the patent approach, it could directly be made use of the flows of innovations from origin industries to user industries. It is the way adopted by Robson, Townsend and Pavitt (1988) in a descriptive analysis of the sectoral patterns of production and use of technology in the UK during the period 1945-1983. Unfortunately, this innovation-based intersectoral technology flow analysis has not been continued by an econometric estimation of the social rate of return of these innovations. In this descriptive study, the information was collected through a survey of significant innovations commercialised in the UK. Their sample covers more than 4 000 innovations which are identified with respect to the innovating industry and the first user industry. Five "core" sectors appear to be at the origin of about two third of the innovations : chemicals, machinery, mechanical engineering, instruments and electronics. The ratio of products to process innovations is about four in the core sectors against two for the full sample. From a comparison of their data with Scherer's, they observe that sectoral structures of production and use of technology are very similar in the UK and US. A trend analysis in the production and use of technology shows that there has been an increase in the proportion of product innovations used outside manufacturing and considerable shifts in the distribution of production within manufacturing where innovations increase in instruments and electronics and decrease in chemicals and steel.

4.3. The Spillovers in the Technology Space

Alternatively, as summarized in table 4.1. one can also measure the technological proximity between firms by characterizing their positions in the technological space. It is possible, for example, to use the distribution of the firm's patents over patent classes to characterize their technological position. This approach was developed by Jaffe (1986). He quantifies the effects of exogenous variations in the state of technology (technological opportunities) and of the R & D spillovers on the R & D productivity of firms. He observes that the R & D productivity is increased by the R & D of technologically proximate firms though their R & D lowers the profits and market value of low-R & D-intensity firms. Firms appear to adjust the technological composition of their R & D in response to technological opportunity. He defines the technological opportunity as the exogenous variations in the cost and the difficulty of innovation in different technological areas.

To look for the effects of technological opportunities and spillovers, he identifies the technological areas of firms. The technological position of firms is captured through the distribution of the firms' patents over patent classes. Assuming that the existence of technological spillovers implies that a firm's R & D success is affected by the research activity of its neighbors in technology space, a potential spillover pool, which is the weighted sum of other firms' R & D, is measured. On the basis of position vectors, firms are classified into technological groups. Firms whose technological focus is sufficiently similar are assumed to face the same state of technological opportunity. In a second stage, he relates the firm's patent applications, profits and market value to its R & D, the potential spillover pool, dummies for the technological opportunity, its capital stock, its market share and the concentration ratio. The main results are presented in table 4.2. The patent elasticity of R & D is .88 for the average firm and increases with the value of the average pool. The patent elasticity with respect to the R & D pool is about 1.1. This result shows that more than one-half of R & D impact on patents comes from the spillover effect. The results from the profit equation convey a gross rate of return on R & D of 27 percent against 15 percent for physical capital. The profit elasticity of R & D is .18 and is increased by the spillovers. Yet the direct effect of the pool is to lower profits. About one-third of the net increase of profits due to R & D comes from the spillovers.

For firms with largely less R & D than the mean, the net effect of the pool is negative. While from a purely technological standpoint R & D spillovers constitute an unambiguous positive externality, they are potentially blurred with a negative competitive effect of competitors' R & D. This competitive effect of the pool comes into play when we turn to the economic return on R & D. Finally, the average elasticity of the firm's market value to the pool is about .05 and the pool effect is negative for firms with a low R & D-capital ratio.

In a complementary study, Jaffe (1988) quantifies the effect of technological opportunity, market demand and R & D spillovers on R & D effort and productivity growth. The elasticity of own R & D with respect to the research pool is statistically significant and equal to .27. This result indicates that the technology position is an explanatory factor of R & D investments. The fraction of cluster pool in total pool is also included to estimate if there is a premium for the within-cluster firms. The absence of a cluster premium effect gives evidence that there is no further differential to the in-cluster firms. In order to distinguish between demand-pull and technological opportunity effects, he introduces in his model the fractions of sales going to distinct markets as indicators of market position. This variable proves significant, which allows us to say that innovative activity

Table 4.2. Technological Opportunity and Spillovers in US

	log (patents)	log (profits)	log (market value)	log (R&D)	log (sales) [1]
log (R&D)	.88 (4.78)	.18 (4.29)			R&D/sales 1.34 (31.16)
log (R&D) * log (pool)	.35 (7.29)	.06 (2.90)			
log (pool)	.51 (4.89)	-.10 (1.79)	-.06 (1.87)	.27 (3.34)	log (cluster pool stock) 0.10 (2.41)
R&D/capital			3.31 (15.84)		
(R&D/capital) * log (pool)			.80 (8.19)		$(\frac{\text{out of cluster}}{\text{cluster}})$ pool stock .0004 (1.59)
log (capital)		.83 (18.75)			
cluster pool/total pool				-.06 (0.20)	

Note : values between parentheses are t-statistics.
[1] Equation estimated with logarithmic differences.

Source : Jaffe (1986, 1988).

is the result of both the pull of market forces and the push of exogenous technological factors on the supply side of innovation.

In his productivity function, both technological position and market position are not significant. The measure of the growth excess return on R & D (data not having been corrected for double counting) is significant and implies an annual rate of return of 27 percent (the initial coefficient being calculated over 5 years). The elasticity of the cluster pool stock says that a 10 percent increase of the R & D pool yields 1 percent more output of the firm. The coefficient of the relative value of the out-of-cluster pool stock with respect to the cluster pool stock is very small, which gives evidence of an apparently localized effect of spillovers. So, R & D generated outside the cluster seems to considerably influence the R & D of the firms belonging to a cluster but not directly their productivity.

4.4. The Econometric Measurement of Total Spillovers by Industry

The measure of the spillover effects by considering the unweighted outside pool of R & D knowledge was essentially initiated by Bernstein (1988) and Bernstein and Nadiri (1989) in their analysis of both intra-industry and inter-industry spillovers in seven Canadian industries and of intra-industry spillovers in four US industries. In the study of the spillovers between Canadian industries the production technology is characterized by a cost function with labour, materials, physical capital and R & D capital as variable inputs and the R &D capital of all rival firms in the same industry and the R & D capital of other industries as intra-industry and inter-industry spillover variables respectively. From the estimates of a translog cost function and of cost share equations, the author derived the elasticities on unit costs of production and factor demands with respect to the spillover variables and the rates of return on R & D. His main findings are that :

- the estimates related to the spillover variables are generally significant;

- the inter-industry spillovers exert greater downward pressure on average production costs compared to intra-industry spillovers;

- unit costs decrease more in response to an increase in the intra-industry spillover in industries with relatively larger R & D cost shares and in the inter-industry spillover in industries with relatively smaller R & D cost shares;

- for all industries, the inter-industry spillover acts as a substitute for the own R & D capital input;

- for firms operating in industries with relatively smaller propensities to spend on R & D, the intra-industry spillover acts as a substitute for their own R & D while for industries with relatively larger R & D propensities, it acts as a complement to their own R & D;

- there is a substantial difference between the social and private rates of return, and R & D-intensive industries show higher social rates of return than other industries;

- the intra-industry spillovers exceed the inter-industry ones, the latter being similar across all industries.

Consequently, from the results summarized in table 4.3., we observe that spillovers create an incentive for firms to free ride on the efforts of other firms by substituting for their own R & D capital demand, except regarding the intra-industry spillovers to R & D intensive firms. On the other hand, the differential between the social and private rates of return are due to the intra-industry spillovers, the R & D-intensive firms being the most important sources of R & D spillovers.

The analysis of intra-industry spillovers in US industries is an application of the theory of dynamic duality in which physical and R & D capital stocks face internal adjustment costs and the operating costs are the variable factor. In this approach, the net rates of return are calculated as net of depreciation as well as net of marginal adjustment cost. The main findings obtained from the estimates are reported in Table 4.4. The speed of adjustment for R & D capital corresponds to a mean lag in the adjustment of R & D to its desired level of about three to four years. For each industry, the long-run R & D elasticity with respect to the intra-industry spillover is negative which implies that the spillover is a substitute for own R & D capital. So, on the one hand, a firm's R & D investment reduces the production costs of rival firms and, on the other hand, its spillovers generate free-riding as they diminish a firm's incentive to invest in R & D. For all industries, the net social rate of return greatly exceeds the net private return and varies significantly across industries.

These two case studies give some support to Spencer (1984)'s theoritical finding that an increase in intra-industry spillovers reduces the incentive to invest in R & D. However, contrary to the argument that the disincentive effect impringes most strongly in

R & D-intensive industries, the Canadian study provides a counter-evidence. A similar observation is emphasized by Levin (1988) from an industrial survey on the nature of appropriability and technological opportunity.

Table 4.3. Intra and Inter-Industry R & D Spillovers between Canadian Firms (1978-81)

Industries	Spillover elasticities on R & D capital		Net Social rate of return on R & D capital		
	Intra-industry	Inter-industry	Private	Intra-industry spillover	Inter-industry spillover
Food and coverage	-.67	-5.77	.12	.06	.02
Pulp and paper	-.34	-6.50	.12	.07	.02
Metal fabricating	-.86	-5.10	.12	.16	.02
Non-electrical machinery	-1.29	-3.65	.12	.16	.02
Aircraft and parts	.54	-3.87	.12	.09	.02
Electrical products	.54	-3.64	.12	.12	.02
Chemical products	.37	-3.54	.12	.13	.02

Source : Bernstein (1988).

Table 4.4. Intra-Industry R & D Spillovers between US Firms (1965-78)

Industries	Speed of adjustment	Long-run spill-over elasticities on R & D capital	Net social rate of return	
			Private	Intra-industry spillover
Chemicals	.36	-.08	.07	.05
Petroleum	.32	-.16	.07	.09
Machinery	.26	-.11	.07	.02
Instruments	.22	-.07	.07	.07

Source : Bernstein and Nadiri (1989).

4.5. Tracing the Sources of Spillovers

In the preceding methods, the R & D spillover was approached through a single aggregate. Yet, each industry generates specific spillover effects on other industries. For the policy maker, it is important to correctly identify the industries which generate the highest social rate of return on R & D. By entering separately the stock of each potential source of R & D spillover in the production cost function of each industry, Bernstein

(1989) and Bernstein and Nadiri (1988, 1991) have empirically demonstrated that tracing the sources and beneficiaries of each inter-industry spillover is econometrically feasible. Contrary to other approaches, this one does not rely on any arbitrary technology flow matrix. Each producer is treated as a distinct spillover source and the direction and magnitude of the interindustry spillovers can vary across receiving industries so that the spillover network of senders and receivers can be traced.

As knowledge benefits generated in one industry cannot be completely appropriable, they spill over to other industries which incorporate the freely obtained knowledge into their production process, thereby, causing autonomous technological change to these receiving industries. These spillovers can be captured through the cost function as illustrated in table 4.5. This table describes the theoretical model and the empirical specification used by Bernstein (1989). Factor demands are derived from the cost function by using Shephard's lemma. These equations define the production equilibrium. The gross private rate of return on R & D capital is equal to the real value of marginal cost reduction. The social rate of return differs from the private rate by the spillover effects from one's own industry to other industries. These spillovers are the inter-industry cost effects associated with own R & D capital. So, the social rate of return is equal to the private rate plus the sum of the marginal inter-industry cost reductions.

Bernstein estimated this model on data for nine Canadian industries for the period 1963-1983. R & D capital stock is measured by assuming a depreciation rate of 10 percent. Production cost was defined as the sum of the costs of labor, materials and physical capital and data corrected for double counting and normalized with respect to materials. The estimation results give for each industry some statistically significant R & D spillover coefficients. Both gross private and social rates of return to R & D capital calculated from estimation results are summarized in table 4.6. All industries were influenced by spillovers but not all were sender industries. All industries show very high private rates of return. These values are higher than the rates of return on physical capital whose average value is about 10 percent. Extra-private returns vary a great deal among industries. Nonelectrical machinery, rubber and plastics, petroleum products and chemical products industries are the main spillover sources. Primary metals, nonelectrical machinery, electrical products and petroleum products industries are the main spillover receivers. Metal fabricating, transportation equipment and gas and oil wells industries play a minor role as generators and receivers of spillovers.

Bernstein and Nadiri (1988) estimated a similar model on data for five US industries for the period 1958-81. In this analysis, all industries appear to be spillover senders but the spillover effects and social rates of return highlight a great deal of interindustry variation. In the transportation equipment industry, the social rate of return is 16 percent against 130 percent in the scientific instruments industry. Globally, their results are very similar to those found in their most recent extensive study.

Table 4.5. A Static Model of Inter-Industry Spillovers

1. Theoretical model

- Cost function $C = C(Q, K_r, S_r, W)$
- Factor demand function $F_i = \frac{\partial C}{\partial W_i}(Q, K_r, S_r, W)$
- Private rate of return on R & D capital $\rho = -\frac{\partial C}{\partial K_r} / \rho_r$
- Social rate of return on R & D capital $\gamma = \rho - \sum_{h \neq i} \frac{\partial C^h}{\partial K_r} / \rho_r$

2. Operational model

- $C = \beta_0 + \beta_q q + \sum_i \beta_i w_i + \beta_r k_r + \sum_i \sum_{j=i+1} \beta_{ij} w_i w_j + \sum_i \beta_{ir} w_i k_r + \sum_h \beta_{hr} k_r s_r^h$
- $F_i = \frac{W_i V_i}{C} = \beta_i + \sum_{j \neq i} \beta_{ij} w_j + \beta_{ir} k_r$
- $\rho = -\frac{C}{\rho_r K_r}(\beta_r + \sum_i \beta_{ir} w_i + \sum_h \beta_{hr} s_r^h)$
- $\gamma = \rho - \frac{C^h}{\rho_r K_r} \sum_{h \neq i} \beta_{rh} k_h$

Source : Bernstein (1989).

R & D spillovers do not only affect production characteristics but both output supply and input demand decisions. There are economic and technological externalities associated with spillovers which influence product price and production costs. Moreover, spillovers are intertemporal externalities because they result from present and past decisions about R & D investment process. Such features were taken into account by Bernstein and Nadiri (1991) in their analysis of six US industries for the period 1957-86. They assume that producers maximize the expected present value of the flow of funds by selecting output supply and input demands. Market incentives are a determinant of R & D capital demand and producers exhibit market power which makes them able to influence product prices through output and R & D capital decisions. On the other hand, the existence of spillovers affects the decision-making process of receiving producers. R & D investment undertaken by other producers can generate both positive and negative effects on one's own profitability by reducing production costs, improving product quality, eroding market power and enhancing competition.

Table 4.6. Structure of Canadian Inter-Industry R & D Spillovers

Source industry	Private rate of return	Social rate of return	Receiving industries of spillovers	
Primary metals	.26	.42	Metal fabricating	0.16
Metal fabricating	.29	.29	-	
Nonelectrical machinery	.24	.94	Metal fabricating	0.39
			Transportation equipment	0.07
			Electrical products	0.23
			Chemical products	0.01
Transportation equipment	.28	.29	Rubber and plastics	0.0
			Gas and oil wells	0.01
Electrical products	.38	.38	-	
Rubber and plastics	.47	.89	Nonelectrical machinery	0.42
			Gas and oil wells	0.0
Petroleum products	.40	.87	Primary metals	0.03
			Nonelectrical machinery	0.10
			Electrical products	0.34
Chemical products	.25	.81	Primary metals	0.03
			Petroleum products	0.53
Gas and oil wells	.33	.37	Nonelectrical machinery	0.04

Source : Bernstein (1989).

Bernstein and Nadiri's model is a cost of adjustment one based on the theory of dynamic duality in which capital stocks are defined as quasi-fixed factors of production. Costs of adjustment are associated with these quasi-fixed inputs and what distinguishes R & D capital stocks from other forms of capital accumulation is the existence of R & D spillovers. They give a specific form to both cost and product demand functions from which they derive the intertemporal profit maximization conditions. The key equations of their model are given in table 4.7. The cost effect of R & D cannot be beforehand determined. Actually, R & D capital affects variable cost in three ways :

Table 4.7. A Dynamic Model of Inter-Industry R & D Spillovers

1. Theoretical model

Normalized variable cost function : $C^V = C\ (W, Q, K, \Delta K, S)$

Product demand function : $P = D\ (Q, K_r, Z, S)$

Expected present value of the flow of funds :

$$E = E\ \{\alpha\ [D\ (Q, K_r, Z, S)\ .\ Q - C\ (W, Q, K, \Delta K, S) - P_K\ (\Delta K + \delta K_{-1})]\}$$

For the sake of convenience time subscripts have been left out.

W	=	relative variable factor prices (i.e., normalized by i^{th} variable factor price)
Q	=	output quantity
K	=	capital inputs
ΔK	=	net investments
S	=	R & D capital for each of the other producers
K_r	=	own R & D capital ($K_r \in K$)
Z	=	exogenous variables
α	=	discount factor
P_K	=	normalized capital purchase prices
V	=	variable factor quantities

Production decision rule : $\max_{(Q,V,K)} E$

2. Operational model

Variable cost function net of adjustment cost :

$$C^V = \beta_0 + \beta_q q + \sum_i (\beta_i w_i + \beta_{iq} w_{iq} + \sum_j \beta_{ij} w_i k_j) + \sum_j (\beta_j k_j + \beta_{jq} q k_j + \sum_{g,g\neq j} \beta_{jg} k_j k_g) + (\sum_i \beta_{is} w_i + \beta_{qs} q + \sum_j \beta_{js} k_j) \sum_h \beta_h s_h$$

Adjustment cost function :

$$C^a = .5 \sum_j \sum_g \mu_{jg} \Delta K_j \Delta K_g$$

Product demand function :

$$p = \alpha_0 + \alpha_q q + \alpha_r k_r + \alpha_{qr} q k_r + \sum_f (\alpha_{qf} q z_f + \alpha_{rf} k_r z_f)$$

$$+ (\alpha_{qs} q + \alpha_{rs} k_r) \sum_h \alpha_h s_h$$

Pool of borrowed R & D capital affecting variable cost : $\sum_h \beta_h s_h$

Pool of borrowed R & D capital affecting product demand : $\sum_h \alpha_h s_h$

Applying Shephard's lemma to the maximization function, the equilibrium conditions are :

. Variable factor cost shares :

$$W_i V_i / C^V = \beta_i + \beta_{iq} q + \sum_j \beta_{ij} k_j + \beta_{is} \sum_h \beta_h s_h \qquad \forall\, i, t$$

. Revenue to cost ratio :

$$P Q / C^V = (\beta_q + \sum_i \beta_{iq} w_i + \sum_j \beta_{jq} k_j + \beta_{qs} \sum_h \beta_h s_h) /$$

$$(1 + \alpha_q + \alpha_{qr} k_r + \sum_f \alpha_{qf} z_f + \alpha_{qs} \sum_h \alpha_h s_h) \qquad \forall\, t$$

. Non-R & D capital inputs :

$$W^e_j K_j / C^V + \beta_j + \sum_i \beta_{ij} w_i + \beta_{qj} q + \sum_{g, g \neq j} \beta_{jg} k_g$$

$$+ \sum_g \mu_{jg} (\Delta K_g - (1 + \rho)^{-1} \Delta K^e_{+1,g}) K_j / C^V + \beta_{js} \sum_h \beta_h s_h = 0 \qquad \forall\, j \neq r, t$$

. R & D capital input :

$$W^e_r K_r / C^V + \beta_r + \sum_i \beta_i w_i + \beta_q q + \sum_{g, g \neq r} \beta_{rg} k_g$$

$$+ \sum_g \mu_{rg} (\Delta K_g - (1 + \rho)^{-1} \Delta K^e_{+1,g}) K_r / C^V + \beta_{rs} \sum_h \beta_h s_h$$

$$- (P Q / C^V) [\alpha_r + \alpha_{qr} q + \sum_f \alpha_{rf} z_f + \alpha_{rh} \sum_h \alpha_h s_h] = 0 \qquad \forall\, t$$

where $W^e_j = P_j [(1 - (1 + \rho)^{-1} (1 - \delta_j) P^e_{+1,j} / P_j] \;\; \forall\, j$ is the relative rental rate on the i^{th} capital input

ρ is the discount rate

the superscript C denotes the conditional expectation of the corresponding variable

Notational conventions for subscripts :

- they are specific to the corresponding variables
- i refers to the (n - 1) relative variable factor prices
- j and g refer to the m capital inputs ($r \in (j, g)$)
- h refers to the *l* other producers investing in R & D
- f refers to the x exogenous variables

Small letters are for the logarithm of variables.

Spillover effect on product price and production cost :

$$\frac{\partial p}{\partial s_h}\Big|_{Q,K} = (\alpha_{qs}\, q + \alpha_{rs}\, k_r)\, \alpha_h \qquad \forall\, h$$

$$\frac{\partial c^v}{\partial s_h}\Big|_{Q,K} = (\sum_i \beta_{is}\, w_i + \beta_{qs}\, q + \sum_j \beta_{js}\, k_j)\, \beta_h \qquad \forall\, h$$

Equilibrium effects of R & D spillovers :

. Output supply elasticity :

$$\frac{\partial q}{\partial s_h} = [\gamma^{1}\, (\eta_h - \varepsilon_h) + \beta_{qs}\, \beta_h\, (1 + \varepsilon_q)^{-1} - \alpha_{qs}\, \alpha_h\, \eta_q\, (1 + \varepsilon_q)^{-2}]\, /\, \gamma\, (1 + \varepsilon_q - \eta_q) \qquad \forall\, h$$

. Product price elasticity :

$$\frac{\partial p}{\partial s_h} = \varepsilon_h + \varepsilon_q\, \frac{\partial q}{\partial s_h} \qquad \forall\, h$$

. Variable cost elasticity :

$$\frac{\partial c^v}{\partial s_h} = \eta_h + \eta_q\, \frac{\partial q}{\partial s_h} \qquad \forall\, h$$

. Variable factor demand elasticity :

$$\frac{\partial v_i}{\partial s_h} = e_{ih} + (\beta_{iq} + \gamma_i\, \eta_q)\, \gamma_i^{-1}\, \frac{\partial q}{\partial s_h} \qquad \forall\, h$$

where γ = $C^V / P\, Q$

η_h = cost reduction effect

ε_h = price effect

ε_q = inverse price elasticity of product demand

η_q = output elasticity of variable cost

e_{ih} = spillover elasticity on conditional demand of i^{th} variable factor

γ_i = cost share of i^{th} variable factor

Net private rate of return on capital stocks :

$$\rho_j = \rho + \sum_g \mu_{jg} \Delta K_g (1 + \rho) / P_j \qquad \forall j$$

Joint industry expected discounted flow of funds :

$$\Phi = \sum_h E^{h}$$

where the superscript identifies each producer

Additional profit accruing from internalizing R & D spillovers :

$$\frac{\partial \Phi}{\partial K_r^l} = \sum_{h, h \neq l} [(\alpha_{qs}^h q^h + \alpha_{rs}^h k_r^h) \alpha_l^h / \gamma^h - (\sum_i \beta_{is}^h w_i^h + \beta_{qs}^h q^h + \sum_j \beta_{js}^h k_j^h) \beta_l^h] C^{vh} / K_r^l \qquad \forall j$$

Social rate of return on R & D capital stock :

$$\gamma_r^l = \rho_r^l + (1 - \rho) \frac{\partial \Phi}{\partial K_r^l} / \rho_r^l \qquad \forall j$$

Source : Bernstein and Nadiri (1991).

- if R & D is process-oriented, an increase in own R & D capital stock will reduce variable costs. Yet, if R & D is product-oriented, quality improvements will induce higher costs;
- producers face adjustment costs when they divert variable factors to R & D investment so that variable cost will increase;
- spillovers lead to cost reductions for the receiving producer.

Regarding product demand, R & D capital is a product quality indicator which generally implies product price increases. However, spillovers can either generate positive or negative price effects. As R & D capital is not separated into process R & D and product R & D, the product and process influences of R & D are measured through both the variable cost and product demand functions.

In the production demand function, spillovers affect output and R & D capital through due parameters (α_{qs} and α_{rs}) and each spillover source generates a distinct effect on product price (α_h). Moreover, interaction terms are introduced between the spillovers and factor prices, capital inputs and output quantity (β_{is}, β_{qs} and β_{js}). Each borrowed R & D generates a distinct effect on these variables (β_h) and so one can test whether a given producer is a source of spillover.

From the maximization of the expected present value of profits the equilibrium conditions for the variable inputs, each variable factor cost share being directly affected by the pool of borrowed R & D (β_{is}). In equilibrium, the revenue to cost ratio is also influenced by spillovers through their impact on product price elasticity (α_{qs}) and on variable cost elasticity (β_{qs}). Conditions for the non-R & D capital inputs imply that the marginal cost of a non-R & D capital input is offset by the expected marginal benefit at the equilibrium and that R & D spillovers affect these equilibrium conditions (β_{js}). A last equilibrium condition concerns the R & D capital input which is influenced by conditions ruling both variable cost and product price (i.e. both β and α coefficients) and by the extent of spillovers (β_h and α_h). Under this condition, the marginal benefit from R & D capital input is equal to the increase in marginal revenue net of changes in variable cost and in adjustment cost.

As not all producers are a source of spillovers, the search of spillover sources is based upon the idea that spillovers must generate a negative impact effect on variable costs. This acceptance condition is compatible with some established facts :

- consistency with the assumption of free disposability in production : producers can costlessly benefit from spillovers and avert them if they are cost increasing;
- capability to promote R & D investment : increasing total cost can result from supplementary R & D investment engaged to absorb the spillovers;
- alteration of competitive strengths : R & D spillovers can freely affect product demand and thereby generate various economic externalities.

From this model, we are able to evaluate the distinct influence of spillovers on product price and production cost for receiving industries. Any increase in the product price as a result of R & D spillovers will increase the revenue of the recipient industry and conversely. As a result of the acceptance condition, an increase of R & D spillovers will reduce variable factor cost. Furthermore, the measurement of the spillover elasticities of output supply, product price, variable cost and variable factor demands emphasizes the direct impact of spillovers on each of these variables and their indirect impact through changes in output supply. In these elasticities, output expansion can cause variable cost to increase, output growth effect outweighing the initial cost reduction due to spillovers. A similar effect can be detected for product price and variable factor demands.

If we turn to the rate of return on R & D, private rate of return can differ from other types of capital because they include marginal adjustment costs which differ from one type of capital to the other. In equilibrium, the rate of return equals the discount rate plus the capitalized value of marginal adjustment cost. The social rates of return are calculated by considering that industries internalize the R & D spillovers. To do that, the joint industry expected discounted flow of funds is maximized, so that the solution will take into account the additional profits earned by industries through their spillover effects. This additional profit equals the difference between the product price effect and the cost production effect arising from the R & D spillovers. The social rate of return will differ from the net private rate to the extent that an industry's R & D capital reduces both the product price and the costs of other industries.

In their application of this model to six US industries, the authors consider as variable factors, labor and intermediate inputs and as quasi-fixed factors, physical capital and R & D capital. The depreciation rate of R & D capital is considered to be 10 percent. The exogenous variable affecting product demands is the real gross domestic product net of the industry output per capita.

The estimate of the model emphasizes the existence of adjustment costs. All the own adjustment cost parameters are significant. The cost parameters are also significant and positive, except for electrical products, which indicates that an increase in physical capital increases adjustment cost of R & D capital. These adjustment costs imply the existence of an intertemporal trade-off in the investment decisions.

The results, summarized in table 4.8., show that each industry is a receiver of R & D spillovers and that only the fabricated metal industry is not a spillover source. For each receiving industry, the spillover sources are concentrated in a few industries. This observation emphasizes the limits of more aggregated approaches. The sender-receiver network is relatively narrow, links some enterprises through cross spillover effects and points out the key role of scientific instruments, chemical products and nonelectrical machinery industries as the main sources of spillovers. The cost reduction effect of spillover is generally higher than the product price effect and it is only in the case of chemical products and scientific instruments that spillovers increase their product price. On the cost reduction side, fabricated metal appears to be the main beneficiary of spillovers and chemical products the one that benefits least. The output effect of spillovers is to expand output. For the two industries where spillovers increase product price, the expansion effect overcomes the price effect, causing product prices to fall.

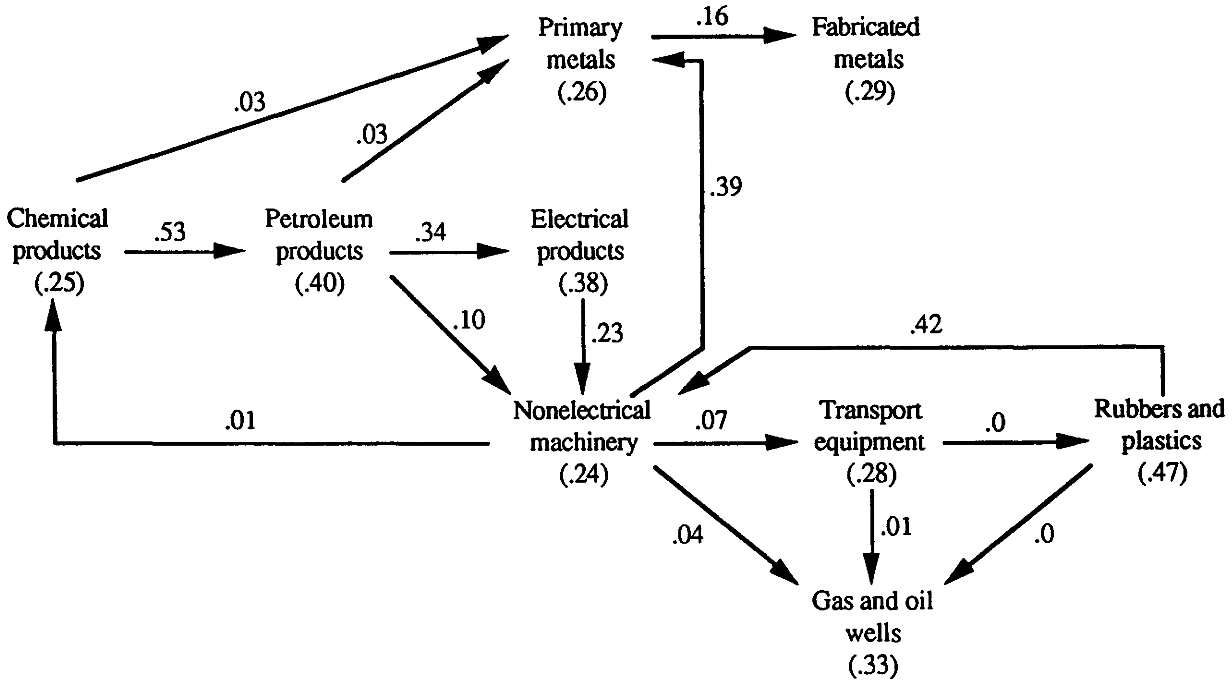
Table 4.8. Structure of US Inter-Industry R & D Spillovers

Source industry	Private rate of return	Social rate of return	Receiving industries of spillovers	Spillover return by type		Product price effect	Cost reduction effect
				Product price	Variable cost		
Chemical products	.22	.46	Nonelectrical machinery	-.23	.38	.05	-.05
			Scientific instruments	.03	.06		
Fabricated metal	.22	.22	-			-.16	-.24
Nonelectrical machinery	.25	.40	Transportation equipment	-.20	.36	-.06	-.12
Electrical products	.27	.31	Scientific equipment	.02	.03	-.07	-.12
Transportation equipment	.23	.35	Fabricated metal	-.12	.16	-.05	-.11
			Nonelectrical machinery	-.07	.12		
			Scientific instruments	.01	.02		
Scientific instruments	.28	.87	Chemical products	.26	.19	.03	-.08
			Electrical products	-.36	.49		

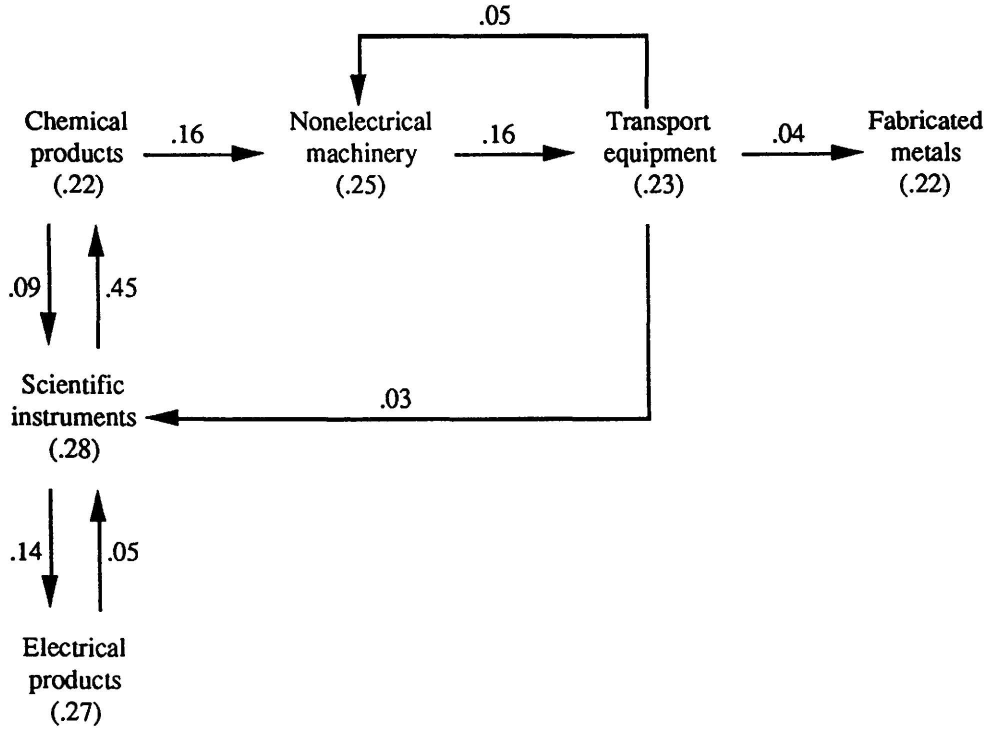
Source : Bernstein and Nadiri (1991).

Figure 4.1. Traces of External Returns on R & D

1. Canada



2. United States



Note : The data between parentheses are the private rates of return and the others are the social rates of return per receiver.

Source : Bernstein (1989) and Bernstein and Nadiri (1991).

Figure 4.1. summarizes the distribution of spillovers between the different industries for both the Canadian and American studies. In both cases, fabricated metals, transport equipment and electrical products are not major sources of spillovers. Chemicals, nonelectrical machinery and scientific instruments concentrate a large part of external returns arising from spillovers. There is no important closed loop of R & D externalities between industries. In the United States, there is a slight give and take relationship between chemical products, scientific instruments and electrical products, on the one hand, and between nonelectrical machinery and transport equipment, on the other hand.

4.6. More on the Input-Output Approach[1]

4.6.1. Decomposition of Growth in Real Output

The focus question is to decompose output growth into portions attributable to changes in technology (represented by the changes in coefficients of the Leontief inverse matrix) and to changes in final demand.

Induced output, X, is expressed by multiplying production technology, B, and final demand, F. Therefore, any increment in induced output, dX, is expressed as follows :

$$\begin{aligned} dX = X^t - X_0 = B^t F^t - B^0 F^0 &= (B^0 + dB)\,(F^0 + dF) - B^0 F^0 \\ &= B^0 F^0 + F^0\,dB + B^0\,dF + dB\,dF - B^0 F^0 \\ &= B^0 dF + F^0 dB + dBdF \end{aligned}$$

Thus, output growth can be decomposed into different components :

- first, the part of growth due to changes in final demand;
- second, the part resulting from technological change;
- third, the cross product term measuring the interdependencies between demand and technology.

The increment in final demand, DF, can also be decomposed into three elements :

- the aggregate demand;
- its distribution into final demand components such as consumption and investment;

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1 This section has largely been inspired by Uno (1989).

- the technical coefficients describing the industrial composition of a particular demand item.

Consequently :

$$F = c\,\hat{e}\,f$$

where f = aggregate final demand
c = technical coefficients (n x n)
e = composition ratios of final demand items (1 x n)
$\hat{e}$ = diagonal matrix of e.

Any increment in final demand, dF, is equal to :

$$\begin{aligned} dF = F^t - F^0 &= c^t\,\hat{e}^t\,f^t - c^0\,\hat{e}^0\,f^0 \\ &= (c^0 + dc)\,(\hat{e}^0 + d\hat{e})\,(f^0 + df) - c^0\,\hat{e}^0\,f^0 \\ &= c^0\,\hat{e}^0\,df + c^0\,d\hat{e}\,f^0 + dc\,\hat{e}^0\,f^0 + c^0\,d\hat{e}\,df + dc\,\hat{e}^0\,df + dc\,d\hat{e}\,f^0 \\ &\quad + dc\,d\hat{e}\,df \qquad (1) \end{aligned}$$

where $c^0\,\hat{e}^0\,df$ is attributable to changes in the aggregate level of final demand
$c^0\,d\hat{e}\,f^0$ is attributable to changes in the components of final demand
$dc\,\hat{e}^0\,f^0$ is attributable to changes in the technical coefficients
the cross product terms can be ignored because their impact is very weak.

The usefulness of input-output tables is strongly impaired by the fact that they are rarely available annually and for a sufficiently long period. Furthermore, they are based on very stringent hypotheses about the nature of production relationships :

- each industry produces only one good (no joint products or by-products);
- the production technology is identical for all the production levels of a good;
- the returns to scale are constant.

For the year of construction of the matrix, the data are supposed to give a satisfying representation of the reality. It is hardly credible, though, that the technical coefficients calculated for a specific year do not move over time. Several elements can influence the matrix of technical coefficients :

- any change in the relative price of factors will entail to a reaction from firms which will turn to alternative production processes, thereby inducing a reallocation in the use of factors.

- in some industries, short-term decreasing returns to scale may seem to be due to the fact that the production capacity limits have been reached; in other sectors, increasing returns to scale can result from an expansion of the production.
- technical change permanently affects technical coefficients.

In order to update and forecast input-output coefficients, one makes use of the RAS method which is based on the following philosophy :

- the flow matrix is corrected for price changes between the two periods in order to express the technology of the initial period in the prices of the new period.
- in a second stage, a new correction of the matrix is operated in order to take into account the substitution effects between intermediate products which are due to technical progress. This effect is supposed to materialize in the same way for all the sectors using a same intermediary good. Furthermore, this effect will be greater than unity for expanding products and less than unity for declining products.
- a last correction is applied to take into account that the manufacturing degree is liable to change. The fabrication effect measures the extent to which the production makes use of intermediary inputs. This effect will be greater than unity if the degree of fabrication has decreased and less than unity if it has increased.

The new matrix so estimated can be written :

$$\hat{A} = r \, \rho_0 \, A \, \rho^{-1} \, s$$

where ρ_0 is the diagonal matrix of prices in the initial period

ρ, the diagonal matrix of prices in the new period relatively to those of the initial period

r, the diagonal matrix of substitution effects

s, the diagonal matrix of fabrication effects.

The matrices r and s are iteratively estimated on the basis of the known sectoral values of output, intermediate demand and intermediate input.

This method has some drawbacks[1] :

- if an element of the matrix of coefficients is zero, its estimate in a future period will be zero, which makes it difficult to take into account new products and processes which combine inputs which are very different from those used in the preceding period.

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1 Alternative methods of actualisation have been developed, they are surveyed by d'Alcantara (1986).

- due to the hypothesis of identical substitution effects, the rate of substitution of factors is supposed the same in each production branch, which is not always very realistic.
- as there is an additivity constraint (total of both intermediate demand and intermediate input being known), if an element is underestimated, an other will be overestimated.
- this method is unable to indicate if changes in the elements of the flow matrix are due to a modification of the price structure or to technological change.
- when the results are used to analyse further years, it is automatically assumed that future periods face the same changes in the economic and technical environment than the reference periods.

4.6.2. The Treatment of R & D in Input-Output Tables

Business services are production factors linked to economic activities which deal with goods production. From this standpoint, research is a form of current service but it cannot be assimilated to a current business service because it is the originator of knowledge production. Part of R & D expenditure is oriented towards the acquisition of basic knowledge in science and technology and the operational implementation of new knowledge. As such, R & D is an activity which extends the spectrum of production possibilities, which distinguishes it from labor and capital factors.

According to Uno (1989), input-output tables do not adequately deal with R & D. While European input-output tables do not take R & D into account, the Japanese ones include it. On the one hand, R & D conducted by the private sector for their own internal use is integrated through the creation of a dummy sector where only the intermediate inputs are accounted for. On the other hand, R & D by research institutions and universities is fully endogenized. While for the private sector labor cost and the purchase of tangible fixed assets are excluded, only the latter is excluded for research institutions and universities. So, the treatment of R & D appears not to be homogenous within the input-output framework. Furthermore, R & D expenditure is only partially accounted for. Finally, as R & D activities are treated as an endogenous sector, any analysis of inter-industry relationships of R & D activities is unfeasible.

Furthermore, such a treatment does not record the output of R & D activities. The economy-wide impact of R & D escapes the analysis except for the indirect effect which can be grasped by measuring the increase in production efficiency (i.e., through changes in technical coefficients) or in the sales of a branch of production (i.e., increased marketability of output). Consequently, the outcome of R & D may not be reflected in the output of the industry in a pecuniary sense, as the output of this activity is the scientific and technological knowledge. A specific method for recording the output of this activity needs to be devised.

Another important aspect is that R & D activities are listed within the production expenditures and not as an independent activity in the input-output structure so that any increase in R & D activities would increase production cost. Yet, since R & D produces scientific and technological knowledge, which increases the future production potential, and not principally the production of the current period, it should be treated as final demand. The input structure should include the costs in production and external R & D changes should be treated separately. R & D investment is a strategic policy variable for business firms and government whose level does not passively react to current production but is determined by the decision to invest in production knowledge. Thus, R & D activities cannot merely be regarded as an appendage to current directly productive activities or as a technological adaptation cost (of adopting new technologies or of imitating new technologies), they are a component of final demand as long as they are not exclusively used in the production process.

In order to make up for the fact that the conventional input-output tables do not take R & D into account, we can seek what would be the ideal treatment of such an activity. This conceptual framework is considered without questioning the availability of empirical statistics. The proposed scheme consists of nine layers as shown in figure 4.2 :

1. ***a financing account*** which records the financial flows from financing sources to R & D execution sectors. This would permit to highlight the role of public and private organizations in the resource allocation.

2. ***an R & D expenditure account*** which records, for each execution sector, the R & D expenditure by field or product. The expenditure items would be broken down into tangible fixed assets, wages and salaries and material consumption in order to identify the components of value-added, investment and consumption.

3. ***an R & D interindustry flow matrix*** which corresponds to an extended input-output table including an R & D expenditure disaggregated account. The associated R & D matrix would serve to establish the linkage with interindustry relations. In this framework, R & D investment represents the expenditure on tangible fixed assets and R & D consumption is defined as expenditure of materials and assimilated. The wages and salaries and the depreciation of tangible fixed assets are components of value-added. The R & D input consists of R & D labor cost, R & D capital depre-

ciation, user cost of existing knowledge and intermediate input, this last item being treated as input to industry. The R & D output is recorded among the final demand items, it is composed of R & D capital formation and R & D consumption. As current expenditure for R & D is not an input to produce goods and services as defined in the input-output framework, it would be more logical to treat it as final demand and not as intermediate input. R & D spending is directed toward the knowledge acquisition for future use and not toward immediate physical production. In order to distinguish R & D components from other components of final demand, both R & D consumption and investment are separated as an independent final demand item. The R & D input-output table would be a disaggregation of R & D final demand between consumer sectors and producer sectors.

4. ***an R & D employment matrix*** which gives the industry-occupation employment patterns and would help to analyze the impact of the changing industrial structure of the varying levels of R & D expenditures on R & D employment.

5. ***an R & D capital stock account*** which gives information on the stock of fixed tangible assets for R & D purposes in each sector and corresponds to the R & D capital formation. This correction departs from the definition of R & D capital stock used in econometric studies. To recall, in the latter, all R & D expenditures are taken into account in the measure of R & D capital stock.

6. ***an R & D performance account*** which deals with the outcome of the research activities. While the preceding table was concerned with the measurement of the R & D capital stock, this account brings on the evaluation of the end results of R & D in terms of R & D benefits, patents or publications. The appreciation of the performance concept can highly vary accross research fields and so far there does not exist any well-established standard indicator to appreciate performances inside a research field. Consequently, the measurement of performances remains a tricky issue.

7. ***a knowledge capital stock account*** which brings on the stock of scientific and technological knowledge. Although there are a variety of forms of knowledge stock, this aggregate is alternatively approximated by the accumulated total R & D expenditures, as is the case in econometric works or by the number of patent applications or patents granted. The main criticism against these approximations is that, on the one hand, R & D expenditure is an input measure of the knowledge production process and that, on the other hand, patents are only a rough measure because not all knowledge is patented and not all patents are valuable.

8. ***an R & D benefit flow matrix*** which traces the interindustry repercussion of R & D activities. In the case of product innovation, the benefits of R & D activities spill over to sectors using the goods as intermediate input or as investment goods or to consumers who consume the improved or new products. In the case of process innovation, higher efficiency attained by the purchasing sectors induces lower prices and a better quality of their products. This technology flow matrix should take into account not only technology benefits resulting from domestic R & D expenditures but also technology imports. Furthermore, due consideration should be given to the gestation period of both domestic technology and imported technology.

9. ***evaluation indicators*** which are calculated according to specific concerns as the performance and the improvements in a particular vital field, the levels of industrial productivity achieved and the international technological position.

Figure 4.1. R & D Accounts

Scheme 1 - R & D Financing Account

Financing sectors / Real activity sectors	Private sector	Public sector	Foreign countries	Total
Industry (establishment)				
Research institution				
University				
Foreign countries				
Total				

Scheme 2 - R & D Expenditure Account

Financing sectors / Real activity sectors	Product fields	Total	
Industry (establishment)		R & D consumption	R & D capital formation
Total			

Scheme 3 - R & D Interindustry Flow Matrix

Output Input		Intermediate Industry	R&D	C	IP	G	E	M
Intermediate	Industry	Intermediate transactions	R&D con-sumption & invest-ment					
R&D	Output	R&D benefit Own R&D R&D in other sectors	(b)	R&D benefit				
Value added	Labor	L	R&D L					
	Capital	K	R&D K					

Scheme 4 - R & D Employment Matrix

	Occupation	
Industry		Total by industry
	Total by occupation	Total

Scheme 5 - R & D Capital Stock Account

	Technology fields	
Industry		Total by industry
	Total by technology fields	Total

Scheme 6 - Knowledge Capital Stock Account

	Technology fields	
Industry		Total by industry
	Total by technology fields	Total

Scheme 7 - R & D Benefit Flow Matrix

		Final demand					
		C	G	IP	E		
Industry engaged in R & D							
Total benefit accruing	Benefit to industry			Benefit	to F-D		

Source : Uno (1989).

Uno investigated the empirical feasibility of this analytical schema in the case of Japan. The linkage to the input-output framework is done using the aggregate data for R & D consumption and investment. As converters are not available to transform these data into demand for individual sectors, the intermediate input structure is used as an approximation. For R & D investment, the converters are assumed to be identical to those calculated for private investment in plant and equipment. It is on this basis that he estimates the input-output structure of the R & D activities. The stock of knowledge is measured by combining the number of applications for both patents and utility models and the average life expectancy of patents. The life expectancy of patents is defined as the period during which a patent yielded returns from outside the firms or when the products incorporating such patents yielded profits. Assuming that the economic value of patents declines proportionally over time, the rate of depreciation of patents is given by the reciprocal of the average life. To trace the technological flows among industries, R & D expenditure is used rather than patent data. After estimating the time lag between R & D expenditure and the implementation of new knowledge so created in actual production on the basis of information on gestation period, the flow of R & D benefits received by other sectors through intermediate inputs is measured by the ratio of sales to intermediate demand multiplied by the R & D expenditure in the producing sector. For the flow of R & D benefits received by other sectors through purchase of investment goods, a similar procedure is applied by using the fixed capital formation matrix instead of intermediate demand. Flow of R & D benefits to consumption and exports are estimated by the ratios of sales to these final demand items respectively. A same measurement method is applied for technology flows from new contracts of technology imports.

Chapter 5. The impact of Government-financed R & D

Assessing economic impacts of policy intervention by public authorities is a very difficult task because a variety of effects as well as other causes may contribute to specific outcomes. From this standpoint, the use of econometric models to evaluate the potential impact of alternative sets of economic policy is now a current practice in economics. Econometric models have asserted themselves as a tool of great value for improving our understanding of the intricacies of economic phenomena. They play a role in the design of economic policy both as a tool in the impact analysis in order to assess the global economic fallouts of policy measures and as a tool in the decision making processes.

Yet, these methods are only very marginally used for the design of science and technology policy. The exogenous status of technical change in macromodelling, the scarcity of data in this field and the skepticism of experts regarding the usefulness of econometric methods are certainly the three main reasons why econometric methods are not regarded as a sufficiently efficient impact evaluation technique. Nevertheless, the recent availability of better data, the multiplication of empirical and theoretical researches on the interdependencies between economic growth and technological change and the difficulty in appraising the economic impacts of science and technology policies when only qualitative methods are used should lead to an increasing use of econometric methods.

Most efforts in the econometrics of R & D have been devoted to measuring the impact of overall and industrial R & D. The public R & D investment is often included in models as an explanatory variable without the measure of its impact being the actual objective of the undertaken analysis. Moreover, these estimates are only pinpoint approaches which evaluate the impact of public R & D on an economic variable and not on the economic system as a whole. In this field, the main evidence comes from U.S. case-studies. Regarding this country, the apparent high variability of results can, to a large extent, be explained by the data characteristics. Unfortunately, for other countries, the experiments reported in the literature are not sufficient to draw clear conclusions.

5.1. Why to evaluate the Economic Impact of Publicly-Funded R & D ?

So, how science and technology resources should be allocated so as to have a maximum impact on economic growth has become an important focus for technology assessment. The answer to such a question should be based on both qualitative criteria of evaluation and formalized quantitative methods. Although qualitative methods of evaluation produce useful guidelines for the organization and implementation of R & D policy, they are not suited to measure the economic impacts of public R & D programmes quantitatively. As pointed out by Roessner (1989), "efforts to evaluate government programs intended to stimulate industrial innovation through various types of R & D subsidies are confronted immediately with serious design and measurement challenges".

Although the need for more information about the economic effects of public support of R & D activities has long been debated, the credibility of econometric methods as evaluation tool is often questioned. The American Office of Technology Assessment (1986) considers that quantitative methods "does not provide a useful practical guide to improving Federal research decision making" and that the influential factors are too complex and subjective "to allow quantitative models to take the place of mature, informed judgement".

The mastery of technological change, and particularly technological innovation, is increasingly viewed as a major driving force of economic growth and competitiveness. If we glance at the normative literature on the economic analysis of technological change, it appears that, in the present state of the art, although it provides a good understanding of some basic factors, so far it has given practitioners little ground to build on. Hence, some economists argue that governmental funding of R & D is likely to reduce private R & D expenditure because firms may receive support from the public sector for projects they would otherwise finance themselves. Taking an opposite stance, others say that publicly-funded R & D is complementary to and stimulates privately-funded R & D. Futhermore, little is known about the efficiency of alternative forms of public intervention. As a consequence, innovation policy may be said to be today more a matter of faith than of understanding [Rothwell and Zegveld (1988)].

The R & D policy must rest on an appropriate set of actions aimed at influencing or controlling factors which restrain the technological performances of firms. The fuzzy and uncertain nature of R & D policy makes the assessment of the impacts of the instruments used a major analytical issue. Hence, if governmental action induces only small additional private R & D expenditure, then, to justify public intervention the social return must be relatively high. Conversely, if public subsidization results in high additionality and high private return, but with weak positive externalities (the subsidized firm appropriates most of the benefits of the research), then the government must wonder whether its intervention is meant to compensate for market failure and whether the overall economic benefits outweigh the costs. Hence, the design of appropriate policy instruments should be based on the following economic rationale :

- the support should be additional in the sense that the generated activity would not have occurred in a similar form or at all without public intervention.
- the support should result in greater social benefits than otherwise.
- the support should provide higher extra benefits than its opportunity cost.

Given that these outcomes cannot be a priori guaranteed, the economic effects of R & D policy actions have to be evaluated ex post. In case of ex ante impact assessment, since the changes in the exogenous circumstances are unknown, it is difficult to define the reference situation.

Science and technology policy is not implemented in order to achieve intrinsically technological goals, or at least should not be viewed as such, but as a mean of action aiming at improving the economic and social welfare. Its objective is not the search of scientific and technological achievements for its own sake. This policy is ultimately concerned with wealth creation and should be seen as part of economic policy dealing with short-term and long-term economic growth.

The relevant questions for the design of a science and technology policy are :

What is the ultimate *goal* of a science and technology policy ?
What are the *objectives* to achieve ?
What are the *targets* aimed at ?
What *instruments* have been designed ?
How *efficient* have the policies implemented been ?

In accordance with the usual functions recognized to public policy, the goal should primarily be to promote an efficient allocation of resources [1]. In order to attain this goal, several objectives are fixed, among which fostering R & D activities, promoting the

[1] It does not mean that science and technology policy is not concerned with other goals, i.e. stabilisation and equity. For example, a science and technology policy aiming at fostering technological capabilities in lagging regions is, primarily, designed to satisfy the equity principle.

diffusion of new technologies and ensuring the access to technological opportunities as well as to economic opportunities offered by the developments in science and technology. Then, specific targets are chosen for each objective. For example, R & D activities can be fostered by acting on private R & D investments. The instruments, which are the action means, are under the control of public authorities. They can be general or selective and principally bear on tax deductions, grants, loans, guarantees, purchases and investments. Each of these components is vital for the design of an efficient policy. Besides, policy assessment is also vital as it gives grounded recommendations to adapt the existing policy or to implement future policies. In the process of policy assessment, ex post impact assessment will give information on the changes in the targets caused by the implementation of instruments.

The purpose of impact assessment is to have information about the costs, the benefits and the effectiveness of the implemented policy. The impact analysis may cover different and complementary objectives :

- quantitative and qualitative effects on firms' R & D activities (spin-off effect).
- impact on the economic performance(s) of firms (productivity effect)
- impact on the economic performance(s) of industries (spillover effect).
- impact on the economy as a whole (global effect).

To date, only a few empirical studies have endeavoured to estimate the economic impact of R & D policy. Three different types of economic assessment methods are used. The first is the case study. Case studies always leave open the question of how representative they are. Their results are often only valuable for a specific context and any generalisation is a highly risky experiment. The second method consists in surveys conducted among those who have been concerned by the policy. Surveys may provide detailed information on factors influencing decision-making processes and on perceptions of a subsidization policy. However, this method often suffers from lack of accuracy in the way questionnaires are built and measurement errors, which may cause perceived effects to be mistaken for actual ones. An other limitation of the first two methods is that they usually cannot provide information about the effects on variables in a causal chain, they are very costly and time consuming. The third method is the use of econometrics to emphasize the relationship between subsidization and R & D intensity across firms as well as between publicly-financed R & D and productivity performances of firms. This method allows to estimate only direct effects of policy instruments on an impact variable. All these methods belong to the class of micro-studies, they are complementary and they are able, within their own limits, to add some pieces of information to our present puzzle of knowledge about the intricate interdependences between innovative activities and economic performances.

The third method can also be used for two other types of studies : mesostudies and macrostudies. Hence, it is useful to cluster the third method in micro-econometrics, meso-econometrics and macro-econometrics. As far as mesostudies are concerned, input-output models can be used to calculate the effects of technical change on production and demand. Although input-output analysis is a very useful method of recording the effects of public R & D policy, its usefulness is seriously limited by its rigid structure and the scarcity of data. Conversely, macromodelling as a tool for macrostudies is not restricted to recording transactions between industrial sectors. The causal chain of interdependencies can be reproduced by introducing causal variables among the explanatory variables. Only with such an approach can one measure the direct and indirect effects of public policy, provided, however, data are available on a large number of variables. An alternative approach is to combine input-output analysis and macromodels, which is now largely used in the existing macromodels. So far, there does not exist any macromodel that has been designed to deal with public R & D policy. Developing such a model will imply endogenizing private R & D investments and identifying their relationship with publicly-funded R & D investments and the other economic variables. Despite many bottlenecks, macromodels can be adapted so as to be used as a tool for the ex post assessment of R & D public programmes. The outcomes of the econometric pin-point approaches can certainly be very helpful in the implementation of extended macromodels [1].

The efficiency of direct subsidization of private R & D by government and tax-credit public policies is a very controversial subject. In a survey of the production function approach, Griliches (1979) asked different questions concerning the real contribution of publicly-funded R & D to productivity growth : are the returns to government-financed R & D similar to those of company-financed R & D ? Does Federal R & D substitute for or complement private R & D investment ? What are the spillover effects of government-financed R & D ? As the rationale for government funding industrial R & D is more and more questioned, it is of major importance that we should improve our knowledge of the interaction between public and corporate funding of R & D and the contribution of public funding of R & D to economic growth. To date, a number of analyses give some pieces of information on this issue.

The recent literature has essentially focussed on two direct approaches :

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[1] A taxonomy identifying the areas to be investigated for an extensive policy assessment is suggested by Capron (1992a).

- The productivity approach which measures the respective effects of privately-funded and publicly-funded R & D expenses on the growth rate of output, so giving an evaluation of the output elasticity of public R & D or of the rate of return on public R & D.
- The investment approach which measures to what extent public R & D allocations influence privately-funded R & D expenditures, the idea being to look at whether, by doing its own R & D and funding private R & D, a government affects (positively, negatively or not at all) the privately-funded R & D and the magnitude of the effect.

Besides, econometric methods have also been used outside these two conceptual approaches. It is the case of probabilistic models, which are required when data are not quantitative but qualitative. On the other hand, a supply approach has been suggested as an alternative to the productivity approach. Its advantage is to allow an indirect measure of the internal rate of return on R & D as well as the marginal internal rate of return on R & D.

5.2. How Productive is the Publicly-Financed R & D ?

In successive studies using alternative measures of total factor productivity growth, Terleckyj (1974, 1980a, 1980b) found that privately-funded R & D was significantly associated with industrial productivity growth but that government-financed R & D was not. Besides the own sectoral R & D variables, he introduced a measure of borrowed R & D investment obtained by crossing the own R & D expenditure and an input-output matrix. His results show that the spillover effects of privately-financed R & D are very important whereas the indirect effects from publicly-financed R & D are not significant. In his analyses, he uses different measures of total factor productivity growth, i.e. based on net and gross measures of output and inputs and taking into account or not quality characteristics of inputs. For these different sets of productivity data, both direct and indirect productivity effects of government-financed R & D are captured. In a comment accompanying the paper, Globerman criticizes Terckelyj's observation of an apparent inefficiency of government R & D by pointing out that, "to the extent that federally financed R & D is primarily directed towards improvements in product quality as opposed to cost reduction, the methodology used in deriving industry productivity estimates could contribute to the finding that government-financed R & D is not significantly related to productivity change. Furthermore, ... the time lag ... might be too short to fully incorporate the effects of federally financed R & D which is presumably aimed at effecting greater changes in underlying production conditions".

Table 5.1. Impact of R & D Capital Stock on Factor Productivity

Study	Sample	Specification and additional variables	Subsamples and other details	Total R & D	Company R & D	Public R & D	R^2
Griliches (1980a)	United States 1957-65 883 companies	- Partial factor productivity growth - Approximated physical capital	Pooled data	.08 (5.85)	.06 (5.25)	-	.11
			Chemicals and petroleum	.09 (2.45)	.09 (2.37)	-	.23
			Metals and machinery	.10 (4.64)	.09 (3.78)	-	.21
			Electric equipment	.11 (3.53)	.06 (2.89)	-	.41
			Motor vehicles	.13 (1.80)	.14 (2.60)	-	.49
			Aircraft	.11 (1.39)	.03 (0.68)	-	.23
			Other	.05 (3.47)	.05 (3.40)	-	.56
Levy-Terleckyj (1983)	United States 1949-81 Private business sector	- Partial factor productivity - Unemployment and fixed capital	Government R & D	-	.27 (3.96)	.05 (1.63)	-
			Government contract R & D	-	.27 (4.10)	.09 (2.13)	-
			Other government R & D	-	-	-.05 (1.14)	-
Griliches (1986)	United States 1966-77 500-1000 companies	- Production function - Labor, capital services and basic research - Alternative results reported for the partial productivity growth and the gross profit rate indicating a positive premium on privately financed R & D	1967	.11 (4.91)	.19 (1.96)	-	.39
			1972	.14 (5.19)	.25 (2.33)	-	.39
			1972	.17 (8.68)	.07 (0.68)	-	.39
			1972	.13 (6.63)	.13 (1.51)	-	.31
			1972	.12 (6.39)	.14 (1.57)	-	.31
			1977	.09 (5.23)	.04 (0.52)	-	.29
Levy-Terleckyj (1989)	United States 1958-85 US telecommunications industry	- Production function - Labor and capital	-	-	.26 (7.20)	.04 (2.20)	.999

Note : Values between parentheses are t-statistics.

Table 5.2. Impact of R & D Intensity on Factor Productivity

Study	Sample	Specification and additional variables	Subsamples and other details	R & D intensity				R^2
				Conducted in industry		Embodied in purchases		
				Privately financed	Government financed	Privately financed	Government financed	
Terleckyj (1974, 1980a, 1980b)	20 manufacturing industries United States 1948-66	- Total factor productivity growth - Sales not to government, union membres, cyclical change in output	Kendrick data - 1973	.27 (2.92)	-.05 (0.53)	.81 (3.66)	.12 (0.26)	.69
			Gallop-Jorgenson data - 1975	.20 (0.64)	-.18 (0.63)	1.83 (2.53)	1.67 (1.10)	.30
			Gallop-Jorgenson data - 1977	.03 (0.31)	.00 (0.02)	.07 (0.33)	.68 (1.48)	.28
			Kendrick data - 1978	.31 (1.62)	.08 (0.44)	.07 (0.15)	.34 (0.36)	-.01
Griliches-Lichtenberg (1984a)	27 manufacturing industries United States 1959-76	- Total factor productivity growth	1959-68	.09 (1.96)	.15 (1.00)	-	-	.21
			1964-73	.20 (3.28)	-.01 (0.84)	-	-	.31
			1969-76	.34 (4.20)	.01 (0.29)	-	-	.46
Reiss (1990)	27 manufacturing industries United States 1959-76	- Total factor productivity growth	Deletion of influential outliers	.26 (2.91)	.18 (2.45)	-	-	.54
			Results for the 4 outliers	.27 (0.52)	-.01 (0.10)	-	-	.23
Lichtenberg-Siegel (1991)	Over 2000 companies United States 1973-85	- Total factor productivity growth	Pooled data	.35 (13.09)	.03 (0.81)	-	-	.05
			1973-76	.25 (7.52)	-.00 (0.02)	-	-	.05
			1977-80	.42 (5.34)	.10 (1.24)	-	-	
			1981-85	.51 (9.59)	-.01 (0.14)	-	-	
			Pooled data with deletion of influential outliers	.29 (11.96)	.07 (1.81)	-	-	.05

Note : values between parentheses are t-statistics.

Contrary to Terleckyj, from a more extensive study, Griliches (1980a) concludes that he was unable to discover any direct evidence of the superiority of company-financed R & D as against federally-financed R & D in affecting the productivity growth. This observation results from a comparison of estimates obtained by using alternatively total R & D growth rate and company R & D growth rate by industry at the firm level. Yet, from the relationship between company profitability and R & D investment and from the elasticities obtained by estimating the production function, he derives the rate of return on R & D and so observes that the two industries with the largest federal involvement in the financing of R & D (electrical equipment and aircraft) yield the lowest rates of return. His explanation is that in these industries the large federal support to R & D creates externalities and restricts the appropriability opportunities, which drive down the private rates of return below the prevailing rate in other industries.

A problem already emphasized by Leonard (1971) in a preceding study in which he looks at the relationship between various measures of industry growth rates, company R & D intensity and federal R & D fund intensity for sixteen US industries over the period 1957-63. He reports a highly positive correlation between industry growth rates and company R & D intensity. For federal R & D intensity, the relationship with industry growth rates only becomes significantly positive when aircraft and missiles and electrical equipment industries are excluded. Yet, productivity reveals a poor association with federal R & D intensity, a result which the author does not find surprising since federal R & D is not aimed at discovering and applying productive processes which result in lower unit costs. So, it is the disproportionate allocation of federal R & D funds to two industries that impairs the contribution of these funds to growth. A possible explanation is that the high concentration of federal funds in these industries may diminish returns on R & D. A second hypothesis, i.e. that the low growth yield of federal R & D results from its noncommercial objectives, does not seem verified as the contribution of federal R & D to industrial growth is significant except for two industries. Concerning a third hypothesis advanced by the author, i.e. that defense and space industries suffer from lack orientation towards commercial markets and are less fit to exploit sales opportunities of federal R & D than market-oriented industries, the results provide some support to the idea that the extreme concentration of federal R & D resources in defense and space industries yields excessive wastes.

In a more recent study, Griliches (1986) tested the hypothesis of a differentiated impact of private and public R & D expenditure more directly. He found that privately-financed R & D expenditure has a significantly larger effect on private productivity than federally-financed R & D. This finding is based on estimates of both production functions and gross profit rate regressions at the firm level for several years. Amongst the topics explored, he asks whether federal R & D and private R & D are equally patent in generating productivity growth. To do that he introduces in his equation besides total R & D capital stock the ratio of company-financed R & D stock on total R & D stock to measure to what extent there is a premium on privately financed R & D[1]. The results indicate that there is a positive premium on privately financed R & D which amounts to 180 percent for the most older established firms. Yet, this variable does not appear significant for the most extensive recent sample. He also estimates the existence of a premium on the basis of growth rate of partial productivity. Here too the premium effect is significantly positive but more cumbersome to calculate. In the gross profit rate equations, the premium effect turns out to be insignificant once industry differences are allowed for. Although he concludes that privately financed R & D expenditures are more effective at the firm level than federally financed ones, his results are actually very mitigated and unstable.

Wondering about the change in the relationship between the total factor productivity growth and R & D stock observed by Griliches (1980b) during the 1970's, Griliches and Lichtenberg (1984a) used new data to show that the relationship between productivity intensity and R & D intensity did not really disappear but was obscured by the productivity slowdown. They estimated a model of total factor productivity growth with R & D intensity as the explanatory variable for several subperiods under alternative assumptions about the rate of depreciation of R & D capital. They also considered two variants of the model : one with total R & D and one with a distinction between privately-financed R & D and federally-financed R & D. The best results were obtained for the assumption of a rate of depreciation of zero percent and when the coefficients on the two types of R & D are not constrained to be equal. For all the subperiods, the coefficients on private R & D intensity are significant and do not give any evidence of a decline in the potency of R & D. On the contrary, its value increases over time, so indicating that the rates of return on R & D go up. Yet, if the intensity of private R & D expenditure was found to be highly significant, there appeared to be no significant relationship between the intensity of federal R & D expenditure and subsequent growth in productivity.

In a methodological paper about the search for outliers, Reiss (1990) reviewed Griliches and Lichtenberg's results and provided clues as to why federal R & D has been found non-significant. Furthermore, he argued that low estimates of the return to R & D was principally due to the presence of outliers. From a selective analysis of outlier

1 He approximates the premium by the relation $\alpha \log R + \alpha \delta s$ where R is the total R & D stock, s is the company-financed R& D stock as a ratio to the total R & D stock, α the R & D elasticity and δ the premium rate.

diagnoses, he identified four outliers out of a sample covering 27 manufacturing industries. These four outliers are respectively the industries of missiles and spacecraft, engines and turbines, farm machinery and equipment and computers. Among these four industries, the first one is the most highly federal R & D-intensive industry. The regression results for the nonoutlying sample show how much the exclusion of these anomalous observations dramatically affects parameter estimates. Indeed, his results report a significant estimate of the social excess rate of return on private R & D equal to 26 percent (against 35 percent for the full sample) and a significant estimate of the social excess rate of return on federal R & D equal to 18 percent (against a nonsignificant 1 percent for the full sample). For the four outlying industries, no coefficient is significant. This study illustrates how cautious one must be when one analyzes such flawed data as total factor productivity growth. In the measurement of productivity, a better status is allowed to traditional production factors than to knowledge investments. What the R & D data are asked to do is explaining residuals, a real challenge.

In a recent paper, Lichtenberg and Siegel (1991) re-examined the relationship between productivity growth and R & D using a large sample of firm-level data for three subperiods covering the years 1973-1985. In their model, the R & D intensity is the explanatory variable of productivity growth. Besides testing the returns by research orientation (basic research, applied research and development), they discriminate R & D by source of funds, i.e. company-funded versus federally-funded R & D. Their estimates of the private rate of return on R & D are globally in accordance with Griliches and Lichtenberg (1984a)'s findings. During the slowdown in productivity growth observed in the 70's, the rate of return on R & D increased. Basic research appears to provide higher rates of return than other types of research. The federally-funded R & D does not appear to influence productivity growth significantly. As a possible explanation, they point out the measurement problem : "In industries with relatively high level of publicly-financed R & D, such as defense and space sectors, output is poorly measured and price indices do not accurately reflect improvements in quality. A related concern is that federal R & D may have an indirect positive impact on productivity which is difficult to capture in our econometric framework. For example, federal R & D may improve economic welfare as a result of a) stimulation of additional privately-financed R & D or b) "spillovers" or benefits that accrue to industries or firms from R & D that is performed outside a given firm or industry ... At the present time, it is difficult to know whether the standard econometric framework underestimates the impact of federal R & D on economic growth". Yet, in their analysis, they examine how sensitive the full sample regression results are to influential outliers. When the latter are discarded, the parameter for private R & D declines and the one for federal R & D triples and becomes slightly significant. The variation of the private R & D coefficient is of the same order of magnitude as the alteration reported by Reiss. Although it is not the case for the federal R & D coefficient, the direction of the modification is the same.

While studies discussed so far were based on cross-sectional data, the Levy-Terleckyj (1983,1989)'s analyses use a time series approach. The first study examines the effects of R & D capital stock on output in the US business sector at the macroeconomic level. The authors make a distinction between private and government R & D and explore the effects of different types of government R & D, i.e. on the one hand, government-financed R & D performed in industry and overhead allowances for private R & D of the Defense and Space procurement contractors and, on the other hand, government R & D outlays other than contract R & D on private R & D spending. Assuming a six-year embodiment lag and no depreciation, they find a relatively large coefficient for the private R & D capital stock and a relatively small and statistically insignifiant coefficient for the total government R & D capital stock. When the hypothesis of an equal effect of both government contract R & D and other R & D is relaxed, the first variable is significantly positive and the second is insignificant and negative. The magnitude of this effect, however, is much smaller than that of the private R & D. According to the authors, " the effect of government-contract R & D on private-sector productivity which is observed here may represent either the direct effect on the productivity of performing companies or the indirect effects of producer goods developed as spillovers of government contract R & D on the productivity of the users of these products". Their second study deals with the problem of measuring physical returns to R & D in which they report estimates for the US telecommunications and computer industries. They estimate both Cobb-Douglas and CES production functions with and without the restriction of constant returns to scale for the telecommunications industry. The estimated impact of both public and private R & D are quite close in the two equations but with high variability in their significance. However, the R & D elasticities are very sensitive to the hypothesis about the returns to scale. Inside the traditional Cobb-Douglas formulation, the government R & D proves to have a positive and significant impact on output but less than the private R & D. Moreover, separating physical returns to R & D from returns to scale turns out to be a very difficult task. According to them another difficulty is in really measuring the effect on productivity growth and price change of an industry of R & D performed in other industries. The full effects of this outside R & D may not appear in an analysis of productivity growth because they are fully internalized by the source industry. As an example, they show that changes in the R & D capital stock in the computer industry explain a large part of the decrease in the price of computers. Although government-funded R & D performed in the industry has largely influenced computer technologies, its marginal impact on the price, when this variable is jointly introduced with private R & D, is insignificantly positive but significantly negative when introduced alone.

From the analysis of French panel data, Cunéo (1984) provides evidence against the hypothesis that the rate of return on R & D in an industry is all the weaker as the share of public funding is high [1]. Yet, as public funding is more oriented towards risky projects and the support of private R & D, Cunéo argues that it may not directly influence the productivity of firms but that it may create value added at the research process stage and not at the production stage. So, the R & D capital stock of a firm will be all the more useful and its impact on productivity all the higher as the firm will benefit from public funding. The same argument holds for fundamental research. If this argument is right, the R & D elasticity should not be a constant but a function of the public contribution to total R & D. Nevertheless, in order to simplify estimations, he picks up these effects by introducing dummy variables in his empirical model for enterprises receiving more than 1 percent in public funding or investing more than 1 percent in fundamental research. He also considers that the two types of research have a specific effect on productivity. The model is separately estimated on a firm sample of the scientific industry and the heavy industry. For the latter, the impact of fundamental research is insignificant. The main results reported by Cunéo are presented in table 5.3. and his main findings can be summarized as follows. First, the effects of publicly-funded R & D only become positive when it exceeds a certain threshold of total expenses of R & D per capita. Below this threshold, enterprises which do not benefit by government-supported R & D are more productive than enterprises which do. Above this threshold, the level of R & D activities seems to be sufficient to ensure a return to government support. The estimated relative thresholds are two for the heavy industry and four for the scientific industry, i.e. the R & D capital stock for enterprises benefiting by public support must be respectively twice and four times as big as the average R & D capital stock of the sector involved. Second, the publicly-funded research lengthens the research process, thereby involving firms in long-term research, which explains why enterprises must have a high R & D capital stock. Indeed, if enterprises have a low R & D capital stock, yielding a profits from these researches will be more difficult than for more R & D intensive enterprises.

None of the studies reviewed so far tackles the problem of the differential impact of the components of publicly-funded R & D. What is the contribution of publicly-funded basic research to the productivity growth ? In the hypothesis that public funding as a

[1] This idea was clearly made explicit by Griliches (1979) who points out that "a concentration of federally supported R & D expenditures in one area may lead to an overall decline in the rate of return to all R & D there".

Table 5.3. Impact of Public Financing in France

Sector	Constant term for enterprises		Output elasticity of R & D for enterprises			Productivity discrepancy for enterprises conducting fundamental research (FR) and receiving a public financing (FP)		Threshold from which the discrepancy is positive
	Not conducting fundamental research	Without government support	Not conducting fundamental research	With government support	Without government support			
Scientific industry $R^2 = .54$	.59 (5.24)	.43 (4.60)	-.16 (4.97)	.40 (11.85)	.32 (10.6)	PF	-.43 + .08 log (K/L)	$4 * \overline{(K/L)}$
						FR	-.59 + .16 log (K/L)	$1.5 * \overline{(K/L)}$
						Both PF & FR	-1.02 + .24 log (K/L)	$2.5 * \overline{(K/L)}$
Heavy industry $R^2 = .31$	-	.22 (4.17)	-	.19 (9.50)	.10 (7.92)	PF	.22 + .10 log (K/L)	$2 * \overline{(K/L)}$

Sample : 84 companies of the heavy sector and 98 companies of the scientific sector, 1972-77.
Specification : partial factor productivity.
Additional variable : fixed capital.
Values between parentheses are t-statistics.

Source : Cunéo (1984).

Table 5.4. Rate of Return on Basic Research in the United States

Study	Sample	Additional variables	Basic research		Applied research		R^2
			Company-financed	Government-financed	Company-financed	Government-financed	
Mansfield (1980)	20 manufacturing industries	Unionization	1.33 (1.51)		0.11 (0.59)	0.06 (0.80)	.63
		Unionization and expected R & D payoff	0.68 (1.27)		-0.02 (0.21)	0.12 (2.88)	.87
Link (1981)	51 manufacturing firms	Unionization	2.31 (3.87)	1.17 (2.13)	0.19 (1.83)	-0.0 (0.31)	.43

Note : values between parentheses are t-statistics.

whole is ineffective, we cannot conclude that all the components of publicly-funded R & D are not potent. Only few studies have tried to shed light on this issue. Although not directly investigating the issue of the effectiveness of public funding, Mansfield (1980) has attempted to estimate the rate of return on basic research as opposed to applied research and development. This analysis is an extension of Terleckyj's studies. In this analysis, the sources of funds are considered separately for applied research and development (privately financed versus publicly financed) but not for basic research. As shown in table 5.4, all the variables are insignificant. Yet, an alternative result based on total applied research and development expenditure gives significant coefficients of respectively 1.49 for this variable and .07 for basic research. Another regression introducing an expected R & D payoff variable (calculated as the percentage of the industry's firms that expected their R & D expenditures to pay off in no less than six years) shows a significant rate of return on publicly-financed applied research and development but not on the privately-financed one. From complementary regression results, Mansfield concludes that the productivity growth of an industry seems to be directly and significantly related to the extent to which its R & D is long-term investment. Yet, although the results are very mitigated, they throw a new light on Terleckyj's negative findings about the real rate of return on publicly-financed R & D. An additional evidence against the negative diagnoses about the effectiveness of publicly-funded R & D is given by Link (1981b) from a more disaggregated analysis of firm data. In his model, he separately introduces company-financed and government-financed basic research and applied research plus development expenditures. In addition to results similar to Mansfield's ones, his results suggest that government-financed basic research is also a significant determinant of firm productivity growth but its impact is about half the value observed for company-financed basic research as shown in table 5.4. The impact of government-financed applied research plus development is near zero and insignificant. On the other hand, the private applied research and development is marginally significant and compared to basic research its impact its quantitatively marginal.

In a nutshell, the studies dealing with the impact on productivity of government funded R & D generally lead to conclude that public support to R & D may be largely unproductive[1]. Yet, some studies emphasize that the relationship between government R & D support and productivity may be more subtle than the link between private R & D and productivity growth. The objectives of public support (defense, prestige and economic activity), the rules that govern the allocation of public funds to R & D (competitive contracts, cost sharing) and the character of use of government R & D (basic

[1] While not reporting his results, Klette (1991) also points out from the analysis of a large sample of Norwegian firms that his estimate of the private rate of return to publicly-financed R & D has turned out to be non-significant.

research, applied research and development) are all elements which strongly influence the effectiveness of public R & D investments. While the incentive of an enterprise to invest in R & D may to a large extent come down to the profit maximization rule, the incentives of public intervention are more complex and cannot easily be summarized in a single rule. Defense-oriented R & D is not directly aimed at furthering economic growth, basic research certainly sustains more long-term economic growth than short-term economic growth and the effectiveness of public support to new economic products and processes produced by business enterprises strongly depends on the own economic effectiveness of recipient private enterprise. As pointed out by Mansfield (1988b) the higher effectiveness of applied R & D in Japan compared to the US is to have been much faster and more efficient imitators than American firms. Yet, there is no evidence that Japanese firms have been faster or more efficient innovators than American firms. He adds that "American firms might respond by putting more resources into process R & D, which would make it more difficult for Japanese firms and others to appropriate a large share of the benefits from American product innovations. Also, American firms might increase their own capacity to imitate quickly, efficiently, and creatively". This shows that if public support is only an economically non-discriminant R & D support, the rate of return on private R & D will to a large extent be the single mirror of its rate of return. The main question regarding government support is perhaps more whether it is efficient than whether it is effective. In other words, if public support to R & D only sustains the private technological trends, its impact on productivity will be a duplication of the effect of private R & D. What productivity studies shed light on is the relative inefficiency of government support to R & D, not its ineffectiveness. In our view, the investment approach is more appropriate to answer to the question of whether effective government R & D support is, i.e. effective in promoting private R & D.

5.3. How Stimulating is the Publicly-Financed R & D ?

In an early attempt to measure the impact of publicly-funded R & D, Blank and Stigler (1957) arrive to contradictory conclusions on the basis of two alternative methodological approaches. The first one which rests on aggregate data for seventeen industries in which firms are classified into two groups according to whether they are engaged in government research or not, gives strong support to the substitution hypothesis. They hypothesize that public R & D support is a substitute for private R & D if the ratio to total employment of scientists and engineers engaged in private research is higher for the first group of firms than for the second. This hypothesis is verified for fifteen industries and for industry as a whole, which strongly buttresses the substitution hypothesis. In the second approach they only consider firms that perform R & D and only take their size into account. Industries with high ratios of scientists and engineers in private R & D also appear to have high ratios of scientists and engineers engaged in government R & D. This observation is particularly apparent for large firms. These findings lead the authors to conclude that public R & D is complementary to private R & D. Their global comment from these contradictory results is that the substitution effect derived from the aggregate data is grossly exaggerated in this type of approach.

However, this study used an indirect approach based on R & D manpower to measure the effect of public R & D on private R & D. The recent literature covers a more direct approach to analyzing to what extent public resources allocated to R & D modulate privately-funded R & D expenditures, the investment function approach. Like the production approach, the investment models may be classified as either based on aggregate time-series, industry-level cross-sections or firm-level cross-sections. While in this approach, the interpretation of estimates is less ambiguous than in the production function approach, the models greatly diverge according to the specification of models and variables. Some models simply investigate the link between company-financed R & D and government-financed R & D by either using or not using transformed data and only controlling for industry- or firm- fixed effects or demand shift. Others are designed in the Schumpeterian tradition and introduce additional relevant variables to measure market structure effects. A last class of models are inspired by macroeconomics in that they are derived from demand models in which changes in output and relative factor prices, the adjustment process to equilibrium and/or the economic conditions are taken into account. The main characteristics of these empirical models are summarized in tables 5.5 and 5.6. Only models dealing with the impact of publicly-financed R & D on private R & D are reviewed. In table 5.5, the estimated coefficients are elasticities while in table 5.6 they are marginal effects.

Using a general disequilibrium demand model, Nadiri (1980) examines how publicly-funded R & D capital stock influences privately-funded R & D capital stock in three aggregated industries. The estimated effects noticeably differ according to the industries considered. They are positive and statistically significant for total manufacturing and in durables industries and significantly negative in non-durables industries. His tests give some evidence that the effect of government financing is felt within the year but he suspects that the aggregation of data could conceal the true timing relationship. The elasticities obtained are very small in all cases. Although it could be concluded from this study that government support globally complements private R & D

Table 5.5. Company-Financed R & D Elasticity of Publicly-Financed R & D

Study	Sample	Specification and additional variables	Subsamples and other details	Public R & D	R^2
Nadiri (1980)	United States 11 manufacturing industries 1966-75	- Company R & D capital stock - Ratio of wage to user cost of capital, output level, lagged employment, lagged capital, lagged utilization rate, lagged private R & D capital stock	Manufacturing	.01 (2.25)	.97
			Durables	-.04 (4.34)	.99
			Non durables	.02 (3.44)	.96
Holemans-Sleuwaegen (1988)	Belgium 236 companies 1980-84	- Company R & D investment - Sales, employment, royalties and fees, concentration index, foreign-owned companies, dummy, diversification index	Multinationals	.32 (4.44)	.89
			Domestic firms	.35 (4.71)	
Scott (1984)	United States 3387 lines of business 1974	- Company R & D investment - Sales, dummy variable controlling for companies without government support	Without dummies	.08 (2.3)	.44
			Company dummies	.08 (2.3)	.70
			Industry dummies	.06 (1.6)	.66
Antonelli (1989)	Italy 80 companies 1983	- Company R & D investment - Profit, size, export, growth rate of profit, diversification dummy, average ratio of US R & D expenditures to sales	-	.37 (3.20)	.56

Note : Values between parentheses are t-statistics.

Table 5.6. Marginal Impact of Publicly-Financed R & D on Company-Financed R & D

Study	Sample	Specification and additional variables	Subsamples and other details	Marginal impact	R^2
Carmichael (1981)	United States 46 transport companies 1976-77	- Company R & D investment - Sales	Full sample	-.08 (2.31)	.96
			Big firms	-.07 (1.42)	.95
			Small firms	-.06 (3.39)	.59
Link (1982)	United States 275 companies 1977	- Company R & D intensity - Relative profits, diversification index, concentration index, ownership dummies	Private R & D intensity	.09 (2.01)	.39
			Percentage allocated to basic research	-.08 (1.75)	.46
			Percentage allocated to applied research	-.01 (1.59)	.32
			Percentage allocated to development	.09 (2.31)	.40
Levy-Terleckyj (1983)	United States Private business sector 1949-81	- Company R & D investment - Output, taxes, unemployment, weighted average age of the R & D stock	Government R & D	.21 (6.97)	-
			Government contract R & D	.27 (8.86)	-
			Other government R & D	.19 (1.76)	-
Levin-Reiss (1984)	United States 20 industries 1967, 1972, 1977	- Company R & D intensity - Relative basic R & D expenditures, industry age, concentration index, new and improved products-oriented R & D	-	.12 (2.86)	-
			Government R & D	2.69 (2.68)	-
			Government R & D concentration index	-24.08 (2.61)	-
Scott (1984)	United States 3387 lines of business 1974	- Company R & D intensity	Without dummies	.10 (9.9)	.03
			With company dummies	.08 (58)	.36
			With industry dummies	.09 (62)	.34
Switzer (1985)	United States 125 companies 1977	- Company R & D investment - Lagged R & D, concentration index, change in sales, financial variables	-	.08 (0.92)	.96
Antonelli (1989)	Italy 80 companies 1983	- Company R & D investment - Profit, size, export, growth rate of profit, diversification dummy, average ratio of US R & D expenditures to sales	Ratio of public subsidies to total R & D	8.27 (2.94)	.47

Note : values between parentheses are t-statistics.

the substitution effect obtained for non-durables manufacturing makes the analysis inconclusive.

More conclusive were the tests made by Scott (1984) on the basis of a large sample of observations on lines of business for 437 companies. He estimates two alternative models. First, he regresses company R & D intensity on goverment-financed R & D intensity with and without controlling for company and industry effects. His first result, in which there is not control variable for fixed effects, shows that company R & D intensity is greater in lines of business where government-financed R & d is greater. In other words, government financing goes to firms that do a lot of R & D. When company indicators are introduced, the estimate remains significant which gives some evidence that government funds do not principally go to firms that invest a lot in R & D. Instead of controlling for differences across firms, one can verify how the results can be altered by simply taking into account the industry effects. This will provide some information on the possible concentration of public funds towards R & D intensive industries. The amplitude of the estimated coefficient and its significance imply that of this hypothesis has to be rejected. From a last regression in which both company and industry effects are jointly intercepted, the author concludes that the significant impact of government financing on company R & D expenditures obtained is not simply the result of government funds going to R & D intensive firms in R & D intensive industries. Not only does government financing appear to be a complement to private R & D but it also stimulates R & D. An extra dollar spent by government in R & D generates an extra investment in company R & D of eight to ten cents. Yet, these results may only be spurious because sales are used in the construction of both the dependent and explanatory variables. To confirm his results, he specifies an alternative model. In this second model, logarithmic values of company-financed R & D are regressed with respect to logarithms of sales and government-financed R & D and a control variable for companies which do not receive any government support. Although far less significant than in the preceding regression, the estimated coefficients are marginally significant and do not lead to a rejection of the complementarity hypothesis. Moreover, in the margin, an increase in public financing stimulates an extra private R & D expenditure.

In a comment on this paper, Link, referrring to his own works, insists on the subtleties of the relationship between government-financed and company-financed R & D. Indeed, government-financed R & D not only stimulates the company-financed R & D but also affects the composition of R & D by category of use. An illustration of this is given by Link (1982) in an analysis of the determinants of R & D expenditures by character of use, i.e. basic research, applied research and development. The stimulus coefficient of federal R & D intensity obtained from his firm-level data analysis is significant and of the same order of magnitude as those reported by Scott. His regression results on the composition of R & D, that is on the percentage of the company R & D category of use, suggest that the impulse given to private R & D by an increase in federal R & D is primarily directed away from basic research and towards development and only very marginally influences applied research. In his discussion of results, he refers to complementary tests based on a desaggregation of federal R & D data showing that the positive relationship between federal R & D intensity and private R & D intensity and the share of private funds allocated to development is primarily a result of federal applied research plus development expenditures. In the case of the share of private funds allocated to basic research, it is the federal basic allocations which is the determinant factor.

Contrasting with Scott's and Link's findings, Carmichael (1981) reports empirical evidence regarding the crowding-out hypothesis. He develops a capital asset pricing model in which companies view R & D investments in terms of their risk and return characteristics. The latter are altered by R & D investments through the expected profits from sales and intra-firm spillover. By public R & D contracting, companies are to some extent able to separate these two sources of risk and return. In his model, the author tends to demonstrate that while some public crowding-out of private R & D is likely, this is almost certain to be incomplete. From the theoritical model, he deduces that private R & D is an increasing function of the scale of the firm measured by sales and a decreasing function of publicly-financed R & D. The application of this model to a sample of US transport firms gives some support to the partial substitution hypothesis. Yet, this hypothesis is more conclusive for small firms than for large firms. By and large, this model implies that each dollar spent by government in R & D adds around 92 cents to total R & D spending, and decreases private R & D by 8 cents.

Schrieves (1978) analysis, whose results are summarized in table 5.7, also suggests a crowding out of private R & D by federal R & D. In an analysis of the relationship between market structure and the intensity of innovative effort, he regresses, among other variables, the logarithm of privately-financed R & D employment on the percentage of R & D activity financed by the federal government for a sample of 411 firms classified into four industry groups. For non-specialized producer durable goods and specialized durable equipment the crowding-out hypothesis is accepted. For materials, public financing marginally stimulates the R & D activity in this industry. The complementarity hypothesis cannot be rejected for consumer goods. Yet, as the two durables industries concentrate a large part of R & D activities, the crowding-out hypothesis cannot be globally rejected. As these industries are heavily oriented towards electronics, aerospace, mechanical and electro-mechanical fields, public support is particularly intensive in these industries. So the government finances 26 percent of total R & D in durables against 4 percent in other industries. The results show that the marginal crowding-out effect is roughly about -.20 and the government R & D elasticity -.04 for the industry as a whole. The government R & D elasticity is highest for specialized durable equipment, its value is -.08. For durables, the elasticity is about the same as that obtained by Nadiri, and for non durables, it is equal to zero.

In a funds flow approach of determinants of industrial R & D applied to firm-level data, Switzer (1984) observes that government R & D expenditures do not significantly influence private R & D and, therefore do not raise total R & D.

From a study reappraising the Schumpeter hypothesis that technological innovations are more likely to be initiated by large rather than small firms, Rosenberg (1976) tests the hypothesis that government R & D financing stimulates private R & D. His dependent variable is defined as the percentage of total employment allocated to professional R & D personnel and his proxy for government R & D is the fraction of the firm's shipments originating in industries whose research is heavily subsidized by the government. The estimates confirm the stimulus hypothesis as shown in table 5.7. Yet, as his explanatory variable is contructed by accounting the ratio of firm's shipments to government on total shipments from industries whose R & D is subsidized at more than 50 percent by government, the stimulus may arise from government R & D contracts as well as from government non-R & D contracts.

In an examination of the simultaneous relationship between market structures and research intensity, Levin and Reiss (1984) tests how government policy affects technological opportunity and appropriability and how technological opportunity and appropriability conditions influence government R & D decisions. In their model, R & D intensity depends on the elasticity of unit cost with respect to own R & D, which is a measure of technological opportunity, and on the elasticity of unit cost with respect to industry wide R & D, which is a measure of technological appropriability multiplied by the conjectural variation with respect to R & D and divided by the Herfindahl index of concentration. On the one hand, the technological opportunity variable indicates the responsiveness of cost to own research effort and on the other hand, the technological appropriability variable represents how much a firm benefits from an increase in the common R & D pool. Among the determinants of opportunity, they assume that

Table 5.7. About two Models Based on Other Specifications

Study	Sample	Specification and additional variables	Subsamples and other details	Impact of public R & D	R^2
Rosenberg (1976)	United States 100 firms 1964	- company R & D employment intensity - concentration and entry barrier dummies, market share, firm's revenue, technological opportunity - shipment fraction in heavily R & D subsidized firms	R & D intensity	2.35 (2.64)	.43
Shrieves (1978)	United states 411 firms 1965	- logarithm of privately financed R & D employment - logarithm of sales, product-market and technological characteristics - percentage of R & D activity financed by government	manufacturing	-.53 (2.05)	.56
			non-specialized durable goods	-.89 (1,77)	.68
			materials	1.26 (1.63)	.59
			specialized durable equipment	-1.02 (2.61)	.56
			consumer goods	-.78 (1.08)	.77
			durables	-.82 (2.62)	.55
			materials and consumer goods	.10 (0.2)	.64

Note : values between parentheses are t-statistics.

government-funded R & D is complementary to private R & D and thus increases the elasticity of unit cost with respect to private R & D. They also consider that government of R & D restricts appropriability and thus increases the extent of spillovers in an industry. The government-financed R & D intensity is entered in the model to measure the first effect and the government R & D intensity is multiplied by the Herfindahl index to grasp the second effect. In the government R & D equation industry, technology bases, opportunity and appropriability conditions of industries as well as defense and non-defense oriented government purchases from industries are assumed to be the main determinants of government R & D intensity. Their empirical model is run on a sample of twenty industries over three years. When the appropriability effect of government R & D is not taken into account, the magnitude of the coefficient for the opportunity effect of government R & D implies that a one-dollar extra increase in government R & D funding spins off a twelve cents extra increase in company R & D spending. When both opportunity and appropriability effects are accounted for, the extra increase is about seventy-four cents. Yet, it seems that while government R & D stimulates private R & D by increasing technological opportunities, it also increases technological appropriability and so diminishes spillovers. The authors explain these contradictory results by the fact that "much government funding supports R & D for large-scale, capital-intensive defense systems which are not cheaply replicable despite mandatory licensing and technology transfer provisions". Another explanation is that as government R & D funding principally flows into industries with a high concentration rate, the technological appropriability variable may also capture the diminushing return effect of public funding on private R & D spending. In the government R & D equation, defense procurement is the most significant variable. Technological opportunity appears to offer little incentive to the government, which moreover seems to react with a substantial lag compared to private industry. The extent of interindustry R & D spillovers appears to increase the likelihood of government support.

Together with their analysis of the effects of government R & D funding on productivity, Levy and Terleckyj (1983) studied at a macroeconomic level how effective government funding was to generate additional private R & D investments. Besides the total federally-funded R & D performance, they look at how the allocation of these funds makes difference by distinguishing R & D contract from other categories of government R & D spending. They find some evidence that total government R & D spending stimulates an additional private R & D expenditure of 21 cents per dollar. However, this indirect effect seems attributable to R & D contracts and not to other forms of government R & D. The impulse effect of government R & D contracts is of 28 cents per dollar against no effect for other government R & D. The search for a lag structure of R & D contract has shown that the major impact occurs within the same year as the R & D contract. Their explanation is that "the performing companies have learned to form realistic expectations about future government support by developing R & D proposals for the government in a way which takes into account their plans for future complementary R & D funded with their own resources". For other federal R & D, an average three-year lag was estimated. When this lagged effect is taken into account, federal outlay for R & D performed outside industry appears to induce an additional private R & D expenditure of 19 cents per dollar. However, this impact is only marginally significant. These estimates of the effect of government R & D on private R & D are largely higher than those obtained in the other studies. The authors' interpretation of those divergences is that at the macroeconomic level, the estimates reflect the cross effects of government contract R & D on private R & D expenditures in companies other than those performing the R & D contracts.

Studies measuring the indirect effects of government R & D funding on private R & D in other countries than the United States are not plentiful. Holemans and Sleuwaegen (1988) focused on the role of government support in stimulating private R & D investment of foreign and domestic companies in Belgium. Their sample bears on time-series of firm-level data. The other variables introduced in the model are sales and employment which are shown not to be simply a substitute for size measures, as often assumed in tests of the Schumpeterian hypothesis, but also to capture other effects. Payments for royalties and fees are also included to measure to what extent foreign firms do less R & D than domestic firms due to a centralization of R & D functions within multinational companies. Their estimates suggest complementarity between government-financed R & D and privately-financed R & D and that the effects do not differ between foreign and domestic companies. The elasticities are largely higher than those obtained for the US but similar to those reported by Antonelli for Italy.

In his study, Antonelli (1989) investigates how declining profits and increasing competition can stimulate innovative efforts. In his failure-inducement model, he introduces, besides the profitability, the size of firms, the export and a dummy for large financial groups to explain the level of R & D expenditures for a sample of Italian firms. He also takes into account the pressure of the international technological environment by including the private R & D intensity of US firms. Concerning public subsidies, he argues that they have helped Italian firms "to fund levels of R & D expenditures beyond those allowed by short-term payback criteria". He respectively tests the linear and multiplicative specifications of the model which turn out to adjust itself in a noticeably similar way with regard to the ratio of public subsidies to total R & D expenditures. According to the estimates, the marginal effect and the elasticity are very high, which indicates a strong incentive effect of public subsidies on private R & D.

Levy (1990) argued that the absence of significant effect of government R & D on productivity is due to the confusion of zero value of marginal product with zero marginal physical product. If one supposes that government R & D can be employed without private cost, it is a public good that a firm uses at zero wage and, therefore, in equilibrium, the value of government financing's marginal product is zero. In other words, the zero coefficient associated with government-financed R & D in the production approach results from the equalization by the firms of the value of the marginal product of public R & D to their cost of utilizing this public R & D. This implies that the measurement of the impact of government R & D on output cannot be directly evaluated when the production is measured in value terms. Hence he suggests to use the indirect approach which consists in measuring the impact of public R & D on the supply of private R & D. To test this account he pools the data of nine countries for the period 1963-1984. In his time series cross-section analysis, he regresses private R & D on public R & D, both variables being subjected to the Box-Cox transformation. His main results are summarized in table 5.8. The adding of country-specific dummies interacting with the transformed government R & D variable improve the model significantly. Next, he tests how consistent the results are with the theory by considering three joint hypotheses. First, is the contribution of government R & D (R_{iG}) on private R & D (R_{iP}) really negative for countries for which the country-specific R_{iG} variable has a negative coefficient ? Second, is the contribution of R_{iG} systematically negative for countries for which the global impact (i.e. average impact plus additional country-specific impact) is negative ? Third, is the contribution of R_{iG} positive for countries for which the country-specific R_{iG} variable is positive ? The application of a resampling inequality procedure gives good evidence to support the supply hypothesis in the US, Japan, Germany, Sweden and France (countries with a positive country-specific coefficient and tested through the third hypothesis). This hypothesis is rejected for the UK and the Netherlands (second hypothesis) and the test is inconclusive for Italy and Switzerland (first and second hypotheses). In other to fix ideas about the impact of government R & D on private R & D, we have calculated both marginal effect and elasticity for each country on the basis of the mean value for several years. The range of marginal effects varies from -1.43 for the UK to 7.18 for Japan and the elasticities stretch from -.73 for the UK to .41 for Sweden. If we compare the values obtained for the US, the only country for which alternative estimates are available we observe that the elasticity estimated is comparable to Levy-Terleckyj (1983)'s estimates. Yet, the marginal effect is noticeably higher than the estimates obtained by other studies. The most contrasting results are the strong negative estimates obtained for the UK and the high marginal effect measured for Japan. From these results, we are not able to draw a clear-cut conclusion about the incentive or disincentive effect of defense-oriented R & D. The elasticities obtained for the US, Sweden and France are higher than the elasticities obtained for Japan, Germany and Switzeland, all of them countries devoting a very weak part of public credits to defense R & D. Yet, as the last countries spend less on R & D than the first ones, they are located at a higher point on the curve of marginal effects so that the spin off effect of an extra dollar invested by public authorities in industrial R & D is higher. In the UK and the Netherlands, the negative coefficients indicate that publicly-financed industrial R & D crowds out private financing with average large marginal effect.

Evenson (1984) uses a rather different way of looking at how government funding influences the innovative efforts. In a large-scale analysis of patents, he regressed

(12)

patents awarded to nationals in the US by industry over the period 1964-1978 on R & D efforts, the proportion of government support, the proportion of basic research and the proportion invested in development[1]. The introduction in the equation of the proportion of different types of R & D besides total R & D investment allows to control for some characteristics of the research system on patenting and provides a test similar to that performed by Griliches (1986) in order to verify if private R & D and federal R & D were equally potent. The potent elasticity of R & D is 1.23, which shows increasing returns of R & D in patenting while one cannot really reject the hypothesis of constant returns. The coefficient for government-funded R & D is 1.93, which indicates a large positive premium on federal R & D of 150 percent. This result is very surprising given the often emphasized argument that federal R & D carries restrictions on appropriability. The coefficients of basic research and development are respectively 13.77 and 1.38, which provides evidence of the less patentable character of basic research and of the near-the-market character of experimental development.

In several successive articles, Lichtenberg (1984, 1987, 1988) has harshly criticized studies which found that the federal R & D expenditure in the US has a positive and significantly different from zero impact on private R & D expenditure. He argues that studies of the relationship between federal and company R & D are generally upward biased (Lichtenberg (1984)). First, the hypothesis of exogeneity of federal R & D impulse on company R & D is largely unacceptable at the micro level because firm characteristics play an important role in the allocation of federal R & D contracts. He strongly suspects that the disregard for these firm characteristics causes an upward bias of estimates. To obtain an unbiased estimate, he recommends to work on changes in the variables over time. Second, he points out that deflating both company and federal expenditures by the same error-ridden deflator to measure the real inputs devoted to R & D induces spurious positive correlation between both variables, i.e. company and federal R & D expenditures. As the bias is of unknown magnitude and direction, he suggests to supplement data with an analysis of direct quantity indices of R & D input such as R & D employment. Third, he underlines that the conventional practice of dividing both company and federal R & D by sales is likely to produce an upward bias in the estimates. Subsequently, he reports estimates which support his arguments. Results of pooled regressions of changes in privately-funded R & D expenditure and employment on corresponding changes in federally-funded R & D at the industry level over the period 1963-1979 give an estimate insignificantly different from zero for the first measure and a negative coefficient with the second measure, which implies a crowding-out effect of federal-sponsored employment on company-supported employment. He also presents a

[1] He also includes industry indicators and some year dummies.

Table 5.8. Impact of Government R & D on Private R & D in the Main Industrial Countries

Specification	Country	Coefficient	Marginal[1] effect	Elasticity
	Average impact including USA	0.33 (4.89)	0.43[2]	0.30[2]
	UK	-1.21 (5.26)	-1.43	-.73
$(R_{iP}^{\lambda} - 1)/\lambda = \beta (R_{iG}^{\lambda} - 1)/\lambda + \beta_i D_i (R_{iG}^{\lambda} - 1)$	Italy	-0.23 (2.10)	0.57	0.05
+ others variables :	Japan	0.14 (0.81)	7.18	0.16
. country dummies . country GDP	Germany	0.03 (0.15)	1.00	0.23
. other continent fitted R_P	Sweden	0.34 (2.62)	2.30	0.41
$R^2 = .996, \lambda = .28$	Netherlands	-0.58 (3.52)	-1.23	-0.13
Sample : 9 countries, 1963-84.	France	0.11 (0.96)	0.85	0.33
	Switzerland	-0.25 (1.95)	1.51	0.02

Note : 1 the elasticity is given by :

$$\frac{\partial R_{iP}}{\partial R_{iG}} \frac{R_{iG}}{R_{iP}} = \beta \left(\frac{R_{iG}}{R_{iP}}\right)^{\lambda}$$

and the marginal effect by :

$$\frac{\partial R_{iP}}{\partial R_{iG}} = \beta \left(\frac{R_{iG}}{R_{iP}}\right)^{\lambda-1}$$

These values are calculated on the basis of the mean over several years and are own calculations.

2 USA
Values between parentheses are t-statistics.

Source : Levy (1990).

second analysis based on firm data in which he successively regresses the levels and the changes in the R & D - sales ratios. From his results summarized in table 5.9, one can observe for the level version a significant positive impact of federally-funded R & D in 1967 and 1972 whilst the estimated coefficient is negative for 1977. For the variation version, all the coefficients are negative and highly significant. To conclude, he points out that his findings "make heavier the burden of proof on those who would claim that federal contract R & D makes a positive contribution to aggregate technical progress".

Another argument puts forward by Lichtenberg (1987) is that previous estimates introducing sales or GNP as an explanatory variable are seriously upwardly biased because they fail to control for shifts in the composition of final demand. This misspecification is due to the existence of a correlation between the federal demand and the federal R & D funding. He contests the a priori hypothesis that sales to each customer identically affect the marginal returns on R & D and, therefore, that the composition of final demand does not influence the equilibrium private R & D expenditure. As we are primarily interested in a consistent estimate of the impact of publicly-funded R & D, the restriction of identical coefficients for sales to the government and to other customers cannot be maintained and this, for two reasons. First, an increase in government purchases will tend to stimulate more private R & D investment than any increase in purchases from other customers. Second, if the government is a major source of R & D financing, it is also an important customer. So, not only the impact of government purchases is likely to be substantially higher than the effect of other purchases but government purchases are also expected to be strongly positively correlated with government-financed R & D. If these propositions are right, part of the estimated effect of public R & D support on private R & D is statistically spurious. The author provides some empirical evidence by estimating both restricted and unrestricted models for US aggregate time-series data and firm-level data. From his main results reproduced in Table 5.10, on can observe that the federal R & D funding variable becomes insignificant when federal purchases are separately introduced into the equations. So, controlling for the components of sales inverts the finding of a positive significant effect of federal R & D on private R & D and this, at both micro and macro levels. What has been interpreted as the effect of federal R & D is nothing else than the effect of government demand.

Continuing his analysis about the effectiveness of public R & D in promoting private R & D, Lichtenberg (1988) gave further evidence by estimating regressions of private R & D expenditure on the value of competitive and non-competitive R & D and

Table 5.9. Impact of Federal R & D on Company R & D in the United States

Year	$\frac{\text{Federal R \& D}}{\text{Sales}}$	$\Delta\left(\frac{\text{Federal R \& D}}{\text{Sales}}\right)$
1967/1967-72	0.05 (2.11)	-0.48 (21.84)
1972/1972-77	0.10 (4.72)	-0.17 (14.05)
1977/1967-77	-0.22 (5.03)	-0.26 (14.06)
Sample : 991 firms.		

Note : values between parentheses are t-statistics.
Source : Lichtenberg (1984).

non-R & D government contracts and on non-government sales for a sample of industrial firms. Before synthesizing this analysis, it may be useful to specify that the firms composing his sample span a major defense buildup. In the US, the government promotes private R & D investment by awarding contracts according to a procedure referred to as procurement by design and technical competition. Firms are invited to submit proposals in response to requests by qualified departments (principally the Defense) which select the most interesting proposal. Such contracts are designed as competitive contracts. The firms which have been awarded the contract receive subsequent contracts which are designed as noncompetitive ones. These follow-on contracts are very substantial and it is often suggested that contractors can incur losses on the initial competitive contracts since they are virtually sure to make higher profits on the follow-on contracts. Therefore, it is useful to question how private R & D responds to changes in the volume of competitive and noncompetitive procurement as well as their R & D and non-R & D orientation. In his empirical analysis, Lichtenberg reports both ordinary least squares and instrumental variable estimates of total and within regressions. He uses the instrumental variables method to take into account specification errors due to the omission of time-varying variables. In his discussion of results, he essentially interprets the instrumental variables total estimates because he regards these estimates as the most consistent ones. From the main estimates presented in table 5.11, it appears that non-competitive procurement tends to highly crowd out private R & D investment. At the stage of follow-up contracts, firms reduce R & D spending, a behavior particularly marked in R & D procurement. In order to compare the results with previous studies, alternative aggregated estimates are reported for total R & D contracts (competitive plus

Table 5.10. Impact of Government Sales and Federal R & D on Private R & D in the United States

	Federal R & D	Government sales
Aggregate time series 1956-83	0.33 (2.45)	
	0.11 (0.60)	0.05 (2.09)
Firm-level data 187 firms 1979-84	0.13 (4.91)	
	-0.0 (0.06)	0.07 (5.98)

Note : values between parentheses are t-statistics.
Source : Lichtenberg (1987).

Table 5.11. The Private R & D Response to Competitive Contracts in the United States

Variables	Ordinary least squares		Instrumental variables	
	Total	Within	Total	Within
Competitive R & D	-0.05 (1.29)	0.09 (1.87)	0.86 (1.01)	0.17 (0.08)
Noncompetitive R & D	0.16 (3.09)	0.01 (0.17)	-2.11 (2.18)	-1.68 (1.24)
Competitive non-R & D	0.07 (2.07)	0.12 (6.05)	1.21 (3.89)	1.08 (1.90)
Noncompetitive non-R & D	0.04 (4.05)	0.05 (6.42)	-0.07 (0.96)	-0.05 (0.32)
Nongovernment sales	0.03 (33.5)	0.03 (20.2)	0.02 (3.53)	0.04 (2.03)
R & D contracts	0.04 (1.98)	0.05 (2.56)	-0.48 (2.63)	-0.93 (2.05)
Non-R & D contracts	0.05 (7.09)	0.05 (7.92)	0.15 (7.14)	0.13 (1.94)
Nongovernment sales	0.03 (33.4)	0.03 (20.4)	0.02 (5.73)	0.04 (3.04)

Sample : 169 companies, 1979-84.
Specification : private R & D investment
weighted regressions using the reciprocal of sales.
Values between parentheses are t-statistics.

Source : Lichtenberg (1988).

noncompetitive) and total non-R & D contracts. The net effect of government R & D contracting on private R & D investment turns out to be significantly negative, the negative effect of non-competitive R & D outweighing the positive effect of competitive R

& D. In contrast, the net effects of non-R & D contracting is significantly positive, which indicates that the positive effect of competitive non-R & D procurement outweighs the negative effect of noncompetitive non-R & D contracts. As non-R & D procurements are largely higher than other forms of procurement, the net effect of procurement as a whole is positive and quantitatively important. Nevertheless, in contrast to previous studies and in agreement with his preceding findings, Lichtenberg finds that the net effect of R & D procurement on private R & D is negative. The important role that the US government plays in the allocation of R & D resources is apparently stronger when it acts as a purchaser of goods and services than when it directly stimulates private R & D via R & D contracting. Hence, the relationship between government-financed and company-financed R & D is more subtle than suggested by global approaches. The allocation process of publicly-funded R & D and market structures heavily influence the effectiveness of directly and indirectly publicly-funded R & D programmes.

5.4. How Effective is the Public Support to R & D Projects ?

Another method was used by Meyer-Krahmer (1990) to evaluate the impact of public incentives for the R & D and innovation activities of small and medium-sized enterprises in Germany over the period 1979-1981. During the period, aid to R & D personnel expenditures was granted by the German government to enterprises "without regard to the field of technology concerned, the magnitude of the attendant risks, the quality of the work or the prospects of economic success". The idea is to make a comparison of R & D personnel expenditures between subsidized and unsubsidized enterprises before and after the launching of the programme by regression analysis. He considers that the incentives can change either the level of R & D or the R & D intensity or both. If the government support changes the level of R & D, this effect can be captured by a dummy variable which has the value 0 before and 1 after the governmental action. The stimulus effect on R & D intensity, for its part, can be picked up by measuring how the slope of the relationship between turnover and R & D expenditures has changed. The explanatory variables of the model are turnover and time. The latter is included in order to separate the conjunctural effect from the input of the incentives. According to the author, the programme did not change the R & D intensity but it did change the R & D level. The model was run for different subsamples of enterprises grouped according to the branch to which they belonged and R & D intensity and fitted better for branches and enterprises with a high R & D intensity than for those with a weak R & D intensity. Although his results give evidence of a positive effect of government support, he declares the model inappropriate to calculate accurately the additional R & D expenditures caused by the government policy due to data heteroscedasticity[1].

Although not based on the econometric approach, Mansfield and Switzer (1984) gave some evidence of the complementarity effect of federal support by analyzing answers of firms to a questionnaire. Their sample covers 25 US firms investing in energy R & D. For each dollar increase in federal support these firms have, on average, increased their own support of energy R & D by 6 cents in each of the first two years and nothing from the third year. Conversely, for each dollar cut in federal support they would reduce their own support by 25 cents in each of the first two years and of 19 cents in the third year. So, federal support appears to exert asymmetric effects on private R & D. Any reduction has a higher impact on private R & D than any increase. Moreover, these estimates are consistent with the complementarity effect detected by econometric studies. They also tested the relationship between sales, R & D expenditures and federal support without success. Another question tackled by Mansfield and Switzer is to what extent firms receive government support for projects they would otherwise have financed alone. To answer this question, they constructed a sample of 41 federally-funded energy R & D projects carried out by eleven firms. They evaluated that about 20 percent of the work would have been carried out with the firm's funds if government support had not been available. In addition, they observe that, on average, about 64 percent of the funds allocated to the projects would have been spent on R & D if the projects had not been carried out. A last question considered by the authors is how likely a project supported by government is to spin off projects in which the firm invests its own funds[2]. This topic is investigated by estimating a logit model giving the probability that a government-financed R & D project results in a spinoff. The explanatory variables are the originator of the project (government or enterprise) and the degree of separation between government-financed and company-financed R & D. With the first binary variable, they measure to what extent the contribution of the firm to the formulation of the project is likely to create spinoffs because the firms can so orientate the proposals in a direction that suits the commercial objectives of the firm, which leads the firm to invest its own funds. The second binary variable is concerned with the integration or the separation of the project into or from the firm's R & D program because the interaction and coupling of both financing sources are likely to promote spinoffs. Their results indicate that the probability of a spinoff is about 20 to 30 percent lower if the project does not originate within the firm. On the other hand, the separation of resources does not seem to impair

1 By comparing participating and non-participating enterprises, he nevertheless ascertains that 60 percent of public subsidies was invested in additional R & D expenditure.

2 See also Switzer (1985).

the likelihood that a government-financed project will lead to spin off of private R & D. Finally, they observe that, because of spinoffs, the effect of government-financed R & D on productivity is higher than its direct effect. On average, the projects directly contribute 50 percent of what could have been achieved with the company's own funds. These results are consistent with the econometric studies that have found that federal R & D has a relatively weak impact on productivity. Yet, the federally-financed R & D to a large extent generates further R & D into which the firm invests its own funds. On a whole, government support proves to be more a complement to private R & D than a substitute for it.

A probabilistic approach was also used by Bhanich Supagol (1990) in his analysis of a sample of 45 R & D contracts in the area of transportation in Canada. From a contractor survey about these contracts, he observed that the commercial spinoffs were greater for unsolicited projects than for government-initiated projects and for contracts with property rights vested in the contractors. A project officer survey gave him a more contrasted assessment in that no clear-cut divergence was detected about the spinoffs by sources of project and with respect to property rights. This evidences how different the perceptions can be depending on the person in charge who is being surveyed. A second issue examined is the probability of making commercial benefits depending on contract and contractor characteristics. Among the relevant explanatory variables, he introduces an initiation indicator (i.e. industry or government), the proportion of government-financed R & D, the squared term of the proportion of government-financed R & d and a government utilization indicator (i.e. contract successfully used by the government or not). He estimates a linear probability model but assumes that the relationship between the probability of a spin-off and the proportion of government-financed R & D is non-linear. This is why the uses a squared term variable. His estimates confirm that the more the contractor is engaged in the formulation of the project, the higher the likelihood of commercial spinoffs is. The proportion of government-financed R & D negatively affects the probability of commercial spinoffs. Yet, the existence of a non-linear relationship cannot be excluded. His explanatory is "that a firm with significant R & D dealing with the government may have established a special unit or facility for managing government research and bringing research results to their commercial applications". About the last variable which concerns the government utilization of the contract, it does not provide evidence of a possible trade-off between government and commercial benefits. Among the other variables taken into account, the retrocession of property rights to the contractor stimulates the private commercial exploitation. The probability of a spin-off is also all the higher if the number of patents granted to the firm is high, if the size of the firm is large and if the firm is young. The last result may be explained by a higher incentive in younger firms to pursue commercial spin-offs. Finally, foreign ownership and the use of resources which otherwise would have been idle prove to affect the probability of spin-offs negatively.

Seldon (1987) suggested an extension of the production function approach to measure the rate of return on research investment in terms of consumer and producer surpluses. He rightly underlines that in the traditional production function approach it is the marginal productivity or the value of the marginal product of R & D from which the value of the marginal internal rate of return on R & D is derived but not the internal rate of return. Both are different as the former is represented by the discount rate which equates marginal benefits to marginal cost while the latter is the discount rate which equates total benefits to total cost. The measures of the internal rate of return and of the marginal rate of return allow to evaluate to what extent government underinvests or overinvests in R & D. Indeed, according to the economic theory, the internal rate of return is maximized when it is equal to the marginal internal rate of return. It increases when it is inferior to the latter and decreases in the opposite case.

His development of the supply function approach is based on the estimation of a production function for the industry from which the industry supply function is derived by applying the rule of profit maximisation as illustrated in table 5.12. In the industry production function, both private and government R & D efforts are assumed to have separated lagged impacts on productivity. So, in this model, both private and government R & D effects are considered not to influence the productivity immediately but after a gestation period which differs according to the sources of financing. Moreover, these effects are not punctual but assumed to decrease geometrically over time. Assuming equilibrium in each period so that the maximum profit is zero, the supply function is obtained by substituting the production function into the profit equation, solving the profit maximization problem for traditional production factors and replacing the latter in the zero profit equation. An industry demand function is then specified. On the basis of these supply and demand functions, the changes in the producer and consumer surpluses due to government R & D spending in any period are measured by keeping all other variables at their initial levels and considering the convergence process to the equilibrium price. The economic benefit as a whole is equal to the sum of producer plus consumer surplus calculated at their present values. Subtracting R & D expenditures, the internal rate of return in each period is given by the value of the discount rate which equates the net economic benefit to zero. Besides, the marginal rate of return on government R & D expenditures in any period is derived from the estimated production function.

Seldon (1987) and Seldon and Hyde (1991) applied this approach respectively to the US softwood plywood and softwood lumber industries for the 1950-1980 period. Their results are summarized in table 5.13. In the softwood plywood supply equation, lagged total revenue is used as a proxy for private R & D and government scientists employed in these fields of research for government R & D efforts. The optimal lag structure was obtained for a two-year lag on private and public R & D efforts. The output elasticity for government R & D employment is equal to .19[1]. The estimated rate of return on government R & D expenditures is 499 percent, a higher value than those suggested by other studies of agricultural market. In the second study, private R & D efforts are not taken into account and government scientists employed in sofwood lumber research are used as the measure of government R & D efforts. Seldon and Hyde obtain an output elaticity for government R & D of .92 in the sofwood lumber industry. The best fit is yielded when government R & D efforts are given a five-year lag. The internal rate of return on government R & D expenditures (taking the average cost of implementation into account) is estimed at 27 percent while the marginal internal rate of return amounts to 15 percent. The lower value of the latter by comparison with the former provides evidence that average returns decreased during the period and that, therefore, government overinvested in this field of research.

Table 5.12. The Measurement of the Return on Government Financed R & D by the Supply Function Approach

1. Framework

Production function

$$Q_t = Ae^{\theta t} L_t^{\alpha} K_t^{\beta} R_t \qquad (1)$$

where : A = efficiency parameter
θ = rate of disembodied technical change
L = labor
K = physical capital
R = R & D capital

and

[1] Given the lagged effects, this elasticity is equal to $\mu / (1 - \lambda)$.

$$R = \prod_{i=i_o}^{\infty} (G^{\mu}_{t-i-k_o} \; C^{\upsilon}_{t-i})^{\lambda^{i-i_o}} \qquad (i_o, k_o) \geq 0$$

with : i_o = lag on the initial private effect
k_o = difference between the public and private R & D lags
λ = lag coefficient net of depreciation rate
G = government R & D
C = private R & D

Objective function of the firm

$$\max_{L_t, K_t} \; \pi_t = P_t \; Q_t - W_t L_t - P_k K_t - C_t \qquad (2)$$

where : P = price of the output
W = wage rate
R = user cost of capital

$$C_t = \gamma P_t \; Q_t \qquad (3)$$

where : γ = fraction of total revenue spent on private R & D

2. Derivation of demand and supply functions

Substituting (1) into (2), solving (2) for L and K, substituting (3) for C and solving for $\pi = 0$ gives the supply equation :

$$Q_t = B \; P_t^{\;\delta(\alpha+\beta)} \; e^{\theta t} \; W_t^{-\delta\alpha} \; R_t^{-\delta\beta} \prod_{i=i_o}^{\infty} (C_{t-i}^{\delta\upsilon\lambda^{i-i_o}} \; G_{t-i-k_o}^{\delta\mu\lambda^{i-i_o}}) \quad (4)$$

where B is a mixed constant term composed of the coefficients ($\alpha, \beta, \gamma, \delta$)

$$\delta = (1 - \alpha - \beta)^{-1}$$

Taking the log of (4) and subtracting $\lambda * q_{t-1}$, we obtain the supply function to be estimated :

$$q_t = (1 - \lambda) \, b + \delta \, (\theta_t - \lambda\theta_{t-1}) + \delta \, (\alpha + \beta) \, (p_t - \lambda p_{t-1}) - \delta\alpha \, (w_t - \lambda w_{t-1})$$
$$- \, \delta\beta \, (r_t - \lambda r_{t-1}) + \delta\upsilon c_{t-i_o} + \delta\mu g_{t-i_o-k_o} + \lambda q_{t-1}$$

where small letters represent logarithms of capitalized letters.

Similarly, the demand equation is defined as :

$$q_t = \sigma + \varepsilon p_t + z$$

where z is a log-linear function of prices of outputs and costs of inputs to the downstream industries so that the components of the derived demand from other industries are taken into account.

Given an R & D level of G in period t, keeping all other variables at their levels at time t except output price, the supply and demand system may be written :

$$Q_{t+i_o+k_o+l} = Q_t^s \; G_t^{\delta\mu\lambda^l} \; P_{t+i_o+k_o+l}^{\delta(\alpha+\beta)}$$

and $$Q_{t+i_o+k_o+l} = Q_t^D \; P_{t+i_o+k_o+l}^{\varepsilon}$$

where Q_t^D and Q_t^S are the level terms of predetermined variables.

Calculated on the basis of these equations, the equilibrium price P^E is equal to :

$$P_{t+i_o+k_o+l}^{E} = P_t \; G_t^{\delta\mu\lambda^l/[\varepsilon-\delta(\alpha+\beta)]}$$

3. The internal rate of return on government R & D

The changes in the consumer and producer surpluses due to government R & D in period t are respectively equal to :

$$\int_{P_{t+i_o+k_o+l}^{e}}^{P_t} Q_t^D \, P_t^{\varepsilon} \, dP = Q_t^D \, (1+\varepsilon)^{-1} \, (1 - G^{\eta\mu\lambda^l}) \, P_t^{1+\varepsilon}$$

$$\int_0^{P_{t+i_o+k_o+l}^{e}} Q_t^S \, (G_t^{\delta\mu\lambda^l} - 1) \, P^{\delta(\alpha+\beta)} \, dP - \int_{P_{t+i_o+k_o+l}^{e}}^{P_t} Q_t^S \, P^{\delta(\alpha+\beta)} \, dP$$

$$= Q_t^S \, [1 + \delta(\alpha+\beta)]^{-1} \, (G^{\eta\mu\lambda^l}) - 1) \, P_t^{1+\delta(\alpha+\beta)}$$

where $\eta = \delta(1 + \varepsilon) / [\varepsilon - \delta(\alpha + \beta)]$

The present values of the consumer and producer surpluses at time t due to government R & D in period t are respectively approximated as :

$$S_t^C = [1+\varepsilon]^{-1} \; P_t Q_t \sum_{i=i_0+k_0}^{\infty} (1+\rho)^{-i} \left(1 - G_t^{\eta\mu\lambda^{i-i_0-k_0}}\right)$$

$$S_t^P = [1+\delta(\alpha+\beta)]^{-1} \; P_t Q_t \sum_{i=i_0+k_0}^{\infty} (1+\rho)^{-i} \left(G_t^{\eta\mu\lambda^{i-i_0-k_0}} - 1\right)$$

where ρ = discount rate.

Net economic benefit from government R & D in period t is equal to :

$$NB_t = S_t^C + S_t^P - (1+\xi)\, G_t$$

where ξ is the ratio of the private cost of implementation of government-financed R & D to government-financed R & D. The internal rate of return is defined as the value of ρ which equates the equation NB_t to zero.

4. Marginal product and marginal internal rate of return

The marginal internal rate of return of government-financed R & D in period t upon the output in period t+n is calculated by estimating the value of the marginal product as :

$$VMP_{t+n} = P_{t+n} \frac{\partial Q_{t+n}}{\partial G_t} / (1+\rho)^n (1+\xi) \qquad \forall\, n \geq i_0 + k_0$$

With the Cobb-Douglas specified above, we obtain :

$$VMP_{t+n} = \mu\lambda^{n-i_0-k_0} \, P_{t+n} \, Q_{t+n} / G_t (1+\rho)^n (1+\xi)$$

The total value of the marginal product of R & D expenditures at time t is given by :

$$VMP_t = \sum_{m=0}^{\infty} \lambda^m \mu P_t Q_t / G_t (1 + \rho)^{i_o+k_o+m} (1 + \xi)$$

$$= \mu P_t Q_t / (1 + \rho - \lambda) (1 + \rho)^{i_o+k_o-1} G_t (1 + \xi)$$

Source : Seldon (1987), Seldon and Hyde (1991)

Table 5.13. Applications of the Supply Function Approach

Industry	Private R & D	Government R & D	λ	Implementation cost ratio	Internal rate of return	Marginal internal rate of return
Softwood plywood	.066 (3.03)	.025 (1.89)	.869 (23.0)	.26	4.99	-
Softwood lumber	-	.026 (1.73)	.972 (42.46)	.09	.27	.15

Note : values between parentheses are t-statistics.

Source : Seldon (1987) and Seldon and Hyde (1991).

In a recent paper, Leyden and Link (1991) have argued that infratechnology is the critical link between governmental and private R & D and that the stimulus-response effect is a consequence of technical complementarity at the production level between funding, infratechnology and knowledge sharing.

In their model, they assume that the firm engages in private R & D in order to increase its profits and that it receives a governmental R & D allocation to engage in a separate government-oriented R & D process. As a result, both R & D processes lead to private technological knowledge and governmental technological knowledge respectively through separate production functions. Nevertheless, the latter are assumed to share the same infratechnology if conducted within the same firm. Consequently, a proportion of private and public funds will be devoted to the production of infratechnology which will also depend on spillovers. These spillovers are represented by the level of the firm's activity in sharing intellectual activities and the level of R & D activity of the firm's competitors. Then, they consider that the firm maximizes its profits over its own contribution to R & D activities and its knowledge sharing effects as decision variables. Given that a governmental R & D allocation will increase the level of infratechnology at no net cost, a firm will never refuse such a contract because it will increase profits. Then, they define a third equation which represents the government's demand for infra-technology.

They test their model on a sample of data covering 137 US R & D laboratories in 1987. Three equations are simultaneously estimated and bear on the private R & D, the governmental R & D and the shared technical knowledge. The exogenous explanatory variables of the model are respectively a proxy for the R & D effort of competitors, an indicator of the presence of cooperative sharing agreements, an indicator of the presence of basic R & D activity and a dummy variable for enterprises engaged in biological or chemical research. The main estimates are summarized in table 5.14.

Table 5.14. Infratechnological Complementarity of Publicly-Funded R & D

Equation	Shared technical effort	Private R & D	Government R & D	Cooperative sharing agreement
Private R & D	3.35 (2.08)		1.99 (2.57)	-5.73 (2.40)
Government R & D	- 0.72 (1.35)	0.29 (4.31)		8.61 (2.15)
Shared technical knowledge		-0.10 (0.35)	0.32 (2.49)	1.92 (1.68)

Source : Leyden and Link (1991).

The results provide evidence that governmental R & D not only stimulates private R & D but also encourages technological spillovers. Taking into account the feedback effects which link the equations, the authors find that a one dollar exogenous increase in governmental R & D stimulates a 2.3 dollar increase in private R & D. Furthermore, a same increase in governmental R & D impels about 1% increase in the proportion of time spent on sharing technical knowledge.

Chapter 6 - Publicly-Funded R & D in a Competitive Environment

Henri Capron and Olivier Debande

Since Arrow's major contribution emphasizing the incomplete appropriability of the output of R & D activity, it has generally been accepted that public funding in this area should correct market failure. Yet, while Arrow underlined that underinvestment in R & D was likely, he also pointed out that "from the standpoint of efficiently distributing an existing stock of information, the difficulties of appropriation are an advantage". Despite works undertaken to improve our knowledge of R & D process on competitive markets, economic theory is presently unable to give normative guidance for public policy in the field of science and technology, which policy largely remains fuzzy and uncertain about the real attainment of objectives.

At the roots of public funding, there are strategic issues which motivate government action. The strategic issues of the technological race explain why public authorities have reinforced their science and technology policy and thoroughly integrated it as a structural competitiveness instrument of economic policy.

Strategic issues are vital in the design of science and technology policies because their main concern is international competitiveness. Furthermore, governments often act as strategic oligopolists in the design and the implementation of their policies. Only some of these issues, which are presently covered by the theoretical and empirical literature, will be discussed hereafter.

Some important theoretical papers dealing with both technological rivalry between firms and public incentive policies promoting R & D investments have been developed in recent years. Therefore, in the present state-of-the-art of the literature about strategic issues, what can we learn from an approach like game-theoretic models in order to implement appropriate R & D policies ? Another issue concerns the design of R & D policies, which, among other components, must take into account the specificities of each industry and international trends in R & D activities. Finally, a last issue investigated is how advisable modelling strategic issues in policy assessment and impact evaluation is.

6.1. Technological Rivalry and Public Incentive Policies

As technology has become a competitive weapon, technology policy is increasingly being viewed as a strategic activity. The role of governments in organizing, stimulating and funding R & D investment clearly is of the utmost importance in shaping a favorable environment and in channeling resources for technological innovation. Yet, enterprises move in dynamic interactive economic surroundings where the decisions taken by public authorities influence their allocation of resources. So, according to Weiss and Birnbaum (1989), a technological strategy is a functional strategy, i.e. "a set of means and errors chosen within a specific function within a business unit, which is a part of the overall strategy of a business unit". Especially in the technological field, strategies are long-term plans, created with a view to achieving general objectives, such as increasing the market share in high-technology industry or becoming the leader on the international market for specific products. However, the potential objectives and the behaviour differ with the type of firm. For example, larger firms might be thought not to pursue the same objective as small or medium-sized firms. Hence, they might have recourse to different instruments to achieve their objectives and the efficiency of incentives might be different depending on the size of the enterprises[1].

Among the important strategic issues enterprises are faced with technological change is a crucial one. Yet, technological change is not a homogeneous process and, therefore, may be thought to be linked to different stages of the decision-making process inside the enterprise depending on whether research is oriented toward product innovations and process innovations[2] :

- product innovation is developing specialized (radical innovation) or improved (incremental innovation) products as part of establishing or protecting a competitive advantage based on product differentiation and is more demand-oriented.
- process innovation aims at achieving cost or quality leadership within the product markets and may be expected to affect supply.

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1 Acs and Audretsch (1988) provide evidence that innovative activities in the small-and large-firms are likely to respond to different economic and technological conditions. In an industry, small-firms tend to perform better by using alternative strategies to those adopted by large firms. Regarding R & D policy effectiveness, Fölster (1991) observes on the basis of a survey of Swedish firms, that small firms are more sensitive to subsidies than large firms.

2 While we agree with Baily and Chakrabarti (1988) that in some cases "since a typical new product is just a variant of an old product, the old products do have to compete with new products. The rapid productivity gains that occur for new products also had down the prices of old products and, hence, reduce the increase in the industry price index even if it excludes these new products ... New products do increase measured productivity, but the increase as now measured is understated relative to a true economic measure of productivity", we think that product innovations are driven by the potential demand and that they are a major component of actual demand to enterprises. Besides, process innovations mainly affect costs and only indirectly influence demand through price reductions and quality improvements.

In order to establish a generic competitive advantage, a firm endeavours to develop capabilities that distinguish it from and cannot be copied by its competitors. It tries to implement a strategy that enables it to acquire uniqueness through differentiation and cost leadership. Hence, Lunn (1986) has shown that the determinants of both product and process innovations differ and that the latter have a differentiated impact on the endogenous variables of the firm (such as cash flow, capital intensity, advertising). Process innovation aims at reducing cost and, hence, may more directly lead to concentration while product innovation may be conducive to product differentiation and advertising. His main results are summarized in table 6.1.

Table 6.1. Differentiated Effects of Firm Variables on Innovative Activity

	Concentra-tion	Cash flow	Market size	Capital intensity	Technologi-cal opportu-nity	Advertising
PROCESS	.51	1.37	60.51	0.36	21.63	-
	(2.23)	(2.30)	(6.76)	(2.18)	(2.62)	
PRODUCT	.43	3.03	89.10	-	94.62	3.55
	(0.86)	(2.50)	(4.66)		(5.33)	(1.69)

NOTE : Values between parentheses are t statistics. Technological opportunity is captured by a dummy variable identifying technologically progressive industries.
Source : Lunn (1986).

Yet, to maintain its technological advantage, a firm must continuously invest in the improvements of its products and processes or in the creation of new ones because information rapidly leaks out to rivals. On the basis of the analysis of a random sample of firms, Mansfield (1985) measured the speed at which a firm's decision to develop a new product or process leaks out to its rivals. His results help to explain why industrial innovations are so rapidly imitated after being introduced. Indeed, in a preceding study, Mansfield, Schwartz and Wagner (1981) found that about 60 percent of the patented innovations were imitated within four years. Information about the decision to develop a new product or process is known to the rival firms within , on average, one to one and a half years after the decision. Moreover, rival firms know the nature and operation of a new product or process developed by other firms within about a year after development. As Mansfield points out, "these results provide new insight into the problem involved in providing proper incentives for innovation in a free-enterprise economy". Turning then to issues of public policy, his results provide evidence of "the magnitude of the difficulties faced by ... attempts by the US government to prevent the outflow to other countries of new American technology".

One way often put forward to improve technological capabilities is to promote cooperation between firms through different research programmes. The debate on the potential advantages or disadvantages of R & D cooperation is still largely open and it might therefore be useful to recall some of the positive social welfare effects resulting from cooperation. Jacquemin (1988) distinguishes between the private and public costs or/ and benefits of cooperative R & D and, on the private side, he finds three potential benefits to cooperation.

First, cooperative agreements can be used instead of pure market transactions or complete integration into an economic entity. Pure market transactions may, indeed, be costly and inefficient principally because, on the one hand, an R & D project requires repeated and prolonged interaction between the different partners to exploit or develop complementarities, and on the other hand, the market transactions in the R & D field hold two main risks, moral hazard and adverse selection. A merger or a take-over is not optimal to achieve an R & D project either. Indeed, an increasing size generates diseconomies of scale due to rigidities in the corporate structure. The time-span required for the research capabilities, strategies and partners to fit in with each other is too long. The second advantage of R & D cooperation is that it accelerates the speed of invention and innovation with less risk. Through cooperation, the money required to undertake an R & D project can be gathered more rapidly. Moreover, the partners profit from the risk-spreading advantage (i.e. sharing the benefits and the costs of the project) and the risk-pooling advantage (i.e. realizing more risky projects). Thirdly, by pooling complementary resources in R & D, they can benefit by three main advantages : better conditions on borrowed financial capital, sharing the high fixed and sunk costs of technological development and the creation of synergetic effects by pooling R & D knowledge from firms which may be located on different but connected technological trajectories.

Yet, if the potential benefits of R & D cooperation can be important, the implementation of R & D agreements remains a difficult task. In the starting stage of cooperation, an important impediment is the selection of partners. Because of imperfect information about the level of technological knowledge of potential partners, the risk of strengthening a competitor is real. An other restraint is the definition of a well-balanced contribution, i.e. a trade-off between collaboration and independence, which is more easily achieved in vertical agreements than in horizontal ones and which will often cause a complicated organizational structure to be set up. In the operational phase, in order to fully exploit the benefit of cooperative research, concerted manufacturing development and cooperation in the marketing policy have to be implemented, which will not be without causing problems.

Jacquemin's conclusion is that "limiting cooperation to pure R & D or to the so-called precompetitive level will then exercise a strong deterrent effect on the emergence of such cooperative arrangements".

This description must be fitted to take into account the characteristics of each product or process. The risk and necessity to cooperate at the competitive level will be different depending on the innovation rate of the industry considered. With regard to the public cooperative R & D, the problem that needs to be taken into account is whether there is market failure or not, i.e. absence or not of complete appropriability of returns. With or without substantial R & D spillovers, the potential benefit for the innovator firm will lead to underinvestment compared to the socially optimal amount of R & D and to pricing R & D results at a cost above the marginal cost of dissemination. Cooperative R & D can be viewed as a means of internalizing the externalities created by significant R & D spillovers and sharing information among firms more efficiently. Other side-effects are generated through partial appropriation, among which, inefficiently low levels of utilization by other firms, wasteful duplication of research and opportunism as well as asymmetric information limiting the effectiveness of the market for R & D.

Katz and Ordover (1990) suggest different ways to correct the gap between private and public returns to R & D investment and the insufficient sharing of the fruits of R & D projects, i.e. direct or indirect subsidies to restore incentives, strengthening incentives to engage in ex post cooperation and encouraging greater ex ante cooperation. Table 6.2. gives an overview of the advantages and disavantages of these alternative policies. To evaluate the impact of ex ante cooperation versus ex post cooperation, we must take into account the induced effect (of the firms forming an R & D coalition) on the consumer surplus as well as on the non-member firms' responses to changes in R & D levels.

Moreover, when evaluating the global positive or negative effect of cooperative decision-making on the R & D investment, competitive and technological spillovers are to be taken into account. Even with strong intellectual property rights protection, R & D investment by one firm may affect other firms through competition in innovative activities as well as on the market. Without technological spillovers, cooperative decision-making reduces (increases) R & D incentives if the products are substitutes (complements). Yet, the intensity of the spillovers is function of the quality of the protection effected by intellectual property rights. When innovators are product-market competitors and intellectual property rights are strong (weak), cooperative decision-making tends to decrease (increase) R & D investment incentives.

Table 6.2. Pros and Cons of Alternative Policies

Advantages	Disadvantages
1) Direct or indirect subsidies to restore incentives	
• effective in markets where technological spillovers are high	• insufficient dissemination of R & D results not corrected • moral hazard, i.e. the government has no perfect information about the cost structure of the firm... • require to levy additional taxes
2) Strengthening incentives to engage in ex post cooperation	
• incentive to conduct R & D because they allow a firm to appropriate the benefits of innovation more fully • better diffusion due to the better information control exerted by the innovator	• limit the possible spillover and, hence, the efficient sharing of R & D • reduction in R & D investment incentives for non first-generation innovators • risk of cartel by using licensing contracts in a downstream product market
3) Encouraging greater ex ante cooperation	
• greater amount of R & D investment : internalizes the externalities created by technological spillovers while continuing the efficient sharing of information • greater efficiency of R & D investment : - more R & D projects are started due to costs being shared - the effective amount of R & D is higher - intangible assets are shared, financial problems resolved and the unavailability of insurance against the failure of an R & D investment due to moral hazard is made up for - eliminates wasteful duplication	• intense rivalry between the different firms at the competitive stage

Reaching an agreement at the ex ante level might lead to an increased monopolistic power on the product market which can compensate for the gains accruing to consumers rather than to the firms, generating a lower collective effect of R & D. Regarding international competitiveness, the technology transfers through a cooperative agreement may substantially strengthen the foreign partner and diminish the rents accruing to domestic firms which are not members of the coalition.

An ex post cooperation is possible by concluding a licensing agreement against a fixed fee. When strong intellectual property rights exist, ex ante cooperation leads to weaker R & D investment incentives. Given that the licenser has the bargaining power, each firm is motivated to conduct R & D in order to appropriate surplus that might otherwise accrue to its rival. The collective R & D investment incentive under ex ante cooperation is lower than the individual incentive under ex post cooperation. When the protection afforded by secrecy is strong, when spillovers are high, ex post cooperation may be limited. The fact that the ex post market power of firms can exceed their ex ante market power implies that ex ante cooperation can lead to less severe monopolistic pricing distortions in the pricing of R & D results.

Consequently, a potential strategic public policy is to implement cooperation in sectors with some specific characteristics. These policies might for instance :

- meet the need to increase the international competitiveness of domestic firms;
- stimulate industries with a high spillover;
- induce precompetitive research which furthers long-run relationships between firms and by-passes the problem of benefit sharing;
- implement programmes dealing with complementary products.

The technological positions of the different countries are not unalterable. The capacity to innovate changes over time. Since the Second World War, the US has been the reference level against which the technological positions of the industrial countries have been evaluated. Any technological policy must build upon a check-up of innovative capabilities, i.e. assessing the present situation and the possible modifications of the "country's position" on a potential performance scale.

A study by Glismann and Horn (1988) looking at the invention performance of the main industrialized countries on the basis of patents granted in the United States shows that the heterogenous economic structures which characterize the main European countries materialize in distinct technological advance rates.

Their analysis covers the innovation performances in France, Italy, Japan, United Kingdom, the former USSR and West Germany, compared with the United States over the past twenty years. Japan has filled the technology gap between itself and the United States by using imitation as its strategy. Today, Japan and the United States are often thought to be more successful in producing new technology than West European countries. Glismann and Horn's analysis provides evidence of the position of the seven countries in the technological race. To assess the innovative activities by country and field of activity, they use the patents granted in the US between 1963 and 1983.

They consider respectively,

- the relative average invention performance of countries over time calculated as the ratio of the number of patents granted to country j in field i to the number of patents granted to the United States in field i :

$$RAIP_j^i = \frac{1}{n} \sum_{t=1}^{n} \frac{Patents_j^i}{Patents_{US}^i}$$

- the estimated relative starting position of country j as measured by coefficient "a" in the equation :

$$\frac{Patents_j^i}{Patents_{US}^i} = a.e^{b.t}$$

- the estimated relative evolution of patent activity of country j as measured by coefficient "b" in the previous equation.

They observed that the number of non-US patents represented only 25 percent of the number of patents granted to the United States with West-Germany and the United Kingdom having a leading position. On the one hand, non-US patents per year rose six percentage points faster than the United States patenting. On the other hand, Japan, West-Germany and the USSR performed significantly better than the United States, while France and Italy did only just a little less well. For its part, the United Kingdom revealed a similar profile to that observed for the US. The US lost less in high-technology fields than in average technologies. Regarding the highest country share of patents granted to non-US citizens, West-Germany and Japan had a leading position and only Japan in high-technology fields. They also emphasized a positive correlation between the performance in technological activities and the countries' economic performance and stressed the reduction of the technological gap between European countries and the United States, an adjustment process highly contrasted for each European country with West-Germany in a leading position and the development process in the United Kingdom matching to the American business cycle. The heterogeneous economic structures among European countries result in distinct rates of technological advance.

An important factor determining the innovative performance and the catching-up process is the increase in the level of investment devoted to inventive activities. Another major factor is the institutional change. The development of the European Patent Office, for instance, allows the European firms to develop innovation in a favourable context in terms of appropriability conditions.

The working horizon and the cost constraints are also crucial factors to implement an R & D program. Especially to develop technology, long-term investments that need not meet very short-term performance criteria have to be made.

So, Mansfield (1988a) showed that innovation time and innovation cost are central to success. Japanese firms tend to develop and commercially introduce new products and processes more quickly and cheaply than American firms. As a consequence, there has been a technological depreciation of American products. Here, it is worth noting that the perception of American and Japanese products has been completely inverted in forty years' time. This example illustrates how important a technology policy is to preserve and improve competitiveness.

In his examination of the outcome of the technological race between Japan and the US on a sample of American and Japanese firms he questions how quickly and economically each nation's firms can develop and commercially introduce the new products and processes and how essential it is for them to succeed. He looks at two variables of innovation :

- the innovation time : which is the length of time elapsing from the beginning of applied research by the innovator on a new product or process to the date of the new product's or process's first commercial introduction;

- the innovation cost : which is all the costs involved in developing and introducing the innovation, including R & D, plant and equipment, and startup costs.

The Japanese advantage is confined to external technologies (i.e. technologies developed outside the innovating firm). In internal technology, developed within the innovating firm, there is no significant difference between both countries. Innovation based on external technologies is an imitation process. The higher commercialization cost in the US arises from the inability of American firms to improve significantly on the imitated products and to reduce their production costs substantially. The process of resource allocation differs between the US and Japan. The Japanese firms devote more resources in the innovation process to tooling and manufacturing equipment and facilities, which include preparation for manufacturing, design, construction, and acquisition of manufacturing facilities for the new product, as well as tooling and equipment. The

American firms spend more money on the manufacturing startup, which is linked to the quality problem of their products. There has been a technological depreciation of the American products over time. The US has now acquired a reputation for quality problems that compels the US to offer its goods at a lower price than Japanese or German manufacturers, for instance.

A recent study by van Hulst, Mulder and Soete (1991) emphasizes the narrow relationship between a country's technological ability and its export performance. The case of the US is relevant to look at the link between technology and competitiveness. In 1970, the US had a lead in technology over other industrial countries, which allowed it to maintain a trade surplus in manufactured products in spite of higher unit labor costs in most industries than elsewhere. But suffering from too high a currency and interest rate, and above all from an upgrading of the products provided by Japanese and German firms, US firms have lost market share in manufactured goods. The US advantage in technology and quality has eroded a way and the US products have now acquired a reputation for quality problems that compels the US to offer its goods at lower prices than its rival manufactures. The American case shows how important it is to conduct a technological policy that gives the home firms the capacity to compete with foreign firms and to increase their market shares in sectors with high added value.

The public policy has to take into account the original characteristics of each country. Moreover it has to be oriented to create new comparative advantages. According to van Hulst and al. (1991), "the degree to innovativeness of each country in any one particular technology is explained through the complex interplay between (i) science-related opportunities, (ii) country-specific and technology-specific institutions which foster/ hinder the emergence of new technologies and (iii) the nature and intensity of economic stimuli, which stem from abundance of particular inputs, or, alternatively, critical scarcities, specific patterns of demand as well as levels and changes in relative price".

In an analysis of the erosion of the American leadership, Nelson (1990) argues that it will be investments in R & D and in physical and human capital, and perhaps particularly the latter and not so much organizational differences, that will determine the classification of countries regarding technological and economic levels. According to him, "technology is only a public good for those who have made the investments to be able to tap in ... it is differences in these that largely explain why Japan has done so well and the US recently relatively poorly ... it is these latter investments (investments in new plant and equipment, and in worker skills) that will largely determine who is in the best position to develop and exploit technological developments, and relative national living standards".

In a recent study, Dornbusch, Krugman and al. (1990) emphasized the important gap between the US and Japan. While education expenditures are slightly weaker in Japan than in the US, studying hours, the study of mathematics and foreign languages and the number of students in technological fields are higher in Japan than in the US. These differences may point to inadequacy of the American educational system to train enough human capital able to improve and develop the know-how and the technical knowledge which high-tech industries need.

6.2. Models of R & D Strategy

Game-theoretic models are more and more used to describe the competitive process. However, a restriction to the use of this type of model is the great variability of results depending on the initial assumptions made. Indeed, depending on the assumptions of the model, the conclusions can substantially differ. Reinganum (1984) showed how sensitive the result is to the selected assumptions by studying the model of Loury (1979) and Lee and Wilde (1980). These models use a process of stochastic invention in which the probability of success by firm i at the given time t is an exponential function. They only differ in the specification of costs, i.e. Loury uses lump-sum R & D expenditure (fixed cost) whereas Lee and Wilde use a flow cost of R & D expenditure. On the basis of these alternative hypotheses, they obtain the opposite results summarized in table 6.3. So, the predictive power of a game-theoretic model is strongly limited by the assumption at the basis of the model.

Table 6.3. Compared Results of two Game-Theoretic Models

Loury (1979)	Lee and Wilde (1980)
1. The amount invested by an individual firm decreases with the number of firms engaged in R & D; however, aggregate industry investment increases with the number of firms.	1. The rate of investment by an individual firm increases with the number of firms engaging in R & D; a fortiori, the aggregate industry investment rate increases with the number of firms.
2. In a Nash equilibrium with unrestricted entry, there will be excess capacity in the R & D technology.	2. In a Nash equilibrium with unrestricted entry, there will be no excess capacity in the R & D technology.
3. At equilibrium, an increase in aggregate rival investment results in a decrease in investment by a single firm.	3. At equilibrium, an increase in aggregate rival investment rate results in an increase in the rate of investment by a single firm.

Table 6.4. gives a general overview of the main theoretical models of R & D competition developed in the literature, which can be viewed as significant benchmarks of this research field. Complementarily to this general description of models, one may add the following comments :

1. Symmetric models give an appreciation of the extent to which rivalry and appropriability interact to determine the incentives for individual firm investment in R & D. The main issues investigated are : what is the aggregate noncooperative investment in R & D and how it is distributed across firms and across time ? How many firms enter the race and what is the resulting equilibrium date of innovation ? The extent of appropriability will guide the investment decision of firms under entry. Firm will overinvest compared to the cooperative optimum if rewards to innovation are appropriable and conversely [Reinganum (1989)].

2. Asymmetric models are developed by referring to the auction and stochastic racing paradigms. The choice of paradigm proves to be important because the associated models are found to give opposite results. Under uncertainty, a firm with a large market will invest at a lower rate than a potential entrant for an innovation promising the winner a large market and conversely under a determinist scheme. As innovative activity may take more or less time and money than expected and might not yield a worthwhile end-product, the stochastic racing model seems more accurate while the auction model may well be preferred for the analysis of the development phase as any substantial technological uncertainties have already been resolved [Reinganum (1989)].

3. These models provide evidence of the existence of market failures, and hence justify public intervention. Yet, they remain relatively silent on how government policy may act to reduce market failures. When government action is taken into account in these models, their counterfactual settings limit the practical range of results. Therefore, so far they have not been able to guide an efficient R & D policy. For example, the next two questions remain largely open : Where are the most prominent sources of market failure in R & D ? How efficient is a public policy encouraging research joint ventures to correct market failures ?

One difficulty, stressed by Cohen and Levin (1989), in testing the implications of game-theoretic models of R & D rivalry is that they analyze behaviors in highly simplified models, omitting important aspects of industrial competition. Moreover, the utilization of game-theoretic tools implies that we must use unverifiable assumptions concerning the

Table 6.4. An Overview of Strategic Models of R & D

1) Innovation production in the context of symmetric models

General hypotheses :
. Simultaneous competition for an identical potential innovation
. Global and indefinite protection from imitation or duplication for the patented innovation.
. Cost of invention being a decreasing convex function of the time prior to invention.

Authors	Assumptions	Results	Remarks
1) Loury (1979)	1) The success probability is an exponential time function. 2) R&D expenditures are fixed costs. The costs of carrying out an investment project may be regarded as known at the initial moment, independently of subsequent developments.	1) The equilibrium level of firm R&D investment declines as the number of firms in the industry increases. 2) A zero expected profit industry equilibrium with initial increasing returns to scale in the R&D technology and with a finite number of firms will always involve "excess capacity" in the R&D technology. 3) Given a fixed market structure, industry equilibrium will have each firm investing more in R&D than is socially optimal. 4) With increasing initial R&D returns to scale, competitive entry leads to more than the socially optimal number of firms in the industry, each of them investing too little.	1) Symmetry between the different firms. 2) Exponential assumption to incorpore strategic rivals implying no learning by doing or by using. 3) Inappropriate investment process assuming R&D expenditures committed up front. 4) No entry cost.
2) Lee and Wilde (1980)	1) Cf. Loury. 2) R&D expenditures are flow costs i.e. firms are able to choose a research intensity; once this intensity is fixed, the firm must either sustain this level of investment or cease investing altogether.	1) Increasing equilibrium investment as the number of firms increases. 2) In industry equilibrium, higher investment rate than jointly optimal for fixed number of firms. 3) With increasing initial R&D returns to scale, competitive entry results in too many firms, with too high an investment rate.	1) Cf. Loury 1). 2) Cf. Loury 2). 3) The instantaneous probability of introducing a new technology should be a function of both the current investment rate and the stock of knowledge. 4) Cf. Loury 4). 5) Strategic response to rival's success limited to the possibility of stopping R&D investment.

3) Delbono and Denicolo (1991a)	1) Cf. Lee and Wilde. 2) Prize to the winner depends on the number of firms (quantity - setting Cournot players in the product market) and losers may reap positive profits in the post-innovation equilibrium. 3) Before the innovation, firms may make positive profits, and social and private benefits from the innovation differ.	1) An increase in the number of firms may result in a decrease in the equilibrium R&D effort of each firm and in the equilibrium total effort. 2) In equilibrium there may be underinvestment with respect to the social optimum. 3) Lee and Wilde's result still holds when the post-innovation market profits of the winners as well as those of the losers do not depend on the number of firms.	Continuation of Lee and Wilde's model.
4) Reinganum (1982)	1) Flow expenditures determining the likelihood of success, with knowledge accumulation. 2) Firms may adjust the rate of expenditure in response to elapsed time and state variables which summarize rival progress. 3) Imperfect patent protection. 4) Leader's or innovator's payoff (P_L) ≥ follower's or imitator's payoff (P_F). 5) Finite planning horizon. 6) The value of the patent is not constant over time and may decrease or increase if additional uses are discovered. 7) The conditional density of success depends only on current investment. 8) Use the concept of Nash equilibria in feedback strategies.	1) In the no-success case, the expected amount of additional knowledge is independent of accumulated knowledge. 2) For $P_L > P_F$, an increase in P_L stimulates each firm to acquire knowledge at a higher rate, while an increase in P_F causes each firm to reduce its equilibrium rate of knowledge acquisition. 3) For the case of perfect patent protection, an increase in n (number of firms) increases the equilibrium rate of investment for each firm and decreases the expected time till innovation. For the case of imperfect patent protection, the result is ambiguous and function of the relative payoffs to innovators and imitators.	
5) Reinganum (1981)	1) Cooperation among firms through coordinating research strategies and exchange of knowledge. 2) Spillovers in knowledge are complete. 3) There is actually no duplication. 4) All knowledge is transferable.	1) Noncooperative rivals will (on average) succeed sooner than cooperative firms who are unable to share knowledge. 2) Assuming that the social value of innovation exceeds half private value, then the noncooperative rate of knowledge acquisition is less than is socially optimal. Innovation will on average be delayed compared to the socially optimal date. Innovation by Nash rivals will on average occur later than the cooperative date.	1) Cf. Loury 1). 2) Appropriability is taken into account by modulating the effectiveness of the patent protection. Patents are not the most effective protection system of innovation. Other decision variables are more powerful and influence the strategic behaviour of the firm. 3) No effective public policy about cooperative agreement. 4) Cf. Loury 4).

6) Spencer and Brander (1983)	1) Two-stage game (R&D and output) played by two competing firms, located in different countries. 2) Introduction of industrial strategy policies in the context of an imperfectly competitive world. 3) R&D is undertaken before the associated output is produced, with firms anticipating the effect of R&D on how output shares can be won. 4) Government interventions take different forms : R&D subsidization and/or export subsidies. 5) A Government can credibly commit itself to R&D (or output) subsidies before the R&D decisions are made by private firms. 6) Outputs of each firm are substitutes.	1) Overuse of R&D in the absence of government policy. 2) With a single government allowed to subsidize R&D, the outcome is equivalent to the one obtained in the leader-follower equilibrium case. 3) When both governments are allowed to subsidize R&D, they do it. 4) If Government can subsidize both export and R&D, it will have an incentive to tax R&D (efficiency objective) and to subsidize export (market share objective).	1) Countries are symmetric. 2) Results are valuable for any kind of investment and not only R&D. The major insights can be obtained by any subsidy policy aimed at reducing costs. 3) The Cournot model implies that a subsidy is always worthwhile because it increases the demand for the domestic firm and thus its profits.
7) Dixit (1988)	1) Continuum of firms engaged in the R&D competition. 2) A lump-sum cost at the outset and recurrent flow costs during the R&D race. 3) Success independent across firms. 4) Firm's hazard rate independent of time and of R&D flow expenditures. 5) No new information during the race. 6) Success puts an end to the competition.	1) The optimal policy is to alter the appropriable benefit of the winning firm by means of an award (tax) if the market is providing insufficient (excessive) R&D effort according to the balance between externalities. 2) The larger the firm, the more it will internalize negative externalities (i.e. competition for the innovation leading to a socially excessive amount of R&D investment).	1) Cf. Lee and Wilde. 2) Partial progress in the R&D race not considered. 3) Continuum of firms in a symmetric world.

2) *Innovation production in the context of asymmetric models*			
a) The difference among firms did not confer an ex ante advantage upon any particular firm.			
Authors	Assumptions	Results	Remarks
8) Reinganum (1985)	1) Each innovation is drastic i.e. one which leaves the inventor a monopolist. 2) An incumbent monopolist competes with (n - 1) identical challengers for a new innovation. 3) Firms are symmetric in all other respects i.e. they face the same innovation production possibilities. 4) The equilibrium concept is the subgame perfect Nash equilibrium. 5) The value of winning the current race is higher than the value of losing it (true by induction). 6) There always exists an investment level for a challenger for which gross profits exceed the value of losing immediately.	1) The Nash equilibrium in the current stage is symmetric among the challengers and the incumbent invests less than each other challenger. The latter conclusion gives rise to a turnover of the technological leadership similar to Schumpeter's "process of creative destruction". 2) Each firm would prefer to be the incumbent in the current stage rather than a challenger.	1) In this model, the monopolist has no advantage in the technological process. If the incumbent has some cost advantage, it may have a higher incentive to invest in R&D to avoid entry. 2) The question of appropriability is resolved through the notion of drastic innovation. 3) There is no spillover effect and no learning effect. 4) Since innovation is drastic, the profit incentive only interfers and the challenger has the greatest incentive to innovate.
9) Vickers (1984)	1) A sequence of not-so-drastic innovations is considered so that the profit flows of the two firms typically depend upon the levels of technology. 2) The technological race takes the form of a simple auction. 3) Firms are assumed not to discount the future.	When the product market is very competitive, there is increasing dominance; in other cases, there is a reaction process.	Neither spillovers nor learning effects.

b) The nature of the asymmetry confers a strategic advantage upon one firm.			
10) Fudenberg and al. (1983)	1) Both firms are suffering from information and/or response lags regarding the research activities of their rivals. This feature allows firms that are only slightly behind to catch up before the leading firm can act to prevent it. 2) Invention occurs as soon as one firm has accumulated enough knowledge (total research and development spending). 3) Variation in the rate of learning and the cost of learning are strictly convex. 4) Within the current period, each firm must choose its rate of knowledge acquisition without knowing its rival's choice. 5) Both players value the patent equally and face the same cost conditions.	1) The result is conditioned by the lag in terms of accumulated experience between the firms. If they are sufficiently close each other, they choose a high rate to try to win the technological race. In the other case, it drops out of the race and the remaining firm chooses a lower rate. 2) As the period of information lag decreases, the lag in experience for which the follower still competes also decreases.	1) Restriction on the firm's abilities to vary its research intensity. 2) The result crucially depends on the initial lag in experience.
11) Harris and Vickers (1985)	1) The two firms move alternatively and the first firm to reach a goal, wins the prize. 2) Progress is function of the invested amount. 3) The notion of equilibrium is subgame perfect Nash equilibrium. 4) Firms place different values on the reward and face different cost functions.	If one player is far enough ahead, then the other gives up. The notion of distance corresponds to the value placed on winning and the costs of achieving a win. A distinction is operated between safety and trigger zones. In the first case, the winner is determined and proceeds as though no rival existed, this rival investing nothing. In the trigger zone, the firm which is allowed to make the first move jumps immediately to its safety zone.	1) This model is a deterministic race in which equilibrium is characterized by all firms but one exiting the competition right at the outset. The equilibrium outcome is a function of the initial distance, in terms of additional units of knowledge, which each firm is faced with. 2) The strategic advantage of each player is function of the valuations of the patent, of the value of the discount factor, of the efficiency of performing R&D and of the amount of acquired knowledge and experience. 3) There is a place for public intervention which may speed up the pre-emption process.

12) Grossman and Shapiro (1987)	1) Extension of the formulation of Lee and Wilde (1980). 2) A firm wins the race when it has completed the two equally difficult phases of research and development. 3) Full information about the position of rivals during the technological race. 4) Four investment levels are specified regarding the position of each firm in the technological race. 5) The equilibrium concept is the subgame perfect Nash equilibrium rates of investment.	1) Competition is most intense when both firms are even and each has completed the initial phase of the research project. 2) When a lagging firm draws even with a rival that was formerly ahead in the race, both firms increase their R&D efforts. 3) When the two firms are at different stages in the innovation process, the one that is ahead has a greater incentive to invest in R&D than the one that is behind. 4) When there is room for agreements with or without public authorities' intervention, alternative forms of cooperation are most likely to increase joint expected profits when competition between non-cooperating firms is intense.	1) Cf. Lee and Wilde 2). 2) No spillover effects. The existence of two stages and the ability of a follower to catch up with the leader should allow to introduce these effects.
13) Judd (1985)	1) Firms' strategic advantages are not exogenous but are acquired endogenously over time, through the research process. 2) Two types of project are considered with regard to the risk degree. 3) Firms' chosen research intensities affect the likelihood but not the magnitude of the resulting jumps. 4) Price and social benefits are small.	1) Non-cooperative equilibrium results in overinvestment relative to the joint optimum and non-cooperative firms undertake more risk than is jointly optimal, especially if the price equals the social benefit. 2) If one firm advances in the research process, the other firm reduces its R&D intensity on the riskiest project and may increase its R&D intensity of the less risky project. 3) In terms of public interventions, the optimal way is to allow competition to proceed until one firm has completely achieved the research process.	1) One restriction is that the winner's price is of arbitrarily small value. 2) Spillover effects are not taken into account.

14) Beath, Katsoulacos and Ulph (1988)	1) Duopolistic homogeneous product industry, facing equal constant unit costs and undertaking R&D in order to reduce their unit costs. 2) The time until a firm introduces the innovation is distributed exponentially. 3) The hazard rate solely depends on the firm's current flow rate of R&D expenditure. 4) Innovation is protected by a patent implying that the profit of the innovator is higher than the profit of the loser. 5) The easiness of imitation is related to the protection offered by the patent.	1) R&D expenditures will be greater (lower) in a research joint venture (RJV) than under rivalry when imitation is easy (difficult). 2) Firms prefer an RJV to rivalry when imitation is easy due to the higher present value of the expected payoffs. Firms prefer rivalry when imitation is difficult, especially when product market competition is intense (market competition effect > coordination effect).	1) Cf. Loury 1), 2). 2) In contradiction with Grossman and Shapiro's model (1987), they suppose that the rewards on completion of the R&D process are different in an RJV and under rivalry, due to the market competition effect. 3) Limitation on the type of cooperation : there are no economies involved by running an RJV rather than allowing the firms to proceed independently and the RJV involves running the R&D laboratories of all firms. 4) There is no cooperation on the product market, which can restrain the attractiveness of such RJV and moreover, the problem of appropriability of the result is not elucidated.

15) Beath, Katsoulacos and Ulph (1989)	1) Two firms engaged in a single one-stage race to be the first to innovate. 2) Cf. Beath and al. (1988) 2). 3) Cf. Beath and al. (1988) 3). 4) A firm may have a competitive advantage over its rivals resulting from a previous race. 5) Current profits and the profit of winning or losing are known with certainty by both. 6) Both firms face the same innovation technology and decreasing returns.	Two forces are in action : the profit incentive and the competitive threat. The former corresponds to the desire to increase profits through the investment in respect of the cost of investment. The latter is reflected by the difference between the innovator's and the non-innovator's profits. A major determinant of the relative magnitude of these two forces is the ease of imitation. 1) If imitation is impossible, the competitive threat dominates the profit incentive and the leader firm undertakes more R&D than would be optimal given the profits it would make if it were sure to be the winner. 2) If imitation is easy, the profit incentive dominates the competitive threat and firms are prompted to engage less in R&D and will increase profits by free-riding. 3) In the case of a public subsidization policy, if the competitive threat dominates the profit incentive, a subsidy to the home firm will result in an increase in the R&D performed by the rival firm (overinvestment). 4) In the case of a public subsidization policy, if the profit incentive dominates the competitive threat, a subsidy is not optimal due to the free-rider problem.	1) Cf. Beath and al. (1988) 1). 2) They have a complementary approach to Brander and Spencer's model, allowing to derive some preliminary conclusions about an optimal subsidization policy. 3) The two forces being at the basis of any dynamic adjustment process, this model should be extended accordingly.

16) Delbono and Denicolo (1991b)	1) Duopolistic product market facing the assumptions 1) to 5) of Beath and al. (1989). 2) Two different possibilities regarding the specifications of the R&D technology : - well-behaved R&D technology exhibiting smoothly decreasing returns; - increasing returns modelled by assuming that R&D activity is completely indivisible.	1) Under the smooth technology, either the profit incentive or the competitive threat may prevail, depending on the ratio between the discount rate and the "productivity" of R&D expenditures. If the discount rate is high (low) and/or the productivity of R&D expenditure is low (high), then the profit incentive (the competitive threat) tends to dominate. 2) Under increasing returns, the firm with the higher profit incentive invests in R&D at least as much as the firm with the higher competitive threat. In equilibrium either the former has the same probability as the latter to win the patent, or the former innovates with probability one. 3) Under quantity competition in the product market with high size of the market and/or reduced cost gap, both the profit incentive and the competitive threat work in favour of the currently high cost firm, which therefore has a greater probability of innovating. If the market is small and/or the cost gap is large, profit incentive and competitive threat go in opposite directions, while the former works in favour of the currently high-cost firm and the latter in favour of the currently low-cost firm (same conclusions as under price competition).	1) Cf. Beath and al. (1988) 1). 2) Cf. Beath and al. (1989) 3). 3) They derive a large range of different behaviours which rest on the previous model of Beath and al. Their model is limited to the interfirm competition without public intervention.

distribution of information, the identity of the decision variables and the sequence of moves. Reinganum (1984) also questions the availability of data.

If theoretical developments yield statements which should be investigated empirically, they are, as such, of little help. Basic hypotheses drastically condition the results of theoretical models and very often, a slight modification of hypotheses results in controversial conclusions. However, the strategic game-theoretic approach is still in an early development stage and future researches will certainly substantially improve our understanding of firm behavior in the technological race framework. As Reinganum (1984) pointed out in her survey article, "although individual models have unambiguous implications, the array of existing models still generates considerable controversy ... In order to move in the direction of empirical testing, we must both extend these models in more realistic directions to accommodate existing data, and attempt to gather the specific data required to test directly such models of firm behavior". She also concludes from her survey [Reinganum (1989)] that, so far, the analyses "have used stark models in order to identify the significant characteristics of firms, markets and innovations which are likely to affect incentives to invest and/or adopt. But since it is largely restricted to these special cases (e.g. deterministic innovations, drastic innovations, two firms, symmetric firms) this work has not yet had a significant impact on the applied literature in industrial organization; its usefulness for policy purposes should also be considered limited. For these purposes, one needs a predictive model which encompasses the full range of firm, industry and innovation characteristics".

These different studies which use the game-theoretic approach have derived some general results regarding an optimal subsidy policy. In general, they only look at the effect of a subsidy at the R & D investment level and its direct effect on the market share, the competitiveness of the home firm compared to rival firms. Yet, they remain silent about the real design of public R & D policies. Regarding this point, Fölster (1988) has tried to make out an optimal structure for a subsidy. He suggests that the government "can save public funds by supporting only projects that are socially valuable and that firms would not conduct of own initiative". But identifying research projects that are socially worthwhile in order to subsidize only projects that firms would not conduct without subsidies, on the one hand, and, on the other hand, in order to prompt firms to behave efficiently, requires quite a lot information.

The incentive subsidy requires no ex ante judgement by the public authorities because the exact size of the subsidy is determined after the project has been conducted. This ex post judgement allows to have a more accurate assessment of social and private values of research projects. The incentive subsidy contains different elements that directly affect the cost function of the firm :

- compensation for a loss due to the project,
- tax on the profit made on the project,
- reward equal to a fraction of the social value of the project.

Such a policy implies that a firm does not apply for subsidies on the basis of a project that has an expected negative social value. According to Fölster, the incentive subsidy policy is socially more efficient than the normal subsidy policy or conditional loans. The arguments that support the incentive subsidy as a superior alternative are summarized in table 6.5.

6.3. Imitation, Purchase or Inducement : The Search for an Optimal Strategy

When a potential strategic public policy is being designed, the endogenous characteristics of each industry must be taken into account to use the most appropriate instruments. Indeed, different innovative contexts will induce different effects of R & D policies. The firm's behaviour will be different depending on whether it is part of a high-, stable- or low-technology industrial sector. In the case of high-technology industries like aerospace, chemicals, pharmaceuticals, computers or other electronic and electrical industries, firms' incentives to promote internal R & D can be higher if the environment is rich in opportunities for appropriation by the firm and spill-over into other projects. If it is not the case, the firm may prefer to imitate or purchase in order to minimise the risks. Moreover, high technology industries are unstable, which property decreases the possibility of creating lasting advantage in these sectors. The alternative potential ways of acquiring innovations are : imitation, purchasing, internal R & D. The cost-benefit characteristics of these innovation routes is presented in table 6.6. As can be seen, each way has its own advantages and disadvantages and the choice between these alternative roads must be the result of a technological audit of the investigated sector.

By subjecting the amount of subsidies granted to the R & D strategy adopted by a firm, i.e. by granting a certain amount of subsidies if, for instance, a firm imitates and a different amount if the firm purchases a licence, public authorities have a powerful tool to induce firms to improve their R & D's. This selective approach incorporates the specific

Table 6.5. Comparison of Some Intervention Instruments

Normal subsidy	Conditional loan [1]	Incentive subsidy
Advantage : Potential tool to correct the gap between the private value and the social value of the innovation process.	Advantage : If government uses ex post information, it allows to have a more accurate estimate of the social value of a research project than in the case of a normal subsidy. Ex post information allows to expect an increase in the social value of a project.	Advantages : . By playing on the reward fraction, the government is able to induce some improvement in the social value of the project, i.e. reward social efficiency. . The risk to subsidize a project that a firm would realize, whether it is granted subsidies or not, is minimized. . This subsidy takes the risk of losses for the firm more into account than the conditional loan thanks to the more efficient ex post reevaluation.
Disadvantages : . Normal subsidy uses only ex ante information, which causes the decision to subsidize to be based on less accurate information than the other two forms. . No reward for increase in social value. . The risk to firms is not reduced as much as with the other two means.	Disadvantages : . One cannot tax the firm if the project turns out to be privately profitable. . No reward for improvement in social value. . The ex post reevaluation is constrained by the size of the initial subsidy.	

[1] Its main characteristic is that the firm is required to pay back its subsidy if the project returns a private profit.

Source : Based on Fölster (1988).

Table 6.6. Cost-Benefit Characteristics of Each Innovation Channel

	Costs	Benefits
1) Purchase	. Purchase price of the technology. . The firm's specific requirements have to be met. An adaptative process must be implemented to integrate the new technology into the production process of the firm. Some additional training may be necessary to allow the manpower to assimilate the new process. . The organizational structure of the firm has to be modified to ensure an efficient internal transmission of the required information, ... The firm becomes dependent on external technology. The purchase of technologies must be incorporated into a long term strategy aimed at acquiring one's own technology.	. Less technological uncertainty. In the innovation process, uncertainty arises because an abstract idea must be translated into a workable process design. By contrast, in the case of technology transfer, if the transfer process is efficiently managed, it can induce a technology mastery dynamic that could lead to innovation and diffusion.
2) Imitation	. Entails dependence and requires adaptation time. . Adaptation costs are higher than in the purchase case because the market only provides imperfect information (moral hazard, adverse selection) and there is little information about the characteristics of the imitated technology. The development of a technology involves learning by trial and error, which is more or less arduous depending on the ability and skill of the innovator firm. These elements are important to master a technology and not readily transferable (key personnel or laboratories). . Cost of the information related to the knowledge of all the available technology.	. Less technological uncertainty because the main characteristics of the most appropriate process design are known. . Need not be bought. . Improvement of the original product and production at a lower cost.
3) Internal R & D (or initiating technology)	. Direct cost of research higher than the sale price of a purchased technology. . Uncertainty of the research process. . Imperfect appropriability of the result.	. The results of the research process meet the firm's set of requirements and firms can sometimes appropriate some additional technical knowledge acquired during the innovation process. . R & D investment enhances the firm's ability to assimilate and exploit existing information.

technological trajectory of each industry by allowing firms to choose between several optional ways of improving technological efficiency : imitation, purchase and R & D initiation. Besides, they can also choose not to engage in R & D at all.

If the firm is rational, i.e. makes choices that maximize its expected benefits, the expected welfare that firms get from a specific choice can be measured by the income flow. This income flow can be decomposed into different variables. On the one hand, we have variables that are functions of the selected option and, on the other hand, we have variables which are independent of the selected option. For the former, the main variables are expected profits, subsidies and/or tax credit from public authorities. For the latter, the structural characteristics of the firm which are not affected by any alternative have to be considered. To model and assess the determinant of alternative choices whose impact on the firms can be assumed to be constant, it is preferable to resort to conditional logit rather than multinomial logit [1] [Hoffman and Duncan (1988)]. A mixed conditional logit should be used because some explanatory variables are sectoral characteristics and the other variables are characteristics related to the selected alternatives i.e. varying from one option to another. The function associated to the firm i under the option j is, then, defined as the following latent variable :

$$V^e_{ij} \{P^e_{ij}, S_{ij}, T_{ij}, X_i\}$$ [2]

where P^e_{ij} : expected profits of firm i under the option j

S_{ij} : subsidies to firm i under the option j

T_{ij} : tax credit to firm i under the option j

X_i : structural characteristics vector associated to firm i.

In fact, V_{ij} stands for the value of alternative j to firm i. Such models are especially well suited for the analysis of situations in which the government policy affects the attractiveness of an alternative by changing some relevant characteristics. Obviously, to assess the effect of government policies such as a subsidy policy, when possible, the policy parameters have to be directly included in the choice structure.

Assuming that the indirect utility function is additive, we have :

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1 By contrast, the multinomial logit model hypothesizes that the explanatory variables (individual characteristics) are constant across the alternatives. So, it measures the specific impact of these characteristics (across individuals) on each choice.

2 Other variables can be used such as the level of R & D expenditures which differs across industries and alternatives. The variables selected here are only a potential representation which must be modified according to the amount of available information.

$$V^e_{ij} = \beta P^e_{ij} + \gamma S_{ij} + \sigma T_{ij} + \theta'_j X_i + \varepsilon_{ij}$$

where $\beta, \gamma, \sigma, \theta'_j$: unknown parameters

ε_{ij} : residual that captures the effect of unmeasured variables and the imperfection in the optimization program.

The mixed conditional logit is based on the assumption that the error terms in V^e_{ij} follow an extreme value distribution and are independent across alternatives. This independence assumption is crucial because any other assumption leads to substantial computational difficulties involving the computation of multivariate integrals.

With a set of n firms facing m options, we can define :

- $C_{ij} = 1$ if the i^{th} firm makes the j^{th} choice

  i.e. $V^e_{ij} = \max \{V^e_{i1}, \ldots, V^e_{im}\}$ $\quad j = 1, \ldots, m \quad i = 1, \ldots, n$
- $C_{ij} = 0$ otherwise.

If we assume that ε_{ij} are independently and identically distributed with an extreme-value distribution, then the probability P_{ij} that the firm i chooses alternative j, in the mixed conditional logit, is :

$$P_{ij} = \text{Prob}\,(C_{ij} = 1) = \text{Exp}\,(\beta P^e_{ij} + \gamma S_{ij} + \sigma T_{ij} + \theta'_j X_i) \Big/ \sum_{k=1}^{m} \text{Exp}\,(\beta P^e_{ik} + \gamma S_{ik} + \sigma T_{ik} + \theta'_k X_i)$$

The estimation of the structural parameters of this equation through a maximum likelihood procedure allows to simulate the different policies and determine the consequence of policy changes on the rate of R & D effort of each alternative. The expected profits P^e_{ij} can be obtained by using questionnaires or sound estimates based on past profits.

Another possible application of this sort of model is to classify the firms in respect of their R & D expenditure. Once again, using subsidy as an explanatory variable, we can study the effect of a modification in the subsidy level on the R & D expenditure of the firm. However, to measure the impact of the subsidy on the technological efficiency, it might be preferable to use a measure of output such as the number of patents issued.

6.4. Centres of Excellence and Agglomeration Economies

Through setting-up R & D programmes a country can avail itself of strategies that go beyond the subsidy policy. So, a potential alternative policy is to develop European centres of excellence in research and innovation.

The creation of a centre of excellence is a cumulative process if decisions taken previously increase the likelihood of locating a research facility in a European centre. Hence, repeated investments in these centres strengthen their international position and their R & D ability, so creating agglomeration effects. These agglomeration effects may result from the user-producer interaction. Indeed, users' sophisticated requirements support the research facilities of the technology producers and the ensuing feedback and joint testing procedure leads to incremental technological improvement. In addition, such centres of excellence improve the diffusion process and make a wider range of technological products available to the users. However, a major potential cause of failure is that these centres are 'locked in' to a path of technological development.

At the European level, the creation of centers of excellence, which go beyond the national boundaries, allows to develop and reorganize a network of research facilities. It is important to strengthen the interaction between the different centers and to organize the participation of the European countries in function of their technological ability in a specific field and not in function of political considerations of balanced representation.

Cantwell (1991) tested the significance of such a proposition on the basis of the previous argument that research tends to agglomerate geographically. He showed that the geographical concentration of technological activity has risen outside the U.S. and that Japan has increased its share. His analysis emphasizes the fact that many sectors show an agglomerative consolidation of their comparative (dis)advantages [1].

In his empirical study, he draws up an index of the revealed technological advantages (RTA) of locations in the following way :

$$RTA_{ij} = (P_{ij}/\sum_j P_{ij})/(\sum_i P_{ij}/\sum_i \sum_j P_{ij})$$

where P_{ij} : number of US patents granted in sector i attributable to research in country j.

[1] He also assessed the contribution of foreign-owned research facilities to technological agglomeration and concluded that the location of foreign-owned research has, in general, contributed to technical agglomeration but not in a significant way.

Table 6.7. Distribution of Sectors according to the Strength of Technological Agglomeration

		Foreign patenting shares			
		1	2	3	4
Cross-country RTA	1	Construction and mining equipment	Motor vehicles Bioengineering	Metals Radio and TV receivers Other transport equipment Non-metallic mineral products Cool and petroleum products Instruments Wood products	Chemicals Synthetical resins Semiconductors Other manufacturing
	2	Tobacco Agricultural machinery	Industrial engines	Cleaning agents	Agricultural chemicals Pharmaceuticals Rubber and plastic products
	3		Nuclear reactors	Electrical equipment Transmission equipment Paper, printing and publishing	Drink
	4	Food Aircraft Textiles		Metal products Mechanical engineering	Dyestuffs Office equipment Lighting and wiring

Note : 1 = no agglomeration as locational concentration falls.
2 = weak agglomeration but with a significant mobility effect.
3 = weak agglomeration without a significant mobility effect.
4 = strong agglomeration.

Source : Adapted from Cantwell (1991).

If $RTA_{ij} > 1$: country j is comparatively advantaged in research in sector i
If $RTA_{ij} < 1$: country j is comparatively disadvantaged in research in sector i.

He makes a cross-country regression of the national shares of patenting (S_{jt}) over the period 1978-1986 on the equivalent shares during the period 1963-1972 and, alternatively, using the RTA, i.e. :

$$S_{jt} = \alpha_1 + \beta_1 S_{jt-l} + \varepsilon_{1jt-l}$$

$$RTA_{jt} = \alpha_2 + \beta_2 RTA_{jt-l} + \varepsilon_{2jt-l}$$

To ascertain the proposition of agglomeration of technological activities two hypotheses are made :

1) in any sector the variance of the cross-country distribution of patent shares or the RTA index has risen over time. This hypothesis of geographical concentration of the technological activity over time is measured by $\hat{\beta}/R > 1$ where $\hat{\beta}$ is the estimated slope coefficient and R the estimated correlation coefficient.

2) the weight of the initial important centres for innovative activity remains the same, i.e. $\beta \geq 1$.

Two different regressions were made : a first one on the cross-country distribution of national share of US patenting including the US and a second one excluding the US. When the regression is run using the cross-country distribution of national shares of US patenting, the agglomeration hypothesis must be rejected. Nevertheless, the first agglomeration hypothesis is accepted and the second is partly accepted when the regression is run for each sector (but excluding the US). On the basis of these results, neither the hypothesis of an increase of the geographical concentration of technological activity nor the hypothesis that the more important centres have on average retained their position can be rejected.

Table 6.8. Regressions of the Patent Shares

	α	β	β/R
with US	2.13	0.74 (14.84)	0.76
without US	0.60	0.93 (2.95)	1.33

Table 6.7., which summarizes Cantwell's results shows that the trend towards agglomeration is higher when patenting shares are used than when RTA is the reference measure. Such an observation is only the consequence that patent shares are similar at an absolute value of technological advantage while RTA is a relative value measuring comparative technological advantages. The first four quadrants show the sectors for which no agglomeration effect was detected. The four following quadrants show the sectors characterized by a reinforcement of spatial concentration in foreign patenting shares combined with a weakening of comparative technological advantages. This contrasted finding is explained by the high weight of small countries in the measurement of the RTA for these sectors which is not reflected by the patent shares. Some of these sectors also correspond to cases in which Japan made strong absolute but not relative gains. The next four lower quadrants represent the sectors for which the spatial concentration in patent shares becomes more dispersed and the concentration in terms of RTA rises. So, in these sectors, while the patent shares come closer to each other, the leader countries strengthen their initial technological position. The last four quadrants give the sectors for which both types of measurement provide evidence of strong agglomeration effects. Only two high-technology sectors belong to this category : office equipment and electrical equipment. The other high technology sectors, such as bioengineering, instruments, semiconductors and pharmaceuticals, do not seem to be faced with a strong agglomeration trend. Yet, the trend towards a higher concentration of these sectors in absolute value might be the source of future RTA. Finally, it is worth noting that the analysis of patent shares does not include the US. The map of sectors presented in table 6.7. would certainly have been different if the US had been included. Indeed, as shown in table 6.8., the results of total regressions with and without the US are noticeably different.

However this may be, this analysis stresses that technological concentration exists and that the Japanese position is stronger, both in absolute and in comparative terms. The U.S. position is weaker and the European situation is relatively contrasted. One observes, however, a positive correlation between the technological position of a country and its industrial competitiveness. The poor performance of the U.K. points to the weak performance in its industrial sector whereas Germany affirms its dominant position both in absolute and in comparative advantage terms. The existence of a European network of centres of excellence requires the availability of research professionals, i.e. a highly skilled human capital. Once again, a manpower that is highly skilled in the scientific and engineering field is a crucial factor to increase competitiveness. Besides, a favorable institutional environment, both on the labour market and on the capital market, should be created. In this respect, the completion of the European internal market offers the possibility to generate an environment conducive to R & D investment.

The existence of critical mass is the main reason why R & D tends to agglomerate. The subsidization of R & D at one location will benefit R & D at the location and will attract researchers from other locations. It will be beneficial as long as domestic scale economies are available and can induce an international redistribution of research activities. Such a policy strategy has clear advantages at the European level where lots of research centres do not reach the critical mass. Yet, its disadvantages are threefold. First, it may depress research activities in some regions and countries. Second, if other governments adopt a similar strategy, a large part of the redistributive effect may be lost. Third, the implementation of a selective subsidy policy will encourage the beneficiaries to lobby for more and divert subsidies for non-innovative activities [Casson (1991)].

6.5. Technological Competition and R & D Policy in Oligopoly

R & D is a non-price competitive element and requires to be associated with all the other elements of the firm's strategy. The issue of a firm's optimal levels for all decision instruments has received considerable attention in the marketing literature. These extensions of the profit maximisation rule have tried to take into account other decision-making process variables than just the price. All these normative models have been developed along the lines defined by Dorfman and Steiner (1954)'s theorem for monopolistic competition.

Following the original contribution of Dorfman and Steiner, Hay and Morris (1991) have recently presented a basic model of innovation. Besides the firm's own decision variables, they also include the rival's decision variables as determinant of the firm's demand.

The demand curve for firm i is a function of its own price p_i and its own expenditure on R & D, x_i, and of p_j and x_j vectors of prices and R & D expenditures of other firms. The expenditure x_i shifts the demand curve, $\partial q_i / \partial x_i > 0$, but at a diminishing rate.

The first order conditions can be obtained from the profit maximization process π_i :

$$\pi_i = p_i \, q_i \, (p_i, x_i, p_j, x_j) - c \, (q_i) - x_i$$

where $c \, (q_i)$ is the production cost.

By deriving, we obtain :

$$\frac{\partial \pi_i}{\partial p_i} = p_i \cdot \frac{\partial q_i}{\partial p_i} + q_i - \frac{\partial c}{\partial q_i} \cdot \frac{\partial q_i}{\partial p_i} = 0$$

$$\frac{\partial \pi_i}{\partial x_i} = p_i \left(\frac{\partial q_i}{\partial x_i} + \frac{\partial q_i}{\partial x_j} \cdot \frac{\partial x_j}{\partial x_i}\right) - \frac{\partial c}{\partial q_i} \left(\frac{\partial q_i}{\partial x_i} + \frac{\partial q_i}{\partial x_j} \cdot \frac{\partial x_j}{\partial x_i}\right) - 1 = 0$$

Then $\dfrac{p_i \cdot - \dfrac{\partial c}{\partial q_i}}{p_i} = \dfrac{1}{|\varepsilon_i|}$ with ε_i : price elasticity of demand

and $$\frac{x_i}{p_i\, q_i} = \frac{p_i \cdot - \dfrac{\partial c}{\partial q_i}}{p_i} \left(\frac{\partial q_i}{\partial x_i} \cdot \frac{x_i}{q_i} + \frac{\partial q_i}{\partial x_j} \cdot \frac{x_i}{q_i} \cdot \frac{\partial x_j}{\partial x_i}\right)$$

$$= \frac{1}{|\varepsilon_i|} (\eta_i + \rho\, \eta_j)$$

where η_i : elasticity of response of sales to one's own R & D expenditure

η_j : elasticity of response of sales to other firms' R & D expenditure

ρ : conjectural variation, i.e. degree to which the firm expects an increase in its own R & D expenditure to be matched by rivals.

We observe from these results that the more elastic demand is with respect to R & D, the higher the R & D intensity will be. Furthermore, the R & D intensity depends on the firm's expectations regarding competitors' R & D reaction. If, besides, there are also conjectural variations on the price side, one can easily show that the R & D intensity will also depend on the firm's expectations regarding competitors' price reaction. These relationships make clear that R & D decisions may depend on expectations relative to competitors' decisions.

According to the market situation ρ can take different forms. ρ is equal to zero in the Cournot case, i.e. there is no reaction from rivals.

In conditions that are optimal with respect to the level of R & D expenditures, we note the impact of the price elasticity of demand regarding R & D expenditures. The higher the elasticity with respect to the price, the lower the part of R & D expenditures in the total output of the i firm. A strong price inelasticity stimulates R & D investment by the firm

5)

due to the fact that non-price instruments are more efficient to obtain important market shares.

This analysis can be extended to include the effects of a public incentive to private R & D. Suppose the subsidy be equal to a fraction α of the private R & D so that the profit is equal to :

$$\pi_i = p_i\, q_i - c_i - (1 - \alpha)\, x_i$$

with $0 \leq \alpha < 1$

In such a case, the R & D intensity equation becomes :

$$\frac{x_i}{p_i\, q_i} = \frac{1}{(1 - a)\, | \varepsilon_i |} (\eta_i + \rho\eta_j)$$

which shows that the higher α is, the higher R & D intensity will be.

However, this model is too simple to express a real situation. Considering zero conjectural variations is irrealistic. But the definition of rational conjectural variations is not easy due to, for instance, the great part of uncertainty associated with R & D investment. Moreover, each different non-zero conjectural variation implies a different type of reaction function and, therefore, another equilibrium.

Lambin and al. (1975) have derived an optimal marketing behavior model that is more consistent for the analysis of oligopolistic competition. We can extend this model to incorporate R & D and obtain an expression in terms of market share.

In the process of maximization, a firm can use a set of decision variables, among which the level of R & D expenditure, the purpose being to determine the conditions in which each decision variable is likely to yield maximum profit.

We can derive the optimality conditions, considering first the company profit function for the case of monopolistic competition :

$$\pi = q \, . \, [p - c\,(q, o)] - x$$

where p : price
o : organizational cost
x : R & D expenditure.

Let us write that u' = (p, x, o), this variable representing the company decision variable vector.

Deriving π with respect to each decision variable included in the u' vector and setting these expressions equal to zero, we obtain :

$$\frac{\partial \pi}{\partial u} = \frac{\partial q}{\partial u} [p - c (q, o)] + q \left(\frac{\partial p}{\partial u} - \frac{\partial c}{\partial u} - \frac{\partial c}{\partial q} \cdot \frac{\partial q}{\partial u}\right) - \frac{\partial x}{\partial u} = 0$$

After transformation, one obtains :

$$- \eta_{q,p} = \eta_{q,x} \cdot \left(\frac{q\,p}{x}\right) = \eta_{q,o} \cdot \left(\frac{p}{o\left(\frac{\partial c_i}{\partial o}\right)}\right) = \frac{1}{w^*}$$

where $\eta_{q,m}$: elasticity of demand to the m decision variable

w^* : percentage of gross margin [1].

which is similar to the Dorfman-Steiner rule.

At the optimum, marginal cost must be equal to marginal revenue for each decision variable and the marginal revenue product of R & D expenditure must be equal to the inverse of the percentage of gross margin :

$$p \frac{\partial q}{\partial x} = \frac{1}{w^*}$$

Otherwise, from the preceding optimality conditions, one deduces that :

$$\frac{x}{q \cdot p} = - \frac{\eta_{q,x}}{\eta_{q,p}} = \frac{\eta_{q,x}}{|\varepsilon|}$$

We find a result similar to the one obtained by the first model where $\frac{x_i}{p_i \cdot q_i} = \frac{1}{|\varepsilon_i|}$ $(\eta_i + \rho\, \eta_j)$. In this case, we see that the ratio of R & D expenditures with respect to total output or sales is equal to the ratio of R & D elasticities with respect to price elasticities. $\eta_{q,x}$ corresponds to $(\eta_i + \rho\, \eta_j)$ when ρ, representing the conjectural variation, is equal to zero. Thus, we have a Nash-Cournot equilibrium.

1 $w^* = (p - MC) / p$ where MC = marginal cost.

The preceding relation shows that the higher the percentage of gross margin w* is, the lower the marginal product of R & D expenditure is and the higher the profitable level of R & D expenditure is since we expect diminishing returns on R & D expenditure. We know that $\frac{1}{w^*} = |\varepsilon|$. Hence, the previous situation implies a low price elasticity, i.e. the possibility for the firm to charge high prices.

A competitive situation is characterized by strong interdependences between rival firms. In parallel with the concept of conjectural variations, one can express two different forms of interdependence. First, the performances of any firm depend on the level of its rivals' decision variables, in particular R & D expenditure. Second, if a firm modifies its R & D expenditure, other rival firms will react.

To extend the model, let us decompose the $E_{q,u}$ vector of total sales elasticities into three components which are :

1) the industry sales or output effect;
2) the direct partial effect in the company market share due to a change in the company decision variables [1];
3) the indirect partial effect in the company market share due to modifications in rival firms' decision variables, i.e. brought about by a change in the competitive mix pressure of rival firms.

By definition :

$$m_i = \frac{q}{Q_T}$$

where m_i : market share of the company
q : company sales
Q_T : industry sales.

[1] The company market share can be represented as :

$$m_i = \frac{k_i\, p_i^{e_1}\, x_i^{e_2}\, o_i^{e_3}}{\sum_i k_i\, p_i^{e_1}\, x_i^{e_2}\, o_i^{e_3}}$$

where the e_j are the market share sensitivities with respect to each decision variable and for each firm the numerator of this relationship can be defined as the competitive mix pressure of the firm. The elasticity of the market share to each variable is defined as :

$$\varepsilon_j = e_j\,(1 - m_j)$$

$$q = m_i \, . \, Q_T$$
$$= m_i (u, U) \, . \, Q_T (u, U, Z) = m_i (u, U (u)) \, . \, Q_T (u, U (u), Z)$$

where u : company decision variable vector
U : competitors decision variable vector
Z : environmental variable vector.

We derive q with respect to the u decision vector :

$$\frac{\partial q}{\partial u} = m_i \frac{\partial Q_T}{\partial u} + m_i \frac{\partial Q_T}{\partial U} \cdot \frac{\partial U}{\partial u} + Q \cdot \frac{\partial m_i}{\partial u} + Q \cdot \frac{\partial m_i}{\partial U} \cdot \frac{\partial U}{\partial u}$$

where $\frac{\partial U}{\partial u} = [\frac{\partial U_1}{\partial u}, \ldots, \frac{\partial U_n}{\partial u}]$.

Then : $E_{q,u} = E_{Q,u} + E_{m_i,u} + R \, [E_{Q,U} + E_{m_i,U}]$

where E refers to demand elasticities and R to multiple competitive reaction elasticities.

According to Lambin (1976), this result can be summarized regarding the alternative types of behavior and the nature of the industry demand :

Non expansible industry demand ($E_Q = 0$)	Expansible industry demand ($E_Q \neq 0$)
No reaction ($R = 0$)	
$E_{q,u} = E_{m_i,u}$	$E_{q,u} = E_{m_i,u} + E_{Q,u}$
Simple competitive reaction ($R = R_d$)	
$E_{q,u} = E_{m_i,u} + R_d \, E_{m_i,U}$	$E_{q,u} = E_{m_i,u} + E_{Q,u} + R_d \, [E_{m_i,U} + E_{Q,U}]$
with R_d, diagonal matrix from R	
Multiple competitive reaction ($R \neq 0$)	
$E_{q,u} = E_{m_i,u} + R \, E_{m_i,U}$	$E_{q,u} = E_{m_i,u} + E_{Q,u} + R \, [E_{m_i,U} + E_{Q,U}]$

Taking into account the intrinsic characteristics of each industry and using a multiple competitive reaction behavior, one can measure the R & D-output elasticity for the different cases.

First, we consider the case of an industry in its maturity phase. We know that in this case, the total demand is stable and has no influence on the R & D-output elasticity. This elasticity is only made up of market-share components. One can write this decomposition in the following form, capital letter subscripts referring to competitors :

$$\eta_{q,x} = \eta_{m,x} + \rho_{P,x} \cdot \eta_{m,P} + \rho_{X,x} \cdot \eta_{m,X} + \rho_{O,x} \cdot \eta_{m,O} \qquad (1)$$

This expression represents a general multiple competitive reaction in a stable industry demand. ρ expresses the different reactions of rival firms to an alteration in the level of R & D expenditure. Using this approach, one can formulate the reaction of American and Japanese firms to a modification in the R & D expenditure level of European firms. Moreover, all strategic variables could be taken into account so that one should be able to describe different kinds of strategic behaviour.

Second, we look at an industry using new and expanding technologies (high-technology industry). This kind of industry is characterized by an expansible industry demand. In this case, R & D-output elasticity must take into account the reaction of the total demand to a modification of the R & D expenditure level and the ~~impact of~~ the induced multiple competitive reaction of rival firms on the total demand. So, we have the following decomposition of the R & D-output elasticity :

$$\begin{aligned}\eta_{q,x} = \; & \eta_{QT,x} + \eta_{m,x} + \rho_{P,x} (\eta_{QT,P} + \eta_{m,P}) + \rho_{X,x} (\eta_{QT,X} + \eta_{m,X}) \\ & + \rho_{O,x} (\eta_{QT,O} + \eta_{m,O}) \qquad (2)\end{aligned}$$

In comparison with the first equation, we note that R & D-output elasticity includes both market share elements and total demand elements. The former equation is a particular case of the latter equation when the total demand is stable, which implies that $\eta_{QT,X} = \eta_{QT,P} = \eta_{QT,X} = \eta_{QT,O} = 0$.

The previous analysis allows to analyze the effect of public policies. By stimulating the R & D decision variable, the public R & D policy will have a direct effect on the behaviour of the firm and on the competitiveness [1]. The last two equations (1) and (2), defined in terms of R & D-output elasticity, allow to take into account the reaction of the demand to an increase or decrease in the R & D subsidy and the impact of the induced multiple competitive reactions of rival firms on the demand. Moreover, the differentiated effects linked to the type of industry are integrated into the model.

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[1] In such a case, for the sake of convenience, one can define x_i as being the sum of both private and public R & D. However, more complex analytical hypotheses should be investigated by taking these two variables into account separately, public R & D not being a company decision variable.

These relationships based on a concept of competitive mix show that a competitor may react to a change in R & D expenditure not just by changing his own R & D expenditure (simple competitive reaction) but also by changing other non-price instruments or the price itself (multiple competitive reaction). This approach allows to express competitive interaction in terms of market share and to model the existing competition between European, Japanese and American firms.

This approach using market share models can alternatively be used to describe the technological competition between the American, European and Japanese blocks.

Indeed, if one assumes that :

MS_{E_t} : market share of European firms for a specific industry at time t
MS_{A_t} : market share of American firms for a specific industry at time t
MS_{J_t} : market share of Japanese firms for a specific industry at time t

then, one can try to study the evolution over time of these respective market shares.

In other words, our purpose is to value the evolution dynamic of market shares. To do that, we can define a transition matrix in which the different elements are probabilities of technological dominance (or alternatively competitive dominance) of each block. This matrix can help analyze the evolution of tendencies towards change inside the industry. By linking market shares and this matrix, we obtain an estimate of market shares in the next period. For example, a way to define this matrix is to use patent statistics. One knows the limits of such a measure but it gives an idea of the technological ability of each block. So, the process can be summarized as follows :

$$(MS_{E_t}\ MS_{A_t}\ MS_{J_t}) \begin{pmatrix} P_{EE} & P_{EA} & P_{EJ} \\ P_{AE} & P_{AA} & P_{AJ} \\ P_{JE} & P_{JA} & P_{JJ} \end{pmatrix} = \begin{pmatrix} MS_{E_{t+1}} \\ MS_{A_{t+1}} \\ MS_{J_{t+1}} \end{pmatrix}'$$

where MS_{it} = market share of i at period t
P_{ij} = transition probability of technological dominance of block i within block j.

By definition, the sum on a line is equal to one and, in our example, P_{EE} is equal to the number of patents granted in Europe to European industries divided by the total number of patents granted in Europe for a specific industry. The fact that the sum on a line is equal to one allows to relate it to the market share concept, since the sum of the market shares is also equal to one. Thus, the transition probabilities also correspond to market shares in terms of patents. Obviously, more complex technological indexes (or, alternatively, competitiveness indexes) could be designed.

In order to define robust market share indicators, we can use the "sales" variable. Thus, MS_{ik} (i = E, A, J) is equal to country i's volume of sales divided by the total volume of sales for a given industry k. A correction or extension can be made to take into account or specifically analyze imports and exports.

Through this approach, an equilibrium structure can be measured, i.e. when t tends towards infinity, one has :

$$(MS_{E_t}\ MS_{A_t}\ MS_{J_t}) \begin{pmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{pmatrix}^n = \begin{pmatrix} MS_E^* \\ MS_A^* \\ MS_J^* \end{pmatrix}$$

where $n \rightarrow \infty$.

The equilibrium value is obtained after n iterations and gives an estimation of the technological leadership.

However, we know that the absolute equilibrium value is a function of the endogenous characteristics of each industry. The position of a product on the life cycle influences the level of demand. To take this effect into account, we can combine this approach with a diffusion-modelling framework. In this way, we can draw a parallel with the two expressions decomposing the R & D-sales elasticity which have been discussed in the preceding section.

The matrix of transition probabilities can be interpreted as being the result of two sets of interactive parameters, a retention factor r_i which can be interpreted as a measure of the acquired technological advantage (or, alternatively, acquired competitive advantage) and an attraction factor a_i as a measure of technological dynamism (or, alternatively, competitive dynamism) where $\Sigma\, a_i = 1$, all $a_i \geq 0$ and $0 \leq r_i \leq 1$.

Thus, we have :

		Market shares acquired over the next period		
		Europe	U.S.	Japan
Market shares acquired over the last period	Europe	$r_E + (1 - r_E)\, a_E$	$(1 - r_E)\, a_{US}$	$(1 - r_E)\, a_J$
	U.S.	$(1 - r_{US})\, a_E$	$(1 - r_{US})\, a_{US} + r_{US}$	$(1 - r_{US})\, a_J$
	Japan	$(1 - r_J)\, a_E$	$(1 - r_J)\, a_{US}$	$r_J + (1 - r_J)\, a_J$

This matrix defined in terms of patents must only be viewed as an example. More representative indicators of technological competition should be substituted for this elementary variable.

This model remains very prospective and needs further investigations.

Conclusion

While econometric methods are extensively used as a tool for the evaluation of economic policy, its credibility and usefulness in the field of science and technology policy is very controversial, if not contested. The main arguments invoked against these techniques are the problem of causality links, the time lag structure, the variability of results, the complexity and uncertain nature of the innovation process which rend econometric investigations difficult. On the other hand, lots of evaluation studies point out that the evaluation processes are mainly focused on technological aspects and do not deal with the economic impacts. When the latter are covered, methods used are essentially case studies and surveys. Yet, these methods have their own shortcomings and, in any case, only consider some direct and partial economic impacts. What must take the lead in the choice of a method is the issue at stake. As the evaluation process is fundamentally a heuristic and subjective process, there is seldom a clear-cut definitive answer. In order to avoid costly erroneous decisions, any experiment should be, if possible, complemented by another one performed on the basis of an alternative method.

Theoretical and empirical studies of the relationship between technical change and improvements in economic performance are principally based on the concept of production function. While the production theory is well developed, the treatment of technical change is still very abstract. This abstraction results from the neo-classical paradigm of exogenous technical change. In empirical works, despite their large efforts to analyze how technical change affects the production process, the way in which it works is not analytically dealt with.

The most commonly used approach to materialize technical change in production functions is to use R & D investment as a proxy and to treat it as a production factor. Although this variable is only an input measure of the knowledge production process, output measures, like inventions and patents, are considered to be less appropriate to grapple with the full spectrum of knowledge activities. The accumulated empirical expertise about the relationship between R & D investment and productivity emphasizes the significant impact of R & D on productivity growth. Two types of measure can be captured by the productivity approach, the R & D elasticity with respect to output and the rate of return on R & D. The apparent diversity of results can be, to a large extent, explained by data characteristics. Yet, this approach suffers from some problems, among which, the interpretation of the rate of return (distinction between gross or net, private or social, in excess or not rate of return), data measurement (distinction between gross output, net output and total factor productivity), the specification of models (distinction between total regression, within regression, regressions with dummy variables and on average values) and choice of variables (distinction between R & D investment and R & D stock). So far, studies have essentially been concentrated on the measure of the impact of total R & D expenditure. More efforts should be devoted to the analysis of the time lag structure of the R & D effects on productivity growth and on the effects of R & D by character of use (basic research, applied research, development, R & D on processes, R & D on products), the simultaneity between the firm's decisions and data improvements. The simultaneity problem has been considered in some studies making use of an adjustment cost model from which the input demand functions are derived. These studies provide evidence that R & D investments respond to changes in demand, prices and other inputs and that there are interactive adjustments between inputs. The latter model represents an important methodological step in the formalization of relationships between R & D, output, prices, employment and physical investment.

The measure of the impact of research efforts of a firm or an industry on the productivity growth of this firm or this industry only provides a piece of information on the economic impact of research efforts. As research results are not fully appropriable, they spill over to other firms and industries. These spillover effects which make the difference between the social and private rate of return on R & D are generally very high but greatly vary across industries. Several methods have been suggested to measure these spillovers. A first category includes the approaches based on a proximity measure. The main drawback of these approaches is that the proximity weights are derived from intermediate input, patent or innovation flows, which are only able to capture a part of knowledge transmission. The second category distinctively considers industries as sources or receivers of R & D spillovers whose rates of return are estimated by specifying cost or cost and demand functions of industries in a static or dynamic framework. The advantages of this approach are to capture the diversity of spillover effects across industries and to trace the flows of these effects by identifying the source- and receiver-industries and to measure what is the magnitude of spillovers for each source- and receiver-industry. It provides evidence that the spillovers are circumscribed in some industries. Furthermore, a recent model based on the dynamic duality theory showed that spillovers affect both costs and demand and that adjustments are not instantaneous. A further extension of this model should be to emphasize how international competition affects both cost and demand functions by taking into account the spillover effects of foreign R & D.

An important issue in the analysis of the economic impact of R & D is the issue of the differentiated effects of components of R & D investment. A disaggregation of interest is the distinction between privately-financed R & D and government-financed R & D. Empirical investigations showed that the impacts on productivity growth of both types of investment were largely different. On the one hand, government-financed R & D appears to influence at most marginally productivity growth while, on the other hand, privately-financed R & D significantly affects productivity growth. Yet, regarding government-financed R & D, some studies showed that its relationship with productivity growth was more subtle than for privately-financed R & D. A peculiarity of government-financed R & D is that it affects not only productivity growth but that it may also stimulate private R & D. So, concurrently to the productivity approach, an investment approach has been developed in order to measure to what extent government-financed R & D crowds out, complements or stimulates private R & D. The empirical observations showed that publicly-financed R & D might only marginally crowd out private R & D in some cases but that, in a majority of cases, it stimulates private R & D. Yet, some studies have emphasized that specification problems might greatly affect the evaluation. Indeed, what is captured as a stimulation effect of government-financed R & D might simply be the stimulation effect of government purchases or the result of spurious correlation. These studies show that results obtained from the investment must be cautiously interpreted but, in any case, do not support the crowding-out hypothesis.

The implementation of science and technology policy is, to a large extent, guided by strategic considerations. Technology is a non-price competitive weapon on which governments act by developing their science and technology policy. Not only technological rivalry between firms leads them to engage in a strategic race to innovate but also governments adopt a strategic behavior in the design of their policies. In the past few years, some normative models of technology rivalry have been developed but, so far, this new theoretical modelling approach has not provided clear-cut prescriptions about the guidance of R & D policy. Besides, some more pragmatic studies which consider certain strategic issues show how difficult it is to implement an efficient R & D policy because of, among other things, the existence of agglomeration economies, the differences among industries, the outflow outside national borders of new knowledge, the specificities of the different types of R & D. As government actions in the field of science and technology are increasingly prompted by strategic issues, the evaluation of the economic impact of R & D policy should take this dimension into account. Future empirical investigations might consider models of competitive behavior in oligopolistic markets. In this approach, the firm's behavior is captured by estimating a market share model to measure how sensitive the market share of a firm is to the competitive mix of rival firms and competitive reaction models to evaluate how a firm moves in reaction to a shift of the competitive mix of rivals. These models might be extended by including public policy variables and by modelling government behavior to evaluate to what extent government strategies are designed under oligopolistic behavior.

The methodological choice for the conduct of the analysis has been to review the available methods for the evaluation of the economic impacts of R & D programmes, asking oneself how empirical economics deal with technical change. This way of proceeding has drastically reduced the field of investigation since it considers methods really in use. Yet, there are other candidate methods which might be fruitfully implemented. They are measurement methods which can be implemented in a large variety of contexts and whose use is conditioned by four interdependent criteria : the objective of the evaluation, the data availability, the time to be devoted to the evaluation and the implementation cost. The measurement methods can be split into four large categories.

A first category concerns quasi-experimental methods. In the field of policy formation, real controlled experiments are rarely performed because they are practically unfeasible and when they are, they are cost- and time-intensive. An alternative way is to conduct quasi-experiments by surveying a sample of firms affected by the policy instrument or by comparing some relevant variables obtained for the firms affected by the policy to those characterizing a control group. This method can only cover a limited number of variables, only provides information on the direct effects of the programmes and may suffer from a bias between the actual effects and the perceived ones.

In a second category, there are intervention analysis methods which consist in modelling a target variable in order to estimate by means of interrupted time series analysis techniques to what extent the evolution of the target variable has been influenced by the policy. In this analysis, the prepolicy variable is distinguished from the postpolicy variable on which the policy has exerted its impact and the time series data structures can bear on a single time series design or a time series panel design. Policy interventions can produce a wide array of effects, which leads to consider some alternative intervention models depending upon the duration of the impact. Three response patterns to a policy variable are generally contemplated. So, the impact is transcent if there are one-time shifts in the observations, permanent if the effect remains constant throughout the postintervention series or dampened if the initial effect declines over time toward the intervention level. This approach can be used when only some target variables or both target variables and the policy variable are known and other relevant explanatory variables are missing. Its main disadvantage is to only allow an evaluation of the direct impact of the policy on the target variable.

Single multivariate methods represent a third category which essentially differs from the preceding one by the availability of information on the other relevant explanatory variables for the modelling of the target variable. In these models, the impact analysis is performed by distinguishing between policy-on and policy-off periods and introducing the policy variable as additional explanatory variable. These two last approaches are single equation impact models. If there are several targets, a single equation impact model can be specified for each target variable. Yet, if there are interdependencies between target variables, the estimated impact effects can be biased.

The general multivariate methods allow to cope with interdependencies and causality links between target variables, policy variables and explanatory variables and to estimate both the direct and indirect effects of the policy instruments implemented. Input-output analysis and macroeconometric modelling are the two main classes of methods dealing with these problems. While largely used by policy makers as a tool for economic policy formation, these methods are regarded suspiciously in the field of science and technology policy. The main reason is their difficulty in dealing with technical change, and, concretely, the fact that they do not include target variables of science and technology policy. In order to increase their credibility as a science and technology policy tool, R & D investments should be endogenized in macromodels.

If R & D subsidies are regarded as an instrument to recover technological leadership or to promote knowledge production for its own sake, as the latter are not actually economic objectives, the measurement of their economic impacts is not a vital element in the evaluation process as only technological performances are at stake. On the other hand, if the objective is to improve the efficiency of production structures, any evaluation of the efficiency of R & D policy cannot dodge the issue of the measurement of its economic impacts. The economic quantitative methods may help to cover this issue. The recourse to these methods and the choice of an appropriate method will depend on the question under scruteny and, in any case, the results should be only viewed as a piece of information in the evaluation process.

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