NORTH-HOLLAND

Technological Forecasting & Social Change
70 (2003) 135–161

Technological Forecasting and Social Change

From R&D management to knowledge management An overview of studies of innovation management

Mariano Nieto*

Departamento de Dirección y Economía de la Empresa, Facultad de Ciencias Económicas y Empresariales, Universidad de León, Campus de Vegazana s/n, 240071 León, Spain

Received 14 August 2001; received in revised form 15 February 2002; accepted 19 February 2002

Abstract

This article is intended to establish links and seek connections between the contributions made to the study of innovatory phenomena. Specifically, it analyzes the evolution undergone by studies on the topic of the technological innovation (TI) process carried out by different disciplines from the point of view of the objectives they pursue and the suppositions on which they are based. Hence, it attempts to provide evidence for the relationships existing between research done at macro level (sociology, history, economics, and industrial economics) and that undertaken at micro level (management).

Keywords: Technological innovation; Technology management; R+D; Knowledge management; Methodology

1. Introduction

The process of technological innovation (TI) embraces a wide range of activities that contribute to the generation of new technological knowledge and/or improved use of the knowledge available. It has been recognized that the TI process has had varying effects both at macro (society, economic system, and industry) and at micro level (firm). At the macro level, the TI process: (1) modifies the structure of industries, (2) changes the composition of demand in the labour market, (3) alters the competitive position of nations, (4) stimulates economic growth, and (5) increases the well-being of society as a whole. At the micro level,

* Tel.: +34-987-29-1876; fax: +34-987-29-1454.
E-mail address: ddemna@unileon.es (M. Nieto).

0040-1625/03/$ – see front matter
PII: S0040-1625(02)00196-8

the TI process: (1) affects the competitiveness of businesses and (2) gives an orientation to the design of their strategies.

The extent of the effects of technological progress has aroused growing interest in the study of innovatory phenomena. The TI process has been studied by all the disciplines having to do with socioeconomic phenomena: history, sociology, economics, industrial economics, and management. Thanks to this research, our understanding of the nature of the TI process has improved notably.

However, a great part of the efforts undertaken by researchers in each of these disciplines is not made use of by the other academic communities. This is due to the presence of a number of obstacles standing in the way of communication and exchange of knowledge among the various groups of investigators. On the one hand, there are barriers between these disciplines because each employs different units of analysis and they all have different preferences for the study of a limited number of points. The truth of this can be easily shown simply by observing the absence of bibliographical cross-references between scholars of different disciplines in the articles they publish in any of the academic journals. On the other hand, the members of one and the same academic community also encounter difficulties in making use of results from within in it, owing to the lack of a generally accepted common terminology and the use of different methodological approaches. These obstacles slow down research activity and render more difficult the study of the nature of the TI process.

Over recent years, advances have been made in bringing together contributions proceeding from differing disciplines and methodological approaches. This is demonstrated by the fact that the most widely used text books on managing innovation (e.g., Refs. [1–3]) usually include studies on innovatory phenomena drawn from other disciplines. Furthermore, some theoretical works have tried to integrate and find coherence among the research undertaken by distinct academic communities [4–7]. Such works implicitly recognize that TI is a highly complex process and postulate that its study should have a multidisciplinary character. They strive to integrate different approaches and thus contribute to the presentation of a wider and more consistent vision of the TI process.

This article lies within this orientation and is intended to look into the evolution of studies carried out in the innovation management. It also considers the influences exercised over these studies by the whole range of research into the process of TI undertaken by other disciplines such as sociology, history, economics, and industrial economics.

To this end, the main contributions to the study of innovation are split into two levels: macro and micro studies (Section 2). Thereafter, the concepts noted in macro level studies allow these to be further divided into two clearly differentiated approaches, which are static approaches and dynamic approaches (Section 3). The development of micro level studies carried out by the management is then considered, allowing them to be grouped into three phases or stages that relate to the predominance of three differing methodological approaches. These are: an operational approach; a structure–conduct–performance approach (SCP); and a resource-based approach (Section 4). While in the first two phases the influence of static approaches is evident, the third and last show a dominant position for dynamic approaches (Section 5).

2. Levels of analysis in the study of innovatory phenomena

The study of innovatory phenomena has been undertaken by different academic disciplines such as sociology, history, economics, and business management. Each of them has taken an interest in analyzing differing aspects of the TI process, using a wide range of methodologies and choosing different units of analysis (see Table 1). As a first approximation, these studies may be grouped, as a function of the unit of analysis considered, into two categories:

- Studies at macro level, utilizing aggregated units of analysis such as a whole society, the economic system, or an entire industry.
- Studies at micro level, in which the unit of analysis is a business, a department, a project, or a product.

2.1. Studies at macro level

In studies at macro level, the TI process is conceived of as a complex social system in which numerous entities, such as research centres, universities, nonprofit organizations, and businesses, are involved [8]. Seen from this perspective, analysis of the TI process involves consideration of the whole system: science–technology–society taken together. At this level, the TI process has been studied with an eye to the behaviour of all the elements in the system, their interactions, and the international connections between all the national systems of innovation [9]. The principal difficulty lies in considering as a single whole all the factors affecting the process of innovation: social, cultural, political, economic, psychological, and technological. As is shown in Table 2, differing units of analysis have been used in such studies: (1) a human society as a whole, (2) an economic system, and (3) an entire industry.

Work undertaken in the field of sociology has analyzed the impact of new technologies on social behaviours and the problems associated with social control of technology. A large number of historians of technology and researchers into technological change have put forward striking explanations for the causes determining intensification of the process of innovation in a given society. Economic theory has concentrated on the effects of the process

Table 1
Levels of analysis in TI research

Unit of analysis	Principal discipline
Macro level	
Society	Sociology/history
Economic system	Economics
Industry	Industrial economics
Micro level	
Firm	Management
R&D department	
R&D project	
Product	

Table 2
Macro level studies

Unit of analysis	Discipline	Principal features studied
Human society	Sociology	• Technological progress and social change [10] • Technology assessment [11,12] • Social control of technology [13–15] • Ethical implications of technological change [16,17]
	History	• Nature of technological change [18–23] • Evolution of technology in different societies [24–26]
Economic system	Economics	• Innovation and economic growth [27–29] • National innovation systems [9] • Technology policies [30,31] • The economics of patents [32–34] • Innovation and employment [35] • Economic analysis of the process of innovation [36–40] • Diffusion of innovations [41,42]. • Technological change and international trade [43,44]
Industry	Industrial economics	• Concentration [36,45] • Conditions of appropriation [46] • Differentiation [47] • Technological opportunities [48] • Market opportunities [49] • Firm size [50] • Patterns of innovation [51,52]

of innovation on growth and the economic nature of stimuli to innovate. Industrial economics has modelled relationships between the process of innovation and market structures.[1]

2.2. Studies at micro level

At micro level, the TI process goes on within organizations. From a business management point of view, using disaggregated units of analysis, studies have been undertaken of the problems arising from management and organization of innovatory activities. To this end, as reflected in Table 3, several different units of analysis have been utilized: (1) a firm in its entirety, (2) an R&D department, (3) an R&D project and (4) a product.

The contributions of all the disciplines mentioned have aided in the comprehension of certain aspects of the nature of phenomena of innovation and have allowed tools to be designed for managing innovation within businesses. In view of the heterogeneity of all this work, it might be thought that no type of link could be established between them. However, as is discussed in the sections below, this is not the case. Firstly, studies undertaken at macro level may be grouped into two clearly differing categories in accordance with the objectives

[1] An excellent summary of contributions in the field of the economics of innovation can be found in Stoneman [53]. There are also very useful overviews of empirical work done in industrial economics [54–57].

Table 3
Micro level studies

Unit of analysis	Chief features studied
Firm	*Technology strategy*
	• Means of integrating technology into strategy [58–61]
	• Tools for analyzing and formulating technology strategies [62–67]
	• When to innovate: leading or following technology [68–70]
	• Access to new technologies: internal R&D, cooperation on technology, licensing [71,72]
	Organizing innovation
	• Innovation and organizational changes [73,74]
	• Designing innovatory organizations [75–78]
	• Relationships between R&D/production/marketing [79,80]
	• Innovation and learning [81,82]
R&D department	*Organization of the R&D department*
	• Organizing activities in R&D departments [83,84]
	• Management of technical personnel and reward systems [83,85,86]
	• Transmitting technological information [87]
R&D project	*Managing R&D projects*
	• Budgeting and financing R&D activities [88]
	• R&D project evaluation [89]
	• Planning, programming, and controlling R&D projects [90,91]
	• Project directors and teams [83,92]
Product	*New product development*
	• The process of developing new products [93,94]
	• Exploiting technological capabilities [95,96]
	• Product platforms [97,98]
	• Success factors in developing new products [99,100]
	• Reducing development times [101,102]

they pursue, the assumptions on which they are based, and the methodologies they adopt (Section 3). In the second place, it is possible to detect a clear developmental trend in the objectives, assumptions, and methods used in studies performed at micro level on managing innovation within firms (Section 4).

3. Approaches in studies at macro level

Each of the disciplines that have studied innovatory phenomena at macro level has investigated varying aspects of the TI process. To this end, they have employed very disparate methodologies as an outcome of the varying approaches present in the delimitation of the formal objects of study (society, economic system, industry) and in the objectives being pursued. Despite this, in the majority of research done at macro level by economics, industrial economics, sociology, and history, it is possible to detect numerous points of contact [4,23]. As is argued next, all work carried out at macro level may be classified into one of the two following categories: (1) static approaches and (2) dynamic approaches.

3.1. Static approaches

Models of technological change derived from neoclassical economic theory and the greater part of the empirical work carried out in the field of industrial economics on the relationships between the structure of an industry and innovatory activities constitute the paradigm adopted by static approaches. This research is oriented towards analysis and modelling of conditions of equilibrium at a given moment. Hence, it evinces certain limitations when it comes to studying processes, such as TI, having marked development over time. Work carried out by some sociologists and historians of technology from a deterministic viewpoint may also be included in the category of static approaches (see Table 4). A brief commentary on the principal characteristics of these contributions will now be provided.

3.1.1. Neoclassical economics

It is well known that in neoclassical models the process of innovation is presented as an exogenous element [29]. The flow of innovations has weighty economic consequences, as it determines the results obtained from processes of production, but it is not seen as affected by them [117]. In these models, it is considered that technologies arising from the process of innovation are information-intensive goods [36]. In accordance with these assumptions, firms cannot go beyond the technological limits established by their productive function, these being determined exogenously, nor can they modify the attributes of the products they make, other than in respect of prices and quantities. Faced with technological changes, firms react instantly, since they are assumed to have perfect information about all existing technologies, which can be acquired on the open market and assimilated without need for a prior learning process. Although these are clearly simplifications, the influence of these models has been noteworthy and neoclassical economics has contributed to reinforcing a static view of the process of TI [118].

Nonetheless, it should be noted that recent developments in the sphere of influence of the neoclassical paradigm have brought into question the exogenous nature of technical change. They take it that firms have expectations about technical advances. Consequently, the theory of rational expectations has given rise to a new growth theory that "endogenizes" technical advances [119–121]. For instance, it has been pointed out that the productivity of human resources in future periods depends on current assignments (Ref. [119, p. 17].

Table 4
Research with macro level approaches

Discipline	Static approaches	Dynamic approaches
Economics	Neoclassical economics [29,36,103,104]	Evolutionary economics [8,105–107,123]
Industrial economics	Traditional industrial economics (SCP) [45,47,108,109]	New industrial economics [110–112]
Sociology	Sociology of technological determinism [10,113,114]	Sociology of social constructivism [15]
History	Traditional historians of technology [115,116]	Evolutionary historians [18,20]

3.1.2. Industrial economics

Empirical research undertaken from within industrial economics under the so-called SCP paradigm do not break away from the deductive logic of neoclassical economics [56]. Underlying this paradigm, there is a basic causality relationship according to which the results of the TI process depend on innovatory behaviour on the part of firms, this in its turn being determined by the structure of the industry. Hence, in it firms are presumed to have a fundamentally passive role and their behaviour to be necessarily limited to adapting to the structural conditions of the technological environment, seen as exogenous, as they are supposed to have no capacity to modify them [122]. Thus, this approach offers a static view of the TI process and takes no account of the fact that technological competition is a historical and evolving process, in which innovatory behaviour by businesses can modify the structure of industries.

3.1.3. Sociology of technological determinism

As in the previous case, numerous pieces of research work on technical change done by sociologists have approached the matter from typically static angles. In such work, there is an underlying deterministic conception of the TI process that is far from unconnected with the neoclassical supposition that technology is an exogenous element [4]. These scholars take it that technology evolves autonomously and that technical forces determine social and cultural change [10,21,113,114]. According to this approach, social structures evolve by adapting to technological change. That is, given a specific technological state of affairs, later developments in the society in question should be predictable, regardless of the actions of social agents. The direction of technological advances defines a path along which society must advance, irrespective of the wishes of individuals. Thus, the history of societies is predetermined by scientific laws that are discovered in sequence by individuals and that through inexorable application give rise to technology. Individuals can exercise an influence only within the limits imposed by their logic [113].

3.1.4. Traditional historians of technology

Just like determinist sociologists, some historians [115,116] consider that technology determines all human activities and beliefs. In their research, they describe the TI process as a succession of events (scientific discoveries and inventions) without offering an explanation for the social causes encouraging the appearance of innovations. They present a vision of the TI process in isolation from the social context in which it takes place.

To sum up, the work done by neoclassical economics, industrial economics, the sociology of technological determinism, and traditional history of technology present static views of the TI process. In general, static approaches are founded on two assumptions: (1) the TI process is an exogenous factor escaping control by social agents and (2) its principal product, technology, is information. On the basis of these assumptions, mechanistic models are constructed that permit only the study of situations of equilibrium and the representation of timeless phenomena. In these models, the decision to adopt a given technology is not conditioned by past decisions and the first stages in the diffusion of an innovation do not affect its future evolution. That is, the TI

Table 5
Characteristics of macro level approaches

Characteristics	Static approaches	Dynamic approaches
Basic assumptions	• The TI process is exogenous • Technology is information	• The TI process is endogenous • Technology is knowledge
Objectives	• Emphasis on studying situations of equilibrium	• Emphasis on studying the historical process in which competition between technologies and businesses occurs: equilibrium is never reached
Models	• Methodologies using static analyses at one or more points in time (cross-sectional analyses)	• Methodologies based on longitudinal dynamic analyses
Role of agents in the TI process	• Passive • Adapt to the pace and direction taken by the TI process	• Active • Define the pace and direction of the TI process
Assumptions about the nature of the firm	• Assume maximization: Businesses evince maximizing behaviours • Assume homogeneity: All businesses have access to the same technological resources (which are information)	• Assume satisfaction: Businesses behave in accordance with routines • Assume heterogeneity: Businesses cannot all get equal access to the same technological resources (which are knowledge)

process is independent of its past. So, agents (individuals and firms) play a passive role and have no ability to influence the TI process (see Table 5).

3.2. Dynamic approaches[2]

On the other hand, studies of a dynamic sort do take into account the active part played by actants, whether individuals or organizations, in determining the pace and direction of technological progress. Work done from this angle has developed models permitting the representation of the competition arising between technologies and social agents as historical processes in which equilibrium is never attained. The principal contributions from these approaches come from evolutionary economics and the work of evolutionary historians. Though to a lesser extent, the development of new industrial economics and the social

[2] The term "dynamic" is used here to reflect succinctly a great number of characteristics of the technological innovation process, such as path dependency, cumulative nature, irreversibility, technological interrelatedness, tacitness. These have been noted by evolutionary historians and economists [105,106,123]. The use of the term "dynamic" is intended to stress that research undertaken from this angle recognizes that the process of innovation is shaped by the joint action of forces that follow lines that change over time.

constructivism school within sociology also permit certain dynamic angles on the process of TI. Some commentary on these contributions will now be offered.

3.2.1. Evolutionary economics

Unlike neoclassical models and traditional industrial economics, which concentrate on analyzing static equilibrium situations, evolutionary models pursue an attempt to represent the dynamic nature of the process of innovation. These approaches are consistent with Schumpeter's concept of economic development in which the process of innovation occupies a central position and constitutes the principal explanatory element. According to Schumpeter, the process of TI is a process of mutation that incessantly overthrows economic structures from within, endlessly destroying the old and continually creating new elements. This process of creative destruction constitutes the essential part of capitalism. This is what capitalism consists of and any capitalist enterprise must adapt to it to survive [39].

Ever since the seminal work by Nelson and Winter [123], numerous researchers into the phenomena of innovation have adopted an evolutionary perspective to reflect the dynamic nature of the TI process [106,124,8,125]. All of them consider that the dynamics of the biological evolution of living creatures can act as an explanation, by furnishing more or less close analogies, of how the TI process operates.

The theory of biological evolution employs three key concepts to explain the dynamics of evolution: diversity, selection, and inherited characteristics. The diversity of organic species has its origin in the processes of genetic mutation (equated to the processes of creation of new technological knowledge). The success of each of the genetic varieties or species (parallel to technological knowledge) is determined by its degree of adaptation to the environment (the industry), which acts as a selection mechanism. Genetic varieties spread through inherited features (equivalent to the diffusion and accumulation of new knowledge). This scheme can serve as a framework of reference adequate for setting up analogies allowing study of technological evolution.

In evolutionary models, firms play an active role and are defined as depositories of knowledge and learning sites, rather than on the basis of production functions. Hence, the boundaries of firms are set by the stock of knowledge they possess at any given moment and by their capacity to learn and accumulate new knowledge [118]. A firm's internal knowledge is incorporated into its routines. They contain and transmit the way in which tasks ought to be performed in the organization [126]. Routines are ordered hierarchically. Lower-order routines incorporate knowledge about how tasks of an operational nature are performed. Those of higher status govern the process through which organizations modify their lower-order routines. That is to say, higher-order routines seek solutions for new problems and thus guide the process of innovation [123]. The prime advantage of these models is that they allow us to understand the rules of the game of competition in an industry while keeping in sight the particular characteristics of the players or businesses [127].

3.2.2. Evolutionary historians

Evolutionary angles have also been influential in studies carried out by historians of technology [18,20]. In them, analogies are drawn between organic species and technological knowledge. It is assumed that the appearance of a new piece of technological know-how is comparable to the appearance of a new species. With these analogies as a starting point, a theoretical framework has been defined, which allows analysis of the factors determining the intensity and orientation of the TI process.

3.2.3. Sociology of social constructivism

The current of social constructivism within sociology, opposed to technological determinism, sets out from the assumption that social and cultural forces determine the nature and pace of technological progress (e.g., Ref. [15]). This strand of opinion explains the TI process as a complex social process in which the cultural and political values of the society involved act as selection mechanisms for the technologies that will develop. Seen from this perspective, the system of values of the society concerned configures the TI process and this, in its turn, has an impact on these values and the society holding them. Hence, such work attempts to explore the influence of social, political, and cultural forces on technological progress and to examine the impact of technologies and scientific ideas on people's lives. This approach, by stressing the role of the actants (whether individuals or social groups) in technological progress, has contributed to rendering more explicit the representation of the process of TI in firms [4,5].

3.2.4. New industrial economics

New industrial economics, in order to reflect the dynamic character of economic phenomena, has introduced dynamic elements into the SCP model. For this purpose, it has developed a full range of models based on game theory (i.e., Refs. [110,128]). In these models, bidirectional relationships are established and it is recognized that the strategic behaviour of firms in respect of technology can modify the structure of an industry. The starting point is the assumption that structures determine the strategies of firms, but it is accepted that as time goes by, businesses transform their industrial environment. It is also recognized that firms' conduct can be influenced by results obtained in the past [129].

To sum up, the work performed by evolutionary economics, evolutionary historians, the sociology of social constructivism and new industrial economics have contributed to the presentation of a dynamic view of the TI process. In the majority of these studies, there are two underlying basic assumptions: (1) the TI process is endogenous and controllable by social actants and (2) technology is not to be identified with information but rather has the attributes of knowledge. Upon these assumptions, dynamic models are constructed in which TI is represented as a historic process (see Table 5).

4. Trends in micro level studies

The evolution of studies on managing innovation, just as has happened in other areas of management, has been influenced and conditioned to a considerable extent by advances achieved by other disciplines in getting to know the nature of innovatory phenomena. This is probably due to the fact that study of the TI process in businesses (at micro level) was undertaken very late, after other disciplines such as economics, history, or sociology had studied the TI process (at macro level).

From the 1960s onwards, this being when the first works on managing innovation appeared, academic and consultants have being investigating the process of TI in businesses from a range of radically different viewpoints. It is easy to identify these on the basis of: (1) the aspects preferentially studied, (2) the methodologies for analysis employed, and (3) the assumptions made about the nature of the process of TI and its principal product, technology. In the evolution of these approaches the following three stages can be distinguished:

- first stage (1960s and 1970s): operational approach,
- second stage (1980s): SCP approach,
- third stage (1990s onwards): resource-based approach.

Tables 6 and 7 show the main pieces of research carried out and the characteristics of each of these three approaches.

4.1. Operational approach

The first studies to appear in the field of managing innovation concentrated on solving problems arising from carrying out R&D activities in large industrial firms. From a methodological angle that was clearly operational, a series of tools were developed to aid in the management of R&D departments and projects. This work assumed that

Table 6
Trends in micro level studies

Operational approach (management of R&D projects)	SCP approach (strategic management of innovation based on sectorial analysis)	Resource-based approach (strategic management of innovation based on the exploitation of internal resources and capabilities)
Main models and tools to assist decision-making		
• Techniques for evaluation of projects [89] • Planning and control of R&D projects [91] • Management of R&D projects [90,83,84] • Managing professionals in R&D [86] • Management of R&D/production/marketing interfaces [79]	• Strategic analysis of technology [62,67] • Portfolio models [130,66] • Technological forecasting [131] • How to integrate technological strategy into corporate strategy [132]	• Internal technological diagnostic: Grappes [133], technological maps [64] • Design of organisational structures promoting the creativity [3] • Learning organization and continuous improvement [134,76] • Product platforms [97]
Some empirical studies		
• Ref. [87]	• Refs. [135,60]	• Refs. [95,75,136–138]

Table 7
Characteristics of micro level approaches

Characteristics	Operational approach	SCP approach	Resource-based approach
The central plank in managing TI in a firm	• The management of R&D activities to adapt to the pace set by the TI process	• Formulation of a strategy for innovation suited to the characteristics of the industrial environment	• Formulation of a strategy for innovation that would permit exploitation of a firm's technological resources
Main activities in managing innovation in a firm	• Efficient assignment of resources to R&D activities • Managing R&D projects	• Identify the structural features of its industry • Design up a technological portfolio • Formulate the technological strategy: Choose the moment (the when?) and the most adequate way of accessing a new technology (the how?)	• Identify internal technological resources and capabilities • Develop new products based on resources and capabilities
TI process assumption	• Exogenous	• Exogenous	• Endogenous
Firm ability to control the TI process	• Null • The firm can only adapt to the intensity and management of TI process	• Scarce • The firm can orient the direction taken by the process but its actions are circumscribed by the structure of the industry	• Wide • The firm plays an active role in TI process and could orient it so as to modify the structure of the industry in which it competes
Technology assumption	• Information	• Information	• Knowledge
Innovation sources in a firm	• Very limited • Emphasis on R&D activities	• Limited • R&D and emphasis on external sources (licences, cooperation, etc.)	• Wide • R&D, external sources, and emphasis on internal mechanisms for learning: by doing, by using, by failing

success in the process of innovation is guaranteed if efficient assignment of resources to R&D activities can be achieved. Thus, the central plank in managing innovation in a firm is the selection, evaluation, budgeting, planning, controlling, and the carrying out of R&D projects.

4.1.1. Aspects studied

Owing to the above, in this stage, a great variety of models and tools to assist decision-making in the area of managing R&D activities developed[3] (e.g., Refs. [84,88,90,139]).

[3] Although the bulk of publications arising from this viewpoint appeared in the 1960s and 1970s, it should be pointed out that work on these lines has continued since then, with papers still published at intervals.

Sophisticated methodologies were put forward for technological forecasting (e.g., Ref. [131]) and for evaluating investment in R&D (e.g., Ref. [89]). Techniques for programming and control of R&D projects were devised (e.g., Ref. [91]). In addition, attention was given to the specific problems of managing technical and research personnel (e.g., Ref. [86]).

The empirical underpinnings of the majority of this work were quite shaky and it did not provide consistent explanations for the nature of the innovation process within organizations. From a theoretical viewpoint, only a few pieces of research into the problems of communicating and transmitting scientific and technological information inside R&D departments can be noted (e.g., Ref. [87]).

4.1.2. Static analysis methodologies

Work carried out during this stage had noteworthy limitations. In particular, it presented a mechanistic and linear view of the TI process, according to which scientific advances and R&D activities were the principal sources feeding this process. It was assumed that the greater the effort put into R&D activities, the greater would be the output of the TI process. In this way, no account was taken of the feedback occurring in the TI process or the innovatory potential of other forms of learning. On this point, it was strongly influenced by certain pieces of impactful research carried out in the field of the economics of innovation (e.g., Refs. [108,140]).

4.1.3. The TI process is exogenous

In all of this work, thanks to neoclassical influence, there was an underlying idea that the TI process is exogenous in nature. The intensity and direction taken by the TI process were seen as determined by a set of multiple forces escaping the control of social agents (individuals and firms). Organizations play a passive role and can only adapt to the pace set by the TI process, attempting to improve the management of their internal resources.

4.1.4. Technology is information

During this stage, the majority of work done had a restrictive concept of innovation, limited to activities carried out within R&D departments, and not bearing in mind other sources of innovation related to learning capacity, whether by use, practice, trial and error, or whatever, in organizations. In this view, there was an underlying idea that technology is information, implying that other forms of technological knowledge were not taken into account. This attitude originated in the influence exercised by several research projects of a neoclassical bent [36] in which technology was treated as an information-intensive public good.

4.2. SCP approach

During the 1980s, under the influence of industrial economics, efforts were made to identify the structural factors affecting the performance of innovatory activities within firms. Operational aspects of R&D project management were set aside in favour of a series of analytic models in which were encompassed the decisions most relevant to strategic management of technology.

The central idea of these models was to formulate a strategy for innovation suited to the characteristic of the industry involved. Hence, it was assumed that success in the process of TI is guaranteed if a firm was able to: (1) identify the structural features of its industry, (2) design up a technological portfolio, (3) determine the most appropriate moment for the introduction of a new technology (the "when?"), and (4) choose the best way of accessing it (the "how?").

4.2.1. Aspects studied

With the aim of modelling these decisions and aiding analysis and formulation of technological strategies, a wide variety of tools were produced: portfolio models (e.g., Refs. [66,130]), comparative analysis of the productivity of various technologies using S curves (e.g., Ref. [62]), typologies of technologies in accordance with their maturity and competitive impact (e.g., Ref. [67]), systems for technology watching (e.g., Ref. [65]), and the like. These models attempted to provide an answer to several questions: How can a firm's competitive edge be improved by technology? (e.g., Refs. [58,61]); How can technology be integrated into corporate strategy? (e.g., Ref. [132]); When should one innovate? Should one be a leader or a follower? (e.g., Ref. [68]); How should one innovate? Through acquiring licences, as opposed to technological cooperation or internal R&D? (e.g., Ref. [71]).

During this stage, some work aimed to lay theoretical foundations for technological strategy based on sectorial characteristics [60]. Furthermore, some empirical research in the sector established the relationships between effort put into R&D by firms and the structure of industries [135].

4.2.2. Static analysis methodologies

These contributions, to the extent that they brought in the effects of factors in the environment, represented a notable advance with respect to prior studies. They recognized the fact that by using an appropriate technology strategy, firms could improve their competitive position. However, in these models for strategic management of technology there was still a latent static view of the TI process, as they were influenced by the traditional analyses of industrial economics. They laid more emphasis on identifying the causes determining the stock of technological capacities of firms at a given moment than on finding out how they gradually accumulate over time.

These models, just like models for strategic management originating with Porter, represented technological competitiveness as an exercise in comparative statistics [141]. They were useful in analyzing a given situation at one moment in time and in prescribing the most suitable strategy for reaching another, preferred, situation of equilibrium in the future. On the other hand, they could not reflect the process leading from one situation to another. This means disregarding the fact that innovation is a process of a dynamic sort, where success is determined by competition between firms and technologies.

4.2.3. The TI process is partially endogenous

In the greater part of this work, it was held that the process of innovation is “partly” endogenous. A firm has a limited ability to control the process of innovation. It can orient the direction taken by the process of innovation, but its actions are circumscribed by the structure of the industry.

4.2.4. Technology is information

Just like work done in the previous phase, this had restrictive view of the sources of innovation in a firm. It emphasizes the role of R&D activities, downplaying other forms of technological knowledge such as learning by doing, learning by using, and learning by failing.

4.3. Resource-based approach

Work done during this phase was heavily influenced by evolutionary views. They usually characterized firms as a set of routines, that is, as a store of technological knowledge applied to the resolution of problems [137]. They considered that the essence of the TI process within a firm consists of the combining of technological resources so as to generate new technological capacities [142,143]. Hence, its central aspect is constituted by the formulation of a strategy for innovation that would permit exploitation of a firm’s internal technological resources and capabilities and development of new products based on them.

From this perspective, technology strategy acquired considerable prominence and was integrated into, merging to the extent of being identified with, corporate strategy, since technology is the principal factor exploited by firms so as to grow. It was assumed [141] that long-term competitive success was based on the capacity of a firm to: (1) generate knowledge and give it material shape in the form of valuable innovations, (2) to protect its essential technological competence from the actions of imitators, creating effective barriers against imitation, and (3) overcome organizational inertia, quickly imitating valuable innovations of its competitors.

4.3.1. Aspects studied

On the lines laid down by this approach a number of technological diagnostic tools were developed, proving useful for the identification of the technological competition between of firms, such as *Grappes* or technological bunches [133]. Furthermore, congruence models were put forward in respect of the organization of innovation and various design proposals suggested with a view to overcoming organizational inertia [78]. Measures were proposed to encourage creativity within organizations and to ease the way to creating new technological knowledge [76]. During this stage, the majority of work had greater empirical underpinnings, besides paying more attention to the setting up of theories.

With the seminal work of Ref. [144] as a starting point, a series of models developed in which the dynamic nature of the TI process was reflected [74,145–147]. In this research, the impact of the appearance of standards was studied and emphasis laid on the role of dominant designs in the evolution of industries. Additionally, in other work related to the previous research, it was shown that certain types of innovation, of an architectural character, can have a great impact on competitiveness [73].

Other work concentrated on the study of learning mechanisms and the characteristics of technological knowledge. Learning by using was studied [148,149] as was learning by failing [81]. It was recognized that the acquisition and assimilation of new knowledge takes place through accumulation and thus requires time and the prior availability of some capacity for absorption [150]. Various dimensions of technological knowledge were distinguished, especially those relating to its tacit component [151], and the problems arising from transferring it were analyzed [138,152].

Similarly, the efficacy and level of use of the various mechanisms available to firms to protect their innovations were investigated [46]. On this point, an explanation was offered of how the degree to which income generated by an innovation can be secured depends on the level of control a firm has over complementary assets [70].

4.3.2. Dynamic analysis methodologies

Research during this phase was oriented towards study of the historical process by which competition between technologies and firms arises, in which a situation of equilibrium is never reached. It kept in mind the fact that development of any technology depends fundamentally upon the route it followed in the past (Path dependency). The research held that TI follows an essentially dynamic process. Technologies, as they spread, generate a series of self-reinforcing mechanisms, such as learning through use, learning through practice, the appearance of economies of interconnection and of scale, the development of complementary technologies, all of which contribute to improving its yield.

4.3.3. The TI process is endogenous

This body of work held that firms play an active role in modifying their technological environment and that they have a broad ability to affect the TI process. The potential to innovate of a business would depend on its capacity to create new knowledge, spread it through the organization, and incorporate it in new products, services, and processes [76]. Seen from this perspective, firms would be continually accumulating knowledge in their "memory" in the form of operational routines that contain and transmit the way in which tasks should be performed within the organization (Ref. [123, pp. 76–99]. Hence, firms would play an active role in the TI process and by means of their strategies could orient it so as to modify the structure of the industries in which they compete.

4.3.4. Technology is knowledge

This approach recognized that firms innovate and develop new technologies through various learning processes (by doing, by using, by failing) originating internally in all sectors of the organization. These learning processes generate an output of knowledge in which information (explicit knowledge) represents only a small part, the rest being what is known as tacit knowledge. The concept of tacit knowledge,[4] like other intangible assets, acquired considerable importance in the resource-based approach. Tacit knowledge arises from personal actions and experience and thus is present in all modes of learning. Unlike information, tacit knowledge is difficult to share and in many cases, the individuals possessing it are not even aware of it. Owing to the importance of the tacit dimension of technological knowledge, in the majority of published work from this stage there is a latent idea that technology is not information but rather knowledge.

5. Analysis of the relationships between macro and micro level studies

The models of technological change developed by neoclassical economic theory and industrial economics constitute the paradigm for static approaches. These models are based on two views: (1) the process of TI is an exogenous factor lying outside the control of actants and (2) the principal component of it, technology, is information. These two suppositions have contributed to spreading a timeless image of the process of TI. In them firms are represented by their production functions and these, like technologies, can be shut down or replicated with surprising speed. They present the innovation process in a static way, with instantaneous adjustments naturally tending towards equilibrium.

The alternative dynamic approaches, typical of evolutionary standpoints, see a firm as a historical entity. They consider that: (1) the process of TI is endogenous and (2) the principal component in technology is knowledge. In these models, technologies, represented by routines, at all times reflect the knowledge the firm has accumulated over its lifetime. Routines, as they concentrate past experience of the enterprise, permit representation of the innovation process as cumulative, with the result of each period constituting the initial state for the next (Ref. [123, p. 96]. This implies that in order to understand the technological realities of a firm in the present, it is necessary to reconstruct the historical process of accumulation of technological knowledge that has brought it to its current situation.

In addition, as will be considered next, static and dynamic approaches make very different assumptions about the behaviour (maximizing versus satisfying) and the nature (homogeneous versus heterogeneous) of enterprises.

5.1. Behaviour and nature of enterprises

Firstly, it is a well-known fact that static models assume that actants (firms) adopt maximizing behaviours. This assumption is rather unconvincing and cannot provide an analytically consistent explanation of how the process of innovation comes about within a business. It is more realistic to suppose, as dynamic approaches do, that firms react to changes

[4] The concept of tacit knowledge was introduced into the literature on economics and management by Nelson and Winter [123] benefiting from the studies into knowledge carried out by the philosopher of science Michael Polanyi [153].

in their environment by varying their routines in an incremental way (Ref. [123, p. 14]. Adaptation takes place along the lines offering least resistance in the organization. Existing routines do not change if they are functioning well, and if they are subjected to alteration, it is by adoption of the closest routines to those currently used. Such changes are not guided by maximizing behaviours but instead seek an adequate level of satisfaction. At the end of the day, the objective of surviving is what rules the decisions and behaviour of the firm.

Secondly, analyses based on static models assume that all the businesses in a given industry are homogeneous, meaning that they have access to the same technological resources and capacities. Firms can be differentiated through variations in the use of productive factors in a specific production function. As soon as any business introduces an innovation, its productive efficiency increases and it attains rapid growth. This logically draws the attention of competitors who start imitating it by adopting the new technology. As a consequence, in the long run the new technology will be used throughout the industry, and this must contribute to reducing differentials between firms.

However, the reality is that the competitive process does not tend to smooth away the differences between the businesses competing in a single industry, but rather that such difference persist over time (e.g., Ref. [154], p. 161). The explanation for this phenomenon is to be found in the fact that during the process of diffusion of a technology and consequent imitation there is friction. On the one hand, firms have difficulty in identifying precisely the relevant knowledge and technologies developed by their competitors. This effect, termed *causal ambiguity* [155], renders transfer of technological knowledge difficult, to the extent that it increases the risk that the outcome of the imitation will not be as expected. On the other hand, even if a business were capable of identifying the relevant technology, it would encounter the problem that technological know-how is not easily transferable and are not endowed with perfect mobility [156]. Firms need a certain *absorption capacity* [150], that is, they must have available a base of previous knowledge permitting assimilation and efficient use of new technologies.

These assumptions as to the nature and behaviour of firms have influenced research carried out at micro level. Models and guidelines for managing innovation within a business that were developed in the first two stages (operational and SCP approaches) reproduced a static image of the process of innovation (e.g., Refs. [60,66,67]). In them, more importance was accorded to analyses of a static (*cross-sectional*) character than to dynamic or longitudinal analyses [157]. It was believed more relevant to identify the causes determining the stock of technological know-how in businesses at a given moment, than to become acquainted with how they are accumulated over time.

By contrast, work carried out during the third phase (resource-based approach) shows an appreciable influence from dynamic assumptions. These associate the process of innovation in a business with the concepts of learning and knowledge creation: “firms innovate by means of a continuous process of learning through which they generate new technological knowledge” (Ref. [76, p. 3]. This process basically consists of the development of new routines, since “conversion into a routine of an activity in an organization constitutes the principal way of storing operational knowledge specific to that organization” (Ref. [123, p. 99]. The process of innovation has also been identified with essentially dynamic concepts such as the creation of *core competencies* [143], the development of *dynamic capabilities* [158], or the *assets accumulation* [159].

5.2. Dynamic characteristic of the process of innovation

Additional proof can be found of the relationship between work of a dynamic nature carried out at macro level and that done at micro level under the resource-based approach. In both cases, it is supposed that the process of innovation has identical characteristics: (1) path dependency and (2) partial irreversibility.

The first characteristic refers to the fact that the process of TI is subject to historical conditioning factors and depends on the route followed in the past (*path dependency*). This implies that technological decisions adopted in the present will condition later learning processes, determining the future path of the process of innovation (Ref. [160, p. 4]. In the context of the competition between two technologies appearing simultaneously, the content of these first decisions is of great importance. Thus, various insignificant events, such as unexpected success in developing the first prototype, the order in which technologies reach the market, the whims of the first people to adopt it, political circumstances, and so forth, can cause a given technology to reach a sufficient level of spread so as to become the dominant one [161]. The order in which these events occur, insignificant though they may be, will affect the spread of each technological alternative and condition its future development. Recognition that innovation is a process subject to historical conditioning factors is fundamental, since through highlighting the importance of these early events for the future development of a technology, it permits reflection of its dynamic nature [162].

This idea has been taken into various concepts habitually used in studies on innovation management. It is usual to point up the continuous and accumulative character of the process of innovation by representing the evolution of technologies along *technological trajectories* [105] or *innovation avenues* [163]. These technological trajectories or avenues are built up within the framework of given *technological paradigms* [105] or *technological regimes* [123]. These technological paradigms or regimes in their turn provide *technological guide-posts* [163] or define *dominant designs* [123], determining the future development of technologies. In other words, technological paradigms, technological regimes, technological guideposts and dominant designs are similar concepts and reflect the historical conditioning factors that determine future evolution of the process of innovation along technological trajectories or avenues.

The second characteristic underlines the fact that the process of TI is partially irreversible, owing to the effect of mechanisms of positive feedback (the *lock-in* effect). The development of technologies along certain paths eliminates the possibility of competing with older technological alternatives already discarded, even when the relative price structure varies significantly [77]. During the innovation process, a number of self-reinforcing mechanisms arise and these make difficult any change to another route when once a given technological path has been chosen and has gained a position of dominance over the others. Such mechanisms may be of two kinds. Some directly impinge on the functional capabilities of the technology and improve its productivity by means of Ref. [164, pp. 590–607]: (1)

learning by practice and (2) through use, (3) networking economies, (4) economies of scale, and (5) the appearance of complementary technologies. Other mechanisms, while not improving the technology's productivity, contribute to its spread (6) by increasing the flow of information available about it.

Two interesting consequences arise from these two dynamic properties. First, the final result of a process of diffusion in which several technological alternatives compete cannot be predicted at the start of the process. The dynamic view of TI processes implicit in the evolutionary approach assumes that the processes that contribute to the spread of technologies are probabilistic and not deterministic. Second, the end result of the process of innovation need not necessarily be the most efficient from the technical point of view. There is historical evidence of cases in which the technological alternative selected and developed was not the best feasible [162].

6. Conclusions

Thanks to the contributions made by sociology, history, economics, industrial economics, and business management, the comprehension of innovatory phenomena has improved over recent years. Nevertheless, one of the reasons explaining why it has not advanced more rapidly is that many researchers have been unaware of the contributions coming out of other fields of knowledge than their own. Hence, if the conceptual framework of reference is to be established permitting the study of the TI process at the level of the firm, there is a need to break down the methodological and conceptual barriers separating these disciplines.

By drawing comparisons between the results of studies carried out at macro (society, economic system, industry) and at micro level (firm, R&D department, R&D project, product), it is possible to observe that, apart from certain divergences in terminology and methodology, they are highly consistent one with another. Despite the fact that differences in the research traditions of each of the academic communities have led to the use of differing terms and concepts to describe similar or identical phenomena, certain similarities and coincidences can be observed among them.

Indeed, the assumptions made by the various disciplines about the nature of the TI process and the characteristic of technology evolve in parallel over time in almost perfect synchronization (Fig. 1). In general terms, in all these disciplines there has been a move from supposing that the TI process was exogenous and static in character and that in this way no economic agent could impinge on it, to holding that it is of a dynamic and endogenous nature and determined by various social, economic, and business factors. This change has been accompanied by a shift in the perception of the characteristics of the principal product of the process of innovation: technology. From a belief that the fundamental component of technology is information, there has been a move to considering it at bottom as knowledge.

A further question to be broached is the way in which work done at macro level has exercised a notable influence on studies carried out at micro level. The assumptions and methodologies established by static approaches (especially neoclassical economics and

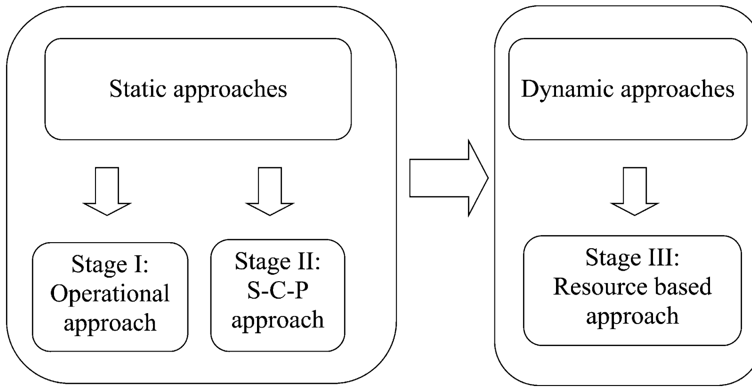

Fig. 1. Relationship between macro and micro studies.

industrial economics) are tightly linked with those taken on board by the first two stages of work on managing innovation within firms (operational approach and SCP approach). In fact, these approaches have contributed to it being seen as more interesting to get to know the causes determining the stock of technological know-how in firms at a given moment, than to identify the factors affecting its accumulation over time. Hence, research effort was oriented towards cross-sectional analyses and developing models that can only reflect static situations.

On the other hand, dynamic approaches (especially evolutionary economics) have exercised noteworthy influence over the third phase of studies on managing innovation (resource-based approach). The most recent contributions in this field attempt to reflect the time dimension of the process of innovation and so seek a foundation in historical evidence and longitudinal analyses.

Acknowledgements

I am grateful for helpful comments of two anonymous referees of this journal.

References

[1] R.A. Burgelman, M.A. Maidique, S.C. Wheelwright (Eds.), Strategic Management of Technology and Innovation, third ed., McGraw-Hill, New York, 2001.

[2] J. Tidd, J. Bessant, K. Pavitt, Managing Innovation. Integrating Technological, Market and Organizational Change, second ed., Wiley, Chichester, 2001.

[3] M.L. Tushman, P. Anderson (Eds.), Managing Strategic Innovation and Change: A Collection of Readings, Oxford Univ. Press, Oxford, 1997.

[4] R. Coombs, P. Saviotti, V. Walsh, Technology and the firm: The convergence of economic and sociological approaches? in: R. Coombs, P. Saviotti, P. Walsh (Eds.), Technological Change and Company Strategies, Harcourt Brace Jovanovich, London, 1992, pp. 1–24.

[5] P.J. Wergragt, P. Groenewegen, K.F. Mulder, Industrial technological innovation. Interrelationships between technological, economic and sociological analyses, in: R. Coombs, P. Saviotti, V. Walsh (Eds.), Technological Change and Company Strategies, Harcourt Brace Jovanovich, London, 1992, pp. 226–247.
[6] R. Coombs, P. Saviotti, V. Walsh, Economics and Technological Change, Macmillan, Hampshire, UK, 1987.
[7] S. Gopalakrishnan, F. Damanpour, A review of innovation research in economics, sociology and technology management, Omega 25 (1) (1997) 15–28.
[8] P. Hall, Innovation, Economics and Evolution, Prentice Hall, New York, 1994, p. 18.
[9] R.R. Nelson, National innovation systems: A retrospective on a study, Ind. Corp. Change 1 (1992) 347–374.
[10] J. Ellul, The Technological Society, Vintage, Paris, 1964.
[11] S. De Hoe, R. Smits, R. Petrella (Eds.), Technology Assessment: An Opportunity for Europe, Commission of the European Communities, Brussels, 1987.
[12] A.L. Porter. A Guidebook for Technology Assessment and Impact Analysis, Elsevier, New York, 1980.
[13] M. Kranzberg, W.H. Davenport, Technology and culture. An anthology, Schoken Books, New York, 1972.
[14] R. Elliott, D. Elliot, The Control of Technology, Wykeham, London, 1976.
[15] W.E. Bijker, T.P. Hughes, T.J. Pinch (Eds.), The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology, MIT Press, Cambridge, MA, 1987.
[16] E.F. Schumacher, Small is Beautiful, HarperCollins, New York, 1973.
[17] L. Winner, The Whale and the Reactor, University of Chicago Press, Chicago, IL, 1986.
[18] G. Basalla, The Evolution of Technology, Cambridge Univ. Press, Cambridge, MA, 1988.
[19] D. Cardwell, The Fontana History of Technology, HarperCollins, New York, 1994.
[20] J. Mokyr, The Lever of Riches. Technological Creativity and Economic Progress, Cambridge Univ. Press, Cambridge, MA, 1990.
[21] L. Mumford, Technics and Civilization, Harcourt Brace, New York, 1934.
[22] N. Rosenberg, Perspectives on Technology, Cambridge Univ. Press, London, 1976.
[23] N. Rosenberg, Inside the Black Box. Technology and Economics, Cambridge Univ. Press, Cambridge, MA, 1982, p. 4.
[24] D. Landes, The Unbound Prometheus, Cambridge Univ. Press, Cambridge, MA, 1969.
[25] J. Needham, The Grand Titration: Science and Society in East and West, Allen & Unwin, London, 1969.
[26] L. White, Medieval Technology and Social Change, Oxford Univ. Press, Oxford, 1962.
[27] M. Abranovitz, Resource and output trends in the United States since 1870, Am. Econ. Rev., Pap. Proc. 46 (1956) 5–23 (May).
[28] P. Mulder, H.L.F. De Groot, M.W. Hofkes, Economic growth and technological change: A comparison of insights from a neo-classical and evolutionary perspective, Technol. Forecast. Soc. Change 68 (2001) 151–171.
[29] R.M. Solow, Technical change and the aggregate production function, Rev. Econ. Stat. 39 (1957) 312–320.
[30] P. Hall (Ed.), Technology Innovation and Economic Policy, St. Martin's Press, New York, 1986.
[31] P. Diederen, P. Stoneman, O. Toivanen, A. Wolters (Eds.), Innovation and Research Policies: An International Comparative Analysis, Edward Elgar, Cheltenham, UK, 2000.
[32] F. Machlup, An Economic Review of the Patent System. Study of the Subcommittee on Patents, Trademarks and Copyrights of the Committee on the Judiciary, U.S. Senate, Study No. 15, U.S. Government Printing Office, Washington, DC, 1958.
[33] W.D. Nordhaus, Invention, Growth and Welfare, MIT Press, Cambridge, MA, 1969.
[34] E. Penrose, The Economics of the International Patent System, Johns Hopkins Univ. Press, Baltimore, MD, 1951.
[35] C. Freeman, J. Clark, L. Soete, Unemployment and Technical Innovation. A Study of Long Waves and Economic Development, Frances Pinter, London, 1982.
[36] K. Arrow, Economic welfare and the allocation of resources for invention, in: R.R. Nelson (Ed.), The Rate and Direction of Inventive Activity: Economic and Social Factors, Princeton Univ. Press, Princeton, NJ, 1962, pp. 608–626.

[37] R.R. Nelson, The simple economics of basic scientific research, J. Polit. Econ. (1959) 297–306 (June).
[38] J.A. Schumpeter, Theorie der wirtschaftlichen Entwicklung (The Theory of Economic Development), Harvard Univ. Press, Cambridge, MA, 1911 (English translation: 1934).
[39] J.A. Schumpeter, Capitalism, Socialism and Democracy, Harper & Row, New York, 1942, p. 121.
[40] P. Stoneman, The Economic Analysis of Technological Change, Oxford Univ. Press, Oxford, 1983.
[41] S.W. Davies, The Diffusion of Process Innovations, Cambridge Univ. Press, Cambridge, 1979.
[42] E. Rogers, The Diffusion of Innovations, fourth ed., Free Press, New York, 1995.
[43] R. Vernon, International investment and international trade in the product cycle, Q. J. Econ. 80 (1966) 190–207.
[44] W.B. Walker, Industrial Innovation and International Trading Performance, JAI Press, Greenwich, CT, 1979.
[45] F.M. Scherer, Firm size, market structure, opportunity, and the output of patented inventions, Am. Econ. Rev. 55 (1965) 1097–1125.
[46] R.C. Levin, A.K. Klevorick, R.S. Nelson, S.G. Winter, Appropriating the returns from industrial research and development, Brookings Pap. Econ. Act. 3 (1987) 783–820.
[47] W.S. Comanor, Market structure, product differentiation and industrial research, Q. J. Econ. 81 (1967) 639–657.
[48] M. Cicera, Patents, R&D and technological spillovers at the firm level: Some evidence from econometric count models for panel data, J. Appl. Econometrics 12 (1997) 265–280.
[49] J. Schmookler, Invention and Economic Growth, Harvard Univ. Press, Cambridge, MA, 1966.
[50] Z.J. Acs, D.B. Audretsch, Innovation and Small Firms, MIT Press, Cambridge, MA, 1990.
[51] K. Pavitt, Sectorial patterns of technical change: Towards a taxonomy and a theory, Res. Policy 13 (1984) 343–373.
[52] P. Patel, K. Pavitt, Patterns of technological activity: Their measurement and interpretation, in: P. Stoneman (Ed.), Handbook of the Economics of Innovation and Technological Change, Blackwell, Oxford, 1995, pp. 14–51.
[53] P. Stoneman (Ed.), Handbook of the Economics of Innovation and Technological Change, Blackwell, Oxford, 1995.
[54] M.I. Kamien, N.L. Schwartz, Market Structure and Innovation, Cambridge Univ. Press, Cambridge, 1982.
[55] W.L. Baldwin, J.T. Scott, Market Structure and Technological Change, Harwood, New York, 1987.
[56] W.M. Cohen, Empirical studies of innovative activity, in: P. Stoneman (Ed.), Handbook of the Economics of Innovation and Technological Change, Blackwell, Oxford, 1995, pp. 182–264.
[57] P.A. Geroski, Market Structure, Corporate Performance and Innovative Activity, Clarendon Press, Oxford, 1994.
[58] A.M. Kantrow, The strategy–technology connection, Harv. Bus. Rev. 58 (4) (1980) 13–21.
[59] K. Pavitt, What we know about the strategic management of technology, Calif. Manage. Rev. 32 (1990) 17–26 (Spring).
[60] M.E. Porter, The technological dimension of competitive strategy, in: R.A. Burgelman, M.A. Maidique (Eds.), Strategic Management of Technology and Innovation, Richard D. Irwin, Homewood, IL, 1983, pp. 211–233.
[61] J.B. Quinn, Managing innovation: Controlled chaos, Harv. Bus. Rev. 63 (3) (1985) 73–84.
[62] R. Foster, Innovation: The Attacker's Advantage, Macmillan, London, 1986.
[63] GEST, Grappes Technologiques. Les Nouvelles Stratégies d'Entreprise, McGraw-Hill, Paris, 1985.
[64] R.A. Goodman, M.W. Lawless, Technology and Strategy: Conceptual Models and Diagnostics, Oxford Univ. Press, New York, 1994.
[65] J. Morin, L'excellence Technologique, Publi-Union, Paris, 1985.
[66] E.B. Roberts, C.A. Berry, Entering new businesses: Selecting strategies for success, Sloan Manage. Rev. 26 (3) (1985) 3–17.
[67] P.A. Roussel, K.N. Saad, T.J. Erickson, Third Generation R&D: Managing the Link to Corporate Strategy, Harvard Business School Press, Boston, MA, 1991.

[68] H.I. Ansoff, J.M. Stewart, Strategies for a technology-based business, Harv. Bus. Rev. 45 (6) (1967) 71–83.
[69] M.A. Cusumano, Y. Mylonadis, R.S. Rosenbloom, Strategic maneuvering and mass-market dynamics: The triumph of VHS over Beta, Bus. Hist. Rev. 66 (1992) 51–94 (Spring).
[70] D.J. Teece, Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy, in: D.J. Teece (Ed.), The Competitive Challenge. Strategies for Industrial Innovation and Renewal, Harper & Row, New York, 1987, pp. 185–219.
[71] D. Ford, Develop your technology strategy, Long Range Plan. 21 (5) (1988) 85–95.
[72] J.M. Ribault, B. Martinet, D. Lebidois, Le Management des Technologies, Les Editions D'Organisation, Paris, 1991.
[73] R.M. Henderson, K.B. Clark, Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms, Adm. Sci. Q. 35 (1990) 9–30.
[74] P. Anderson, M.L. Tushman, Technological discontinuities and dominant designs: A cyclical model of technological change, Adm. Sci. Q. 35 (1990) 604–633.
[75] D. Leonard-Barton, Core capabilities and core rigidities: A paradox in managing new product development, Strategic Manage. J. 13 (1992) 111–125.
[76] I. Nonaka, H. Takeuchi, The Knowledge-Creating Company, Oxford Univ. Press, New York, 1995, p. 3.
[77] D.J. Teece, Managing Intellectual Capital, Oxford Univ. Press, Oxford, 2000.
[78] M.L. Tushman, C.A. O'Reilly III, Winning Through Innovation, Harvard Business School Press, Boston, MA, 1997.
[79] S.A. Bergen, Productivity and the R&D/Production Interface, Gower Publishing, Aldershot, Hampshire, UK, 1983.
[80] A.K. Gupta, S.P. Raj, D.L. Wilemon, The R&D/marketing interface in high-technology firms, J. Prod. Innov. Manage. 2 (1985) 12–24.
[81] M.A. Maidique, B.J. Zirguer, The new product learning cycle, Res. Policy 14 (1985) 299–313.
[82] I. Nonaka, D. Teece (Eds.), Managing Industrial Knowledge, SAGE, London, 2001.
[83] R. Katz (Ed.), The Human Side of Managing Technological Innovation, Oxford Univ. Press, Oxford, 1997.
[84] J.H. Dumbleton, Management of High-Technology Research and Development, Elsevier, New York, 1986.
[85] D.B. Balkin, L.R. Gómez Mejía, Compensation strategies in high technology, Pers. Psychol. 37 (1984) 635–650.
[86] D.B. Miller, Managing Professionals in Research and Development, Jossey-Bass, San Francisco, CA, 1986.
[87] T.J. Allen, Managing the Flow of Technology: Technology Transfer and Dissemination of Technological Information Within the R&D Organization, MIT Press, Cambridge, MA, 1977.
[88] B.C. Twiss, Managing Technological Innovation, third ed., Pitman Publishing, London, 1986.
[89] W.E. Souder, Utility and perceived acceptability of R&D project selection models, Manage. Sci. 19 (1973) 1384–1394.
[90] D.R. Archibald, Managing High-Technology Programs and Projects, Wiley, New York, 1976.
[91] D.G.S. Davies, Research planning diagrams, R&D Manage. 1 (1) (1970) 22–29.
[92] J.M. Howell, C. Higgins, Champions of technological innovation, Adm. Sci. Q. 35 (1990) 317–341.
[93] K.B. Clark, T. Fujimoto, Product Development Performance: Strategy, Organization and Management in the World Auto Industry, Harvard Business School Press, Boston, MA, 1991.
[94] S.C. Wheelwright, K.B. Clark, Revolutionizing Product Development, Free Press, New York, 1992.
[95] V. Chiesa, M. Barbeschi, Technology strategy in competence-based competition, in: G. Hamel, A. Heene (Eds.), Competence-Based Competition, Wiley, New York, 1994, pp. 293–314.
[96] M. Iansiti, K.B. Clark, Integration and dynamic capability: Evidence from product development in automobiles and mainframe computers, Ind. Corp. Change 3 (1994) 557–605.
[97] M.H. Meyer, A.P. Lehnerd, The Power of Product Platforms. Building Value and Cost Leadership, Free Press, New York, 1997.
[98] S. Sanderson, M. Uzumeri, Managing Product Families, Richard D. Irwin, Homewood, IL, 1996.

[99] R.G. Cooper, E.J. Kleinschmidt, What makes a new product a winner: Success factors at the project level, R&D Manage. 17 (1987) 175–189.
[100] B.J. Zirger, M.A. Maidique, A model of new product development: An empirical test, Manage. Sci. 36 (1990) 867–883.
[101] M. Iansiti, Real-world R&D: Jumping the product generation gap, Harv. Bus. Rev. 71 (3) (1993) 138–147.
[102] I. Nonaka, Redundant, overlapping organization: A Japanese approach to managing the innovation process, Calif. Manage. Rev. 32 (1990) 27–38 (Spring).
[103] H. Demsetz, Information and efficiency: Another viewpoint, J. Law Econ. 12 (1969) 1–22.
[104] W.E.G. Salter, Productivity and technical change, Cambridge Univ. Press, New York, 1960.
[105] G. Dosi, Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technological change, Res. Policy 11 (1982) 147–162.
[106] G. Dosi, Sources, procedures and microeconomic effects of innovation, J. Econ. Lit. 26 (1988) 1120–1171.
[107] J. Ziman, Technological Innovation as an Evolutionary Process, Cambridge Univ. Press, Cambridge, 2000.
[108] E. Mansfield, Industrial Research and Technological Innovation: An Econometric Analysis, W.W. Norton, New York, 1968.
[109] A. Phillips, Technology and Market Structure: A Study of the Aircraft Industry, Heath Lexington Books, Lexington, MA, 1971.
[110] P.D. Dasgupta, J. Stiglitz, Industrial structure and the nature of innovative activity, Econ. J. 90 (1980) 266–293.
[111] R.J. Gilbert, D.M. Newberry, Preemptive patenting and the persistence of monopoly, Am. Econ. Rev. 72 (1982) 514–526.
[112] J.F. Reinganum, Uncertain innovation and the persistence of monopoly, Am. Econ. Rev. 73 (1983) 741–748.
[113] R. Heilbroner, Do machines make history? Technol. Cult. 8 (1967) 333–345.
[114] L. Winner, Autonomous Technology, MIT Press, Cambridge, MA, 1977.
[115] T.K. Derry, T.I. Williams, A Short History of Technology From the Earliest Times to A.D. 1900, Oxford Univ. Press, New York, 1960.
[116] R.J. Forbes, E.J. Dijksterhuis, A History of Science and Technology, Penguin Books, London, 1973.
[117] D.J. Teece, Technological change and the nature of the firm, in: G. Dosi, C. Freeman, R. Nelson, G. Silverberg, L. Soete (Eds.), Technical Change and Economic Theory, Printer Publishers, London, 1988, pp. 256–281.
[118] N.J. Foss, Realism and evolutionary Economics, J. Soc. Evol. Syst. 17 (1994) 21–40.
[119] R.E. Lucas, On the mechanics of economic development, J. Monet. Econ. 22 (1988) 3–42.
[120] P.M. Romer, Endogenous technological change, J. Polit. Econ. 96 (1990) S71–S102.
[121] R.J. Barro, The Determinants of Economic Growth: A Cross-Country Empirical Study, MIT Press, Cambridge, MA, 1997.
[122] A. Jacquemin, The New Industrial Organization: Market Forces and Strategic Behaviour, MIT Press, Cambridge, MA, 1987.
[123] R.R. Nelson, S.G. Winter, An Evolutionary Theory of Economic Change, Harvard Univ. Press, Cambridge, MA, 1982.
[124] G. Dosi, Perspectives on evolutionary theory, Sci. Public Policy 18 (1991) 353–361.
[125] J.S. Metcalfe, M. Boden, Evolutionary epistemology and the nature of technology strategy, in: R. Coombs, P. Saviotti, V. Walsh (Eds.), Technological Change and Company Strategies: Economic and Sociological Perspectives, Harcourt Brace Jovanovich, London, 1992, pp. 49–71.
[126] C. Knudsen, Theories of the firm, strategic management, and leadership, in: C.A. Montgomery (Ed.), Resource-Based and Evolutionary Theories of the Firm: Toward a Synthesis, Kluwer Academic Publishers, Boston, MA, 1995, pp. 179–218.
[127] R.R. Nelson, The roles of firms in technical advance: A perspective from evolutionary theory, in: G. Dosi, R. Giannetti, P.A. Toninelli (Eds.), Technology and Enterprise in a Historical Perspective, Clarendon Press, Oxford, 1992, pp. 164–184.
[128] F.M. Scherer, Research and development resource allocation under rivalry, Q. J. Econ. 81 (1967) 359–394.

[129] J. Tirole, The Theory of Industrial Organization, MIT Press, Cambridge, MA, 1988.
[130] Arthur D. Little Inc., The Strategic Management of Technology, ADL, Cambridge, MA, 1981.
[131] H.W. Lanford, Technological Forecasting Methodologies: A Synthesis, AMACOM, New York, 1972.
[132] J.M. Katteringham, J.R. White, Making technology work for business, in: R. Lamb (Ed.), Competitive Strategic Management, Prentice Hall, Englewood Cliffs, NJ, 1984, pp. 499–519.
[133] GEST, Grappes Technologiques. Les Nouvelles Stratégies d'Entreprise, McGraw-Hill, Paris, 1986.
[134] M. Imai, Kaizen. The Key to Japan's Competitive Success, McGraw-Hill, New York, 1986.
[135] K.B. Clark, R.H. Hayes, Exploring factors affecting innovation and productivity growth within the business unit, in: K.B. Clark, R.H. Hayes, C.H. Lorenz (Eds.), The Uneasy Alliance: Managing the Productivity–Technology Dilemma, Harvard Business School Press, Cambridge, MA, 1985, pp. 425–458.
[136] C.K. Prahalad, G. Hamel, The core competence of the corporation, Harv. Bus. Rev. 68 (3) (1990) 79–91.
[137] J.C. Spender, Making knowledge the basis of a dynamic theory of the firm, Strategic Manage. J. 17 (1996) 45–62.
[138] U. Zander, B. Kogut, Knowledge and the speed of transfer and imitation of organizational capabilities: An empirical test, Organ. Sci. 6 (1995) 76–92.
[139] P.H. Francis, Principles of R&D Management, AMACOM, New York, 1977.
[140] C. Freeman, L. Soete, The Economics of Industrial Innovation, third ed., Continuum, London, 1997.
[141] C.W.L. Hill, D.L. Deeds, The importance of industry structure for the determination of firm profitability: A neo-Austrian perspective, J. Manage. Stud. 33 (1996) 429–451.
[142] G. Hamel, A. Heene (Eds.), Competence-Based Competition, Wiley, New York, 1994.
[143] J.F. Christensen, N.J. Foss, Dynamic corporate coherence and competence-based competition: Theoretical foundations and practical implications, in: A. Heene, R. Sanchez (Eds.), Competence-Based Strategic Management, John Wiley & Sons, New York, 1997, pp. 287–312.
[144] W.J. Abernathy, J.M. Utterback, Patterns of industrial innovation, Technol. Rev., (1978) 40–47 (June/July).
[145] W.J. Abernathy, K.B. Clark, Innovation: Mapping the winds of creative destruction, Res. Policy 14 (1985) 3–22.
[146] K.B. Clark, The interaction of design hierarchies and market concepts in technological evolution, Res. Policy 14 (1985) 235–251.
[147] J.M. Utterback, Mastering the Dynamics of Innovation, Harvard Business School Press, Boston, MA, 1994.
[148] D. Leonard-Baton, Wellsprings of Knowledge, Harvard Business School Press, Boston, MA, 1995.
[149] E. Von Hippel, The Sources of Innovation, Oxford Univ. Press, New York, 1988.
[150] W.M. Cohen, D.A. Levinthal, Absorptive capacity: A new perspective on learning and innovation, Adm. Sci. Q. 35 (1990) 128–152.
[151] S.G. Winter, Knowledge and competence as strategic assets, in: D.J. Teece (Ed.), The Competitive Challenge. Strategies for Industrial Innovation and Renewal, Harper & Row, New York, 1987, pp. 159–184.
[152] G. Szulanski, Exploring internal stickiness: Impediments to the transfer of best practice within the firm, Strategic Manage. J. 17 (1996) 27–43 (Winter Special Issue).
[153] M. Polanyi, Personal Knowledge: Toward a Post-Critical Philosophy, University of Chicago Press, Chicago, IL, 1962.
[154] K. Iwai, Schumpeterian dynamics: An evolutionary model of innovation and imitation, J. Econ. Behav. Organ. 5 (1984) 159–190.
[155] R. Reed, R.J. DeFillippi, Casual ambiguity, barriers to imitation, and sustainable competitive advantage, Acad. Manage. Rev. 15 (1990) 88–102.
[156] M.A. Peteraf, The cornerstone of competitive advantage: A resource-based view, Strategic Manage. J. 14 (1993) 179–191.
[157] M.E. Porter, Towards a dynamic theory of strategy, Strategic Manage. J. 12 (1991) 95–117.
[158] D.J. Teece, G. Pisano, A. Shuen, Dynamic capabilities and strategic management, Strategic Manage. J. 18 (1997) 267–284.

[159] I. Dierickx, K. Cool, Assets stock accumulation and sustainability of competitive advantage, Manage. Sci. 35 (1989) 1504–1511.
[160] P.A. David, Technical Choice, Innovation and Economic Growth, Cambridge Univ. Press, Cambridge, MA, 1975.
[161] W.B. Arthur, Competing technologies, increasing returns and lock-in by historical events, Econ. J. 99 (1989) 116–131.
[162] P.A. David, Clio and the economics of QWERTY, Am. Econ. Rev. Proc. 75 (2) (1985) 332–337.
[163] D. Sahal, Technological guideposts and innovation avenues, Res. Policy 14 (1985) 61–82.
[164] W.B. Arthur, Competing technologies: An overview, in: G. Dosi (Ed.), Technical Change and Economic Theory, Columbia Univ. Press, New York, 1987, pp. 590–607.