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THE R&D-PRODUCTIVITY RELATIONSHIP IN THE CONTEXT OF NEW GROWTH THEORIES :

SOME RECENT APPLIED RESEARCH

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THE R&D-PRODUCTIVITY RELATIONSHIP IN THE CONTEXT OF NEW GROWTH THEORIES : Some recent applied research.

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ABSTRACT

The early growth accounting studies paved the way for an assessment of technical change on growth. Early studies showed that total factor productivity growth was significantly influenced by R&D. The more recent studies have focused on R&D at the firm level, and have converged to a value of the R&D elasticity of about 0.1 - 0.3. However, introduction of supplementary factors, particularly those related to human capital and skills, tend to lessen the role played by R&D. Other aspects of technical progress can be considered (learning-by-doing and factors affecting technology spillovers) and R&D expenditures are an imperfect measure of technological innovation. Many "technology variables" may be introduced in productivity regressions, referring to different stages of the innovative process. Technological change, whether appreciated through R&D expenditures or not, can also be seen to influence international competitiveness. Work in this direction is far from being as extended as the one on productivity growth, but some results manifest that this field could be just as rich. Technological change is a most important element of "non-price" competitiveness. Finally, recent growth theories have concentrated on endogenous technological change. The relevance of R&D or human capital at large in the growth process has been emphasized. Still, very few attempts at incorporating the causes and/or consequences of technological change in an applied macroeconomics framework have been made. A few directions are explored here.

LES RELATIONS RD-PRODUCTIVITE DANS LE CONTEXTE DES NOUVELLES THEORIES DE LA CROISSANCE : Quelques recherches appliquées récentes

RESUME

Les premières études comptables de la croissance ont initié l'étude des effets du changement technique à long terme. Les premiers travaux montraient que la croissance de la productivité totale des facteurs était significativement influencée par la R&D. Des études plus récentes se sont concentrées sur les effets de la R&D au niveau de la firme, et ont convergé vers une élasticité de la productivité à la R&D de l'ordre de 0.1 - 0.3 . Toutefois, l'introduction de facteurs supplémentaires, particulièrement dans le domaine du capital humain et des qualifications, tendent à diminuer le rôle joué par la R&D. D'autres aspects du changement technique peuvent être considérés (l'apprentissage par la pratique et les facteurs affectant les spillovers technologiques) et les dépenses de R&D sont une mesure imparfaite de l'innovation technologique. De nombreuses "variables technologiques" peuvent être introduites dans des équations de productivité, en référence à différentes étapes du processus d'innovation. Le changement technique, apprécié au travers des dépenses de R&D ou non, peut aussi être perçu comme une influence de la compétitivité internationale. Le travail dans cette direction est loin d'être aussi étendu que celui sur la croissance de la productivité, mais quelques résultats expriment que ce champ pourrait être aussi riche. Le changement technique est un élément très important de la compétitivité "hors-prix". Enfin, les théories récentes de la croissance se sont concentrées sur le changement technique endogène. L'importance de la R&D ou du capital humain en général dans le processus de croissance a été souligné. Cependant, très peu de tentatives d'incorporation des causes et/ou des conséquences du changement technique dans un cadre macro-économique appliqué ont été faites. Quelques directions sont explorées ici.

Mots Clés : Changement technique, Productivité, Competitivité, Croissance endogène, R&D.

Keywords : Technical change, Productivity, Competitiveness, Endogenous growth, R&D.

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THE R&D-PRODUCTIVITY RELATIONSHIP IN THE CONTEXT OF NEW GROWTH THEORIES : *SOME RECENT APPLIED RESEARCH*

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S U M M A R Y

The R&D-productivity relationship in the context of new growth theories : some recent applied research

Bruno Amable and Robert Boyer

I. Introduction

This paper reviews some, mostly recent, studies in the applied modelling of technological change, in the light of current preoccupations concerning the relationship between technology, competitiveness and growth. A traditional approach, which generated a profusion of empirical studies, links investment in R&D to productivity increases. But whereas the early attempts limited themselves to the consideration of the effects of R&D expenditures on the residual with an extended Solow-type production function, the most recent studies have concentrated on phenomena such as spillovers of knowledge between industries or firms, i.e. on indirect effects of technical change. Besides, other technology variables have been taken into account: not just R&D expenditures but also patents or actual innovations. The new results obtained complement the earlier ones and raise new questions at the same time. How important are knowledge spillovers compared to flows of "embodied" technologies and through what channels do the externalities linked to technological knowledge accumulation travel ? Such questions are also those raised by "new" endogenous growth theories (Romer, 1986; Lucas, 1988; Amable and Guellec, 1992).

The role of technology in international competitiveness and growth has (re)surfaced with the "new" theories of international trade. This has led to a more widespread use of technology variables in empirical work on international trade, but also to a few attempts to model endogenous technical change or to incorporate technical change in macro-oriented empirical models. A very partial review of a few studies argues that, tentative as they may be, these first steps could lead to an applied macromodelling of technological change.

II. R&D expenditures and productivity growth

The early growth accounting studies (Solow, 1957)[1] emphasized the importance of technological progress in the process of growth. Most of these studies perceived technical progress as a residual, unexplained by the growth of factors of production. Research and

1 . For a survey, see Link (1987) and Maddison (1987).

development may have been considered as a contribution to explaining the residual, but it was not regarded as a factor itself until the 1960s. The framework used is simply an extension of Solow's model, with a new factor, the stock of technical capital featured alongside physical capital and labour in the production function.

$$Y = A\, e^{\lambda t}\, K^{\alpha}\, L^{\beta}\, R^{\gamma}$$

with K the stock of physical capital, L labour, and R the stock of R&D.is the trend of exogenous technical progress.

Thus specified, the growth rate of output is:

$$y = \lambda + k + \beta\ l + \gamma\ r$$

The elasticity of production (or labour productivity or total factor productivity) to R&D may then be estimated. One may use an alternative form, with the rate of growth of total factor productivity defined as:

$$tfp = y - \alpha\ k - \beta\ l$$

and one can estimate the following relationship:

$$tfp = \lambda + \kappa \frac{\dot{R}}{Y}$$

with :

$$\kappa = \frac{\delta\ Y}{\delta\ R}$$

approximating the change in R with R&D expenditures.

Most of the early studies found a strong positive association between R&D and productivity growth[2], be it at the firm or the industry level. More recent studies often make use of firms (panel) data. Mairesse and Sassenou have reviewed these studies, and the results they presented are summarized in Tables I and II. Most of the studies present an overall cross-section elasticity of production to R&D ranging from 0.1 to 0.3, depending on whether the sample of firms includes specific sectors or not (Table I). Unsurprisingly, one usually finds that the elasticity to R&D tends to be higher in "high-tech" sectors than in "low-tech" ones. Times series estimates of the elasticity of production to R&D are generally much lower than their cross-section counterparts (Table II), and the estimations are much more fragile. Collinearity of R&D capital and other variables with time is usually the main problem. But difficulties related to the time lags involved in the realisation of the effects of an R&D investment must also be considered. One usually assumes that a cross-section estimate gives a long term coefficient while the short term coefficient comes out of time series estimates. The former proposition holds true if one believes that the space dispersion reveals the diversity of possible positions according to a common model. The relationship observed at a specific moment tells nothing about the immediate effects of R&D expenditures on productivity. Short term effects may very well be small. On the other hand, recent work on time series has brought some new light on the distinction between short term and long term relationships. However the information gathered in panel data is most of the time insufficient to fully explore the time dimension.

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2 . See Link (1987) and Stoneman (1987).

Table I . Cross-section estimates of the R&D elasticity

	Sample	R&D elasticity
Minassian (1969)	17 chemical firms	0.26
Griliches (1980)	883 US firms	0.07
Schankerman (1983)	110 chemical and petroleum firms	0.16
Griliches-Mairesse (1984)	77 US firms	0.18
Cunéo-Mairesse (1984)	98 French firms	0.21
Mairesse-Cunéo (1985)	296 French firms	0.16
Griliches (1986)	491 US firms	0.11
Jaffe (1986)	432 US firms	0.20
Sassenou (1988)	112 Japanese firms	0.16

source: Mairesse and Sassenou (1991).

Table II . Time series estimates of the R&D elasticity

	Sample	R&D elasticity
Minassian (1969)	17 chemical firms	0.08
Griliches (1980)	883 US firms	0.08
Griliches-Mairesse (1983)	343 US firms and 185 French firms	0.02
Griliches-Mairesse (1984)	133 US firms	0.09
Cunéo-Mairesse (1984)	182 French firms	0.05
Mairesse-Cunéo (1985)	390 French firms	0.02
Griliches (1986)	652 US firms	0.12
Jaffe (1986)	432 US firms	0.10
Sassenou (1988)	394 Japanese firms	0.04

source: Mairesse and Sassenou (1991).

Recent analyses are not limited to microeconomic data. A few papers have sought to assess the impact of R&D on aggregate productivity. The more recent findings are summarised in Table III. Studies with sectoral data generally confirm the importance of R&D for technology-intensive activities. Some other studies work with estimates of an aggregate R&D stock, and allow for macroeconomic international comparisons. The reasons for international differences are open to various interpretations: some countries are more specialised in technology-intensive goods than others, or some "national systems of innovation" are more efficient than others. One may notice that the figures from Table II are markedly larger than the estimates from micro data (Table II). Some additional macroeconomic effects of R&D expenditures are present, but problems related to missing variables may appear too. Joly (1992) estimated a production function using pooled time series and cross-section data for five countries (Germany, France, Japan, United Kingdom and the United States). The elasticity of R&D is 0,136.

Table III . Estimates of the R&D elasticity with aggregate data

	Aggregate manufacturing sector (time series, 1960-1982)				
	Japan	USA	FRG	France	UK
elasticity of productivity to R&D	0.33	0.08	0.27	0.06	0.06
source: Soete and Patel (1985)					
	Aggregate manufacturing sector (time series, 1960-1987)				
	Japan	USA	FRG	France	UK
elasticity of productivity to R&D	0.26	0.15	0.28	0.16	0.09
source: Guellec (1991)					

Going deeper into detail, some studies have tried to assess more precisely the effects of R&D according to its use and sources. Mansfield (1980) distinguished basic from applied research and found that there was a statistically significant and direct relationship between the amount of basic research carried by a firm and its rate of increase of total factor productivity. It is as if applied research became more efficient when carried out in conjunction with basic research. In fact, the distinction between the two types of research activity may be blurred. Basic research may act as some sort of long-term R&D. Mansfield (1991), using survey results, estimated that the average time lag between academic research findings and industrial applications was about 7 years. R&D is then a device for utilizing academic research for industrial ends. The role of basic research seems to be important, since 10 % of the innovations from Mansfield's survey could not have been developed without the aid of academic research. The significance of this type of research varies widely across sectors, which does not come as a surprise (Pavitt, 1984).

The source of R&D funds is also an important issue, especially when one wants to assess the impact of government-funded R&D. Link (1981), supporting Mansfield (1980)'s findings, made a difference between government-financed and company-financed basic research. Analysing 51 major U.S. manufacturing firms, he found that both types of R&D expenditures positively influenced productivity growth, although the former seemed to have a lesser impact than the latter. However, government-financed applied research was found to have no significant influence on productivity growth. The positive impact of federally-financed basic research had been denied by earlier studies, but Link's findings rehabilitated government-sponsored research.

Making R&D from one's own laboratories and putting the new ideas thus generated in operation in one's own factory is but one way to benefit from technical progress. For many types of activity, it is indeed a minor source of technological advance. For instance, the advantages deriving from an innovation developed in one sector may be passed on to other sectors through the development of more efficient equipment. One of the most important problems is then to take account of incorporated technological knowledge in an adequate way. The measure of inter-industry flows with the help of input-output matrices (Davis, 1988 ; OECD, 1990) is a first step in incorporating indirect R&D into the analysis of technical change. The R&D intensity of a sector is no longer limited to direct R&D, performed within the sector itself, but includes also the R&D embodied in intermediary consumption. The distinction between medium technology and low technology sectors (Hatzichronoglou, 1985 ; OECD, 1986) may be blurred after such modifications (Papaconstantinou and Zaidman, 1991). However, helpful as they are, such devices remain fragile.

Input-Output tables may be used to weigh R&D expenditures and assess the inter-industry flows of technology, but other methods seem preferable. The use of patents data may be a more precise way of assessing flows of technology. Linking R&D to innovations (measured by patents), Scherer (1982) was able to estimate the inter-industry flows of technology. Productivity growth is found to be more often associated with process- than with product-R&D. R&D embodied in purchased goods is also an important source of productivity increase. Product-related R&D does not benefit the industry which it comes from as much as the industries where it goes to. Goto and Suzuki (1989) found that R&D activities of the input-supplying industries influence positively the productivity growth of user industries in Japanese manufacturing.

Taking account of non-incorporated knowledge is even more difficult. The recent literature on endogenous growth, for instance, has focused on the external effects and spillovers associated with technical change[3]. Knowledge is essentially a public good and one may expect important spillovers related to its accumulation. Jaffe (1986) attempted to measure the importance of spillovers by looking at the effects of other firms' R&D on the productivity of a firm's own R&D. Jaffe identifies the 'technological position' of a firm with the help of the technological classes in which it patents. A 'technological space' thus defined, it is possible to measure the proximity of firms and to weight the impact of other firms' R&D according to this proximity. Thus weighted, other firm's R&D expenditures define a 'potential spillover pool' for firm i: Si

Jaffe then tests the following equation:

$$k_i = \beta_1 r_i + \beta_2 r_i s_i + \gamma_i S_i + \text{dummies}$$

with ki the new knowledge generated by firm i, ri its own R&D, si its potential 'spillover pool', all variables expressed in logarithms. ki may be patent applications, profits or the market value of the firm. The coefficients for the patents equation are 0.875 for the firm's own R&D, 0.509 for the spillover pool and 0.352 for the interaction effect. The spillover effect is thus very large. If every firm increased its R&D expenses by 10 %, total patents would increase by 20 %, more than half of the increase coming from the spillover effect. Each firms' own R&D benefits other firms located in a neigbouring technological area. Mohnen and Lépine (1991) assessed technology spillovers with the help of a technology flow matrix which reports the use of a patent by industries which are not its producer. They found that R&D produced substantial spillovers in the Canadian industry, particularly in a few key sectors (chemicals, machinery, instruments)[4]. Table IV summarizes the technology spillovers.

3 . See Amable and Guellec for a survey

4 . They also found that foreign technology payments and own R&D were complementary factors, wich indicates that one has to built its own technology base in order to benefit from someone else's.

Table IV . The spillover effects

	Equation	Spillovers	Conclusions
Scherer (1982)	productivity	reallocation of R&D capital with a technology flow matrix	importance of "used" R&D (own process and embodied) over own product R&D
Griliches Lichtenberg (1984)	productivity	reallocation of R&D capital with a technology flow matrix	significance of own process and product R&D weak and unstable influence of embodied R&D
Goto Suzuki (1989)	productivity	Other industries' R&D capital with an I/O matrix	Strong effect of input suppliers' R&D
Bernstein Nadiri (1988)	cost	Other industries' R&D capital identified individually	Differences among industries as both spillover senders and suppliers
Mohnen Lépine (1991)	cost	spillover pool = weighted average of other industries' R&D stocks weights are constructed with a technology flows matrix.	Significant spillover effects. Strong inter- industry variability of spillovers
Jaffe (1986)	patents profits and market value	spillover pool defined with the proximity of industries in a patenting space	strong spillover effects
Geroski (1991)	productivity	innovations. either used or produced	weak spillover effects long-run effects of used innovations
Adams (1990)	productivity	spillover pool defined by technological proximity. Scientific articles	long-run effects of own knowledge: 20 years. even longer-run effects of spillovers: 30years.

Other forms of knowledge may be more difficult to trace. Arrow (1962) pointed out the importance of learning by doing. The process of trial and error is a crucial issue for technological innovation for it enables firms to learn how to use innovations more efficiently. One might conceive this factor as operating altogether independently of new

R&D expenditures. Initially noted in assembly line work and mass-production (Alchian, 1959, 1963), this feature was later introduced in growth theory (from Arrow, 1962, to Romer, 1990) with hardly any direct empirical investigations, a procedure that hampers a clear assessment of the origins of technological change.

The usual experience curve describes the decrease of unit cost with cumulative production according to two relations :

$$C = C_0 N^{-b}$$

and :

$$N = \int_{-\infty}^{t} Q(s)\, ds$$

the parameter b is easily related to the rate of decrease of unit cost when production doubles (a) :

$$b = \frac{-\log(1-a)}{\log 2}$$

Ayres (1985) gathered empirical evidence for very old and traditional production (for instance the model T Ford) as well as very recent innovations (such as memory disc drives, integrated circuits or MOS dynamic RAM). Even if the data is far from exhaustive, the trend is apparently towards reinforced experience curves. Therefore the logic of specific equipments division of labour and growing market size is ever more important in industries where product innovations are dominant. Recent research shows that learning-by- doing is very important at the firm level (Adler, 1985) and that new electronic products involve stronger experience effects than their mechanical predecessors.

Several reasons lead to believe that the exchanges of technical knowledge are more complex than suggested by simple I/O flows. The emerging socio-technical system seems to extend learning processes beyond the realm of production; it seems to include the users of the products as well. Powerful mechanical or electronic equipment and convenient software need close links between the people in charge of conceiving them and those who will use them. Learning by using has to be added to learning-by-producing. Preliminary studies suggest the importance of such interactions in orienting and monitoring the creation and diffusion of new technologies. The quality of the linkage could be one of the factors that determines the performance of national systems of innovation (Lundvall, 1988, 1989, 1990). However, a precise specification including such elements remains difficult to implement in an econometric study.

All these elements encourage applied researchers to add new variables in their regressions. Human capital has always been a variable favoured by growth accounting scholars (Maddison, 1987). Therefore, the know-how imparted to people through general education, training and retraining during professional life should be introduced in any productive equation whenever possible. The incorporation of such determinants of knowledge growth tends to reduce the role played by R&D. In traditional growth or productivity equations, the importance of R&D typically decreases with the inclusion of other factors[5]. Variables representing "qualitative" attributes undeniably contribute to lessening the importance of R&D. For instance, Sassenou (1988) considered a sample of 296 French firms and added a few variables to the traditional productivity equation. The result is that the research elasticity drops from 0.17 to 0.12 when variables such as the proportion of engineers and the proportion of administrative clerks in total employment are introduced. Crépon and Mairesse (1991) found a research elasticity of about 0.07 when taking account of the same factors in addition to sectoral effects on a sample of 1484 French firms, a low value considering the estimates of Table I. Taken alone, R&D expenditures may act as a proxy of very mixed effects related to human capital and learning effects. The precise assessment of their impact on productivity growth is thus made all the more difficult.

More generally, the appreciation of the innovative process could benefit from a more precise consideration of the process of technical change. Using survey data on 8220 Italian manufacturing firms on innovative activity at large, Napolitano (1991) aimed at going beyond the R&D laboratories. Actually, the consideration of innovative products or processes allowed to trail the factors of innovation. On average, R&D is only the sixth source of innovation, behind the purchase of equipment, design, proposals from employees, customer requests and staff training. Two elements mitigate this finding. First, innovations are not limited to the implementation of a radically new product or process[6]. Second, there exist important sectoral differences: high-tech sectors rely much more on R&D-based innovations. Three groups of industries may be identified, possessing similar sources of innovation[7]. Nevertheless, the role of R&D appears weakened. Within each sector (apart from petrochemicals and computers), firms which do not carry R&D do not acquire technological knowledge and skills from significantly different sources from firms which carry R&D. The presence of an R&D laboratory does not make significant difference in how technological innovation is gathered by innovating firms. Other influences (links with upstream and downstream firms) should enter the picture first.

This result has enormous implications for industrial policy. Restricting intervention to R&D encouragement is likely to miss the point since R&D activity seems to be a somewhat inadequate measure of innovativeness. It actually emphasizes the findings mentioned above on the importance of non-R&D factors, but an important limitation must be kept in mind. Napolitano's study concerns the Italian manufacturing industry, which is characterized by its low R&D intensity and its overall orientation away from technology intensive industries (Amable and Mouhoud, 1990 ; Amendola and Perrucci, 1990). It would certainly be interesting to compare the Italian situation with those of Japan and the United States. One suspects that the importance of R&D may turn out to be different.

In any case, the consideration of innovations sheds a different light on the relationships between technology and economic performances. Geroski (1989) considers 79 industries in the U.K. for the 1976-1979 period and tests a total factor productivity growth equation with the effects of market penetration by foreign and domestic producers as well as major innovations, making use of the SPRU data base on innovation in the U.K. (Pavitt, Robson and Townsend, 1987 ; Robson, Towsend and

5 . The most obvious supplementary factors are sectorial dummies : the value of the production elasticity of R&D decreases from 0.16 to 0.08 in Sassenou (1988). Including the effects of R&D externalities, the production elasticity with respect to own R&D falls to 0.08.

6 . Radical innovation, as opposed to incremental innovation. For an explanation on the distinction, see for instance Freeman and Perez (1988).

7 . They can be compared with Pavitt (1984)'s sectoral classification.

Pavitt, 1988). Major innovations are found to have a significant effect on productivity growth. Geroski (1991) used the same data to investigate on the cross-industry effects and the assorted innovation spillovers. Sectors differ to one another according to their use and production of innovation. Some industries are typical suppliers of innovations while others rely much more on innovations developed elsewhere. It is found that the use of innovations has a larger effect on productivity growth than the production of an innovation. Innovations have a long-run effect (10 to 15 years) representing as much as ten times the size of the short-run effect. An important finding is that there are very few spillovers associated with innovations, contrary to what happens with R&D as was found in Jaffe (1986) or Mohnen and Lépine (1991). It thus seems that knowledge flows between sectors, but not that embodied in specific products, which is too user-specific. This may provide additional empirical evidence supporting the distinction between tacit and non-tacit knowledge (Dosi, 1988).

Testing explicitely the spillovers associated with knowledge (measured with scientific articles in interaction with scientific personel), Adams (1990) showed that knowledge had a very long-run effect on productivity growth. Lags as long as 20 years must be taken into account. Moreover, spillovers associated with knowledge may have even longer-run effects (30 years). One may then assume that knowledge does flow between sectors.

III. Technical change and international competitiveness

The relationships between technology and the economy can be grasped through different variables, expressing separate stages of the innovation process. The concern for inter-industry flows of technology that can be found in some studies points to the fact that R&D is but one stage of the innovative activity. The effects of innovation can be observed in several areas. International competitiveness is a field where technological change is expected to play a significant role[8], especially in the light of the new international trade theories, which rely on product differentiation or increased quality through innovation to explain trade flows between industrialised countries (Dosi, Pavitt and Soete, 1990 ; Krugman, 1990).

Audretsch and Yamawaki (1988) modelled the relationship between R&D and competitiveness between the U.S. and Japan with a specific question : which components of R&D expenditures – process innovation, product quality improvements, new product or new technology, technology transfer – are most effective ? They tested a trade balance equation for 213 four digit SIC industries for 1977 with relative R&D intensities between Japanese and U.S. firms in a given industry as regressors, as well as other variables. R&D is found to positively influence Japanese trade: an additional dollar of R&D in Japan improves the trade balance by 0.15. On the other hand, the U.S. R&D expenditures are far from being as efficient, an additional dollar of R&D in the U.S. would improve this country's trade balance by only 0.025. The most effective components of R&D expenditures for the improvement of Japan's trade balance are product quality improvements and process innovation, i.e. reducing the cost of existing new products rather than developing new ones. This result may be compared to the

8 . See Stoneman (1983) ch. 17.

emphasis put on product differenciation in some new trade theories (Krugman, 1990 ; Guellec and Ralle, 1991).

Guellec, Magnier and Toujas-Bernatte (1991) tested market share equations on sectoral data between 1975 and 1987 with an indicator of R&D: the share of the country in the sum of R&D expenditures of the five most developed countries of OECD, smoothed over three years. Their results for the impact of R&D on market share evolutions are given in Table V. Amable (1991a) tested exports equations with a technology variable – foreign patenting i.e. the number of patents granted abroad for each country, either lagged or smoothed over 4 years – added to the traditional price and demand effects, in growth rates over 1961-1967 for the five most developed OECD countries, at the aggregate level. The results are displayed in Table V. The comparison of the two sets of results manifests that it is possible to find significant positive effects of a technology variable on aggregate foreign trade equations. Both studies find a similarity in coefficients value for France and Germany, and non significant coefficients for the UK. They differ on the case of Japan, where the impact of R&D seems to be much higher than for other countries, which is not the case with the patenting indicator.

Soete (1987) preferred to use a technology output indicator rather than a technology input one such as R&D intensity[9]. He tested a market share equation for 40 industrial sectors in 1977 with a technology variable as a regressor – the share of each country in U.S. patents over 1963-1977 in each industry – along with investment per worker, population and a distance proxy. The technology variable appeared as significant for most industry regressions. Low technology intensity sectors were the usual suppliers of non significant results. The technology intensive sectors obtained the highest coefficients, but there were a few surprises : drugs had a relatively low value of the coefficient for the technology variable whereas household appliances obtained a higher than expected coefficient.

Table V Technical change and foreign trade

			coefficients:				
source	equation	technology variable	U.S.	Japan	F.R.G.	France	U.K.
(1)	market share	R&D	0.35	0.93	0.11	0.14	-0.02 *
(2)	exports	patents	0.27 **	0.23	0.32	0.32	- *

* not significant ** trade balance equation

sources: (1) Guellec, Magnier and Toujas-Bernate (1991)
(2) Amable (1991a)

Fagerberg (1988) developed a model of international competitiveness that takes account of the ability of each country to compete in technology. The model considers the technological determinants of competitiveness as well as the broader concept of 'ability to deliver', which depends on the diffusion of technology from countries on the world technological frontier area to the rest of the world. The model was tested on pooled cross-

9 . See Basberg (1987) for a discussion of the merits to the patents indicator.

country and time series data with 15 industrial countries over the period 1960-1983. The technology variable used is a weighted average of R&D-based and patents-based measures. Fagerberg's results for growth in exports market shares (ME) and import market shares are given in Table VI, with TL the relative technological level of each country relative to the world technological leading country, INV the percentage of gross fixed investment to GDP, W the growth of world trade at constant prices and RULC the growth in relative labour unit costs. The technology variables (TL and TG) have the expected signs. Relative backwardness hampers net exports whereas technological activity facilitates them.

Table VI . The foreign trade equations of Fagerberg (1988)

ME =	-3.25	- 2.64 TL	+ 0.30 INV	- 0.36 W	+ 0.25 TG	- 0.34 RULC
	(-2.3)	(-3.0)	(5.0)	(-5.4)	(4.7)	(-4.6)
$R^2 = 0.67$ SER = 1.10						
MI =	0.88	+ 3.46 TL	- 0.23 INV	+ 1.25 GDP	- 0.21 TG	+ 0.21 RULC
	(0.6)	(1.8)	(-2.0)	(7.7)	(-2.3)	(2.4)
$R^2 = 0.54$ SER = 1.59						

source: Fagerberg (1988)

Fagerberg's technology variable was a mix of R&D and patents data. Greenhalgh (1990) introduced a more sophisticated variable in a traditional trade balance equation, so as to take account of product quality. Quality is a function of technological innovation and supply reliability. The former is represented by the number of innovations taken from the SPRU innovation data base and the latter by strike incidence. Greenhalgh's technology variable is thus defined as $\alpha_T\, e^{\delta_I I + \delta_S S}$, where I is an innovation and S is a strike. A trade balance equation was tested at the industry level for 31 industry groups over the period 1957-1981. Testing a cointegration relationship, innovations were found to promote exports in at most six industries, excluding sectors such as engineering and motor vehicles. For the ECM relationships, at most nine industries were found to benefit from trade promoting innovations.

Taking actual innovation variables involves the risk of facing the problem of cross-industry spillovers, which cannot be adequately dealt with if one cannot have quantified hypotheses about innovations I/O flows, and which seem to be more associated with disembodied knowledge. Nevertheless, Greenhalgh results lend some support to the idea that innovation facilitates trade performance.

Nothing is said about the inverse relationship though. Taking the specific case of the U.K., it has often been suggested that this country was experiencing a vicious circle or cumulative causation of decline[10], to which interactions between export success and technological success were contributing. Hughes (1986) addressed this particular problem by testing both an exports equation and an R&D equation. R&D is assumed to be influenced by technological opportunity and demand, particularly exports demand. At the same time, R&D, as a proxy for innovation, promotes exports. This leads to Hughes'

10 . Kaldor (1966). Cumulative causation is from Myrdal (1957).

model, displayed in Table VII, with X the exports, Q the gross output, Y the value added, RD the domestic R&D expenditures, RD* the R&D expenditures and Y* the value added of competitor countries, HS the proportion of skilled manual labour in total manual labour, CS a concentration indicator and PL an indicator of the profit margin. The model is estimated for 46 U.K. industries in 1978.

Table VII The trade and R&D equations of Hughes (1986)

$$X/Q = \underset{(3.6)}{3.27} + \underset{(4.3)}{0.69}\ RD/Y - \underset{(-1.8)}{0.22}\ RD^*/Y^* + \underset{(2.9)}{0.819}\ HS - \underset{(-2.1)}{0.50}\ CS$$

$$SER = 0.51$$

$$RD/Y = \underset{(-1.6)}{-2.71} + \underset{(3.0)}{1.26}\ X/Q + \underset{(3.3)}{0.509}\ RD^*/Y^* + \underset{(2.5)}{0.839}\ CS + \underset{(1.8)}{0.874}\ PL$$

$$SER = 0.92$$

The interactions between exports and R&D are as expected, there exists a cumulative causation between exports and innovation. One may also notice the importance of the manpower-qualification variable. The presence of this factor echoes the findings of the studies on R&D and productivity reviewed above.

Hughes' approach might be conceived as a first step towards the building of a more general macroeconomic model. The emphasis on the interactions between technological change and economic growth is not new (Schmookler, 1966), but not often emphasized in macroeconomic modelling. On the other hand, the studies reviewed above emphasize the variety of determinants and aspects of technological change. Therefore, technological change can take diverse forms in different areas. Considering the importance of technological change in the growth process, the need for a framework encompassing the macroeconomic effects as well as the determinants of technical change is more crucial than ever. The simple twin-determination between R&D and growth, helpful as it is, overlooks the more complex effects of technical change.

IV. Macro-modelling of technical change : from theory to econometrics

Technological change has been introduced in macroeconomic analysis for a long time. There exist an abundant literature on the macroeconomic impact of technological change on output or employment growth[11], just as technical change is taken account of in productivity or foreign trade studies. For medium-term effects, one can conceive an endogenous diffusion of new equipment, according to the general macroeconomic conditions. Indeed, vintage models can depict how the pace of investment will set the pace of macroeconomic technical progress, but the improvement of each new vintage is

11. See Stoneman (1983) ch. 12 for an overview. Freeman and Soete (1987) present a macroeconomic model taking account of technical change.

fixed exogenously (Petit and Tahar, 1990 ; Antonelli, Petit and Tahar, 1992, ch.3). Such models take account of technology diffusion, but not of technology creation. However, most macroeconomic models have no sophisticated way of dealing with the determinants of long-term technical change. The effects of technology can be ascertained at various levels of macroeconomic models, but a framework for a macroeconomic synthesis is still lacking[12].

On the other hand, it must be noted that the most recent growth theories[13] concentrate on endogenous technological change, long after Kaldor (1957) and Arrow (1962). Still, the empirical tests performed with specifications inspired from these theories tend to downplay the endogenous nature of technology, sticking to reduced forms that make the distinction between "exogenous growth" and "endogenous growth" theories more difficult to establish. These models rely crucially on the existence of constant returns in a technological progress function, or a unit elasticity on accumulated factors (Amable and Guellec, 1992). Yet, such a function is rarely tested, and technology itself is almost never at the center of empirical investigations, albeit endogenous technological change is the major issue of such studies. An exception is Guellec and Ralle (1991) who, following the logic of their theoretical model in which the number of new products discovered at each period is proportional to the number of researchers, tested an equation relating technological output to the amount of resources allocated to research, for the U.S. over the period 1902-1987 :

$$\underset{(17.6)}{y = 0.86\, y_{-1}} + \underset{(2.2)}{2.6\ 10^{-4} z} - \underset{(-2.6)}{3.7\ 10^{-4} x}$$

with y the rate of growth of the number of goods (a patents-based indicator), z the logarithm of the number of researchers and x the percentage of military expenditures in GDP. Guellec and Ralle obtain a constant rate of growth of technical progress with a fixed number of researchers. Actually, this relationship is reminiscent of earlier studies' findings, linking patenting activity to R&D expenditures[14]. Whether one should interpret this relationship as supportive of new growth theories or not is left open to debate.

In any case, it seems that progress is needed in the direction of integration of technical change in macroeconomic models. It is possible to gather the studies on the influence of technological change on exports and imports to implement a macroeconomic framework that takes account of demand effects. Boyer and Petit (1981) (Table VIII) estimated a complete model which enables to compute a long-run employment multiplier of R&D expenditures. From the estimation, this multiplier is actually negative. R&D stimulates productivity by lowering the employment required for a given production. At

12 . All the more that, in the history of economic thought, most of the errors related to "technological" pessimism derive from an incomplete analysis of the ajustment mechanisms associated with innovation. If, for instance, market size is presumed to be independent of technical change, then, any labour-saving device will produce unemployment. But long-term trends show that real income, especially wages, eventually grow more or less in line with aggregate productivity, creating therefore a moving equilibrium groxth in which demand and capacity expand simultaneously. Similarly, the modern sectors with an above average rate of technical change exhibit a relative price decline, wich makes room for additional growth in demand. According to a third mechanism, real profit associated with technological leadership will turn into an incentive to invest, extend the production of new products or increase productivity. Finally, at the macroeconomic level, a more innovative country will benefit either from currency appreciation or faster growth. By comparison, partial studies concentrate on the labour saving effects of technical change, missing the macroeconomic links.

13 . Reference is made here to the endogenous growth models. See Romer (1986, 1990), Lucas (1988). A survey is presented in Amable and Guellec (1992).

14 . See Griliches (1990) for a review.

the same time, it increases exports demand, which boosts production. But the direct, negative, effects on employment predominate over the indirect effects. Boyer and Petit (1984) confirm the low sensitiveness of aggregate demand to productivity increases.

Table VIII The model of Boyer and Petit (1981)

e	=	5.6	-	0.43 i	+	0.54 q	+	0.002 rat	-	0.027 in1
		(3.7)		(4.4)		(4.5)		(0.03)		(1.6)
i	=	12.4	+	0.26 q	+	1.3 in2	+	1.7 belg	-	1.8 uk
		(11.0)		(1.9)		(2.7)		(3.1)		(2.7)
q	=	-0.4	+	0.32 ex	+	0.56 d				
		(0.9)		(6.9)		(12.9)				
ex	=	4.6	-	0.57 pr	-	0.37 ch	+	0.026 in1		
		(1.2)		(1.9)		(2.4)		(0.5)		

e	:	rate of growth of industrial employment
i	:	ratio of investment to value added
q	:	rate of growth of value added (at constant prices)
ex	:	rate of growth of the volume of industrial exports
d	:	rate of growth of internal demand of industrial products
pr	:	rate of growth of productivity
rat	:	share of equipment investment in total investment
in1	:	percentage of process innovation in total innovation
in2	:	ratio of R&D expenditures to GDP with a 5 year lag
belg	:	dummy for Belgium
uk	:	dummy for the United Kingdom
ch	:	rate of change of the exchange rate in dollars

Pooled cross-section and time series data: six european industries over 1960-65, 165-69, 1969-73, 1973-76.
Method of estimation: FIML

Amable (1991a) estimated a model of growth and international competitiveness, pooling cross-country and time series data for 8 industrialised countries for the period 1961-1987 (Table IX). As well as equations for the growth rates of consumption (tci), exports (tx), imports (tm) and the share of investment in GDP (i), the model includes an equation for the growth of patents (tbr), which constitutes an attempt to model endogenous technological change. Patents grow in relation to economic activity (the growth of GDP: ty). This equation is far from being fully satisfactory, since it is a reduced form itself, and has to rely on time dummies. However, the model features a possibility of cumulative growth through technological change and competitiveness. tw is the growth of world GDP, tpr is the growth of export or import prices of a country relatively to the prices of the industrialised countries.

Table IX . A model of technical change and competitiveness

tci	=	-2.60 + (- 3.4)	1.54 tw + (8.0)	0.09 tbr (1.3)			$R^2 = 0.71$ SER = 1.13
tx	=	-10.52 + (-10.6)	2.03 tw - (4.9)	0.34 tpr + (-3.4)	0.40 i (5.4)		$R^2 = 0.72$ SER = 2.06
tm	=	7.38 + (5.7)	2.48 ty + (8.9)	0.10 tpr - (1.2)	0.38 i - (-4.7)	0.43 tbr (-3.5)	$R^2 = 0.68$ SER = 2.02
i	=	22.66 + (22.4)	1.41 ty - (5.8)	1.27 mili (-6.0)			$R^2 = 0.70$ SER = 2.57
tbr	=	-2.86 + (-3.7)	1.97 ty - (8.4)	5.93 d6873 + (-7.9)	4.06 d7984 (5.2)		$R^2 = 0.82$ SER = 1.92

LogL = - 103.37

Method of estimation : FIML
Source : Amable (1991a)

In a model of growth for 59 countries over the period 1960-1985, Amable (1991b) assumed that the level of education of the population was a positive function of the level of development, and that it influenced positively technological innovation, which in turn promoted growth. The model (Table IX) has four equation, one for the rate of growth of productivity (ty), as a function of the technology gap vis-à-vis the U.S. (gap), the ratio of equipment investment to GDP (eq), the fraction of the concerned population enrolled in primary education (prim) and the ratio of government expenditures to GDP (gov). Other equations concern the determinants of equipment investment, as a function of innovation (sspat, a concave function of the number of patents per inhabitant), which is itself positively influenced by the fraction of the concerned population enrolled in secondary education (sec). Resolution of the complete model allows for contrasted growth paths, and vicious as well as virtuous circles of cumulative causation. Depending on the fraction of population enrolled in primary education and on the share of government expenses (other than education), a country will eventually converge towards an equilibrium technology gap. What matters here is that innovation is linked to education and influence productivity growth.

Attempts to incorporate endogenous technical change in applied macromodelling should of course go beyond the simple frameworks exposed above. They cannot incorporate the many channels through which the innovation process takes place. At least, the questions raised by the new growth theories put the emphasis on the determinants of technical change and its mechanism of diffusion. There is no doubt that many of those determinants do not belong to the realm of microeconomics. "Traditional" macroeconomic influences (interest rates, fiscal policy,...) as well as more structural elements (the education system, industrial relations,...) are expected to matter. Besides, going beyond the blackbox of externalities means investigating the cross-effects between a macro-structure and micro-behaviours.

Table X . A model of growth and technical change for 59 countries

ty	= -0.0337 + 0.0444 gap + 0.483 eq + 0.0150 prim - 0.0827 gov (-2.2) (4.0) (2.6) (1.9) (-2.8)		$R^2 = 0.40$ SER = 0.011
eq	= -0.012 + 0.771 ty + 0.0432 sspat + 0.105 gov (-0.1) (2.3) (5.8) (2.2)		$R^2 = 0.64$ SER = 0.017
sspat	= 0.695 - 0.681 gap + 0.845 sec (1.8) (-1.8) (2.0)		$R^2 = 0.88$ SER = 0.12
sec	= 0.625 - 0.705 gap + 0.176 prim (4.6) (-6.3) (2.3)		$R^2 = 0.70$ SER = 0.12

LogL = 708.49

method of estimation : FIML
source: Amable (1991b)

In this respect, endogenous diffusion of technology equipment could be introduced in applied macromodelling along with endogenous evolution of technological knowledge. Interactions between skills, education, industrial relations and economic performance are certainly worth investigating. There is no doubt that technical change possesses many aspects (productivity improvements, product differentiation, quality improvements,...). But a treatment of such aspects calls for an elaboration of statistics and indicators (Smith, 1990), which are missed on a comparable international basis.

V. Conclusion

The understanding of technological innovation has been radically altered in the recent years (OECD, 1991, ch. I). The traditional "linear" model, which represented the innovation process as a series of successive steps, from an invention to the marketing of a new product, is giving way to an "interactive" model, not precisely defined yet, which insists more on feedback effects between the different stages of innovation. In this new model, the focus of the innovative process is not as much on the R&D expenditures as in the "linear" model. In the latter, the sequence that led from R&D to innovation is guaranteed. In the "interactive" model of technical change, the links between the various stages of innovation are more complex. The consequence is that an R&D/productivity relationship now appears as little more than a reduced form. Additional elements may be taken into consideration, such as spillovers and externalities, and other determinants of technical change are taken into account, related to human capital, the quality of user-producer relationships, etc. This change has been partly reflected in applied studies. Interfirm or interindustry flows of knowledge are a major subject of contemporaneous research on productivity growth.

The current conception highlights the many facets of technological change. It does not only enhance productivity, but improves the quality of production and enables the development of new products. Such effects on the demand for goods differ from the usual price effects. They correspond to the "non price" aspects of foreign trade equations. Consequently, international trade is an area where the inclusion of technology variables may be particularly fruitful.

Finally, the inclusion of technological change in macromodelling may yield important results. First, it constitutes an attempt at estimating the overall consequences of technological change. Second, it addresses a question connected to new growth theories, which stress the importance of technological change: how is it possible to model endogenous technical change ? Progress in this direction may however be inhibited by the lack of adequate statistical data.

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