Essays on the study of technological change and international trade

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ABSTRACT

The purpose of this thesis is to contribute to the understanding of the relationship between technological change and international trade at the level of individual industries. The thesis consists of five essays. The first essay, 'Trade and technological change: the equilibrium approach', looks at the strengths and limitations of the theoretical approach that characterizes mainstream trade theory in the analysis of economic change. The essay concentrates on issues related to product innovation and discusses the treatment given to technical change in neoclassical general equilibrium trade models. The second essay, 'Technology in trade theory: the evolutionary perspective', presents an overview of the evolutionary approach to economic analysis and reviews a series of contributions from the literature on trade and technological change that are relevant for this approach. The final part of the essay outlines an evolutionary argument on the technology trade relationship.

An important conclusion that emerges from the review of the literature on trade and technology of the first two essays is that, in order to advance in our understanding of the role of technological change in international trade, further empirical research on the way in which specific technologies develop and diffuse internationally is required. The last three essays of the thesis seek to make some progress in this direction. The third essay 'Technological change as an evolutionary process', reviews a series of ideas from the literature on technological change and proposes a framework for the analysis of specific technologies. Such a framework and the ideas of the evolutionary argument on trade and technology are applied to two case studies. The case studies are presented in essays four and five, which are entitled: 'Diffusion of innovation and international trade in indirect electrostatic photocopying equipment' and 'Linear low density polyethylene: diffusion of innovation and international trade in polyethylene', respectively. The purpose of these case studies is to establish how patterns of trade emerge and are shaped by the development of the technologies. The fundamental message that emerges from the thesis is that, in order to understand the evolution of the patterns of trade in an industry, it is essential to look at the development of its technology and at the changes in the differences in technology between firms and between countries that are associated with it.

DECLARATION

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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A María del Pilar

1 Introduction

The differences in the relative efficiency in the production of different goods between countries was a fundamental element in Ricardo's theory of comparative advantages. A natural continuation of the ideas of Ricardo would have been to look at the role played by technological change in the changes in the patterns of specialization and trade. However, mainstream trade theory has adopted a framework which is essentially static and is not well suited for the analysis of change. Furthermore, the role of technology in trade has been relegated to a second place in most of the mainstream literature on international trade. Instead, the attention has centred on the differences in relative factor abundance between countries as the major determinant of the patterns of specialization. An early warning on the limitations of this approach is found in Williams (1929). Williams called the attention to the inadequacy of an analysis of trade in which important elements, such as the changes in technology are absent.[1] In the 1960s, Posner (1961) and Vernon (1966) made seminal contributions to trade theory in which technological change occupied a central place. However, until recently, although technological change was not entirely excluded from the analysis, it was seen in most of the literature as exogenously determined and treated as an ancillary element.

In the last fifteen years, the situation described above has started to change. There has been a proliferation of models, within mainstream trade theory, which focus on the role of technological change as a source of trade. Krugman's (1979) paper was a forerunner of a stream of literature on product innovation and international trade. This line of research has advanced considerably and in recent models the relationship between endogenously determined technological change, trade and growth is analysed.[2] However, an important limitation of much of the recent literature on trade and technology is that many of the insights provided by an important body of literature on technological change, rich in both

[1] Williams (1929).

[2] See Grossman and Helpman (1991a) for a representative work of this literature.

theoretical and empirical analysis, is missed.[3] This shortcoming is largely due to the constraints imposed by the theoretical framework used and by the equilibrium perspective that permeates their analysis.

The study of the relationship between technological change and international trade could benefit from the incorporation of important developments that have been taking place outside mainstream economic theory. Of particular interest is the revival of the idea, already found in authors like Marshall and Veblen, that economic analysis could profit from looking at biology and adopting an evolutionary approach. In the last fifteen years, the work of different authors has started to converge to build up the theoretical framework of an evolutionary approach to economic analysis. A distinctive characteristic of this approach is its concern with analysing economic change. The study of the economic implications of technological change is at the centre of the evolutionary approach. By adopting this perspective, it is possible to incorporate aspects of the process of technological change that are missed in the equilibrium perspective and to analyse its role in the evolution of the economic system.

Although the evolutionary approach to economics offers a promising line of enquiry, it still needs considerable development. The purpose of this thesis is to explore the usefulness of the approach for the study of international trade and to contribute to the development of the evolutionary framework of analysis.

In chapter 2, we make a selective review of the recent literature on trade and technology within the equilibrium tradition and make an assessment of its strengths and weaknesses. Chapter 3 presents the basic elements of the evolutionary approach and outlines an argument on trade and technology from this perspective. One of the main conclusions of that chapter is that further empirical research on the analysis of the technology-trade relationship at the level of individual technologies is needed in order to advance further in the evolutionary argument. Chapters 4, 5 and 6 seek to make a contribution in this direction. We focus on the analysis of the development of two technologies and the evolution of the trade flows associated with them.

The case studies seek to establish how patterns of trade emerge and

[3] This issue is discussed in chapters 2 and 4.

are shaped by the introduction and development of innovations. Case studies are a useful research strategy when, as in the present case, one is interested on 'how' type of questions. Although the findings of case studies can not be generalized in an statistical sense, they are a source of valuable insights which are susceptible of analytical generalization.[4]

As point of departure for the two case studies, chapter 4 draws on concepts from the literature on technological change to propose a framework that is useful for the empirical analysis of specific technologies and which is consistent with the evolutionary approach.

The ideas presented in chapters 3 and 4 are applied to the analysis of two innovations: indirect electrostatic photocopying and linear low density polyethylene, which are presented in chapters 5 and 6, respectively. The first objective of these case studies is to establish how the patterns of international trade in an industry relate to the development of technology. The second objective is to advance some theoretical propositions, which can be the basis for subsequent research.

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[4] Yin (1989), pp. 13-26.

2 Trade and technological change: the equilibrium approach

2.1 Introduction

In this chapter, we discuss the treatment given to technological change in mainstream international trade theory. It is not our purpose to make a comprehensive survey. We will limit ourselves to review a small part of that literature that is representative of the way in which technology and technological change are analysed in mainstream trade theory. Our purpose is twofold: first, to illustrate the main characteristics of this theoretical approach and, second, to discuss how a limited but important set of aspects of technological change are modelled and related to international trade. Our brief survey looks at part of the literature of what has come to be known as "new trade theory". This literature looks at questions such as imperfect competition, increasing returns, product differentiation and innovation in relation to international trade. In most of the chapter we concentrate on issues related to product oriented technological change.

In section 2.2, we describe the key features of mainstream trade theory and justify our reference to it as the equilibrium approach. In section 2.3, we comment briefly on the traditional analysis of exogenous technological change in a general equilibrium model of trade under perfect competition. Section 2.4 starts with the analysis of new trade theory and focuses on models of product differentiation. Section 2.5 looks at North-South models that analyse the role of product innovation and imitation among trading countries. Section 2.6 turns to recent work which has tried to capture the endogenous nature of technological change and its relationship with comparative advantages. Finally, section 2.7 concludes the chapter with an assessment of the strengths and weaknesses of the equilibrium approach in the analysis of technological change.

2.2 Neoclassical trade theory

The concept of equilibrium and its use as a tool for analysis is pervasive in economics and is not exclusive of any particular school of thought. However, the meaning of this concept and its relevance as part of the theoretical body varies between the different schools. This chapter is concerned with the analysis of technological change and trade within the neoclassical theory, which is the dominant school of thought in economics. We refer to the theoretical perspective of this school as the equilibrium approach because of the central place that this concept occupies in neoclassical theory, which has no parallel in other schools of economic thought.

There is a great diversity in the modelling approaches that are adopted by authors writing within the neoclassical tradition. This makes it extremely difficult to include all of them under a general characterization. In what follows, we propose an admittedly imperfect characterization of what we call the equilibrium approach which, in our opinion, embraces most neoclassical economic theorizing. The equilibrium approach can be characterized by holding the following views:

1. Economics is the study of the optimizing behaviour of rational economic agents. The essence of economic behaviour is the constant strive of individuals to maximize their well-being, as they perceive it, and this is the key element of the rationality that characterizes all economic agents. The universality of this feature makes it plausible to focus on representative agents when analysing economic behaviour.

2. Market exchange is the basic form of economic interaction by which economic agents can increase their well-being beyond the level that they could reach in isolation.

3. The coordination of the interaction of economic agents in the market produces equilibrium in the economic system. Individuals are considered to be in equilibrium when they cannot improve their position through further exchange at the existing prices. The system is in general equilibrium at that configuration of prices for all goods and services at which all economic agents are in equilibrium. This equilibrium is a stable situation to which the system tends to converge and in which it tends to remain in the absence of disturbances.[1]

4. Through the study of the relationships that prevail in equilibrium one can understand and predict the behaviour of agents and of the system as a whole. Comparative statics (or comparative steady states) is the main analytical tool of the equilibrium approach: the comparison of equilibrium

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[1] The key role of this proposition is made evident by the priority given in modelling to demonstrate the existence of an equilibrium, its uniqueness and stability.

positions that arise under different conditions is the way in which the effects of changes in economic conditions are analysed.

As we mentioned above, the concept of equilibrium is central to the approach. In particular, the general equilibrium that arises in a perfectly competitive economy has become the benchmark on the basis of which the theory has developed. To a great extent, the advance of neoclassical economics has taken place through the building of models which relax one or various of the assumptions that characterize the perfectly competitive equilibrium model and by introducing the modifications required for the analysis of specific problems. The equilibrium model of perfect competition acts as the benchmark in two ways. First, the usefulness and the power of a model is judged by its ability to generate a general equilibrium, like the competitive model does, which makes possible to analyse the same range of issues that are studied in that model. Second, the allocative efficiency that characterizes perfect competition is very often the point of reference against which the allocation of resources that arises in other settings is compared.

Mainstream trade theory is simply the application of the neoclassical general equilibrium framework to the context of a world economy divided in nations.[2] The point of departure of the neoclassical theory of trade is what Jones and Neary call "the classical paradigm":[3] Primary factors are assumed to be immobile between countries but fully mobile between sectors within each country. In every sector, constant returns to scale technology and perfect competitive conditions are assumed to prevail. Goods are assumed to be produced by primary inputs only and intermediate stages of production are neglected.[4] Other assumptions usually made are that there is neither joint production nor transport costs.

International trade arises from asymmetries between countries. These asymmetries can have their origin, in principle, in both the demand and the

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[2] See, for instance, Dixit and Norman (1980).

[3] R. Jones and P. Neary (1984), pp. 2-4.

[4] The neglect of intermediates has meant ignoring the implications of the fact that produced goods enter the process of production as capital. As it has been shown in a series of essays collected in Steedman (1979), the introduction of produced capital goods affects the validity of some of the central propositions of the neoclassical model. It also poses questions about the usefulness of this framework in the analysis of trade in manufactures, to the extent that produced capital goods are used in their production.

supply sides of the economy. It is the latter, however, which is seen as providing the main source of insights and on which most of the attention is focused.

Two basic specifications of the supply side asymmetries have been the workhorses of mainstream trade theory: the Ricardian model and the Heckscher-Ohlin (H-O) models of international trade. The Ricardian model is the neoclassical formulation of Ricardo's argument of the theory of comparative advantages. In this model, homogeneous labour is the only factor of production and the supply asymmetry between trading countries arises from the differences in their relative efficiency in production in the different sectors. In the H-O model there is no difference between countries in their production technologies. The basic model is a two country-two factor-two sector specification. In this model, comparative advantage arises as the combined result of the difference in the intensity with which the factors are used in each sector and the differences in the relative endowments of factors in the trading countries.

Thus, in terms of the explanation of the composition of trade, the Ricardian model looks at differences in technology while the H-O model focuses on relative factor abundance. These two models are often seen as alternative theories of international trade.[5] In practice, however, they are two basic specifications within the same neoclassical analytical framework, which can be suitably modified and even combined in order to analyse specific problems. The two models, however, do not stand equal in importance in neoclassical theory. Often, the Ricardian model is regarded just as a simple way to illustrate the principle of comparative advantages. The widespread use of this, labour only, specification of supply has more to do with its simplicity, that allows to introduce more easily additional complications to the model, than with a belief in a greater relative importance of the relative efficiency hypothesis. The central place in mainstream trade theory is occupied by the H-O model from which the two main propositions of trade theory, known as the factor price equalization and the H-O theorems, are derived.[6] It is well known that the validity of

[5] See Deardorff (1984) for a review of the literature on the relative importance of these and other models in explaining trade flows.

[6] The factor price equalization theorem states that, if trade equalizes commodity prices and if specialization is incomplete in both countries, factor prices are also equalized between countries in real terms. The Heckscher Ohlin theorem, in its quantity form, says that a

these theorems rests on restrictive assumptions in the model such as perfect competition, constant returns to scale, no joint production, absence of factor intensity reversals and identical homothetic demands across countries. It is also widely recognized that the validity of these propositions is sensitive to changes in the dimensions of the model. When the model is extended to include more than two goods and factors, concepts such as relative intensity and relative abundance lose the precise meaning that they have in a two by two context. However, in these more general settings, qualified and softer versions of the theorems have been put forward. It is beyond the scope of this chapter to discuss the extensions of the H-O model and the different approaches that have been adopted in order to rescue the insights of the factor abundance proposition.[7] What is of interest to us is the fact that the general message of this literature has been to suggest that the results of the two by two model points to the right direction. Thus, given the advantage, in terms of simplicity, of working with the two by two Heckscher-Ohlin model, it has been adopted as the basis for further development of the theory. The pervasiveness of elements of the Ricardian and the H-O models in the specifications of recent models of trade that analyse issues related to technological change is evident in our brief survey. In the next section, we comment briefly on the way in which the impact of technological change on trade is analysed in the general equilibrium framework.

2.3 Exogenous technological change in the equilibrium approach

The analysis of exogenous technological change is a classical illustration of the comparative statics method of analysis on which mainstream trade theory is based. Technological change is introduced in the form of an exogenously determined shift in the production function which represents

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country will export the good that uses intensively in its production the factor which is relatively abundant in the country. Other two fundamental theorems of trade are the Rybcynski and the Stopler-Samuelson theorems. These last two propositions refer to relationships within a single country, but are important in a trade context. Here we focus only on the first two theorems.

[7] A summary statement of the relationship between the fundamental theorems of the H-O model and the effect on the theorems of relaxing the assumptions of the model is found in Jones (1987). Surveys on the literature about the extension of the H-O model to higher dimensions are found in Chipman (1966) and in Ethier (1984).

the change in the level of output that could be obtained for any technically efficient combination of inputs. This is represented graphically in an isoquant map as the displacement of isoquants towards the origin.

The analysis of the effects of technological change on international trade is in essence the comparison of two trade equilibria characterized by different technological conditions.[8] The basic elements of the mathematical analysis of this problem in the two by two general equilibrium model of trade are spelled out in Jones (1965). This author shows that technological change can be represented as a matrix of changes in input requirements by unit of output.[9] Jones considers an hybrid Heckscher-Ohlin-Ricardian model with two factors and two sectors in which countries may differ in both relative factor endowments and production technologies.

Space precludes us from looking in detail at Jones analysis. We will only comment briefly on its results. The main insight that emerges from this analysis is that, as Jones points out, technical change acts partly as an increase in factor endowments and partly as a change in commodity prices. Jones analysis expounds very concisely the essence of the mechanism through which generalized technological change in a country operates on prices and output composition. It also exemplifies the main strengths of the comparative statics method of analysis: it not only compares the final results of trade equilibria under different technological conditions, but allows us to follow the way in which such a difference operates across the whole range of interrelationships that characterize an equilibrium. There are, however, various aspects of the analysis that have been recognized as unsatisfactory. A first limitation, pointed out by Jones,[10] is to treat technological change as exogenous. Clearly, to a great extent, technological change is generated within the economic system: partly as a sub-product of productive activity,[11] and partly as the outcome of deliberate research and development (R&D).

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[8] Two of the most important papers of the 1950s on the effect of exogenous technological change on trade are those by Johnson (1955) and Findlay and Grubert (1959).

[9] Jones (1965, 1970). For a different presentation of the problem see Södersten (1964).

[10] Jones (1970), p. 78.

[11] This question was analysed by Arrow (1962).

Another limitation of the traditional treatment of technological change is that it does not look at the improvement on existing products and the introduction of new ones, which are important aspects of the change in technology. Further criticisms can be made of the stylized way in which the change in technology is represented. Atkinson and Stiglitz, for instance, have called the attention to the fact that technological change tends to be localized around the technique in use.[12] Thus, its representation as a change in all the techniques available does not fit well with the nature of the process.

In the last twenty years some progress has been made in the neoclassical research program to incorporate more aspects of technological change in trade models. The task has been mainly one of finding ways of modelling those aspects which can be treated in a neoclassical general equilibrium framework. Much of the research in neoclassical trade theory has shifted away from the standard analysis based on the model of perfect competition. New trade theory has focused on the study of international trade under conditions of increasing returns, product differentiation and imperfectly competitive market structures. The study of technological change in this context has figured high in the research agenda, and the role of innovative and imitative activities in determining trade patterns, rates of growth and relative incomes has been explored. However, as it will be apparent in the sections that follow, in the effort to find representations of technological change which lend themselves to their incorporation in a general equilibrium framework, this research tends to produce very stylized pictures of technological change. This makes them subject to criticisms like the one that stems from the observations of Atkinson and Stiglitz on the nature of technological change.

In the next three sections we will centre our attention on one particular line of enquiry: the study of issues related to product oriented technological change. Questions related to how technological change is made endogenous will also be considered.

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[12] Atkinson and Stiglitz (1969).

2.4 Product differentiation and international trade

One important dimension of technological progress is product development, and one aspect of it is the introduction of new varieties of existing products. The existence of differentiated products and the fact that different varieties are produced in different countries is a potential source of demand in one country for varieties produced in another. This question has been tackled by the literature on product differentiation and international trade. In this section, we discuss a set of models which apply the framework of monopolistic competition to the analysis of international trade.

Product differentiation is an aspect of product development which, as treated in the models reviewed here, does not constitute technological change in strict sense. This is due to a great extent to the static framework that is used in the models and to the notion of competition that they put forward. The models focus only on the implications of the presence of differentiated products for international trade equilibrium. The innovative activity by which such differentiation occurs is addressed by the models discussed in section 2.5. The literature reviewed in this section is, nevertheless, an important piece in the general strategy that has been adopted in the equilibrium approach to model product oriented technological change in an international trade context. This will be more clearly appreciated in subsequent sections where the link between these models and those with more dynamic pretensions will be evident.

There is a relatively large number of models that incorporate product differentiation and one can find a wide variety of model specifications. What is of interest to us is the way in which product differentiation is modelled and the main implications for international trade that are derived from its presence. Therefore, first, we present in detail a model by Ethier (1979, 1982), which is representative of the way in which differentiation is introduced and analysed. Afterwards, we discuss some other important contributions centring our attention on how product differentiation is introduced.

2.4.1 Ethier's model of international returns to scale

There are two distinctive aspects of Ethier's model: its focus on trade in intermediates and its emphasis on international economies of scale in the manufacturing sector. It is assumed in the model that the level of the world output of manufactures is what determines the magnitude of the economies of scale in that sector. These economies of scale are attributed to a process of division of labour that expresses itself in the breaking down of the manufacturing process in a series of intermediate activities. This breaking down of activities is assumed to increase as the market for the final manufactured good expands. To capture this idea, a separable production function for finished manufactures is used, in which output M is given by:

$$M = km \tag{2.1}$$

Where m is an index of the bundles of factors employed in manufacturing and k is an index of scale economies. m has the standard properties of a constant returns to scale production function and k is an increasing function of output which reflects the existence of increasing returns.

To centre the attention on intermediate goods, it is assumed that finished manufactures are costlessly assembled from intermediate components[13]. In order to make abstraction of considerations related to differences in intermediates, it is assumed that all the components are produced from capital and labour via identical production functions.

We will focus on the version of the model presented in Ethier's (1982) paper, which is very simple and brings out very neatly the main features of his approach.[14] The model considers two final goods sectors: one produces wheat and the other assembles a manufactured product. Wheat production takes place under perfectly competitive conditions and is subject to constant returns to scale. For finished manufactures, Ethier specifies a CES production function whose arguments are: x_i ,the quantity

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[13] As Ethier points out, there are other possible stories which are compatible with his analysis: intermediate goods could be seen as successive stages or it could be possible to allow for costly assembly of finished manufactures. Ethier(1982) p. 391, n. 6. We will comment further on this issue after having presented the model.

[14] It ought to be noted that the analysis under this version is also more restricted than the one in the 1979 paper to the extent that it makes use of specific functional forms while the latter presents a more general formulation.

of each component used to assemble it, and n ,the total number of components produced. The total output of the, costlessly assembled, finished manufactures is, thus, given by:[15]

$$M = n^{\alpha}\left[\sum_{i=1}^{n}\frac{x_i^{\beta}}{n}\right]^{\frac{1}{\beta}} ; \quad 0<\beta<1 , \quad \alpha>1 \qquad (2.2)$$

where the parameter α indicates the extent to which the total number of intermediates (i.e. the breaking down of the process of production of final manufactures) generates increasing returns to scale, and the parameter β is related to the degree to which the components can be substituted for each other (the higher β is, the more substitutable the intermediates are between them). Regarding the components, the bundle of factors required to produce the quantity x of intermediates is specified as the linear function $ax + b$. The constant element is included in order to capture the idea that, as scale increases, the firm experiences decreasing unit costs due to the presence of fixed costs. If all intermediates are produced in the same quantity x, the scale of production in the manufacturing sector m is equal to the bundle of factors required to produce x multiplied by the total number of components produced:

$$m = n\,(ax+b) ; \quad a, b>0 \qquad (2.3)$$

The composition of this bundle in terms of capital and labour varies as factor prices and techniques vary, just as it occurs with the capital and labour required for the production of wheat. In fact, as a result of the separability properties of the production function, it is possible to define a transformation curve between wheat and the bundle of factors used in the production of intermediates: $W = T(m)$. This function has the properties of a standard transformation curve relating two goods produced under constant returns to scale.

The demand side of the model is specified by assuming that a constant proportion of income is spent in each good: a fraction γ of income is spent on manufactures, and $(1 - \gamma)$ is spent on wheat. The standard HO assumption of identical demand behaviour in the two countries is also made.

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[15] Since the presence of increasing returns would lead to an infinitesimal amount of an infinite number of components being produced, it is assumed that indivisibilities in production prevent this from happening. In addition, as Ethier points out, the problem of interpreting the fact that n has to vary in integers is ignored. Ethier (1982) p. 391-2.

The specification described above yields a model which is free from the problems of multiplicity of equilibria, the equilibrium in the model is unique and stable. The characterization of the conditions of production generates a monopolistic competition equilibrium in which the level of output, which is the same for every component, is fixed in terms of the parameters of the production function.

$$x_0 = \frac{b\beta}{a(1-\beta)} \tag{2.4}$$

An implication of this is that abstraction is made in the model of the changes in the scale of production of the individual firms, which is fixed. As a consequence, any increase in the output of finished manufactures comes from an increase in the number of components and occurs, thus, in multiples of x_0. The number of components is endogenously determined and depends on the scale of production:

$$n = \frac{(1-\beta)m}{b} \tag{2.5}$$

The index of economies of scale is also found to depend on the size of the market:

$$k = \frac{b}{a}\left[\frac{(1-\beta)}{b}m\right]^{\alpha-1} \tag{2.6}$$

The analysis of international trade is made by considering a free trade situation in which the trading countries are identical in all respects, except in their relative factor endowments, which reflects on the distinct shapes of their production possibilities frontiers. Here, it will be assumed that manufacturing is relatively capital intensive when compared with agriculture, and that the home country is relatively capital abundant.

The set up of the model allows us to concentrate on the implications of both international increasing returns and differences in factor endowments.

Once the domestic economy is opened to trade, it faces a world demand which depends not only on its own income, but on the income of the other country. What is more interesting is that, with trade, the supply curve of manufactures of the domestic economy is not only a function of its own output, but also of the scale of production in manufactures of its trading partner. This follows from the assumption that economies of scale are a function of the world scale of production, which Ethier justifies in terms of international division of labour. Therefore, now we have:

$$k = \frac{\beta}{a}\left[\frac{(1-\beta)}{b}\ (m+m^*)\right]^{\alpha-1} \tag{2.7}$$

Since it has been assumed that manufactures are costlessly assembled, the value of the domestic manufacturing output is $P_S^H\, M = q_0\, n_H\, x$, from where we can obtain the domestic supply function of final manufactures, which is given by:

$$P_S^H = -\frac{T'(m)}{k}$$

where P_S^H is the supply price of manufactures in terms of wheat. After substitution of variables we get:

$$P_S^H = -\frac{a}{\beta}\ T'(m)\left[\frac{(1-\beta)}{b}(m+m^*)\right]^{1-\alpha} \tag{2.8}$$

On the other hand, from the assumptions made about demand, the value of world expenditure in manufactures is given by

$$P_M\ (M + M^*) = \gamma[P_M\ (M + M^*) + (W + W^*)].$$

Replacing W and W^* with the domestic and foreign transformation functions, $T(m)$ and $S(m^*)$, respectively, we obtain the following expression for the world demand price for manufactures:

$$P_D = \frac{\gamma}{1-\gamma}\ \frac{T(m)+S(m^*)}{M+M^*}$$

which through substitution gives:

$$P_D = \frac{\gamma}{1-\gamma}\ \frac{a}{\beta}\left(\frac{b}{1-\beta}\right)^{\alpha-1}\frac{T(m)+S(m^*)}{(m+m^*)^{\alpha}} \tag{2.9}$$

As a result, the supply and demand equilibrium for the domestic economy is defined for a set of different combinations of domestic and foreign allocations of resources. The locus of these different equilibrium combinations is called by Ethier the "allocation curve" of the domestic economy. An analogous development for the foreign country yields its corresponding allocation curve.

The home allocation curve (HH') is defined by:

$$\gamma\ [T(m)+S(m^*)] + (1-\gamma)\ (m+m^*)\ T'(m) = 0 \tag{2.10}$$

And the foreign allocation curve (FF') is:

$$\gamma\ [T(m)+S(m^*)] + (1-\gamma)\ (m+m^*)\ S'(m^*) = 0 \tag{2.11}$$

International equilibrium corresponds to a situation in which the equilibrium combinations of m and m^* for both countries are consistent between them. In Figure 2.1, such a situation is represented graphically by the intersection of the domestic and foreign allocation curves, FF' HH' respectively. The situation in figure 2.1 corresponds to the case in which none of the countries specializes completely.

The locus of points that form the allocation curve of each country is also determined by the countries' resources availability which limits the segments of equations (2.10) and (2.11) that are relevant for their respective allocation curves. In figure 2.1, this boundary is shown by the line m^*_0 E m_0, where m_0 and m^*_0 denotes the total endowment of factors in the domestic and in the foreign country respectively. Point E, thus, gives us the world endowment of resources in terms of bundles of factors used to produce intermediates. The HH' curve is drawn steeper than the FF' one to reflect the fact that the supply curve of a country is relatively more sensitive than world demand to that country's resource allocation with respect to the other country's resource allocation. The equilibrium of figure 2.1 is unique and stable with a non-cyclical approach to equilibrium in a Marshallian adjustment process.[16]

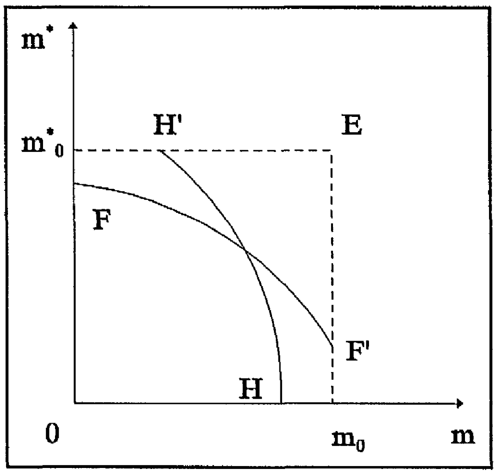

Figure 2.1 Representation of equilibrium by means of allocation curves

Qualitatively different equilibria may be obtained in the model. The cases in which either country specializes completely are shown in Figure 2.2.

[16] The stability of a more general model with multiple equilibria is discussed in Ethier (1979) pp. 14-16.

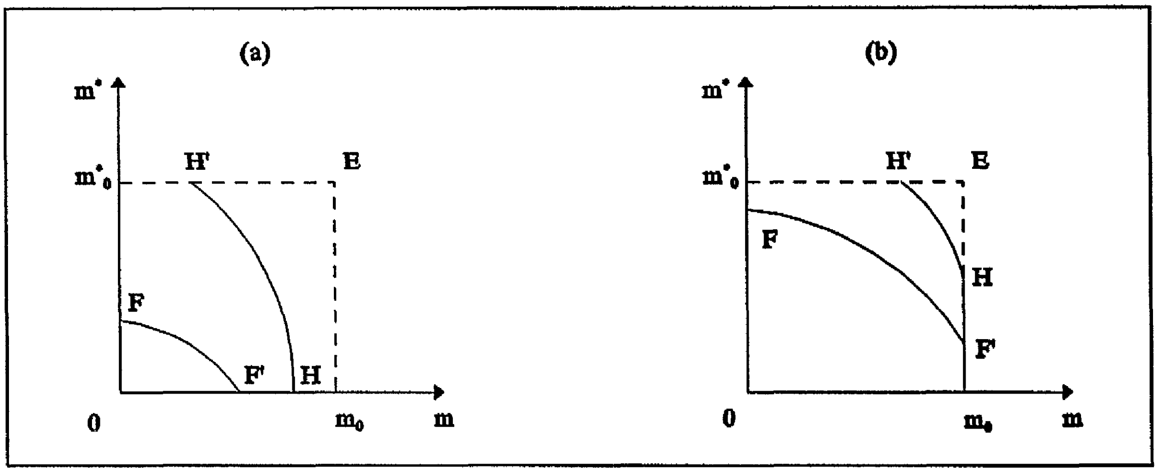

Figure 2.2 Equilibria with complete specialization in one country.

In addition to the incomplete specialization case, shown in figure 2.1 above, there are only three other possible equilibria, under the assumption that the home country is relatively capital abundant. First, when only the foreign country specializes completely in wheat (point H′ in figure 2.2(a). Second, when only the home country specializes completely in manufactures (point F′ in figure 2.2(b). Third, the case (not shown) in which both countries specialize completely with the home country exporting manufactures and the foreign country wheat.[17]

The main point is that the nature of the equilibria, in terms of the pattern of inter-industry trade that arises between the countries, is determined by the relative factor abundance in the trading countries. The inter-industry pattern of trade is in agreement with the quantity version of the H-O theorem of the traditional two by two H-O model. "In international equilibrium, each country necessarily exports the good intensive in its relatively abundant factor, if the two countries are not separated by a factor intensity reversal"[18]

The central propositions of Ethier's model refer, however, to intra-industry trade. As he states in his 1979 paper, "...the principal argument

[17] That no other equilibria are possible can be seen by showing that, under the assumptions on relative factor abundance in the two countries, an equilibrium on the segment 0 m^* E is not possible. See Ethier (1979) p.12.

[18] Ethier (1982) p. 400. The price version of the theorem, however, does not hold. The fact that the scale effect, that results from the expansion of the manufacturing sector, may alter the relation between commodity and factor prices makes autarky prices dependent on the size of the market and not only on factor endowments. This implies that relative autarky prices may be misleading indicators of the patterns of trade. A graphic illustration of this idea for the Ricardian case is presented by Ethier (1979) pp. 12-13.

of this paper is that in the modern world economy, decreasing costs imply (intra-industry) trade in intermediate manufactures rather than 'arbitrary' patterns of industry specialization."[19] The results obtained by Ethier in this respect arise from the following characteristics of the structure of the model. Firstly, each component is produced in one country only. Secondly, since every component is produced in the same quantity and at the same price, all of them enter the assembly of final manufactures symmetrically. Finally, since, whatever the level of income, a constant fraction of it is spent on final manufactures in the two countries, necessarily some proportion of the production of each component has to be traded. Ethier finds that the volume of trade in intermediates must be at least as large as the smaller of the two national outputs of manufactures. Under this same line of discussion, Ethier deals with the relative participation of intra-industry and inter-industry trade and its determinants. In particular, it is shown that a greater similarity in the production possibilities frontiers of the two countries results in a larger volume of intra-industry trade, both absolutely and relative to inter-industry trade. This idea is formally illustrated by supposing that countries "trade" in primary factors so as to reduce the difference between the capital-labour endowment ratios of the two countries, but leaving each country's income unchanged at unchanged factor and commodity prices. It is shown that this endowment equalizing trade of factors tends to increase the relative index of intra-industry trade.[20]

Remarks on the model

It is important to note that, although in the model presented above the final manufactured good is the one that is actually consumed, it is intermediates and not the final manufactured good what is traded. The demand for intermediate components is derived from the demand for final manufactures and the latter in turn determines the demand for bundles of factors in the production of components. On that basis, the model can be

[19] Ethier (1979) p. 17.

[20] A final set of results that is worth mentioning consists of Ethier's propositions aimed at establishing the robustness, within the context of his increasing returns model, of the other three main theorems of the two by two H-O model of international trade that accompany the H-O theorem. See Ethier (1982) pp. 396-400.

interpreted in an alternative way which makes it more clear what is happening in the manufacturing sector.

In the background of the model we really have two perfectly competitive, constant returns to scale sectors: one produces wheat, and the other produces bundles of factors to be used in the production of intermediates. These bundles, as wheat itself, can be seen as a good which has both capital and labour embodied in it, in proportions which vary as factor prices (and as a consequence techniques) change. The next stage is the production of intermediates. There, production takes place under decreasing costs because, for each firm that produces intermediates, there is a fixed quantity b of bundles of factors which is needed in addition to the variable requirements. In the final stage, a finished manufactured good is assembled and it is there where increasing returns to scale occur. The extent of such increasing returns depends on the total scale of production $m = n(ax_0 + b)$ or, to be more precise, on the total number of intermediate components produced, since x is fixed.

Ethier's argument about the importance of increasing returns to scale, which arise from the division of labour at a world-wide level, is plausible; but the way in which this idea is modelled is not satisfactory. When we think about the gains from the division of labour, the economies that are derived from it are the outcome of gains in efficiency achieved in each activity through specialization (i.e. if we see them only in terms of factor inputs, it is a reduction in factor requirements per unit of output). In the model proposed by Ethier, those efficiency gains are not identified with any stage of the production process. They appear at the end. The heart of the problem is that in this model it is the larger number of intermediates that produces the increasing returns. If, for instance, as Ethier suggests, instead of assuming costless assembly, some of the final activities that are considered as production of components where taken as assembly services, increasing returns would then occur after assembly. We have, thus, a model which is able to generate international increasing returns but does not give a good explanation of them.

The interpretation of the model that has been proposed here, in which we decompose the manufacturing process in three levels, makes it easier to disentangle the different sources of the results obtained in the model. At the first level, in which wheat and bundles of factors for intermediates are produced, we have a standard two by two H-O model. And if we consider that it is, in fact, these two "goods" that are being traded, we can draw an ordinary offer curve and determine inter-industry trade according to the relative factor endowments of the two countries. Regarding intra-industry trade, it arises in the next level, that of trade in intermediates. According to the setup of the model, every component is produced in the same quantity and sold at the same price, therefore, all components enter in the finished manufactured good in equal proportions. As a result of the presence of decreasing costs in their production, each component is produced by one firm only and only in one country. As a consequence, each country has to import a quantity of each component produced by the other country which is proportional to the relative share of the former in total world income. As it was mentioned above, increasing returns occur in the last stage and do not play any significant role in terms of trade patterns.

2.4.2 Models of product differentiation and trade with a love of variety specification of preferences

There is a series of models closely related to that of Ethier in which the production of differentiated goods stems from the nature of the utility function of the consumers. There are two different approaches to the specification of consumer preferences, which Helpman and Krugman (1985) call the love of variety and the ideal variety approaches.[21] In this section, we will comment on the former type of approach. The ideal variety specification is discussed in the next section.

The love of variety approach is found in Krugman's (1979a, 1980 and 1981) and in Dixit and Norman's (1980) models of trade in differentiated products. These authors apply Dixit and Stiglitz's (1977) formal representation of Chamberlin's model of imperfect competition to a trade context. Using this framework, they try to explain, among other things, the phenomena of intra-industry trade. The basic idea of the love of variety specification of preferences is that variety in consumption is, in itself, a source of utility. What is of interest is the way in which supply and demand in the differentiated goods sector is modelled. As in Ethier, producers face decreasing costs which arise from the presence of a fixed costs component and the cost function is assumed to be identical

[21] Helpman and Krugman (1985), chapter 6.

for all firms regardless of the differences in the variety of the good that each produces. In the demand side, consumer preferences are represented by a utility function which incorporates desirability of variety. The function used has the same properties that the one used by Ethier for the assembly with differentiated intermediates. Identical and homothetic preferences are assumed. Market demands for each variety are obtained by aggregating the individual demands which result from solving the maximization problem of a representative consumer. Additionally, some restrictions are imposed on demand in order to have an elasticity of demand greater than one (and therefore a positive marginal revenue) as it is required for the existence of a unique and stable monopolistic competition equilibrium.[22]

The equilibrium outcomes of these models are very similar to those of the model in the previous section. A large number of varieties are produced in the differentiated goods sector and each one is produced by one firm only. As a result of the symmetry with which the models are built, all these goods have the same price and are produced in the same quantity.

When trade is allowed between two economies, if in equilibrium both countries produce differentiated goods, there will be intra-industry trade. The basic reason for the existence of intra-industry trade is analogous to that of Ethier's model. In an integrated world market each differentiated product is produced by one firm only and only in one country. Due to the specification of preferences, every good enters in the utility function of every consumer and utility is maximized when the greatest variety in consumption is achieved. As a result, some quantity of every manufacturing good that is produced must be traded.

When a linear cost function is assumed, as in Ethier's model, in equilibrium, the quantity produced of each variety of differentiated good is determined only by the parameters of the model. Therefore, all the gains from trade arise from the extended range of choice available to the consumers.

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[22] According to the particular specification of the model, this is done either by restricting the form of the utility function to one which gives a constant elasticity which is greater than one or, alternatively, with a more general utility function and by assuming that the elasticity of demand declines as production increases. This second approach is adopted in Krugman's 1979 paper, while the former is the one used in his 1980 and 1981 papers, and in Dixit and Norman's (1980) model.

When there is another sector, say one that produces an homogenous good under perfect competition, and assuming, first, that there are differences in the relative factor endowments of the trading countries and, second, that in the trade equilibrium none of the countries specializes completely, there will be both inter-industry and intra-industry trade. Among the different results that are derived from this model it is proved, as in Ethier's model, that greater similarity of relative factor endowments increases the proportion of intra-industry trade in total trade.

2.4.3 Trade in differentiated goods with an ideal variety specification of preferences

An alternative way of characterizing preferences is the ideal variety specification of preferences.[23] This type of preferences are found in the trade models of Lancaster (1980) and Helpman (1981). The specification of preferences used in this model is due to Lancaster,[24] and is more elaborated than the one discussed above. It focuses on the specificity of the preferences of every consumer. Space precludes us from going in detail through the models. In what follows, we limit, firstly, to outline the way in which the differentiated goods sector is modelled in this approach and, secondly, to comment briefly on Lancaster (1980) two country, two sector model of international trade.

In the ideal variety approach, consumers are assumed to have preferences over characteristics of goods, and the latter only play the role of a transfer mechanism. Preferences over characteristics are assumed to have the properties that are usually assumed for preferences over goods in traditional consumer theory, namely: that they are complete, reflexive, transitive, continuous and strongly monotonic.

A consumer will have a combination of characteristics that is ideal for him. This combination is referred to as his or her "most preferred good". The diversity in preferences is captured by considering that the most preferred good will be different for different consumers.

It is assumed that for any good it is possible to define a ratio, called the compensation ratio, which gives the relationship between the

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[23] Helpman and Krugman (1985).

[24] Lancaster (1979).

quantity of that good and the quantity of the most preferred good which would give the consumer the same level of utility. The further away a good is from the most preferred good, the greater will be the compensation ratio. These relationships are formalized by defining a compensation function $h(u)$ that maps arc distances between available goods and the consumer most preferred good (denoted by u) into compensation ratios (denoted by h). The compensation function is "a positive, increasing, strictly convex function of u with special values at the origin $h(0) = 1$ and $h'(0) = 0$".[25] The shape of the compensation function is shown in figure 2.3.

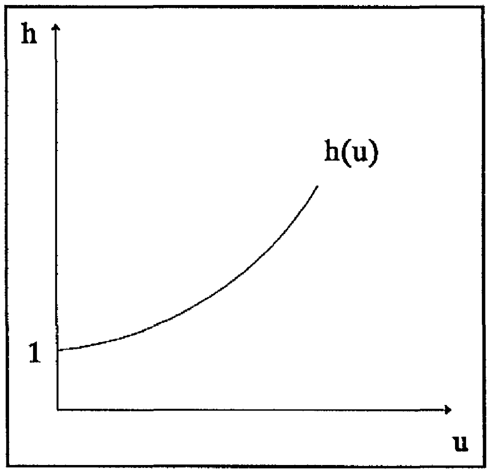

Figure 2.3 Graphical representation of the compensation function

It is assumed that the compensation function is the same for all consumers. This assumption, referred to as "uniformity of preferences", is made in order to make the problem tractable when passing from individual demands to the market demand for a good. Thus, the structure of preferences of the different consumers only differs in terms of their most preferred goods. In what follows, it is assumed that the market consists only of a group of differentiated manufactured goods and one homogeneous good, say food. According to the characterization of preferences, the consumer's problem can be divided in two separate decisions: in a first stage, the consumer chooses which of the group goods to buy. This decision only depends on the prices of these goods relative to each other and on their specification. In a second stage the consumer decides how much to buy of the good, i.e. how to divide his or her expenditure between the

[25] Lancaster (1979), p. 50.

group good that was chosen and food. This second decision depends only on the level of income and on the price of the group good relative to food.

To the two stage decision of the individual consumer corresponds a two level determination of the market demand for any particular good in the group of manufactured goods. The demand function for a good of the group is derived by adding up the quantity functions of all the individual consumers that have chosen to purchase that good.

This specification of consumer behaviour is integrated in a model of perfect monopolistic competition in which the competitive relationship among the firms in the manufacturing sector is as follows: each firm produces only one specification, firms can choose this specification freely and can also fix the price of their good in order to maximize profits. Firms do not collude and there are no restrictions to entry. Finally, firms have full information about the properties of market demand and they sell to fully informed consumers.

In the demand side it is assumed that the elasticity of substitution of group goods with respect to food, is greater than unity in order to satisfy a necessary condition for a stable equilibrium.[26] In the production side it is assumed that the average cost function is decreasing for at least some range of output starting from zero. Additional restrictions are imposed on the costs function to limit the analysis to production in which there are no initial diseconomies of scale and to rule out economies of scale that increase with output, which would generate an average cost curve that is concave downward.[27] With the necessary restrictions on parameters to make the equilibrium feasible and stable, the present setting gives raise to a perfect monopolistic competition equilibrium.[28] Among the main characteristics of such an equilibrium are,

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[26] An elasticity greater than one and smaller or equal to a maximum value determined by the degree of economies of scale is a necessary condition for strong stability of a perfect monopolistic competition market equilibrium. See Lancaster (1979), pp. 197-200, 211.

[27] These restrictions are satisfied by assuming that average cost curves are U-shaped and that they reach their minimum at a level of output relatively small with respect to the size of the market. In equilibrium, firms will operate in the decreasing part of the average cost function.

[28] The necessary conditions that have to be satisfied by some parameters of the model for a viable and stable monopolistic competition equilibrium are treated in length in Lancaster (1979). On the viability and stability of the perfect monopolistic competition equilibrium, see p. 211. See also pp. 191-2 on the required assumptions for "end of spectrum" firms, that is, firms that have only one adjacent competitor.

first, that all firms are producing goods of different specification and, second, that all goods are produced in the same quantity (when brought to a common measure) and sold at the same price. With free entry, the equilibrium is characterized by a large number of firms and zero profits.

In the food sector, firms are assumed to produce subject to constant returns to scale and, in equilibrium, the market structure in this sector will be one of perfect competition.

The main proposition that results from applying the framework presented above to the context of international trade is that the internal diversity of preferences within each of the trading partners gives origin to trade of an intra-industry kind. The way in which these results are brought out is seen more clearly by analysing the trade equilibrium between two identical economies, with the characteristics described above.

If considered in isolation, the equilibrium configurations of the two economies would be identical.[29] The opening of the two economies to international trade creates a single world market with the same properties that characterized each of the two economies considered in isolation, but with double the population, i.e. a larger market and with scope for differentiating. In the equilibrium of this trading world economy, the number of varieties of manufactured goods that will be produced will be, in general, larger than the number of products produced in an economy of half the size. As before, each manufactured good will be produced by one firm only, all the products will be produced in equal quantities and sold at the same price. Since, in equilibrium, no two firms produce the same specification, each good will only be produced in one of the countries. However, all goods will be consumed in both. Thus, there will be intra-industry trade in manufactures.

As Lancaster notes, a configuration in which the number of manufactured goods produced by each of the trading partners is the same, is always an equilibrium configuration. But, under the assumption of constant returns to scale in agriculture, that equilibrium is not unique. However, as long as the income elasticity of manufactures is greater than unity, that equilibrium is the only stable one; it is assumed that this is

[29] In the manufacturing sector both will produce the same number of products, each produced in the same quantity and sold at the same price. In the agricultural sector output and prices would also be the same in the two countries. In this context there are no comparative advantages of any kind.

the case.[30] In these conditions, the free trade equilibrium will be one in which "there is intra-industry trade *only*, each country exporting half the output of each of its manufactured products in exchange for half the output of the manufactured products produced in the other country, while each country covers its own agricultural needs".[31]

Free trade will bring equal gains to both countries. These gains are originated in the ability of the countries to take advantage of economies of scale in manufacturing since, in general, the output level of each firm will be larger with respect to the one that prevailed in the autarkic equilibrium.

In contrast with the love of variety approach, in this model the number of varieties is not central as a source of gains from trade. The assumption of economies of scale, in conjunction with the ideal variety specification of preferences, determines that here the gains from trade arise from the ability of the firms to take advantage of economies of scale in manufacturing. There are also gains from more equity, since with greater variety of products the average difference between available goods and most preferred goods diminishes. A possible extension of the model, which has been proposed by Helpman and Krugman (1985), is to transfer to the production side the modelling strategy that has been used here for consumer preferences. In such a model, one has various specifications of intermediates available for the production function of a finished manufactured good.[32] This leads to an alternative version of the model of monopolistic competition and trade in intermediates proposed by Ethier (1979, 1982).

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[30] See Lancaster (1980), pp. 161-163.

[31] Lancaster (1980), p. 160. In the case of identical economies having multi-group manufacturing sectors, the equilibrium will be "generally similar to that for the single group case with the additional and very significant property that there will not only be bidirectional trade in manufacturing generally, but there will be bidirectional intra-industry trade in every group, with each country producing half the goods in each group". (Lancaster (1980), p. 166).

[32] Helpman and Krugman (1985), p.223.

2.4.4 Concluding remarks on the models of product differentiation and international trade

The literature on product differentiation and international trade has contributed to trade theory by bringing into the analysis the role of product differentiation that originates in the desire of variety and in the diversity of consumers' preferences. Another virtue of these models is that they have shed some light on intra-industry trade, a kind of trade that, until relatively recently, had been neglected by trade theorists.

There are, however, some weaknesses of the theoretical approach that underlies the models. Their main limitations are the notion of competition that permeates the analysis, and the way in which product variety appears in the economic system. These two issues are closely related.

In the model, the role of firms as generators of product variety receives little consideration. All the emphasis is put on consumer preferences. Different specifications of goods are produced because there is desire of variety or diversity in demand but nothing is said about how these new and different products come into being. In this set up, firms do not require of any particular skills, nor do they need to put any special effort to differentiate their products. Differentiation is carried out at the same cost and with equal success by all producers, and one differentiated product has no particular advantage over others. As a consequence, decreasing costs to scale have to be introduced in the model to generate the monopolistic competition outcome. Since nothing prevents a firm from producing the same specification that is being produced by other firms, but neither is there any particular advantage in doing so, the disadvantage of having to share the market in the presence of decreasing costs is what makes it profitable for each firm to produce its own variety.

The fact that the creation of product variety is an innovative activity and the importance that this activity has in the competitive process are, both, ignored by the theoretical approach which is at the heart of the monopolistic competition models that we have discussed. To a great extent, this is due to the notion of competition on which the model rests, which is centred on the atomistic behaviour of typical (i.e. identical) agents. It would be more adequate to try to understand the existence of product variety by looking at the innovative activities of firms that are themselves different from each other. In practice, these activities take place in a competitive process where the firms search for new varieties of products that will perform better in the market than those of their competitors. These ideas, taken to the context of international trade, would lead us to try to find the causes of trade in differentiated products by looking at the diversity and different success of firms within an industry, and how these relate to the fact that firms are located in different countries.

2.5 Innovation, trade and growth in North-South models

There are two major branches in North-South literature. The first branch has focused mainly on studying the effect of structural asymmetries between trading partners. Most models within this branch have attempted to shed light on the idea, suggested by Prebish , of a tendency to the deterioration of the terms of trade of the South and on the validity of Emmanuel's concept of unequal exchange. A second, more recent, branch of North-South models centres the attention on asymmetries in the innovative performance of the different regions. These models have found inspiration in the contributions of Posner (1961) and Vernon (1966), who stressed the role of technological change in international trade.[33] In this section we will look at some models of product innovation, which belong to this second branch of the North-South literature.

The most common assumption in North-South models of product innovation is to postulate that, while the North can innovate and produce new goods, the South is unable to do so, or faces disadvantages in innovative activities, and produces only old goods. Under these conditions, the South's technological development has to be based on technology transfer from the North and on its capacity to imitate. In general, Southern producers are assumed to face lower costs in the production of old goods whose technology is common knowledge. In some of the more recent models, the asymmetry in innovative performance is assumed to arise from differences between the trading regions in their relative abundance of human capital or skilled workers. This gives rise to specifications which are closer to the spirit of the H-O theory of trade.

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[33] For a discussion of Posner's and Vernon's ideas see section 3.3 in chapter 3.

An early work which gives formal mathematical treatment to these ideas of a North-South differential in innovative capacity is Krugman's (1979b) paper.

2.5.1 Krugman's model of innovation, imitation and trade

The main characteristic of Krugman's (1979b) model of North-South trade is that it differentiates these two regions in terms of their performance in conducting technological change. The North innovates creating new products, while the South is only able to imitate. Goods are classified as new and old. The former group consists of those goods that can only be produced by the North, while the latter corresponds to those goods whose technology has become common property and can be produced by either region.

All goods, old and new, are assumed to be produced under conditions of perfect competition and by means of the same production function, in which one unit of labour L_i is required to produce a unit of product q_i. Thus for any product we have:

$$q_i = L_i \tag{2.12}$$

All individuals in both regions are assumed to have the same CES utility function depending on the level of consumption c_i of each good:

$$U = \left[\sum_{i=1}^{n} c_i^{\theta} \right]^{\frac{1}{\theta}} ; \quad 0<\theta<1 \tag{2.13}$$

This functional form implies that all goods, old and new, enter demand symmetrically and it attaches a positive value to an increased variety in the products that are available. It is also assumed that there is a latent demand for additional, yet undiscovered, goods.

Under this very simple specification, we have that, given the level of wages in the North w_N and in the South w_S, since the competitive process drives profits to zero, the price of any good produced in the North will be equal to the Northern wage: $p_N = w_N$, and a similar condition holds for the South: $p_S = w_S$. As long as the ratio of Northern wages to Southern wages is bigger than one, the North will produce new goods only. This is the case analysed in the paper, which has the advantage that we can identify the number of goods produced in each country, n_N and n_S, with the number of new and old goods respectively.

Looking at the demand side we find that for any pair of goods, if we maximize the utility function subject to the budget constraint, the first order conditions give the following relationship for the relative demands for the two goods.

Here, due to our simplifying assumptions, the price and quantity consumed of the goods produced in each region is the same. Hence, we can replace N for i in the numerator and S for j in the denominator in both sides of the expression and refer to a typical Northern and a typical Southern good. Making use of the fact that, according to our specification of supply, prices of goods are equal to wages in each region we can write:

$$\frac{c_N}{c_S} = \left(\frac{p_N}{p_S}\right)^{\frac{1}{\theta-1}} = \left(\frac{w_N}{w_S}\right)^{\frac{1}{\theta-1}} \qquad (2.14)$$

Total production in the North is $n_N c_N$ and, similarly for the South, it is $n_S c_S$. According to the production function assumed by us the demand for labour in each country is $L_i = n_i c_i$, $i = N, S$. Therefore, using equation (2.14), the relative demand for labour can be expressed as:

$$\frac{L_N}{L_S} = \left(\frac{n_N}{n_S}\right)\left(\frac{w_N}{w_S}\right)^{\frac{1}{\theta-1}} \qquad (2.15)$$

Which can be rearranged to give us an expression for the terms of trade and for relative wages as functions of the number of goods:

$$\frac{p_N}{p_S} = \frac{w_N}{w_S} = \left(\frac{n_N}{n_S}\right)^{1-\theta}\left(\frac{L_N}{L_S}\right)^{\theta-1} \qquad (2.16)$$

From this expression, we see that if, the ratio of Northern to Southern goods increases, the terms of trade and the relative wage of the North raise. Expression (6) is the basis of the main results that are obtained from the model. A faster rate of innovation relative to that of technology transfer rises the Northern-Southern goods ratio and therefore widens the wage gap between the two regions, and the opposite happens when technology transfer is faster relative to innovation.[34] These ideas are captured using a very simple specification in which the rate of innovation $\dot{n}$ is

[34] It is interesting to note that in this model the movement in the terms of trade for one region, as a result of technical progress in that region, goes in opposite direction to that derived in other North-South models. This is due to the different kind of technical progress considered here which is in the form of new products rather than increased productivity.

proportional to the total number of products in existence n (where $n = n_N + n_S$):

$$\dot{n} = in \tag{2.17}$$

and the rate of imitation $\dot{n}_S$ is specified as a process of radioactive decay with an average imitation lag of $1/t$:

$$\dot{n}_S = tn_N \tag{2.18}$$

In equilibrium, the system tends to a stable share of Northern and Southern products:

$$\frac{n_N}{n_S} = \frac{i}{t} \tag{2.19}$$

Referring back to expression (2.16), we corroborate the relationship between relative wages and the relative rates of innovation and imitation on which we commented above.

Finally, the model is extended to include capital, which is assumed to be perfectly mobile between regions, it is also assumed that there is a fixed level of the world capital stock and that there is no net investment. Analogously to what was done before, wages in the South are supposed to be lower, and it is assumed that all goods are produced by means of the same constant returns to scale production function. This implies that new goods, as a group, are only produced in the North and can be considered as a composite good, and the same occurs with the old goods which are produced in the South. p_N and p_S represent the price of the Northern and Southern composite commodities respectively. Furthermore, they can be taken to represent the price of any Northern and Southern commodity if we choose units of measure so that the price of every good within each region is the same.

At a point in time, the terms of trade will be determined by the relative demand and relative supply of Northern and Southern goods. The demand is obtained directly from expression (2.14). Noting that n_N and n_S are given at a point in time, the total demand of a consumer for the goods produced in both regions is $q_i = n_i c_i \;\; i = N, S$. Therefore, the relative demand for Northern and Southern goods is:

$$\frac{q_N}{q_S} = \left(\frac{n_N}{n_S}\right)\left(\frac{p_N}{p_S}\right)^{\frac{1}{\theta-1}} \tag{2.20}$$

which gives a downward sloping relative demand curve.

Regarding the relative supply, which in the previous model was fixed, now it is variable because of the possibility of reallocation of world capital. Since we are assuming perfect competition, the rate of profit in both regions is given by the value of the marginal product of capital. We can express the rate of profit in the two regions in terms of the old goods and note that an increase in the terms of trade of the North would rise the rate of profit relative to that of the South and would attract capital. As a consequence, the total production of goods would increase in the North and decrease in the South. This reasoning allows us to say that the relative supply curve of Northern and Southern goods is upward sloping. Plotting these two curves together we can find the equilibrium terms of trade and analyse the effects of innovation and imitation.

Innovation increases the number of Northern goods, leaving the number of those produced in the South unchanged and, thus, shifts demand to the right. In the new equilibrium, workers in the North are better off with respect to those in the South: "...income of Northern workers relative to Southern rises for two reasons: the relative prices of the goods they produce rise, and their real wage in terms of their output rises (while that of the Southern workers falls)...".[35] Technology transfer increases the number of goods produced in the South and decreases the number of those produced in the North by the same amount: "... technology transfer shifts demand toward goods produced in South so that capital moves South and the relative income of Southern workers rises."[36] As a result of the assumptions of perfect capital mobility, the rate of profit in the two regions is equalized. Therefore, the rents derived from the North's monopoly of new goods are received by the immobile factor of production.

2.5.2 Other models on product innovation and trade

Krugman's is a very simple model which has the virtue of bringing into light the fact that innovative and imitative activities may play an important role in the dynamics of income differentials between trading countries. However, the model, to a great extent due precisely to its

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[35] Krugman (1979b), p. 264. The effect on real wages results from the effect on the marginal product of labour that is associated with the reallocation of capital between the two regions: in the North such marginal product rises, while it falls in the South.

[36] Ibidem.

simplicity, has some shortcomings. The representation of technological change is very crude and, as we have mentioned earlier, the exogenous treatment given to it is an unsatisfactory feature. Questions related to the incentives and ability to innovate are not addressed.

Krugman's model has been a source of inspiration for a stream of literature focused on product oriented technological progress. In terms of the treatment of technological change, subsequent contributions have been directed, on the one hand, to model other types of product innovation and aspects of this process not consider in Krugman's model, and on the other hand, to make technological change endogenous. In what follows, we comment briefly on five of the various models that have followed from Krugman's paper. In most cases, the specification varies considerably between models in terms of market structure assumed and other aspects of the characterization of both the supply and demand sides of the economies. In part because of this, and in part due to the different problems that each specific model is meant to address, little can be done in terms of comparing the conclusions that are reached by the different models. Space precludes us from going in detail through each model. Thus, we will limit ourselves to highlight their main contributions to the analysis of technological change and its relationship to trade. In some of the models discussed below, innovation is made endogenous. However, this question is left to be treated in section 2.6.

Two different approaches can be identified in the type of product innovation introduced in the models. The first group follows Krugman and focuses on variety expansion seen either as new products or as new varieties in a product group (i.e. horizontal differentiations), all of which enter consumption. The second group looks at quality improvement, in which new products replace old ones and differentiation within a product group is of a vertical kind. A distinctive feature of this second approach is that it can be used to analyse the implications of the "business stealing effect" that may be associated with innovation and not only to imitation, an aspect that is not consider in the first approach.

Variety expansion

Within the variety expansion stream, Dollar (1986) extends Krugman's model to allow for an endogenous determination of the rate of imitation instead of having an exogenously given one. This is achieved by means of a specification where the rate of technology transfer is positively related to the differential in production costs (relative wage) between the two regions. As in Krugman's model, the ability of the North to introduce new goods allows its workers to enjoy a higher wage than that of their Southern counterparts. But, in this case, it is precisely the cost differential that is associated with that wage gap that creates the incentive for the diffusion of technology to the South. Dollar carries on a comparative steady state analysis to examine the effect on Northern wages of a relatively higher rate of population growth in the South than in the North. The author finds that the effect of a larger labour force in the South is to reduce the real wage of workers in the North. This deterioration follows from a fall in the marginal productivity of labour in the North: in the model, capital is mobile between countries and the new equilibrium is characterized by a shift of capital from the North to the South that lowers the productivity of labour in the North. An exogenous increase in the rate of technology transfer to the South is found to have the same negative effect on Northern wages, while those of the South are increased.

Jensen and Thursby's (1987) model also focuses on technical progress of the horizontal differentiation type. The main innovative feature of their contribution is that they take into account explicitly, the fact that R&D in the North requires resources to be allocated to this activity and that such resources could be used alternatively in production. This provides the model with a mechanism by which the rate of innovation of the North is endogenously determined as the result of firms' profit maximizing decisions. Firms decisions and the innovative outcomes of the model are analysed under three different market structures in the R&D sector. The rate of imitation is assumed to be exogenously fixed and different for different product lines.[37] The model is used to analyse the effects of technology transfer and to establish a comparison between the rates of innovation that are optimal for the firm, and those that are optimal, from a social point of view, for the North, the South and the world as a whole, respectively. It is found that these rates differ from each other. In particular it is shown that the rate which is optimal for the firm is lower

[37] In Jensen and Thursby (1986), the authors present a simpler model in which imitation is endogenously determined.

than the other three, and also, that the rate of innovation that is optimal for the North is lower than the one that would be optimal for the South.

Jensen and Thursby also show that an increase in the transfer of technology to the South increases R&D in the North. However, in contrast with the two models above, the effect of a higher rate of technology transfer to the South on the terms of trade and on Northern wages is ambiguous.

A final model, within the variety expansion group, which is worth mentioning, is that of Grossman and Helpman (1989). Although their model is not presented in a North-South context, it addresses issues relevant for this literature. Their specification offers a perspective of the asymmetries in R&D capabilities very much in the spirit of the Heckscher-Ohlin tradition: comparative advantages in R&D in a country arise from its higher relative endowment of human capital. From a neoclassical point of view, this is seen as more satisfactory with respect to the previous models because (translating the argument to the North-South context) the North's advantage in innovation is not arbitrarily assumed, and also because higher wages in the North do not arise only because of this region's monopoly power, but due to differences in average labour quality.[38]

Grossman and Helpman's model considers three sectors: one producing a traditional commodity under perfectly competitive conditions, another producing a modern differentiated industrial product and, finally, an R&D sector whose output is used in the modern sector to produce new products. The analysis of trade is made under the assumption that a fixed coefficients technology prevails in the two sectors. R&D is assumed to be the most human capital intensive activity, while the production of the traditional good is the most unskilled-labour intensive one. In contrast with the North-South models reviewed earlier, no imitation takes place. In this setting, trade has both intra-industry and inter-industry components. Comparative advantages, generated through R&D, are created as a result of relative endowments of unskilled labour and human capital in the two regions. Inter-industry trade follows the pattern predicted by the Heckscher-Ohlin theorem, with the human capital abundant country being a net exporter of differentiated goods and an importer of the traditional good. A similar model, by the same authors, but with variable

[38] On this see Stokey (1991) pp. 63-4.

coefficients, is presented in section 2.6 to illustrate the endogenous treatment of innovation. As it is shown there, a similar pattern of trade emerges in the long run equilibrium of that model.

Quality upgrading

The second subgroup of North-South models of technical change and trade are built around the idea of product quality improvements. An important new positive feature that is introduced by these models is a mechanism by which old, low quality products are abandoned as new products enter the market, in contrast with what happened in the other subgroup of models in which all goods, old and new, remained in the market.

The model by Segerstrom et. al. (1990) is a good illustration of the modelling of quality upgrading product innovation. We will describe briefly the way in which this type of innovation is introduced and then proceed with a general overview of the model. The authors apply the ideas of the literature on patent races to a dynamic general equilibrium model of North-South trade.[39] In the model, innovation takes the form of quality upgrading. A countable infinite set N of known and yet undiscovered products is assumed to exist. Within this set, n product groups can be identified, and within each group there are product of different quality. Product group j, (j=1,2,...,n), consists of goods j, $j+n$, $j+2n$,.... Goods in each group are assumed to be introduced in the market and indexed in increasing order of quality, with $\alpha>1$ being the extent to which a new product in a group increases its quality over the one that preceded it.

Consumers are assumed to have the following instantaneous utility function:

$$u(x_1, x_2, \ldots) = \prod_{j=1}^{n} \left[\sum_{i=0}^{\infty} \alpha^i \, x_{j+ni} \right] \tag{2.21}$$

Labour is the only factor of production in the model and all goods are assumed to be produced by the same constant returns to scale production function. Therefore, if two products within the same group, say j and $j+n$, were produced competitively and, therefore, sold at the same price, the older one would be made obsolete in the market. In each product group, there is a competitive fringe of firms and there may also be a dominant

[39] See Segerstrom et. al. (1990) and the references there.

firm. These firms are assumed to engage in Bertrand type competition. A firm that innovates and introduces a higher quality good becomes the dominant firm in the product group during a period of time T in which the production of this good is protected by a patent. During that period, the firm has the monopoly of that good, but when the patent expires, the technology becomes common knowledge and is produced in competitive conditions. When this occurs, the product is sold at the same price that the one which preceded it and the latter is made obsolete. It is through this mechanism that the model generates a steady state in which old products are constantly replaced by new ones.

As in other North-South models, innovation is assumed to take place only in the North. R&D requires resources and is financed by borrowing from consumers' savings. The incentive to innovate comes from the perspective of earning monopoly profits. A distinctive feature of the model is that R&D is modelled as a lottery in which the probability of winning is proportional to the amount of labour devoted to R&D. The duration of the patent race, that is, the time that it takes before the successful innovation appears, is assumed to be inversely proportional to the aggregate amount of labour applied to R&D by the participants. In this way, the rate of innovation becomes endogenously determined. The model is used to analyse the effect, on the long-run steady state equilibrium, of changes in the Southern labour force, of an increase in the life of the patents and of tariffs designated to protect dying industries. Like in the models above, sustained innovation in the North allows its workers to earn higher wages than its Southern counterparts.

The results of the comparative steady state analysis are found to depend on whether the wages in the North are higher than or equal to those in the South. We will report here only the main results of the model for the case of a higher wage in the North relative to the South. In this case, an increase is Southern labour force decreases both the innovation rate and the relative wage of Northern workers. This comes about as the result of an expansion of world expenditure which increases the demand for workers in the production sector and shifts labor from R&D to production activities. The effect of an expansion on the patent life is to increase the reward from successful innovation and, with it, the demand for workers to be employed in production by dominant firms. This causes a fall in the innovation rate and an increase in Northern relative wages. A similar effect on innovation and wages in the North arises from a protective tariff on dying industries.

Another model that belongs to this vertical differentiation group is that of Flam and Helpman (1987). Their model considers two types of goods, one homogeneous and the other vertically differentiated. As in the other North-South models, only the North is capable of introducing new products. These new products appear and expand the spectrum of goods that is produced in the North. In the South, in contrast, when the spectrum of goods expands, it only moves to cover qualities that were already produced in the North.

A distinctive feature of Flam and Helpman's model is that, here, quality innovation is not created autonomously but as a result of growth, due either to population growth or to technical progress (in the form of increased productivity). As a consequence, this model also analyses technical change that is a blend of increased productivity and improvements in the quality of the goods produced.

The model assumes that all consumers are identical in everything except income, and that those with higher income consume higher quality goods. Among the qualitatively different possible equilibria that may arise from this model, a "central case" is analysed in which the North produces only the quality differentiated good and the South produces both the quality differentiated good and the homogeneous one. Technical progress not only affects the supply side of the economy, but also the demand side, through its impact on income levels. This two effects combined can generate changing patterns of trade between the two regions. An increase in productivity in the South, for example, would have a negative effect on Northern wages, while it would increase income in the South and expand the range of differentiated products produced in this region, but without introducing new qualities. With respect to trade patterns, the authors find that Southern technical progress has the effect of increasing the share of intra-industry trade in total trade.

2.5.3 Comments on the product innovation trade literature

The treatment of product innovation in North-South models is, in many respects, an extension of the ideas on product differentiation but placed in an intertemporal general equilibrium framework. This appears very clearly in the models of variety expansion. These models introduce the specification of preferences of the love of variety approach in the context of the introduction of new products or of new varieties within a product group.

The models of quality upgrading, on the other hand, show some parallel with Lancaster's characteristics approach: the quality parameter in equation (2.21) of Segerstrom's et al. (1990) model plays a similar role that the compensation function of Lancaster: both are a measure of product quality. However, there is another aspect in which they adopt a simpler approach, which is in some respects similar to that of variety expansion: improved quality increases utility as greater variety in consumption does.

In the North-South models reviewed, in analogy to what happened in the static models, product development is essentially demand driven. The market for the product is seen as being already there, waiting for the product to be introduced. This is an unsatisfactory feature of the model since the process of market creation, a crucial aspect of the diffusion and development of a new technology, is absent from the models.

An important feature of some the models reviewed above is that they make technological change endogenous. This introduces several issues which are relevant in the analysis of the role of the supply side in the process of technological change. Two of them are the recognition that resources are devoted to product development and the incorporation of the profit motive behind the innovative efforts of firms. These topics will be discussed in the next section.

Regarding the comparative steady state analysis, several of the models reach the conclusion that a larger Southern economy and an increased transfer of technology or capital to the South have detrimental effects on Northern innovation or in wages, or in both. This is largely due to the assumption of a permanent inability of the South to innovate. It is clear, by looking at the contrasting results obtained from other of the models reviewed, that whether or not those conclusions are reached depends on the specification of the models. The assumption that the South is unable to innovate is useful in that it allows to analyse the effect of the asymmetry between two regions in innovative capabilities. It is, however, an extreme assumption that does not contemplate the possibility of catching up processes. This topic has been addressed by Chou and Shy (1991) who use a North-South model in which the only asymmetry between the two regions is a head start of the North in the innovative race. In that model, tax financed expenditure on innovation by the Southern government can reverse the situation of the trading regions in terms of who holds the innovative lead.

The main limitation of the models presented in this section is their stylized and rudimentary conceptualization of technological change. The models do not reflect the processes by which the technology develops and its markets are created. Neither do they consider the diversity and specificity of technologies that is found among firms within a same industry. As a consequence, the technological competition that is at the basis of the innovative and imitative activities, which are behind the development and diffusion of a technology, is absent of the model. Therefore, the role of these aspects in shaping the patterns of international trade is not contemplated by this literature.

2.6 Endogenous innovation and comparative advantage

An important feature of several of the models discussed above, which was not discussed in the previous section, is the endogenization of technological change. In this section we direct our attention to this question.

Although the analysis of innovation and trade theory has been closely linked to the study of North-South issues in an innovation-imitation context, the relevance of this topic is of a more general nature. We conclude our review of the equilibrium approach looking at a model developed by Grossman and Helpman (1991a). This model analyses trade relationships between two innovating countries. The model is of interest, first, because it illustrates the way in which product innovation is made endogenous in a neoclassical general equilibrium framework, and, second, because the links between the dynamic models that we have been discussing and the static H-O model that is at the heart of the equilibrium approach appear very clearly in this model.

2.6.1 Grossman and Helpman's model of endogenous innovation and international trade

The model presented here is taken from Grossman and Helpman (1991a).[40] As in the conventional H-O specification, it is a two country-two factor-two final consumption goods model in which the production technology is identical between countries. But here, as in the North-South models of the previous section, one of the consumption goods produced is a differentiated good and the model is dynamic. Technological change is the result of innovation, which is carried out in an R&D sector that produces the blue prints for new varieties of the differentiated good. This activity also generates spillovers which increase the world stock of knowledge. This accumulation of knowledge, in turn, reduces subsequent R&D costs. It is assumed that R&D is financed by households who acquire equities in profit making firms which, in the model, are only the firms with blue-prints to produce a variety of differentiated products.

In the long run, as we will see below, it is the relative abundance of factors of production in each country that determines the inter-sectoral pattern of trade specialization, as in the standard H-O model. Product differentiation, on the other hand, generates intra-industry trade, as in the monopolistic competition models of section 2.4.

In the demand side, households preferences are identical throughout the world. Their intertemporal utility function is assumed to be of the following form:

$$U_t = \int_t^{\infty} e^{-\rho(\tau-t)} \left[\sigma \log C_Y(\tau) + (1-\sigma) \log C_Z(\tau) \right] d\tau \; ; \qquad 0<\sigma<1 \tag{2.22}$$

where ρ denotes the subjective discount rate, C_Y is an index of consumption of a differentiated "high-tech" good Y and C_Z the consumption of a "traditional" homogenous good Z. The utility derived from differentiated goods depends on the quantity consumed of each variety. In particular, the following sub-utility function is assumed:

$$C_y = \left[\int_0^n C_x(j)^{\alpha} \, dj \right]^{\frac{1}{\alpha}} \; ; \qquad 0<\alpha<1 \tag{2.23}$$

where $C_x(j)$ is the quantity consumed of variety j. As it was mentioned in section 2.4, in this specification, variety is valued per se.

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[40] See Grossman and Helpman (1991a), pp. 177-192.

A representative consumer maximizes its utility subject to an intertemporal budget constraint (which is, in general, different between households). The budget constraint is given by:

$$U_t = \int_t^{\infty} e^{-[R(\tau)-R(t)]} E^i(\tau)\, d\tau \leq \int_t^{\infty} e^{-[R(\tau)-R(t)]} I(\tau)\, d\tau + W(t) \tag{2.24}$$

where $R(\tau) = \int_0^{\tau} r(s)ds$ represents the discount factor from time τ to time 0,

with $r(s)$ being the instantaneous interest rate; $E(\tau)$ is the consumption expenditure of the household; $I(\tau)$ is the factor income of the household, and $W(t)$ is the value of the household's asset holdings.

The separability of the utility function implies that the maximization problem can be solved in stages, and the particular form of equation (2.40) implies that consumers will devote fixed proportions of their expenditure to each good: σ to the high-tech differentiated good and $(1-\sigma)$ to the traditional homogenous good. For the sub-utility function, the first stage maximization yields the following demand function for each of the n varieties of the differentiated good that exist at any point in time:

$$c_x(j) = \frac{p(j)^{-\varepsilon}}{\int_0^n p(j')^{1-\varepsilon} dj'} \sigma E \tag{2.25}$$

where $p(j)$ is the price of variety j, $j=1,\ldots,n,$, $\varepsilon = \frac{1}{1-\alpha}$ is the constant

elasticity of substitution between any two varieties, and E is the total consumption expenditure of the household.

The second stage of the maximization consists of choosing the time pattern of expenditure. Households are assumed to be able to borrow and lend freely in each period at the current interest rate and to acquire equities on profit making firms. It is assumed that financial capital is not mobile between countries.[41] The first order conditions of this intertemporal maximization problem give the following differential equation for spending (a dot over a variable denotes its time derivative):[42]

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[41] The relaxation of this assumption is discussed by Grossman and Helpman (1991a), pp. 177-192. We will limit the discussion to the case in which financial assets are not mobile between countries.

[42] See Grossman and Helpman (1989).

$$\frac{\dot{E}}{E} = r^i - \rho \; ; \quad i=A,B \tag{2.26}$$

That is, the value of spending must grow at an instantaneous rate equal to the difference between the interest rate and the subjective discount rate. Equation (2.26) applies to all consumers and to the economy as a whole. Thus, for each country, we have:

$$\frac{\dot{E}^i}{E^i} = r^i - \rho \; ; \quad i=A,B \tag{2.27}$$

with E^i representing aggregate expenditure in country i.

Let us now consider the supply side of the economy. Countries are endowed with two factors of production: L and H, which represent unskilled labour and human capital respectively. The homogenous good Z is produced with a constant returns to scale technology and under perfectly competitive conditions. It is assumed that production technology is identical in both countries, and that there is no technological progress in this sector. The average unit cost associated with this technology is $c_Z(w_L^i, w_H^i)$, where $w_L^i(\tau)$ and $w_H^i(\tau)$ are the rewards in country i, $i=A,B$ to the factors of production L and H respectively. If the good is produced in both countries, the competitive conditions imply that price equals unit costs:

$$p_Z = c_Z(w_L^i, w_H^i) \; ; \quad i=A,B \tag{2.28}$$

The different varieties of high-tech differentiated good are also produced with an identical constant returns to scale technology in the two countries. The production technology has associated with it the unit cost function $c_x(w_L^i, w_H^i)$. Entry in this sector, however, involves the additional R&D costs of introducing a new variety. These costs are assumed to be equal to $c_\gamma(w_L^i, w_H^i)/K_n$, where $c_\gamma(\cdot)$ exhibits constant returns to scale and K_n is the world stock of common knowledge which is assumed to be proportional to n, the total number of differentiated goods produced in the world. With a suitable choice of units, K_n is made equal to n, so that the cost function for blue prints can be written as $c_\gamma(w_L^i, w_H^i)/n$. Each new variety is produced by a single atomistic firm. This is justified by assuming that imitation is costly and that firms engage in ex-post Bertrand competition. Thus, an imitator would earn zero profits and would never recover the cost of imitation. Therefore, we also have that $n = n^A + n^B$ where n^i is the number of varieties that are produced in country i, i=A,B. It is also assumed that each new variety has to be produced in the country were it was developed.

Entry is assumed to be free in the R&D sector. This is captured in the following condition:

$$v^i = \frac{c_\gamma(w_L^i, w_H^i)}{n} \; ; \qquad i=A,B \tag{2.29}$$

Firms finance product development by issuing equities. In a steady state with active R&D in both countries, the stock value of a firm located in country i equals the cost of developing a new variety there.[43]

A producer of differentiated goods maximizes profits by charging the following mark-up price:

$$p^i = \frac{1}{\alpha} c_x(w_L^i, w_H^i) \; ; \qquad i=A,B \tag{2.30}$$

Thus, each producer of differentiated goods in country i captures the same volume of sales. Prices are normalized in every period so that world total consumption expenditure equals one. With E=1, the sales of each producer of differentiated goods are given by:

$$x^i = \sigma \left[\frac{(p^i)^{-\varepsilon}}{n^A (p^A)^{1-\varepsilon} + n^B (p^B)^{1-\varepsilon}} \right] ; \qquad i=A,B \tag{2.31}$$

and its profits by:

$$\pi^i = (1-\alpha)\; p^i x^i = (1-\alpha)\sigma \left[\frac{(p^i)^{1-\varepsilon}}{n^A (p^A)^{1-\varepsilon} + n^B (p^B)^{1-\varepsilon}} \right] : \qquad i=A,B \tag{2.32}$$

The combination of the free entry condition and constant returns to scale technology prevents firms from earning excess returns:

$$\int_t^\infty e^{[R(\tau)-R(t)]}\, \pi^i(\tau)\; d\tau = v^i(t) \tag{2.33}$$

Differentiation of equation (2.33) with respect to t yields the following market equilibrium condition:

$$\frac{\pi + \dot{v}^i}{v^i} = r^i \tag{2.34}$$

According to this condition, the returns on each equity must be normal, i.e., profit rate and capital gains must equal the domestic interest rate.

[43] If at a moment in time there is no R&D in a country, the value of the existing firms in the country may fall short of the cost of developing new varieties there. Grossman and Helpman (1991a), pp. 182.

The analysis focuses on the long run steady state equilibrium of the dynamic model.[44] In the long run, countries' shares of world exports approach constant values and the nominal interest rate of the two countries converges to ρ. In addition, in a steady state with constant factor prices,[45] the value of firms declines at the rate $g = \dot{n}/n$, at which new products are developed (which is the rate at which public knowledge accumulates and at which the R&D costs fall when factor prices are constant). Thus, the asset market equilibrium can be written as:

$$\frac{\pi^i}{v^i} = \rho + g \ ; \qquad i=A,B \tag{2.35}$$

The market equilibrium condition for good Z is given by

$$Z^A + Z^B = \frac{1-\sigma}{p_Z} \tag{2.36}$$

Finally, the factor market equilibrium conditions in the two countries are given by the following equations.

$$a_{L\gamma}(w_L^i, w_H^i)\frac{\dot{n}^i}{n} + a_{Lx}(w_L^i, w_H^i)\,n^i x^i + a_{LZ}(w_L^i, w_H^i)\,Z^i = L^i \ ; \qquad i=A,B \tag{2.37}$$

$$a_{H\gamma}(w_L^i, w_H^i)\frac{\dot{n}^i}{n} + a_{Hx}(w_L^i, w_H^i)\,n^i x^i + a_{HZ}(w_L^i, w_H^i)\,Z^i = H^i \ ; \qquad i=A,B \tag{2.38}$$

where $a_{fZ}(\cdot)$, $a_{fx}(\cdot)$ and $a_{f\gamma}(\cdot)/n$, $f=L,H$ denote coefficients of the two factors of production in the traditional, high-tech and R&D sectors respectively.

In what follows, we assume that there are no factor intensity reversals and that the three activities can be ranked in terms of factor intensity. R&D is the most human capital intensive of the three, followed by the production of high-tech goods, while the traditional commodity is the most intensive in the use of unskilled labour.

Let us consider a steady state equilibrium with incomplete specialization. With both countries undertaking R&D, equations (2.29) and (2.35) hold for both countries. This implies that:

$$\frac{\pi^a}{c_\gamma(w_L^A, w_H^A)} = \frac{\pi^b}{c_\gamma(w_L^B, w_H^B)} \tag{2.39}$$

On substituting (2.32) and (2.30) into (2.39) gives:

[44] The dynamics of a similar model but with a Leontief technology are analyzed in Grossman and Helpman (1989).

[45] Such a constant factor price steady state equilibrium exist, see Grossman and Helpman (1991a) pp. 183-186.

$$\frac{c_X(w_L^A, w_H^A)^{1-\varepsilon}}{c_Y(w_L^A, w_H^A)} = \frac{c_X(w_L^B, w_H^B)^{1-\varepsilon}}{c_Y(w_L^B, w_H^B)} \tag{2.40}$$

This expression and equation (2.28) can only be satisfied if factor prices are the same in both countries. Therefore, factor price equalization is obtained as a long run proposition.

The long run equilibrium can be analysed in the factor endowment box shown below, which serves to compare a trade equilibrium with that which would arise in an hypothetical integrated economy. The diagram allows us to analyse the properties of the different equilibria that correspond to different intercountry distributions of world factor endowments L and H. The price equalization FPE set consists of all the points inside the parallelogram $O^A N^A O^B N^B$. This set includes all those inter-country distributions of endowments for which commodity trade can lead to an allocation of resources which reproduces that of the integrated equilibrium. The resource allocation of the integrated economy equilibrium to R&D, high-tech manufacturing and production of the traditional good is given by vectors $O^A M^A$, $M^A N^A$ and $N^A O^B$, respectively.

Note that the areas $O^A M^A N^A$ and $O^B M^B N^B$ fall outside the FPE set. This is so because of the restriction that each good must be manufactured in the country where it is developed.[46]

It can be shown that for any arbitrary endowment distribution E within the parallelogram $O^A N^A O^B N^B$, there exists a unique equilibrium in which commodity and factor prices are identical to those of the integrated economy and which reproduces the latter's allocation of resources.[47] The uniqueness of the equilibrium, in spite of this being a three sector model, is due to the fact that the model requires that the level of output of innovative goods is consistent with the rate of innovation that takes place in a country: in steady state, the innovation ratio for the two countries $(\dot{n}^A/\dot{n}^B)$ must equal the ratio of innovative products manufactured in the countries (n^A/n^B). Since in the trade equilibrium $p^A = p^B$ we also have

[46] In steady state, the ratio of the number of new goods invented in each country must be equal to the number of innovative products which is manufactured in each country. With product prices and demands for individual products being equal worldwide those ratios are equal to the ratios of the aggregate outputs of the goods in question, which, in turn, are equal to the ratios of the corresponding factor-employment vectors.

[47] See Grossman and Helpman (1991a), pp. 183-186.

$x^A = x^B$, from the assumptions on production technologies it follows that the ratio of the factor-use vectors of A and B in R&D has to be equal to that same ratio in the production of high-tech products.

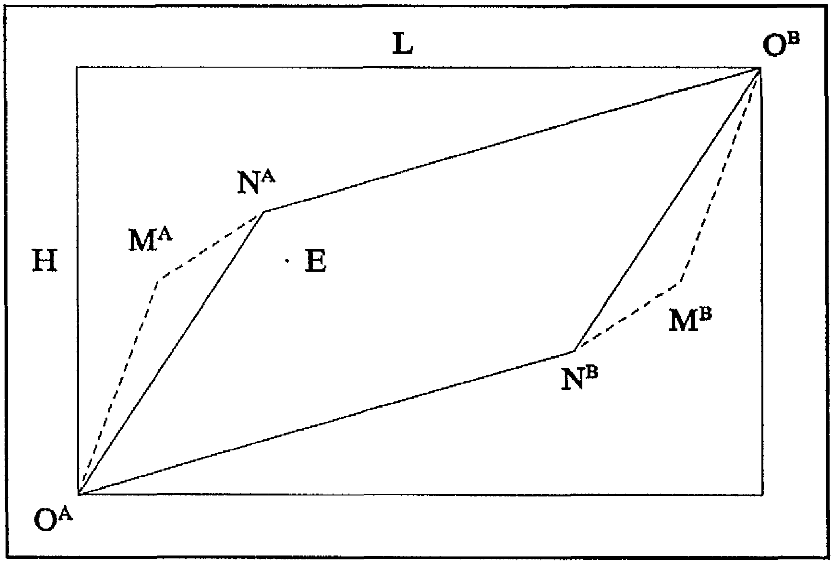

Figure 2.4 Trade and the integrated economy

Specialization and trade

In the free trade factor price equalization equilibrium described above, both countries introduce products at the same rate $g = \dot{n}/n$. But the country with relative abundance of human capital (country A at a point like$E$ in figure 2.4), conducts relatively more R&D with respect to traditional good manufacturing ($\dot{n}^A/Z^A > \dot{n}^B/Z^B$) and produces a relatively larger output of high-tech products ($n^A x^A/Z^A > n^B x^B/Z^B$). Regarding trade, intra-industry trade in high-tech products takes place for exactly the same reason that it occurred in the static love of variety model of section 2.4.2: all varieties are demanded by every consumer while each variety is produced in one country only. With respect to inter-industry trade and under the assumption of no trade in financial assets, the current account is balanced at every point in time. Since country A specializes in high tech-goods, while it has a share equal to E^A in the consumption of every good, it will have a surplus in those goods. The opposite is true for country B, who will export the traditional good and be a net importer of high tech-goods.

In summary, inter-industry trade follows the pattern of trade predicted by the Heckscher-Ohlin theorem.[48]

Outside of the factor price equalization set, the integrated economy equilibrium cannot be reproduced: the wide disparity in relative resource endowments implies that factor prices do not equalize. The upper-left-hand side set of allocations of resources outside of the parallelogram$O^A N^A O^B N^B$ in figure 2.4 corresponds to allocations in which human capital is considerably more abundant in country *A* than in country *B*. This set can be divided in three regions in which one of the following things may occur in relation to R&D activities and traditional good manufacturing: *A* specializes in R&D while *B* undertakes both R&D and production of traditional goods; *A* specializes in R&D while *B* specializes in the traditional good; or *A* undertakes both R&D and production of traditional goods while *B* specializes in the traditional good. With respect to manufacturing of high-tech goods, in the cases in which country *B* does not undertake R&D in the long run equilibrium, *B* will be producing a vanishing quantity of those varieties which were developed there before it stopped R&D.[49] A similar analysis applies to the lower-right-hand side set of no factor price equalization endowments, with the roles of the two countries being reversed. In any case, in the absence of trade with financial assets, the inter-industry pattern of trade will follow the one suggested by the Heckscher-Ohlin theorem, and, as long as high-tech goods are produced in both countries, there will be intra-industry trade.

A final comment is in order, regarding output growth. An effect of innovation is to produce a steady deflation in an ideal price index of final goods since, as we mentioned earlier, the sub-utility function implies that increased variety has a positive effect on utility. The large

[48] In the case in which there is trade in financial assets analysed by Grossman an Helpman, a country may have a deficit in its trade account and it may even have a deficit in both goods. When this is not the case, the trade pattern described above also applies. In the case in which a country runs a deficit in both products, the factor abundance hypothesis still plays a role: if, for instance, the country with deficit has relative abundance of human capital, the share of imports in its total consumption of the traditional good will be higher than the share of its net imports of high-tech goods in its total consumption of those goods.

[49] When factor prices are different between countries, manufacturing costs are different and there may be an incentive to manufacture in a different country than that in which the product is developed. In this model, this has been ruled out by assumption. Imitation of high-tech goods by the low cost country is also ruled out by assuming that imitation costs are sufficiently high to deter it.

share of the high-tech sector in country *A* implies that its real output grows faster than that of country *B*. Real consumption, however, grows at the same rate in the steady state since, through trade, both countries have access to all varieties of the differentiated good.

Extensions of the model

An alternative specification of the model is possible in which innovation is of the quality upgrading type. Grossman and Helpman analyse this case by introducing a specification of preferences similar to the one in Segerstrom et. al. (1990) that was presented in section 2.5. The authors show that the same results in terms of patterns of trade and output growth that were found in the model above hold for this case. Another aspect pointed out by the authors which is worth mentioning is the fact that both the horizontal and the vertical differentiation cases can be reformulated in terms of differentiated intermediates, like in the specification of Ethier's (1979, 1982) model that was described in section 2.4.1. This reformulation requires only minor changes in the model and does not alter the conclusions that were reached above. The main difference that arises from reformulating the model in terms of intermediates is that the effect of innovation is to increase productivity in the assembly of the final consumption good, and it is through the drop in its price and the greater consumption that is made possible that the utility of the consumers is increased.

Several extensions of the model have been explored by Grossman and Helpman to analyse other aspects of international relations, such as the effects of allowing a separation in the location of R&D and the manufacture of differentiated products, the licensing of blue prints to producers in foreign countries, and the implications of spillovers of R&D which are national rather than international.[50] The discussion of these issues, however, goes beyond the purposes of this chapter, which is to centre the attention on the basic elements of the modelling of technical change in neoclassical trade theory.

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[50] See Grossman and Helpman (1991a) pp. 197-236.

2.6.2 Comments on the model of endogenous innovation and trade

The endogenization of technological change is made by modelling technological change as a production process similar to that of any other good.[51] The main difference between R&D and the production of other goods lies in the nature of the product. On the one hand, R&D produces spillovers in the form of common knowledge which generates external economies that make it possible to have continuous growth in the model. On the other hand, it produces the blueprints that are necessary for the production of new goods. The appropriability of blueprints and the profits derived from the monopoly in manufacture that the ownership of blue prints confers, are the inducement to undertake the R&D activities. Profits are also indispensable for innovation because these activities use resources which have an alternative use in the production of consumption goods. Since R&D is financed by households, the returns generated from investing in R&D have to compensate them for forfeiting present consumption. This is captured in the model by the fact that, in the long-run equilibrium, the returns of an equity in a profit generating firm, the interest rate and the subjective discount rate of the consumer are all equal.

The endogenous treatment of technological change represents an advance within the neoclassical theory in the treatment of technological change and introduces some realistic features like the ones just mentioned. However, the modelling of technological change in such a way that is tractable within the neoclassical general equilibrium framework is made at the cost of creating a very stylized representation of this phenomenon.

In spite of the appeal of some of the features introduced in the model of endogenous innovation, there is some inconsistency in the way in which blueprints are treated: on the one hand, they are an essential input for the production of differentiated goods; they require resources and time for their production; they can, in principle, be sold in the market, and they are the basis for making profits. On the other hand, blueprints do not enter as input in the production function and only appear as an entry cost in the model. This unsatisfactory treatment of blueprints cannot be, however, easily avoided since, as it was shown in the capital controversy

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[51] See, for instance, Romer (1990). For a survey of this literature, see Verspagen (1993).

of the 1960s, the inclusion of produced capital goods undermines the basis of the neoclassical theoretical framework.[52]

However, our main concern relates to what is left out in the conceptualization of technological change. The main objection that we raised in relation to the models in earlier sections also apply to the models with endogenous technological change: they miss essential elements of the process which relate to the uncertainty that characterizes technological change and to the nature of the competitive process that is behind the innovative activities of firms. There is uncertainty in innovation not only about whether the R&D effort will be successful (an aspect that the probabilistic treatment of Segerstrom et. al. tries to capture), but also in relation to the nature of the innovation and to the rate and direction that the development of the technology and its market will take. Regarding competition, the models reviewed focus only on representative firms and look mainly at the quantity and price decisions that maximize their profits. There is also, however, a process dimension of competition in which the diversity in the behaviour of competitors and, in particular, their different performance in the development of technology, plays an important role. As it is discussed at length in chapter 4, these aspects are central for an understanding of technological change.

2.7 Concluding remarks on the equilibrium approach to technological change and international trade

In this chapter we have examined some important aspects of the way in which technological change and international trade are analysed in neoclassical trade theory. We have looked at both static and growth equilibrium models which address issues related to product innovation. Throughout the chapter we have accompanied the presentation of the models with comments on both their main contributions and limitations. Particular attention has been paid to the way in which technological change is modelled. We will not repeat these comments here, but rather devote this final section to the more general question of the usefulness of the equilibrium approach as a tool for the analysis of the relationship between technological change and international trade.

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[52] For a summary statement of the problem see Garegnani (1970).

The major strength of the equilibrium approach in trade theory is that it offers a simple theoretical framework to handle the very complicated issue of interdependence within national markets and among trading countries. The models reviewed in this chapter illustrate this point very well. The equilibrium approach has, however, two important limitations. A first problem, which has been pointed out by Dosi and Soete,[53] is its view of equilibrium, as defined in section 2.2, as a property of the economic system. This has been repeatedly stressed by economists writing in the Keynesian tradition, who have argued on the basis of both theoretical and empirical grounds that the full employment equilibrium of the neoclassical model is not a guaranteed outcome of the economic system.[54]

The second problem relates to the capability of the neoclassical equilibrium model to analyse change. The concept of equilibrium, properly conceived as an hypothetical situation, offers a powerful device to examine some of the fundamental relationships of the economic system. This concept, however, is essentially static and this poses problems when it is applied to the analysis of change. The method of analysis is to compare different equilibria: in static models it is comparative statics, in intertemporal "dynamic" models its is a comparison between long run steady states and between the paths of intertemporal equilibria that converge to those steady states. The use of differentials in static models to compare marginally different equilibria, and the construction of intertemporal models in which the intertemporal maximization defines equilibria for all future periods, create an illusion of movement that can be misleading.

It is important to keep in mind two aspects of the equilibrium approach. The first is that the basic method of analysis is comparative statics (or comparative steady state) and that the models are in fact comparing independent equilibria and not describing changes in real time.

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[53] Dosi and Soete (1988), pp. 401-409.

[54] In this spirit, Cimoli, Dosi, Pavitt and Soete have proposed a model of trade, imitation and innovation in which they reformulate Dornbush, Fisher and Samuelson's (1977) Ricardian model of trade along Keynesian-Kaldorian lines. Different versions of this model are found in Cimoli, Dosi and Soete (1986), Cimoli (1988), Cimoli and Soete (1988), Dosi, Pavitt and Soete (1990) and Cimoli (1991a, 1991b). The model is used to highlight, among other things, that although the international economic system "...requires a high degree of symmetry and synchrony in the process of change, it does not automatically provide any functional mechanisms which guarantee it...". Dosi, Pavitt and Soete (1990), p. 212.

The second relates to the meaning of equilibrium as a theoretical construct and its relationship with the real economic system. The long-run static equilibrium can only be seen, at most, as the situation to which the system would converge if all the parameters of the model did not change and all variables were allowed to adjust. The same idea applies to the long-run steady state equilibrium of intertemporal models. The only difference is that the latter tell us the relationships that would hold in an infinite sequence of equilibria when maximizing decisions are made not only for one period, but for all periods, and taking into consideration the conditions of all periods in the future. There is an important limitation in this approach which is apparent in all the models reviewed. Namely, that it does not take into account the uncertain and contingent elements of technological change which alter the conditions of the problem and redefine the equilibria to which the system would converge if all variables were allowed to adjust.

In the next two chapters we adopt an evolutionary approach to the analysis of the relationship between technological change and international trade. Although this approach does not exhibit the power that the neoclassical equilibrium framework has in the analysis of economic interdependence, it is better suited for the analysis of change. The dynamic aspects of technological change, neglected in the neoclassical equilibrium models, can be placed at the centre of the analysis in an evolutionary approach which is free of restrictions imposed by the adherence to an essentially static framework.

3 Technology in trade theory: the evolutionary perspective

3.1 Introduction

In this chapter, we present an overview of the evolutionary approach to economics and review a series of contributions from the literature on the role of technology in international trade, which are relevant for this approach.

The idea of a perspective in economics that would draw on concepts from biology and would make use of ideas from the theory of evolution is not new.[1] However, it has been mainly since the early 1980s that the use of evolutionary analogies in economics has flourished and that the work of different authors has started to converge towards the building up of a common set of concepts and analytical tools. There is not yet a fully articulated theoretical framework, as in the case of the neoclassical approach, capable of embracing the different contributions that have been made following evolutionary lines. However, important elements of such a framework have already been developed, which make it a fruitful approach for economic analysis.

Regarding trade theory, the literature that adopts an evolutionary perspective is very recent and not very abundant. However, ideas akin to this approach had been expressed long time ago by authors addressing issues on international trade. This chapter is concerned, first, with identifying the key ideas of evolutionary thinking in trade theory and, second, with presenting a picture of the evolutionary argument on the role of technology in international trade.

Section 3.2 outlines the main characteristics of an evolutionary approach to economic theory, in terms of its line of enquire and of the views held about the functioning of the economic system. In section 3.3, we comment on some contributions to trade theory which have provided key insights for the more recent arguments on trade theory and technological change from an evolutionary perspective. The basic ideas of these

[1] On the development of evolutionary notions in economics see Hirschleifer (1977), Matthews (1984), Clark and Juma (1987) and Hodgson (1993).

evolutionary arguments are presented in section 3.4. Section 3.5 reviews two models, which introduce evolutionary elements and look in more detail at some of the issues of the evolutionary perspective outlined on the previous section. Finally, in section 3.6 we present our conclusions.

3.2 The evolutionary approach in economic theory

The central concern of the evolutionary perspective is to explain economic change. It sees the economy as a complex and evolving system, which is open in the sense that the outcomes of its development are not predictable. The diversity and mutability of the different components of the system and the pressure exerted on them by selective forces, which emerge both from within and from outside the system, are the fundamental elements shaping the course of economic change.

There is a major difference between the evolutionary approach and the equilibrium perspective reviewed in the previous chapter. The latter looks at the way in which the actions of independent economic agents coordinate. The market is seen as a mechanism which drives the system to stable equilibria and no inherent tendency to change is perceived in the system. In evolutionary thinking, in contrast, the economy is seen as a system in continuous change and the problem is to understand the mechanisms by which it changes. The future states of the system are recognized as inherently unpredictable. However, it is held that by identifying the continuity of elements and processes in the system and by understanding the way in which it has evolved, it is possible to imagine the possibilities of its future development and to identify what is new when it appears.[2]

The term evolutionary has spread widely in recent times and is often used in works that have little in common in terms of their theoretical perspective.[3] Here, we will be using the term for an approach which can be broadly characterized by holding the following views:

1) The diversity of behaviours that exists at different levels within the economic system is a key element of its functioning and evolution.

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[2] See Allen (1988) and Allen and Lesser (1991).

[3] See Hodgson (1993) for a classification of evolutionary approaches. See also Witt (1991) for a critical appraisal of the state of evolutionary theory in economics.

2) Economic activity is a process and its understanding requires us to introduce historical, rather than "logical", time in the analysis in order to capture irreversibilities in the evolutionary processes.

3) The order generating elements in the economic system are forces operating at different levels which exert selective pressure on populations of entities. 4) The fact that we are dealing with human behaviour and institutions is a fundamental aspect which distinguishes economic evolutionary processes from those studied in biology. Two distinctive elements of socioeconomic evolution are the purposeful and boundedly rational nature of human behaviour and the fundamental role played by routines and institutions. The behaviour of individuals and organizations is largely shaped by what they have learnt from their past experience and from what they anticipate about the future.

In what follows we will present some of the main ideas of the evolutionary approach to economic theory. We do not attempt to make a comprehensive review of the different contributions to evolutionary thinking in economics. We will only outline some of the major themes that arise within this approach, in order to place in context the arguments on trade and technology of the sections that follow.[4]

While explaining the characteristics of the evolutionary approach in economics, it will be useful to proceed through contrast and analogy with respect to, both, the equilibrium framework as applied in traditional economic analysis, and the application of evolutionary ideas in biology. The first is a necessary point of reference given its dominant position in the discipline and the fact that it is in terms of this framework that most economists are used to think. The second offers an invaluable source of concepts and parallels, given the more advanced degree (at both the theoretical and the empirical levels) to which evolutionary explanations have been used in biology. There are, however limits to the extent to which one can make use of biological analogies in economic and social sciences. This is due not only to the fact that the theory of evolution in biology remains a highly controversial subject,[5] but also, and more

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[4] See Saviotti and Metcalfe, (1991), for an overview of the key elements and the different research traditions on which the evolutionary approach draws. See Clark and Juma (1987) and Hodgson, (1993) on the presence of evolutionary ideas in economic thinking.

[5] See Mani (1991).

important, because of the specificities of the socioeconomic systems that arise from their human nature. These specificities are the source of fundamental differences in the characteristics of biological and economic evolutionary processes.

In economics as in biology, evolution is seen as primarily driven by two mechanisms: one which introduces novelty in the system and creates variety, and another which selects on the diversity of the entities within the system. In biology, the first mechanism is genetic variation and the second is natural selection. Evolutionary economists have sought to explain economic change in a similar way by identifying in the social domain analogous concepts and mechanisms to those that operate in biology. At the more general level, one may thing of habits and routines as the equivalent to genes in biology, and of the mechanisms that provoke changes in them as the analog to those behind genetic variation. Regarding the selective mechanisms, the institutional settings of economic systems (and at a more basic level the natural environment itself), will act in favour or against the behaviours (of individuals and organizations) associated with those routines. In this way, selection will change the diffusion of routines and modes of behaviour in populations of individuals and organizations. Therefore, in economics, the equivalent to micro evolution are the changes that take place in the routines (and in other observable variables associated to them) and in the diffusion of those routines in the population being studied.

Let us illustrate these concepts by applying them to the particular case of firms competing in a market.[6] The different technologies and organizational rules that the firms articulate can be conceived as complex routines. These routines consist of ensembles of modes of thought, habits and rules of action and interaction which make up the competence of the firm, which can be visualized as being equivalent to the genetic pool of living organisms. They play a fundamental role in shaping the internal and external behaviour of the organization. The performance of each firm in the market, the price and quality of the goods and services that it delivers depends to an important degree on these routines. It is on those goods and services that the selective mechanism of the market operates, and, indirectly, on the firms and on their routines. The application of

[6] What follows draws on Nelson and Winter (1982a).

some technologies and organizational procedures will be discouraged and some of them will eventually be phased out, since the adherence to them would lead to repeated poor performance and could lead to the elimination of firms themselves. At the level of the population of competing firms, the operation of the selective pressure of the market will lead to differential growth and, in some cases, to the elimination of firms.

The example above emphasizes the parallels between biology and economics. However, the apparent similarity, although useful as an illustration, can be deceptive. The example is far from being complete. It still lacks various elements which are needed to render an analytically operational model. These missing elements are related to important specificities of the economic process and are central for the development of the conceptual apparatus of the evolutionary approach. It is to them that we turn the attention in the rest of this section. In what follows, we will focus most of the time on the example above of firms competing in a market and will address three major topics: the mechanisms that generate variety, the mechanisms of selection, and the concept of evolution in economics.

3.2.1 Variety in economics

In economics, as in the natural world, diversity is an essential element for selection to operate. However, in contrast with biological evolution, in which genetic variation of a significant magnitude occurs, in general, at a slow pace, the introduction and spread of novelty in human systems takes place at a much faster rate. The difference with respect to the natural world is not only a question of speed. The mechanisms that generate variety play in economic systems a much more important role in driving the evolutionary process. In the former their relevance lies mainly in being the source of the diversity on which natural selection operates; in economic systems they are sources of evolutionary change that parallel in importance the mechanisms of selection.[7]

A crucial difference between biological and human systems is found in the mechanisms that generate variety. In biology, genetic drift and mutations are random events. However, in economics, the innovative and

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[7] See Matthews's (1984) for a discussion on the interaction of optimizing behaviour and market selection in driving economic change.

imitative activities that create and modify habits, routines and institutions are, above all, the result of purposeful behaviour. The fact that we are dealing with individuals and organizations with intentions, which acquire and interpret information and that are capable of thinking and learning, is a central element which distinguishes evolution in economics from that in biology. New behaviour seeks, in general, to be adaptive.[8] Hence, the environment influences the process of creation of variety.[9] Furthermore, individuals and organizations not only innovate having in mind the present conditions of their environment, but also in anticipation to changes in it.

As a consequence, the following issues are central for the evolutionary research agenda: the study of individual and organizational behaviour, of the way in which knowledge is acquired, transmitted, interpreted and articulated, of the way in which decisions are made, and, above all, of the role of routines in all these processes. It is also of fundamental importance to understand the way in which new forms of behaviour appear and become fixed in new or modified routines.

At this point, it is worthwhile returning to the biological analogy and noting the similar role played by routines in society to the one that genes have in the biological world. According to this idea, which has been traced back to Veblen, socioeconomic evolution is seen "...as a selection process working on institutions as units of selection".[10] The essential element that supports this analogy is that routines, as genes, are depositaries of information and are the means to transmit it. Actions and thoughts are sustained and structured by routines and habits which operate on behaviour as a set of instructions. As genes, routines replicate themselves. However, there is not a clear physical mechanism like that of genetic duplication. There is, instead, a social mechanism which involves imitation and learning. As many authors have pointed out, there is an important Lamarckian element in socioeconomic evolution. Learned routines are carried in the memory of individuals and organizations. These routines

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[8] By adaptive behaviour we understand that which increases the propensity of success in a given environment. See Hodgson (1993) pp. 49-50, on the concepts of adaptation and fitness.

[9] As we will se below adaptation, and in general changes in routines, also has an effect in changing the environment.

[10] Hodgson (1993), pp. 126, 132.

are transmitted from one generation to the other and play an important role in shaping subsequent behaviour.

We can think of individuals and organizations as carrying a set of habits and routines which are equivalent to the genetic pool of living organisms. However, the analysis of evolutionary processes on the basis of routines as elementary units requires of a significant departure from the biological model. Routines do not show the same degree of stability as genetic material, nor is there a clearly identifiable generational parent-offspring relationship. These issues are at the core of the evolutionary approach. Of central concern to this approach is to study the elements that confer stability to the routines (such as inertia), and to understand the mechanisms by which modes of thought are fixed in routines and spread among individuals and organizations. These mechanisms play a similar role to that of heredity in the biological world.

A final question is that of the limits that exist on the generation of variety. The creativity and innovative activities of individuals and organizations build on their existing knowledge and skills and on the material conditions within which they operate. At any point in time, these conditions limit the opportunities for innovation that they are able to perceive and what can be achieved in their pursuit. Learning and adaptation to changes take time, and there are also limits to the extent and speed to which people and organizations can modify their routines without ceasing to be effective in the environment in which they compete.

3.2.2 The mechanisms of selection

The nature of the selection process is the next major theme in the evolutionary approach. Here the main issues are: first, the distinction between routines, which are the elementary units of selection and the direct objets of selection; second, the characteristics of the selective forces; and, third, the attributes of the selection environment. In discussing this point we will take as point of reference our example of firms competing in a market with the understanding that similar ideas would apply to other instances.

The first thing that one has to have in mind is the institutional dimension that is found in all components involved in the process of selection: objects, forces and environment. The market, which acts as the selection environment, is an institution and is itself supported by a set of institutions that facilitate and regulate the exchange of commodities.[11] Individuals and organizations participate in the market according to the values, rules and routines on which the market stands, which are the origin of the selective forces faced by competing firms. The direct objects of selection are the goods and services sold in the market. As several authors have rightly pointed out, in economics, in contrast with what happens in biology, selection is not a matter of life and death.[12] Selection acts as a transfer mechanism that acts indirectly on firms affecting their profits and growth possibilities.[13] Regarding the routines, the operation of the selective forces leads to a change in their economic significance: unsuccessful routines (technologies, marketing and managerial procedures and so on) will tend to lose economic weight. That is, their diffusion in the population of competing firms relative to that of alternative routines will diminish. These will result either from being abandoned, or due to below average growth or bankruptcy of the firms committed to them.

These statements above need to be qualified. The process is not as straight forward as it seems at first sight. Firms deploy a number of different routines which contribute in different ways to their performance and selection operates on bundles of routines. In addition, more often than not, firms participate in more than one market and routines will, in general, differ in their selective value in different environments. An important implication associated with these characteristics of the selection process is that it cannot be equated with that of an optimizing mechanism which selects the best routines. A first reason for this is that the selective value of routines will depend on the (changing) environment. A second reason is that there are neutral and non neutral selective traits, all of which see their economic weight affected by the process of selection. Even routines with a negative value in a given environment may

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[11] On the institutional character of the market see Hodgson (1988).

[12] See, for instance, Matthews (1984).

[13] On this see Metcalfe (1989b).

see their significance increased simply due to the growth of organizations committed to them which owe their success to other reasons.[14]

Regarding the selection environment, three brief observations are in order. The first concerns the two-way relationship between the environment and the generation of variety. Not only the environment affects variety by influencing the direction of the activities by which variety is created, but the introduction of new routines and behaviour changes the conditions in which selection takes place. The implications of these for evolution has been summarized by noting that "...evolution generates diversity and diversity drives evolution."[15] The other two observations relate specifically to the market as a selection environment. The market selects across a number of different aspects (prices, quality, delivery). Therefore, in order to advance in the understanding of the selection process, it is necessary to identify those aspects and to be able to determine the mechanisms by which the diversity of routines within firms translate into each aspect.[16] Finally, it is essential to make a systematic analysis of the environment which captures the different degree of opportunity and selective pressure that it generates.[17]

3.2.3 The notion of evolution in economics

In relation to the notion of evolution, we will focus on two themes: first, on the meaning and relevance of the concept for economics, and second, on the problems associated with building a conceptual framework to analyse it.

In discussing these themes, the biological analogy will be again very useful. In biology, the process of evolution takes place at different levels: at the lower level, we have what is called microevolution, which refers to the changes that one observes in populations of species over generations. At the highest level is phyletic evolution, which relates to the origin and extension of species. The lack of a unifying model able to

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[14] These other reasons need not be even the result of selection over the other routines deployed by the firm. There may be other reasons for successful and unsuccessful performance including chance.

[15] Allen and Lesser (1991), p. 165.

[16] Silverberg (1988).

[17] See Saviotti and Metcalfe (1991) pp. 17-18, on different characterizations of the environment that have been proposed by evolutionary theorists.

relate these different levels manifests itself in the coexistence of different disciplines in biology: population genetics, ecology, the theory of speciation and palaeontology, all of which deal with the question of evolution but remain essentially separate disciplines.[18]

Evolution in economics also takes place at different levels. The process can be observed at the level of technologies, firms, industries, market structures, other socioeconomic institutions, and economic systems as a whole. At these different levels, it is possible to identify the emergence and extinction of new and old forms. As in biology, the time span over which this changes are observable varies and, as there, it may turn out to be very difficult to develop a unifying framework able to give account of and relate all these different levels of evolution.

A key concept, on the basis of which the theory of evolution in biology elaborates at the different levels of analysis, is that of species. There is not, however, an equivalent concept in economics.[19] Taxonomic classifications in economics have to follow, thus, a different logic, one that is appropriate to the different levels at which evolution takes place. The concept of institution, broadly defined as "...commonly held patterns of behaviour and habits of thought, of a routinized and durable nature, that are associated with people interacting in groups or larger collectives...",[20] is a fundamental concept. This concept is not only the basis to elaborate taxonomies at different levels of evolution, but may also serve to establish links between these different levels. Furthermore, organizations, as materialized forms of institutions,[21] are elementary units on which to base the population approach that is essential for evolutionary analysis. The criteria to define a population may vary according to the specific purposes of the analysis and there is no need, as in biology, to tie ourselves to a single concept like that of species.

All these issues mentioned in this section define the broad agenda of the evolutionary approach to economic analysis. In this chapter, we will discuss a small subset of these problems, that which relates to the

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[18] See Mani, (1991).

[19] Matthews, (1984).

[20] Hodgson (1993), p. 253.

[21] Johnson (1988).

relationship between technological change and the evolution of international trade.

3.3 Some contributions to dynamic thinking on international trade and technological change

The dominant position of the equilibrium perspective in economic theory and its focus on aspects of the economic system which are predominantly static, has led to a neglect in economic analysis of issues which are central for the evolutionary perspective. Thus, it is not surprising to find that many of the ideas on trade theory rescued by the evolutionary approach come from work outside the mainstream equilibrium tradition. This ideas often arouse from the dissatisfaction with the treatment given, in the equilibrium approach, to dynamic aspects of international trade. In this section, we present a brief survey of the most important ideas on trade theory that can be considered as forerunners of the evolutionary argument on technological change, trade and economic development.

3.3.1 The effect of trade on technological development

One of the earliest statements emphasizing the relevance of international trade for the technological and economic development of a country is found in List.[22] In opposition to the liberal free trade tradition emanated from the Manchester School, which stressed the benefits arising from international specialization and trade, List focused on the implications of trade for development.[23] List argued that in the presence of large differences in the technological development between countries, in particular in the manufacturing sector, free trade would lead to patterns of specialization that would hinder the technological development of the backward country precisely in those sectors with greater economic potential. Due to increasing returns of both static and dynamic nature the country with a head start in manufacturing would develop an advantage in those sectors. As a consequence, the backward country would be locked in a pattern of specialization that excluded it from the sectors with greater

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22 F. List (1841).

23 See Freeman (1990b).

economic potential. In spite of this view, List was not opposed to international trade. He recognized the benefits that could be derived from it provided that the nations that engaged in trade enjoyed similar levels of technological development. The ideas of List have partially survived to the present day in neoclassical Heckscher Ohlin trade theory, where they have been reformulated in a static framework as the infant industry argument for protection. In this framework, the argument has been reduced to a special case of unexploited internal economies in a world without technological asymmetries. However, List's argument was deeper. First, in that it is based on the recognition of the cumulative nature of technological progress. Second, in that it stressed the presence of technological gaps between countries. Finally, in that the implications of trade for the technological development of countries were the main concern of the argument.

Another important contribution which advances further on the above argument is found in the writings of Kaldor.[24] This author offers an explanation, at the aggregate level, of the way in which technological progress, trade and growth are related. Kaldor's original argument is developed in terms of the asymmetries that exist between industrial and agricultural production. As List, Kaldor argued that countries with different degrees of industrialization would not only benefit differently from trade, but also that, in those conditions, trade would tend to widen the productivity gap in industrial sectors between the trading countries. The argument is based on the application of the idea of cumulative causation, present in Kaldor's growth models,[25] to a context of international trade. This idea rests on two basic points: first, that demand growth and accumulation conditions are different in different sectors; second, that exports are a component of effective demand which not only affect the level of economic activity, but also technological progress and investments. Kaldor's argument has been subsequently developed and formalized by Thirlwall and others.[26] His ideas have also been

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[24] Kaldor (1970).

[25] The concept of cumulative causation is found in Myrdal (1957).

[26] Dixon and Thirlwall (1975), Thirlwall (1979), Thirlwall and Hussain (1982).

incorporated in the evolutionary approach to international trade, as we will see in section 3.4.

3.3.2 Technology gap theory of international trade

The technology gap literature in international trade directs the attention to technological change and to the technological asymmetries that result from it, as a sources of international trade. This literature focuses on the gap that exists between the introduction of an innovation in one country and the setting up of productive facilities in other countries.

The basic argument of the technology gap theory is found in Posner (1961). Posner stressed the fact that, following the introduction of an innovation in one country, its demand in other countries will usually precede the establishment of production facilities abroad. Thus, even in the absence of other sources of trade, the introduction of an innovation will be a source of trade. This trade is due to the difference between what Posner calls the 'demand gap' and the 'supply gap'.[27] Posner presents these ideas in a model of a world with identical demand patterns in which the different access to the new technology across countries is the basis of trade.[28] Thus, variety plays a central role in the emergence of trade. Moreover, since innovation and imitation are processes which occur continuously in modern economies, technological change will be a pervasive element shaping international trade. Innovations open gaps and create trade flows and imitative catching up processes eliminate them.[29] Posner's argument points to the fact that innovation and its diffusion are important factors in the creation of trade flows and in their changes over time. The different pace at which international diffusion takes place in the demand and the supply sides is a key aspect in the role played by technological change in international trade. The differences between the firms located in different countries and between their national environments are fundamental determinants of the differences in diffusion. Thus, Posner

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[27] See Posner (1961).

[28] See Metcalfe and Soete (1984).

[29] Posner also notes the problem of using the concept of factor of production as an all-embracing notion, and stresses the importance of treating adequately elements of entrepreneurial activity, skills and knowledge which are generated and constantly renewed by the production process and play an important role in international trade.

stressed the fact that a focus on diversity is central for an understanding of the role of diffusion of innovation in international trade.

Posner's ideas were further elaborated by Hufbauer, who applied them to empirical analysis.[30] An additional element introduced by this author was to consider the sequential entry of countries in the production of a new technology. This leads to a pecking order of trade where early imitators export to late imitators. Hufbauer also noted the existence of wage differentials between advanced and less advanced countries and the fact that innovations tend to be concentrated in the former group of countries. According to this author, the combination of these conditions creates the possibility of reversals in trade patterns. High wages in the more advanced (innovating) countries, relative to those in less developed (imitating) countries, not only shorten the life of the export period for the innovative country; imitation and wage differentials may combine to produce a flow of low wage trade in the opposite direction.

3.3.3 The product life cycle theory of trade

The product life cycle idea proposed by Vernon (1966) is another major contribution to the study of the role of technology in international trade. The crucial insight of this theory is to note that the patterns of trade will, in general, be affected by the fact that a new technology continues developing and undergoing changes after its introduction. The basic idea is that, as a technology moves along different stages of its life cycle, the weight of the different factors that affect the location of production facilities will change and tend to favour different locations. During the early stages, proximity to markets for which a new product was developed will be favoured by factors such as the state of flux in product and process design, the need for close contact with costumers, suppliers and competitors, and the low price elasticity that often characterizes new products. As the product matures, standardization makes flexibility less important, competition becomes more price oriented and the reduction of costs through economies of scale and lower input prices gain relevance. Therefore, locations offering low wages become more attractive. Consequently, during the first part of its life cycle, a product will tend

[30] See, Hufbauer (1966) for an application to synthetic materials, and Hufbauer (1970) for a multi-sector study.

to be produced in the country where it was introduced and to be exported to other countries. But later in its life, the location of production may change and the direction of the trade flow could be reversed if labour cost differences are wide enough to offset the tariffs and transport costs of exporting from the low wage country to the initial producer.

Vernon developed his theory having in mind the U.S. and the conditions of the postwar period, when that country was considerably ahead in income and innovative performance relative to other advanced countries. The argument was later revised by Vernon (1979) to acknowledge the closure of the income gap between the U.S. and other developed nations and the fact that the internationalization of the operations of multinational corporations may weaken the firm-country ties assumed in the argument. These changes, according to Vernon, diminish the explanatory power of the product cycle hypothesis, in particular when applied to trade between developed countries.

There is an additional reason why the reassessment of the product life cycle model by Vernon is of interest. Vernon's new argument rests on the introduction of changes in international economic conditions and in the characteristics of the organizations that compete in it. This is in line with the evolutionary approach, which stresses the importance of changes in the environment and in institutions for economic evolution. There is, however, one important shortcoming in Vernon's product life cycle argument, which is now widely recognized, namely that it does not take into account that technological progress may continuously modify a product and its technology. This may lead to different life patterns for different technologies which may vary considerably from the one assumed in the trade model. Nevertheless, if the specificities of the products under study are considered and other factors that affect the development of a technology are taken into account, it can offer useful insights for the analysis of international trade in specific industries. The product life cycle framework has been applied in a number of studies. These studies show that the development of a technology that follows its introduction is a key element to understand the changes in the location of production and its associated trade patterns.[31]

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[31] See, for instance, the studies of petrochemicals of Stobaugh (1977), Auty (1984) and Chapman (1991), and the studies for agricultural products by Evenson, Houck and Ruttan (1970).

3.4 Technology and trade: an evolutionary argument

In recent years, a body of literature on international trade that adopts an evolutionary perspective has emerged. This literature shifts the attention away from the traditional questions of allocative efficiency in international trade, towards the analysis of the dynamic elements which modify trade patterns and shape economic development. These contributions introduce ideas which exhibit many parallels with those of the authors reviewed above. The relevance of the new literature lies, first, in that it has reinterpreted the dynamic elements of those ideas and has put them in a framework that is centred on the analysis of economic change, and, second, in that it has advanced the argument considerably from the basic insights found in previous writings. The development of this new approach has been closely related to empirical research on the role of technological change as a determinant of international trade flows and to the theoretical developments on the theory of technological change.

In this section we make an attempt to put together these different contributions under a common evolutionary argument. The argument below is in the spirit of what Nelson and Winter call appreciative theorizing:[32] our main concern is to identify the variables and relationships that are more relevant and to present a general view of the main processes involved in the evolution of trade and in its relationship with technology. This argument offers a point of reference for empirical work and for formal models of the kind that we will review later on. We will discuss three major themes, which correspond to different but interrelated levels of analysis: the relationship between economic and technological development and international trade, the macroeconomic implications of sectoral diversity, and the microeconomic dimension of the patterns of specialization.

There are a number of elements in which the present argument differs from the conventional equilibrium theories of international trade. The first difference is its view of economomic activity as a process and its emphasis on explaining changes rather than states. The second is the conceptualization of international trade as one of competitive struggle in international markets. The third is its concern with taking into account

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[32] Nelson and Winter (1982a), Nelson (1987).

the diversity that exists between countries not only at the national level but also across sectors and within each sector. The final difference, which is closely related to the latter, is the adoption of a population perspective and a focus on relative positions (at country, sector and firm level), since what matters in international competition is the relative position.

3.4.1 International trade, technology and development

Very much in the spirit of List's argument, the differences that one observes in international comparisons of wealth, degree of technological development and trade performance have been the focus of attention of the evolutionary approach. As we saw in the previous section, List held the idea that there was a positive association between these three aspects. Recent research on trade and technology gives some empirical support to List's basic insight. Part of the research of Dosi, Pavitt and Soete on manufacturing sectors of OECD countries can be seen as an exercise that confirms the validity of List's ideas. In this work, the concepts above are approximated with measurable variables:[33] per capita incomes and wages for wealth; R&D expenditure, patenting and labour productivities for degree of technological development; shares in export markets for trade performance.

Three basic conclusions emerge from this research. First, that both in terms of their levels and their changes over time, the income levels and the wages of a country are positively related to the levels and changes in countries' technological capabilities (as approximated by measures of innovative activity and labour productivity). Second, and in line with other research on the role of technology in international trade,[34] that innovative activities, both at sectoral levels and for the average of manufactures, are related with export performance (measured as shares in world exports). These relationships are found to hold in relation to both the levels and the changes in those variables. Third, that changes in trade performance are more strongly related with changes in technology

[33] Dosi, Pavitt and Soete (1990).

[34] Hufbauer (1970), Gruber and Vernon (1970), Soete (1981, 1987).

related variables than to changes in cost related variables.[35] We will focus on spelling out an evolutionary theoretical argument on the development of technology and international trade which seems to find support on the empirical evidence described above.

If looked in terms of macroeconomic aggregates, the argument would be in many respects similar to the post-Keynesian ideas of Kaldor reviewed above. The distinctive element of the evolutionary argument is that, while acknowledging the open nature of the system (i.e. the multiplicity of possible outcomes), it emphasizes the fact that the precise nature of key macroeconomic relationships is heavily dependent on the particular conditions that prevail at more disaggregated levels. In what follows, we present the general views held with respect to macroeconomic relationships.

The differences in the technological capabilities of nations are seen as a fundamental determinant of their different potential incomes. However, there is not an endogenous force which guarantees that potential income levels will be reached. The level of macroeconomic activity in a country is seen as determined in a Keynesian fashion, where factors like expectations and international economic interdependence play an important role. There are, in fact, important factors in the dynamics of the system which prevent a continued achievement of the maximum potential income. Technological change, for instance, is in general disruptive, and at the same time that it increases potential income, it introduces structural changes in the system that make it extremely difficult to meet its potential.[36]

The evolutionary approach shares the post-Keynesian view that technological change is positively related to changes in the actual level of macroeconomic activity, as suggested by the so called Verdoorn law,[37] and that this fact opens the possibility of circles of cumulative causation. Exports, as a component of effective demand, will have an effect on these processes. The evolutionary approach, in addition, emphasizes the fact that the characteristics and magnitude of these effects

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[35] Patents are used to measure technology and wages for input costs. See Dosi Pavitt and Soete (1990), pp 175-185.

[36] On this see Pasinetti (1981).

[37] Verdoorn (1949).

are determined at a microeconomic level and seeks to bring this element into the analysis, as we will see later on.[38]

In this context, with international trade understood as a competitive struggle, a meaningful concept that defines the relative position of a country, in terms of its capacity to maintain or even increase its share in world income, is that of national competitiveness. The competitiveness of a country is defined as the global property related to the efficiency in mobilize resources and modify the technological and social characteristics of its economic activity.[39] The fundamental element of this definition is its dynamic content. Clearly, two key factors of this property will be the technological capabilities of the nation, and the effectiveness of its institutional setting in generating mechanisms of adjustment that not only move it towards its potential income, but also contribute to expanding this potential.[40]

Trade arguments have, in general, tended to focus on the analysis of balanced trade situations. This is analytically useful and has the virtue of acknowledging the existence of a mechanism in the international economic system which tends to make this relationship hold in the long run. However, trade imbalances have a significance that should not be overlooked because of long run considerations. The competitive lead of a country will usually be associated with an increase in its share of world exports and with periods of trade surpluses and outward capital flows (linked to the acquisition of assets abroad). These will be restrained or interrupted by currency appreciations.[41] The processes described will, in general, affect the competitiveness of the economy in question and will tend to bring trade into balance. However, the main point is that these processes are part of the way in which the higher competitiveness of an economy materializes in an increased share in world income and wealth.

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[38] See Verspagen (1993) and the reference to its model in section 3.5.

[39] This follows Mistral's (1983) definition (as quoted in Dosi, Pavitt and Soete (1990), p.150. and in Chesnais (1991)).

[40] The notion of national system of innovation points towards those dimensions of the competitiveness of a country which are at the basis of its capability to develop its technology and expand its potential income. See Nelson and Rosenberg (1993).

[41] We are taking here the simplifying view that exchange rate adjustments are the main mechanism that tends to enforce the trade balance condition. However, other mechanisms will also be at work which have similar effects such as increases in wages.

These general statements is as far as the argument can be developed without explicit consideration of what occurs at a sectoral level.

3.4.2 Sectoral diversity and aggregate dynamics

The foregoing argument has suggested that considerations at a sectoral level are essential for an understanding of key aspects of the role played by the technology element.

The first issue to consider is the relevance of the pattern of specialization in production for the growth potential of an economy. As it has been stressed by Pasinetti,[42] the major factor that drives the long run behaviour of demand patterns is the change in real income levels, rather than the changes in relative prices. In relation to specialization, the goods that offer more growth potential will be new goods, which can be visualized as being at the lower part of their Engel curves, and, in particular, those which are called to gain significant shares in expenditure. On the supply side, the considerations about specialization relate mainly to the potential of different sectors in terms of the opportunities that are associated with their respective technologies.

Therefore, the pattern of specialization matters: different patterns will in general entail different prospects of technological development and long term growth. The implications for international trade are immediate: in general, it would be advantageous for a country as a whole to be able to compete successfully on industries whose markets have good prospects of growth and which rely on key technologies.[43] This is more so, given the path dependent and cumulative nature of technological development and its direct links with production. Past and present patterns of trade and specialization in production will shape the future trajectories of technological development.

An additional element that has to be taken into account is the fact that the growth and technological development of a sector, in general, takes place within a wider group of interrelated sectors.[44] When the

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[42] Pasinetti (1981), pp. 71-72.

[43] See Amable (1993) for a more thorough discussion of this idea.

[44] Different concepts, each with its own particular connotation, have been put forward to capture the idea of the existence of particularly strong linkages and spill-over effects in terms of technological dynamism within groups of sectors: filières and growth poles (Perroux, 1969);

argument above, which was in terms of an individual sector, is extended to this level, it is not only the sum of the effect of individual sectors what matters, but also the linkages and spill-over effects within a group and with the rest of the economy. These elements will distinguish different groups of sectors in terms of their potential to foster economic development.

Clearly, the possibility of pursuing successfully a pattern of specialization varies considerably between countries. Each country can be seen as following a national trajectory of technological development which is defined by their historical pattern of specialization and technological development.[45] This trajectory has shaped the present technological capabilities of each country and is determinant of its possibilities for future development. A crucial issue from the point of view of international trade is the fact that there are overlaps in the direction in which different countries direct their trajectories for future development. In this context, international trade is a struggle for shares in world markets in which what is at stake for each country is the nation's potential for technological development and economic growth.[46] The large gaps that exist in the technological capabilities of different countries are particularly relevant in this competition. More often than not, it will be the advanced industrialized countries that will overlap in the high profile sectors and will compete in the corresponding world markets. Countries with lower levels of technological development will be, most of the time, imitators following their own specific trajectories.[47] This fact is reflected on the empirical evidence which shows that innovative activities are heavily concentrated in a reduced number of OECD countries.

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clusters of innovation (Freeman, 1982); and the concept of technological districts (Storper, 1992) which is inspired on Marshall's (1920) notion of industrial districts.

[45] See Zysman et. al. (1990) and Dosi, Zysman and Tyson (1990).

[46] Zysman et. al. (1990). See also Amable (1993).

[47] This fact is reflected in the North South trade literature in the widespread use of the assumption according to which the North innovates and the South is only capable of imitating.

3.4.3 The dynamics of patterns of specialization

The major trade theories in the equilibrium tradition have been mainly devoted to try to explain the patterns of trade specialization. There is not, however, a definite answer to this problem and empirical testing of rival theories have not yet delivered any conclusive results.[48] There is some consensus among economists in that patterns of specialization are not explained by a single factor but that it is a combination of different elements which explain these patterns. Although different theories agree on the relevance of elements such as natural resources, transport costs, tariffs and consumption patterns, there is dissent with respect to the factors which are considered more important and to the way in which the problem is conceptualized. The Heckscher Ohlin theory, for instance, focuses on the role played by international differences in factor endowments. These differences in combination with the difference in the intensity with which factors of production are used in different sectors are seen as the basis of the international patterns of specialization and trade. The Ricardian theory, on the other hand, centres on international differences in technology and wages, and looks at the trade implications of the associated differences in the relative costs of production within each country.

The evolutionary approach does not aim at giving an alternative explanation for trade specialization patterns of the kind offered by equilibrium theories. Its purpose is rather to explain how patterns of trade change. Patterns of specialization are seen as coming about as the result of an historical process of development along which, in parallel to the development of these patterns of specialization, the technological capabilities of the different nations have been built. Our specific interest here is to examine the role of technology in shaping trade patterns. In particular, we will look at the importance of technological diversity and technological change for the dynamics of trade specialization.

The point of departure is the Ricardian concept of comparative advantage but, in contrast to the equilibrium approach, no comparisons between hypothetical autarky and trade situations are made. Comparative

48 See Deardorff (1984).

advantages are defined in terms of the technological conditions that prevail at a point in time in countries which are already engaged in trade relations. At any particular moment, it is possible, in principle, to take a country and compare the average unit costs of each of its sectors with the corresponding world average unit costs, all measured in a common currency.[49] In this way, we would be able to determine the sectors in which the country has comparative advantage and disadvantage in world trade. The concept of comparative advantage so defined is a dynamic one. From this perspective, in the evolutionary analogue of a perfect competitive market in which unit cost is the only aspect that determines the competitiveness of an individual producer, a country would tend to gain market share in those sectors in which its unit costs are below average.[50] In these conditions, those producers with lower unit costs will have higher profits and more resources to grow, to improve their technology and to gain market share. Clearly, there are differences in other dimensions of firms behaviour, such as their efficiency in translating profits into growth, which may move things in a different direction. But, other things being equal, and with no new entrants to the industry, the group of firms with below average unit cost will be gaining market share at the expense of the rest of the firms in the industry. Thus, it is reasonable to expect that a country with average costs below world average will increase its market share in that sector.

The preceding argument can be translated into one based on the more general concept of competitiveness. The competitiveness of a firm would include all the other aspects that determine its competitive performance and not only those that are captured by its unit costs. In this context, leaving aside the problem of measuring this property, the competitiveness of a country in one particular sector is given by the weighted average of

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[49] By world average we mean the unit cost of each individual producer weighted by its participation in world markets. We are assuming for simplicity that each sector produces an homogeneous commodity. With differentiated goods, the problem is more complicated since, in order to maintain the argument, some criteria would have to be defined to adjust for different qualities and reduce all to a comparable measure.

[50] To be more precise, we assume a perfect market in which there are no differences in the selective pressure that the international markets exert on individual producers, where the national markets for the product are completely integrated and growing at the same rate and selection operates continuously, and in which selection operates at a maximum forcing all firms to sell their products at the world market price. On these see Metcalfe (1989a) and the references to his model in section 3.5.

the competitiveness of all its individual producers in that sector. It is this competitiveness relative to the world average that determines whether a country will be in a dynamic comparative advantage or disadvantage in that sector.[51]

One of the main results that has emerged from the empirical research on the relationship between trade and technology is the importance of the differences in the countries' technological capabilities, at both the global and the sectoral levels, as a determinant of the relative participation in world markets.[52] In sectors in which the technology gap between two trading countries is relatively large, the bilateral pattern of specialization will tend to be insensitive to changes in input prices and exchange rate. At a world-wide level, a country that has a considerable above average competitiveness in a sector and experiences an appreciation of its currency will lose market share relative to those countries which were close to it in competitiveness and now perform better than it. However, as long as its competitiveness remains above world average level, it will continue increasing its share in the world market.[53]

The links between the microeconomic detail and macroeconomic trends are made explicit by carrying the argument to the aggregate level. Firms that maintain an above average competitiveness in the sectors where they compete will increase their shares in their respective markets, at the expense of those below average. The dynamics of the aggregate competitiveness of a country will depend on its balance of winners and loosers. This balance will not only depend on the relative weight of the firms in their particular markets; the other critical consideration is the dynamism of the sectors in which they compete, from the point of view of both their market growth and technological potential. Whether a country will be gaining or loosing participation in the world market as a whole, will depend on this net balance. It is worthwhile stressing an important difference in the concept of competitiveness at the sectoral and the national levels. At a sectoral level, it was meaningful to think of

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[51] See Dosi, Pavitt and Soete, who define sectoral competitiveness at a sectoral and country level in terms of technology, input cost and market structure variables. Dosi, Pavitt and Soete (1990), pp. 154-163.

[52] See Soete (1981), (1987), Hufbauer (1970), Gruber and Vernon (1970) and Scherer (1992).

[53] See Cimoli (1988) and Cimoli and Soete (1988) for an illustration of the role of technology gaps in keeping specialization patterns [53]12.

competitiveness as a weighted average of that of individual firms, and it was useful to make comparisons between the country and the world averages as an indicator of dynamic comparative advantage or disadvantage. The situation is different in relation to the concept of national competitiveness. According to the definition given in section 3.4.1, it ought to be thought of as a set which includes not only a sum of sectoral competitiveness, but also the institutional components at a national level. These institutional components determine the ability to adjust toward the potential income of the country and to increase it through the development of its technology and the transformation of those same institutions.

3.4.4 Competitiveness, terms of trade and specialization

The competitiveness of individual sectors in a country does not exist in isolation, but depends on that of the other sectors with which it is interrelated and of the components of competitiveness at a national level mentioned above.

For analytical purposes, it is useful to distinguish between that part of the competitiveness of a country (and of its individual sectors) of a monetary nature, which is associated to the differences in the price of its primary inputs relative to other countries, and the part that results from 'technological' differences in productive efficiency. The dynamics of these two components of national competitiveness are not independent: international interdependence will, in general, lead them to move in opposite directions. Changes in the technological component of competitiveness of a country relative to that of its trading partners triggers monetary adjustments which tend to bring its trade into balance. These adjustments also affect the remunerations of the primary factors of production of the country relative to those of their trading partners. Thus, "technological gaps" are the basis of the gaps in income and in the remuneration to primary inputs[54] that are empirically observed in international comparisons.

In section 3.4.1, we argued that a country with a competitive lead, which was increasing its share in the world market and experiencing trade surpluses, will eventually experience exchange rate adjustments which will

[54] By primary inputs we mean those which are not themselves the result of a previous process of production.

tend to bring its trade into balance. In general, this sort of adjustment will not only take place in the leading country but in all those whose overall competitiveness is such that they experience trade surpluses at the prevailing exchange rates and input prices.

Clearly, exchange rate adjustments are not the only form of adjustment. Also increases in the remuneration of domestic primary inputs will increase costs relative to other countries and affect negatively the competitiveness of a country. These two types of adjustment are different: exchange rate movements respond to the situation in the market for international currencies, while changes in the prices of domestic primary inputs respond basically to claims within the economy on the distribution of the gains (or loses) in sectoral and national competitiveness. The difference between these two forms of adjustment is not a trivial one. It is not only important that they are created through different mechanisms, but also that they have a different effect on different sectors and, as a consequence, on the economy as a whole. This is so because of the different cost structure with respect to import content and participation of domestic primary inputs in different sectors.

Nevertheless, leaving all these differences aside, a common feature of these 'monetary' adjustments is that, by altering domestic costs measured in foreign currency, all firms in every sector will see their international competitiveness affected. Furthermore, within most sectors, there will be some firms whose costs were sufficiently close to the world average costs of their sector and which will see their dynamic comparative advantage (or disadvantage) reversed. The long run effect of these 'monetary' adjustments on the aggregate trade balance of the country will be the combined effect of two things: first, of their impact on aggregate macroeconomic activity and its implications on sectoral demands; and, second, of their effects on the competitiveness of each sector. The latter will depend, in turn, on the cost structure of the firms in each sector and on the distribution of firms' costs in these sectors. These two effects combined will determine the changes in the sectoral trade balances which add up to the change in the aggregate trade balance of the country as a whole. Whether the adjustment is via exchange rate or via changes in the prices of primary inputs, the tendency will be to neutralize the trade implications of the technological advantages and to bring the trade balance into equilibrium.

Finally, in relation to the effect on the patterns of specialization, all the considerations above are also relevant. However, with the qualifications that those considerations may introduce, one would expect that the patterns of specialization will be preserved in most sectors in spite of 'monetary' adjustments (i.e. adjustments in the terms of trade). Currency appreciations, for instance, will operate against the competitiveness of every sector of an economy. But it is only in those sectors where the competitiveness is near the sectoral world average, that one is likely to observe changes in the sign of the country's sectoral trade balance, that is, a reversal in the patterns of specialization.

3.5 Evolutionary models of trade and technology

In this section, we present two models in which mathematical theorizing is used to represent some of the ideas of the evolutionary argument and to explore with more rigour some of the relationships suggested in the verbal account of the previous section. The models presented below deal with a limited number of issues and by no means constitute a full formalization of the evolutionary argument. Nonetheless, they throw light on important aspects of this argument and help us to have a better understanding of the relationship between international trade and technology.

The first model is due to Verspagen (1993). The argument is largely macroeconomic, but the analysis centres on exploring in detail the role of diversity and intercountry asymmetries at a sectoral level. The structure of the model is explicitly evolutionary: technological diversity and institutional differences between countries and across sectors are introduced, and the market environment is conceptualized as a selection mechanism. The dynamics of the international economy are modelled through a system of difference equations.

The second model was developed by Metcalfe (1989a). This model looks at the microeconomic dimension of the process of evolutionary selection among competing technologies in a context of international trade. The model is used to highlight the relationship of these process with the changing patterns of dynamic comparative advantages and specialization. The framework used is evolutionary: the selective pressure of the market on competing technologies is the regulatory mechanism that drives the evolution of the patterns of international trade in the system.

3.5.1 Verspagen's model of technological change, trade and growth

This model, developed by Verspagen (1993), is aimed at analysing economic growth and the changes in patterns of specialization. The model focuses on different asymmetries that may exist between trading countries. It looks, in particular, at the role of diversity in productivity, learning and income elasticities. Such differences are considered across sectors and between countries. In the model, the market operates as a selection mechanism which affects the shares of each country in the world market of each sector. Endogenous technological progress is introduced in the form of productivity increases.

The model is dynamic and consists of a system of differential equations which is used to explore, through simulation, the path followed by variables such as growth rates and indices of specialization under different conditions. In this way, the behaviour of the system in response to the introduction of different asymmetries can be studied.

We will look here only at those aspects of the model that we consider most relevant and those parts of the specification which are necessary in order to give a general idea of its structure.[55]

The model considers multiple goods and countries. All goods are assumed to be produced by labour only and there are no profits. For each variable we will use superscript i to denote a country and subscript j to denote a sector and its associated commodity. The price of commodity j produced in county i, measured in domestic currency is given by,

$$P_j^i = \frac{W^i}{a_j^i} \tag{3.1}$$

where W^i is the nominal wage and a_j^i the productivity of labour.

Taking the simplest specification, which consists of assuming that the price is the only mode of competition in international markets, the competitiveness of country i in sector j will be given by,

$$E_j^i = \frac{1}{\epsilon^i P_j^i} \tag{3.2}$$

where ϵ^i stands for exchange rate in terms of an international currency.

[55] For the complete specification see Verspagen (1993), pp. 165-194.

The selection process is considered in terms of the import penetration in the market for each good within each country:

$$m_j^i = \frac{M_j^i}{C_j^i} \qquad (3.3)$$

where M_j^i denotes real imports and C_j^i represents total consumption of commodity j in country i.

Denoting by $m_{kj}{}^i$ the import penetration of country k in the imports of commodity j of country i, we can represent the average fitness of world producers of good j in the market of country i as follows,

$$\overline{E}_j^i = E_j^i \ (1 - \sum_k^{k \neq i} m_{kj}{}^i \ ) + \sum_k^{k \neq i} E_{kj} \ m_{kj}{}^i \qquad (3.4)$$

In the present case, in which price is the only mode of competition, average fitness is equal to average price. The first term on the right hand side is the fitness of country i in its own market, while the second term is the fitness of the rest of the world in that same market, which will be denoted as E_{wj}^i

It is important to stress that all the variables above will be changing with the evolution of the system. In order to represent this process, they should carry the additional subscript t to make it explicit that, in general, they will have a different value at each point in time. However, we have omitted these subscripts to avoid excessive notation and will only use them when strictly necessary, as it is the case in the following equation that expresses the operation of the process of selection:

$$m_{j_t}^i = m_{j_{t-1}}^i + m_{j_{t-1}}^i \ \Phi \left(\frac{E_{wj_t}}{\overline{E}_{j_t}^i} - 1 \right) ; \qquad 0 < \Phi < 1 \qquad (3.5)$$

Whenever the sectoral competitiveness of a country in its own market is below average, import penetration will increase, and the opposite will occur when competitiveness is above average.

Regarding demand, the following function is introduced to take into account the fact that, as the level of real income increases, the shares of each commodity in expenditure also change:

$$\frac{\partial S_j^i}{\partial R^i} = S_j^i \sum_{n=1}^{J} \tau_{nj} (S_n^i - S_n^{i*}) - (S_j^i - S_j^{i*}) \sum_{n=1}^{J} \tau_{jn} S_n^i \tag{3.6}$$

where R^i is the country's real income (obtained by dividing nominal income by consumers price index), S_n^i are the shares of good n, (n=1,...,J), in country i total consumption and S_n^{i*} represent the shares in consumption when the country's real income is infinitely large. This term captures the idea of a tendency to saturation in the demand for every good. Finally, the τ's are parameters, with τ_{jj} equal zero and all other greater or equal to zero. Under this specification the share in consumption of a commodity starting from zero consumption describes an S shaped pattern. This attempts to capture the idea, stressed by Pasinetti, that income growth is the dominant factor shaping the patterns of demand for goods.[56]

There are other elements of the specification which characterize the model which for reasons of space will only be mentioned here briefly. Trade is assumed to be balanced all the time and the exchange rates are assumed to adjust partially towards the level consistent with purchasing parity power. In each country, the level of employment in each sector is determined by the level of macroeconomic activity which, in turn, depends on aggregate demand. The changes in wages in each period are assumed to be positively related to productivity growth and negatively related to the rate of unemployment of the countries. Finally, technological change takes the form of productivity growth in each sector. This is done by means of the following sectoral functions, which are similar to Kaldor's aggregate technical progress function:[57]

$$\hat{a}_j^i = \lambda_j^i \, (\hat{Q}_j^i)^{1/\gamma_j^i} \; ; \qquad \lambda_j^i > 0 \; , \quad \gamma_j^i > 0 \tag{3.7}$$

where ^ denotes a rate of growth, Q_j^i is physical output of commodity j in country i, and λ_j^i and γ_j^i are sectoral and country specific learning parameters. In this way, the cumulative character of technological progress is incorporated in the model, and the possibility is opened for circles of cumulative causation like the ones described in the previous section.

56 Pasinetti (1981).

57 Kaldor (1957).

To analyse the effect of different asymmetries, Verspagen performs a series of simulations using a three country-two sector model. We will focus mainly on the effects on rates of growth and on the changes in patterns of specialization.

The basic points that emerge from the simulations are the following. The model exhibits increasing returns: there are scale effects which result on higher income growth. These are associated with two main factors: the size of the sectors and learning. Therefore, with identical learning coefficients among sectors, growth will be higher in a situation when there are sectors which are relatively large than when all sectors are of the same size. This result holds independently of whether or not the larger size of the sectors is associated with trade specialization. Secondly, regarding learning, if a country specializes in a sector where it has learning advantages, this will trigger scale effects which translate on higher growth rates. The introduction of asymmetries between countries either in consumption structures or in learning rates or in both, generates growth differentials. There are in the model opposite feedback effects on competitiveness coming from cumulative learning and wage dynamics. These effects offset each other to a different degree at different times in the evolution of the system. Thus, along the different periods for which the simulation is made, the growth rates in the countries show cyclical patterns; the growth differential between the countries not only varies but may also change its sign. Finally, regarding trade, the cumulative nature of technological change leads to patterns of specialization which can be associated with differences in learning rates or in patterns of consumption or with a combination of both.

3.5.2 Metcalfe's model of evolutionary selection and trade

The following model, due to Metcalfe (1989a), analyses at a micro level the implications that technological diversity has for international trade. It focuses, in particular, on the role of the selection process in changing the economic weight of different technologies, and on how this process relates to the dynamics of trade specialization. Technological diversity is modelled in terms of the differences in unit costs of firms competing in the production of the same homogeneous good. There is no technological change in the strict sense of the word, since there is neither innovation nor imitation. However, as we will see below, the process of selection leads to declining average costs at a sectoral level. The model uses an explicitly evolutionary framework which can accommodate different types of market environment and may be used to analyse different dimensions of the diversity that exists among competing firms.

The model considers two trading countries A and B and analyses a single industry and an homogeneous good. This good can be produced by multiplicity of different technologies. For simplicity, each technology is associated with an individual firm. The distribution of these different technologies is assumed to be different in the two countries. As we mentioned above, the technology set is given: there is no technological change, nor is there capital mobility.

The international market is supposed to be growing uniformly in both countries at a rate g_d. The environment is one of international markets completely integrated in which selection operates continuously and the selective pressure is such that the law of one price prevails:

$$P = P^A = \epsilon P^B \tag{3.8}$$

and a strong bankruptcy rule applies:[58]

$$h_r^A \geq P \quad , \quad h_r^B \geq \epsilon P \tag{3.9}$$

where P is the international price, P^A and P^B are the prices in countries A and B respectively, ϵ is country B exchange rate in terms of A's currency; and h_r^A and h_r^B are the unit costs of a particular firm r in countries A and B, respectively.

Thus, at a point in time the average unit cost in each country is equal to the weighted average of the unit costs of all the individual technologies in use:

$$\overline{h}^A = \sum_r s_r^A \, h_r^A \tag{3.10a}$$

$$\overline{h}^B = \sum_r s_r^B \, h_r^B \tag{3.10b}$$

where the s_r^j, j=A,B denote the shares of the different technologies in their respective country's output.

[58] Any firm with negative profits quits the industry. Note that the specification of the market environment implies that output will be equal to capacity for all firms with the exception of those in the margin for which this may or may not occur.

The selection process over the different technologies leads to differences in profitability, which result on differential growth of each technology. The extent to which profits are translated into growth will depend on the propensity of the firms to accumulate. In order to isolate the effect of the diversity in technologies, the propensity to accumulate from profits is assumed to be the same across firms and countries. Thus, the rate of growth of a technique in each country is given by

$$g_r^A = f(P - h_r^A) \tag{3.11a}$$

$$g_r^B = f(P - \epsilon h_r^B) \tag{3.11b}$$

where f denotes the propensity to accumulate. Thus, sectoral capacity growth rates in each country are given by

$$g^A = \sum_r S_r^A g_r^A \tag{3.12a}$$

$$g^B = \sum_r S_r^B g_r^B \tag{3.12b}$$

The international performance of a country in the industry is measured by its share on world production.[59] Let e be the share of country A in world production. Since (1-e) is B's share, we can concentrate on what happens with A. The share of country A will be changing at a rate equal to:

$$\frac{de}{dt} = e[g^A - g] \tag{3.13}$$

where $g = eg^A + (1-e)g^B$ is the growth rate of world capacity.

Substituting from (3.10) in (3.12) and noting that $\bar{h} = e\bar{h}^A + (1-e)\epsilon\bar{h}^b$ is the world average unit cost level, equation (3.13) can be rewritten as,

$$\frac{de}{dt} = e[\bar{h} - \bar{h}^A] \tag{3.14}$$

This equation expresses, at an aggregate level, the process of selection that operates at a microeconomic level. If the average unit costs of the country are below world average, the country will increase its share in the world market of the industry, and the opposite will occur if they are above world average.

The selective process operates by increasing the economic significance of the more efficient technologies:

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[59] Statements about shares in production can be directly translated in terms of participation in export markets. See Metcalfe (1989a), p. 220.

$$\frac{ds_r^A}{dt} = s_r^A\, f(\overline{h}^A - h_r^A) \qquad (3.15)$$

Thus, it continuously reduces the average unit cost in each country, inducing changes in their relative selective advantages.

$$\frac{d\overline{h}^A}{dt} = \sum_r \left(\frac{ds_r^A}{dt}\right) h_r^A \qquad (3.16)$$

In a context of two countries and multiple industries, the argument developed so far leads to a dynamic reformulation of the chain argument of comparative advantage. Let us denote the average unit costs of country i in sector j as $\overline{h}_j^i$. At any point in time, it will be possible to rank all sectors in terms of the relative average unit costs in the two countries, with the exchange rate breaking this chain:

$$\frac{\overline{h}_1^A}{\overline{h}_1^B} < \ldots < \frac{\overline{h}_r^A}{\overline{h}_r^B} < \epsilon < \frac{\overline{h}_{r+1}^A}{\overline{h}_{r+1}^B} < \ldots < \frac{\overline{h}_n^A}{\overline{h}_n^B} \qquad (3.17)$$

It follows from the argument above that country A will have a selective advantage in all those commodities to the left of the exchange rate and will be gaining market share, while the same is true for country B with respect to the commodities to the right. But as the model also shows, the selection process will continuously change average costs. Therefore, in those sectors for which the ratio of average unit costs is close to the exchange rate, a country may pass from a positive to a negative dynamic comparative advantage and vice versa.

This point can be seen more clearly in a two commodity model. We will assume that at time t country A has a selective advantage in commodity 1 and country B has it in commodity 2. That is:

$$\frac{\overline{h}_1^A}{\overline{h}_1^B} < \epsilon < \frac{\overline{h}_2^A}{\overline{h}_2^B}$$

For simplicity we assume that the exchange rate ϵ is fixed. Equation (3.14) can be rewritten as:

$$\frac{de_i}{dt} = e_i(\overline{h}_i - \overline{h}_i^A) = e_i(1-e_i)\, f[\epsilon\overline{h}_i^B - \overline{h}_i^A]\ ; \qquad i=1,2 \qquad (3.18)$$

$\epsilon\overline{h}_i^B - \overline{h}_i^A$ expresses the selective advantage of country A relative to B in commodity i and will be denoted by Δ_i. Note also that

$$\frac{d\overline{h}_i^A}{dt} = \sum_r \frac{dS_{ri}^A}{dt} h_{ri}^A = -fV(h_i^A)$$

where $V(h_i^A)$ is the variance of unit costs for $h_{ri}^A < P_i$.

Similarly, for B $\epsilon \frac{d\bar{h}_i^B}{dt} = -f\epsilon^2 V(h_i^B)$ and $V(h_i^B)$ is the variance of unit costs.

Thus,

$$\frac{d\Delta_i}{dt} = f[V(h_i^A) - \epsilon^2 V(h_i^B)] \tag{3.19}$$

This means that "Country A's selective advantage increases or declines according as the variance of unit costs across the technology set in A is greater or less than the corresponding variance in country B, when both variances are measured in home (A's) currency."[60] Therefore, a persistent situation in which $\frac{d\Delta_1}{dt} < 0$ and $\frac{d\Delta_2}{dt} > 0$ will eventually lead to a reversal of the selective advantages of the two countries. In relation to this, four points are worthwhile emphasizing. First, that, in general, the loss of selective advantage of the two countries will not be simultaneous. As a consequence, one of the countries may enjoy a selective advantage in both commodities for a period of time. Second, that selective advantages per se tell us nothing about the net balances of the countries in the commodities in question. They only tell us the direction in which those balances are moving. Third, that, as the prices of the commodities change with the process of selection, the variances of unit costs will change, which can reinforce or offset the tendencies in the selective advantages of the countries. Finally, to the extent that the exchange rate and the prices respond to the disequilibria in the aggregate trade balances of the countries, their movements will also affect the selective advantages and the way in which they move in time.

Clearly, situations in which one of the two countries exports both commodities, while the other runs an overall deficit, will not be sustainable, since foreign exchange reserves and credit will eventually be exhausted. International equilibrium is possible only when each country has a selective advantage in a different commodity.

In a setting like the one assumed in the model, in which there is no technological change, the process of selection drives average cost in each country towards those of the best practice. Under the long run restriction of balanced trade, the system would tend to a terminal situation in which

[60] Metcalfe (1989a), pp. 225-226.

each country specializes in those commodities in which it has a comparative best practice advantage. However, in a more real situation, innovation and imitation will continuously change the conditions which define that terminal equilibrium.

3.6 Concluding remarks

One of the main ideas highlighted throughout the argument presented in this chapter is that the relationship between international trade and technological development is better understood in the context of an evolutionary process which takes place at different but interrelated levels. At the more aggregated level, this process is related to the patterns of growth, to the evolution of trade balances and exchange rate movements, and to the changes in the relative competitive position of the countries engaged in trade relations. The more microeconomic aspects of the process are those associated with the competition of individual firms and technologies in international markets, and with the way in which the structure of industries and the technologies change.

The general argument on international trade and the two models reviewed have emphasized the interrelationship that exists between the different levels at which the evolution of trade patterns and the development of technologies can be observed: macroeconomic phenomena arise as an aggregate of microeconomic behaviours and, at the same time, what occurs with aggregated variables, such as exchange rates and rates of economic growth, is a fundamental determinant of the evolution at the microeconomic level.

The perspective of international trade that is adopted in the evolutionary approach is that of a competitive struggle, and the analysis focuses on the changes in the relative position of firms, sectors and countries along the different dimensions that reflect their competitive performance.

The formal models of section 3.5 have looked in more detail at some of the issues mentioned in the general evolutionary argument. This has required, in general, to resort to a stylized representation of complex phenomena; but has, in turn, allowed to put the ideas in a more rigorous and structured framework. The model by Verspagen explored the implications of international interdependence. This model highlights the importance of international asymmetries in technology and demand structures and of the dynamics of wages and technological change for the evolution of patterns of specialization and relative income growth of the trading countries. Due to its aggregated nature, it does not account for the diversity that exists at the level of firms and technologies within each sector. This limitation is reflected in the tendency of the model to produce situations of complete specialization. The question of intra-sectoral diversity is analysed in Metcalfe's model. This model, while analysing the operation of the selection process, illustrates the fact that the presence of firms with different costs within each sector of the trading countries is at the basis of the incomplete specialization that characterizes international trade.

A general message that emerges from the two evolutionary models reviewed in this chapter is the open nature of the paths that the evolution of the international economic system follows. The relevance of technological change, and of the mechanisms that generate it, is a central theme in the evolutionary argument. However, while technological diversity and the mechanisms of selection have been found to be amenable to formal modelling, the introduction of technological change, the other major mechanism driving the evolutionary process, is more problematic. Its treatment in the model by Verspagen is through the introduction of parameters. This has helped to explore some of the relationships between trade and technological development; however, it does not allow us to advance much in the understanding of the process of technological change and its relationship with the evolution of trade.

Although the process of technological change has been subject of formal modelling along evolutionary lines, these models have not been yet extended to the analysis of trade. In our opinion, progress in this direction requires of a better understanding of the way in which new technologies emerge and diffuse internationally, give origin to trade flows and modify trade patterns. The next chapter will focus on the analysis of technological change. This will provide a framework for the second part of the thesis where we will undertake two case studies. The purpose of these studies is to contribute to deepening our understanding of the process of international competition at a microeconomic level and of the way in which the diffusion and development of a technology relates to the emergence and evolution of trade flows.

4 Technological change as an evolutionary process

4.1 Introduction

The theoretical and empirical research on technological change is one of the research traditions that has made the most significant contributions to the emergence of the evolutionary approach to economic theory. In this chapter we draw on a number of these contributions in order to build the theoretical framework that will be used for the analysis of technological change in the case studies of chapters five and six. In sections 4.2 to 4.4, we have made a selective review of concepts and ideas from the literature on technological change. Our purpose has been to articulate those ideas in a framework that is useful for the empirical study of specific technologies. Therefore, our review of the literature has been based on two criteria. First, that the concepts could be made operational for empirical analysis. Second, that the concepts and propositions were consistent with the evolutionary approach adopted in this work. Section 4.5 is an introduction to the case studies presented in the second part of the thesis. There, we describe how some of the concepts introduced in the other sections have been applied to two innovations: indirect electrostatic photocopying and linear low density polyethylene. Finally, section 4.6 states the basic ideas of the evolutionary perspective of technological change on which the empirical analysis of the next two chapters is based.

4.2 Technology and the definition of industry

The definition of technology used in this work is a broad one. Technology is considered to include not only the material elements employed and obtained in the process of production, but also the individual and collective knowledge and skills of the people who participate, and the elements of organization that articulate them in the process of production. We depart, in particular, from the interpretation of technology that limits the concept to its artifacts dimension by defining it as the set of techniques available for the production of a specific good.[1]

The distinction between techniques and technology is an important one. A perspective of technology that overlooks its human and institutional elements is simply inconsistent with the analysis of technological change as an evolutionary process. The changes that one observes at the level of artifacts are only one aspect of more fundamental changes in the knowledge base, skills and decision rules of both the individual and institutional elements of the organization that deploys a technology.

While recognizing the knowledge dimension of technology, it is also important to distinguish technology from science. As E. Layton has pointed out, "the rules of science refer to nature and the rules of technology refer to human artifice. The function of technology is to provide a rational basis for design, not to enable man to understand the universe."[2]

It would be equally wrong to look at science as producing the knowledge and at technologists as merely applying it. The relationship between science and technology is better described as a dialogue in which each contributes to the development of the other. Sometimes, advances in technology precede scientific discovery and pose problems that require scientific explanation; in other occasions, scientific discoveries do provide de spark for invention and innovation.

4.2.1 The three dimensions of technology

Following Layton, we conceive technology as involving a spectrum of activities and objects with ideas at one end, techniques at the other and design in the middle.[3] It is useful, in addition, to distinguish between three dimensions of technology that overlap in different degrees as we move within that spectrum, namely, the knowledge, the routine and the artifact dimensions of technology. The distinction between this three dimensions and an understanding of how they interrelate constitutes a major source of

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[1] That is, our concept of technology is broader than the traditional input-output approach of classical and neoclassical economics. Our interpretation of technology also differs from reformulations of this approach which subsume knowledge, skills and organizational elements under the all purpose category of inputs. (See, for instance, Gomulka (1990), pp. 4-6).

[2] E. Layton (1974) p. 40.

[3] Ibid, pp. 37-8.

insights in the analysis of technological change. In general, it is at the level of artifacts, i.e. in the techniques, where the manifestation of technological change is more evident. However, to assess the significance of such changes, to understand the process by which they come about and to identify the determinants of their rate and direction, it is necessary to move in the spectrum and look into the parallel changes that occur at the level of knowledge and routines.

The existing devices that one identifies with technology are the materialization of the achievements of specific problem-solving activities. Particular kinds of knowledge underlie behind these activities: theoretical and practical, codified and tacit, which provide the rational basis for the design of products and their related processes. This problem-solving oriented knowledge is intimately associated with the satisfaction of human needs and with the values of society.

The final element in our triad is what we have denominated routines. The term routine is used in a broad sense as habits of thought, skills and practical courses of action held individually and collectively within the organization that deploys a technology. These routines consist of ensembles of decision rules, which express themselves in individual and collective skills and procedures.

4.2.2 The representation of technology in a characteristics space

The artifact dimension of technology relates to a transformation process in which energy and materials of one form are added value by transforming them into energy and materials of a different form.[4] The higher economic value of the products of this transformation process is obviously related to, and dependent on, the fact that they respond to the satisfaction of needs for which there is will and capacity to pay.

When a specific technology is considered at this level, three aspects of it are made evident, namely, the transformation process itself, its product, and the services that the latter provides to its user. On this basis, as Saviotti and Metcalfe have proposed, it is possible in principle to characterize technologies by representing each of these three aspects by means of interrelated multidimensional characteristics vectors. This

[4] Metcalfe and Boden (1991), p. 710-711.

framework can be used to give a detailed description that informs us about how characteristics of the process translate into the technical characteristics of the product and how the latter relate to performance.[5]

4.2.3 The paradigmatic character of technology

The knowledge dimension of technology refers to a body of concepts and theories that enable the design and operation of the process of production. This knowledge conforms to an understanding of the process, of its relationship with the needs it satisfies and (of fundamental interest to us) of potential directions for further development of the technology. This last idea has been advanced in different ways by researchers in the area of technological change.[6] Dosi has expressed it through the generic notion of technological paradigm that he defines as a "'model' and a 'pattern' of solution of *selected* technological problems based on *selected* principles derived from natural sciences and on *selected* material technologies...[which] ...embodies strong presumptions on the *directions* of technical change to pursue and those to neglect"[7] (stress in the original).

The recognition of this, less visible, aspect of technology is crucial in the study of the behaviour of the individuals and organizations involved in the evolutionary process of technological change.

4.2.4 Routines, learning and inertia

Organizations compete by deploying specific technologies. The formation of routines is essential for their command of such technologies and for the mere existence of the required individual and collective skills and problem solving strategies. The emphasis on both the individuals and the organization is important since, paraphrasing Henderson and Clark, the skills and knowledge of individuals translates within the organization into a collective competence, while the organization itself is defined in terms

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[5] Saviotti and Metcalfe (1984).

[6] Rosenberg's (1976) "focusing devices", Sahal's (1981a,1981b, 1985) "technological guideposts", Nelson and Winter's (1982a) "technological regimes" and Dosi's (1982) "technological paradigms" are concepts very close in meaning which have been put forward to capture this idea.

[7] Dosi (1982), p. 152.

of a set of communication rules.[8] From this perspective, the specific technology that an organization commands can be characterized, following Nelson and Winter, as a (complex) routine.[9]

This routine dimension of technology is essential for the functioning and effectiveness of the organization that articulates the production process. The formation of habits of thought, action, interaction and communication are an integral part of the learning process and a requisite for the mere existence of the individual skills and of the collective competence of the organization.

The other side of routines is the element of inertia that they carry with them. Technological change involves, in general, modifications in components of that routine and their re-articulation in a new coherent routine. There are, however, limits to the extent and speed at which the organization can make such changes without losing its framework of reference and ceasing to be effective. Clearly, routines are not the only elements that introduce inertia. Factors like sunk costs, contracts, and other kind of commitments operate in the same direction. Whatever its source, inertia is essential in preserving variety and is of fundamental importance for the evolutionary process, since for the selection mechanism to operate, variety has to be stable relative to the speed with which selection operates.[10]

4.2.5 Technology as a system

A final point that is important to stress is the systemic nature of technology. In words of Sahal, "...a system is characterized by the multilateral interdependencies between its parts. That is to say, a system is an *ensemble harmonique*. Thus, the parts of a system unlike those of an aggregate, acquire their characteristics from the whole."[11] This systemic nature is present in the different dimensions and aspects that we have reviewed. A technology constitutes a working whole in which all the elements that we have mentioned are combined. The different elements that

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[8] Henderson and Clark (1990).

[9] Nelson and Winter (1982a).

[10] Metcalfe (1989b), p. 57, 62.

[11] Sahal (1981b), p. 4, n. 1.

integrate a technology in their knowledge, artifact and routine dimensions, only acquire full meaning and become functional as articulated components of the technology system.

4.2.6 A technology based definition of industry

The conceptual apparatus presented so far includes concepts that are, in some respects, very general. An advantage of this is that it allows us to think about technology at different levels of abstraction. In order to make our theoretical framework operative for the analysis of the evolutionary process of technological change, it is necessary to distinguish between different levels of abstraction and introduce more precision in our concepts as we move towards more concrete levels.[12] Our first step in this direction will be to introduce Nelson and Winter's concept of technological regime,[13] interpreted as a basic design, that is, a set of basic design parameters associated with key aspects of a specific technology. The cognitive element of this concept has been emphasized by Metcalfe and Boden. Following these authors, a technological regime is seen as consisting of a "hard core of fundamental scientific and engineering principles" adhered to by a group of firms, which gives coherence to their technological activities. Thus, adherence to such principles defines a firm as belonging to the population of firms working on that regime. As the authors note, "While these principles may be subject to elaboration over time, they are beyond question as agreed principles held in common by all business units operating within the regime."[14]

The concept of technological regime leads us immediately to the question of the definition of industry that is appropriate to our purposes. By industry, we will understand here the population of business organizations that carry on the production and the commercialization of the products associated with the technological regime within which all operate.[15]

[12] See Hagerdoorn (1989), pp. 95-98

[13] Nelson and Winter (1982a).

[14] Metcalfe and Boden (1991), p. 714.

[15] The definition of industry used here is of course arbitrary; different criteria can be used to render an equally valid definition. The merit of our definition rests, thus, on its usefulness for the purposes of the present analysis.

Therefore, the industry is a population of business units that is defined by the technology that is common to all of them. Although we will be using the terms firm and business unit interchangeably, it is necessary to emphasize that our concept of firm is more restricted than the meaning conveyed by the every day use of the word. The firm-business unit equivalence will normally hold only for small enterprises; modern firms are usually an aggregation of business units within a larger organization.[16]

All business units within an industry share the common knowledge base defined by the technological regime and also show some resemblance in other dimensions of their technologies such as artifact and skills involved in the production process and other routines within the organizations.

4.2.7 Technological diversity

In practice, technologies are firm specific. Firms compete on the basis of specific designs and develop capabilities to be effective in the context in which they operate. As the argument in section 3.2 of the previous chapter suggested, this diversity at the industry level plays a central role in the evolutionary process.

It is possible to move to an intermediate level of abstraction between the notion of technological regime and the specificity of each firm's technology and distinguish a relatively small number of competing design configurations within an industry. These design configurations are different "operational routes" to the design and production of specific artifacts.[17] They are a set of particular technological solutions to the problems defined by the regime, which have emerged, diffused and survived in the industry. In this context, each of the specific technologies of individual firms in an industry will be found to correspond to one of these design configurations.[18] The notion of design configuration is a key concept; it allows us to deal with diversity and helps to highlight similarities and differences in the technological routines of the firms.

Competing firms innovate and develop existing designs. They create market niches and may introduce new design configurations and, in this way,

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[16] Metcalfe and Boden (1991), p. 710.

[17] Metcalfe and Boden (1991), pp. 714-715.

[18] See Georghiou et. al. (1986), p. 33-35.

they increase variety.[19] Imitation operates in the opposite direction and tends to create similarity. However, the pervasiveness of diversity is evident for any casual observer. Inter-firm differences go beyond those in their technologies; their sources are varied: the structure of the firm and its links (when this applies) with larger organizations, its history, and ultimately the diversity at the level of the individuals that constitute the firm. These differences are at the basis of the different behaviour and market performance of the firms that drive the evolution of the industry.

4.3 Technological change and the development of an industry

In the previous section we presented a framework that allowed us to characterize a technology and its associated industry. The discussion there was, most of the time, of a static flavour. However, to use the term static when talking about technology is almost a contradiction. In this section we move on to discuss technological change and we focus on the specific question of the co-evolution of a technology and its industry. In what follows, we make a selective review of some of the main ideas of the literature of technological change regarding the evolution of technology and its associated industry.[20]

A landmark in most of the theoretical and empirical work on technological change, since the early studies of the 1950s to the present day, has been the focus on the major breakthroughs that mark the birth of new industries. Independently of whether or not these innovations are the direct object of study, their role as point of reference is widespread in the literature on technological change. Traditionally, these innovations have been termed "radical". Here we take a radical innovation as our starting point. Our purpose is to highlight the most relevant aspects of its evolution on the basis of the framework presented in previous sections. In our opinion, the analysis of technological change and the assessment of its significance is often hampered by two problems. First, a lack of

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[19] In some occasions, a firm may even break with the mould established by the regime of the industry to which she belongs and open the possibility of the development of a new industry.

[20] Surveys of the literature of technological change are found in Gomulka (1990), Stoneman (1983) and Coombs et. al. (1987). On innovation, see Binswanger and Ruttan (1978) and Dosi (1988). On diffusion, see Metcalfe (1988).

precision in establishing the relationship between the concepts of industry and technology. Second, insufficient attention to the knowledge and routine dimensions of technological change and to the way in which they relate to the changes observed at the level of artifacts. It is hoped that the framework presented in this chapter will move us towards overcoming these problems.

4.3.1 On the interrelation between innovation and diffusion

One of the most important achievements of the research on technological change has been its contribution to a clearer perception of the relationship between innovation, diffusion and industrial development. Recent research has called our attention towards three important facts. First, that innovation is a rather continuous process that plays an important role in shaping the process of diffusion of a technology, while the latter modifies the conditions on which further innovation takes place.[21] Second, that the environment in which a technology develops is continuously shaped and to a certain extent created, by the processes of innovation and diffusion themselves.[22] Both the technological and the economic aspects of the immediate environment relevant to the industry are greatly influenced by the patterns of innovation and diffusion.[23] Finally, and of particular interest to us, is the fact that the firms themselves and the characteristics of the industry co-evolve with the technology.

There are two major streams in the literature of technological change that have converged in the exploration of these issues. The first is the literature on the relationship between the life cycle of a technology and that of its associated industry. The second is the research on innovation and diffusion of innovation in the Schumpeterian tradition. In the following three subsections we present very succinctly the main ideas of these two lines of research in relation to the co-evolution of technology and industry. Later in the chapter we attempt a synthesis based on these two streams of literature in order to discuss the factors that determine the rate and direction of technological change.

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21 See Georghiou et. al. (1986), p. 79.

22 See Amendola and Gaffard (1988), Amendola and Bruno (1990).

23 See Freeman (1990a), Hagerdoorn (1989) and Georghiou et. al (1986).

4.3.2 The life cycle of a technology

The product life cycle hypothesis rests, as the term suggests, on the analogy with the life cycle of living organisms in biology. Among the earliest proponents of this idea were Muller and Tilton who noted that new industries where created by the occurrence of major innovations and developed as less radical innovations were introduced.[24] As we saw in chapter 3, the life cycle hypothesis was also present in the writings of Vernon and Hirsch on international trade. The basic idea is that of a pattern of development which follows a series of stages: birth, growth, maturity and decline. From the perspective of the innovation and diffusion aspects of technological change, the life cycle expresses itself in two superimposed patterns of innovation and diffusion. With respect to innovation, the early stage represents a fluid period with frequent changes in the design of the product and of its associated process. This is followed by a tendency to standardization. This is a stage in which the emphasis shifts towards process innovations that seek to exploit economies of scale and reduce costs. A slow down in innovative activity characterizes the mature stage. Finally, the decline phase is in general related to the emergence of a new technology that displaces the old one. Regarding the process of diffusion that runs in parallel, the pattern followed during the life cycle can often be approximated by an S-shaped trajectory, which can be observed in different measures of market penetration. That pattern represents the different rates at which such penetration occurs during the introduction, growth and maturity phases. Less research has been done on the pattern followed by declining industries but it suggests that decline would follow an inverted S pattern.[25]

The basic scheme presented above has been subsequently refined as empirical research has brought to the surface additional elements. A first issue is that the sharp dichotomy between product and process innovation has proven to be inadequate. In some cases it may be useful to think of product and process innovations as separate. However, there are instances, such as cost reduction innovations that relate to the use of new materials,

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[24] Muller and Tilton (1969)

[25] See Chapman (1991) and Markusen (1985).

which convey significant changes in both process and product design.[26]

A second question is that, as several authors have pointed out, the biological metaphor can be in many cases misleading. There may be changes in the economic environment, or significant innovations within the regime, which can be the basis for de-maturity and for a reversal in the trends followed by a technology. A pattern of diffusion different to the S shaped pattern may result from these changes.[27] Furthermore, during its diffusion, the technology changes, different designs compete in the market and new generations of artifacts displace old ones. Thus, the path of diffusion of a technology that one observes is, in a sense, an aggregate of curves corresponding to different design configurations.

The question of the maturity is central to the analysis of the evolution of a technology and of its industry. There are limits to how much a given technology can be improved.[28] It is important to bear in mind the limits defined by a technological regime when judging innovations in order to distinguish whether we can talk of de-maturation or, rather, of the emergence of a new regime. Another important consideration is that, as Georghiou et. al. have pointed out, maturity is also largely a socio-economic phenomenon. It depends on the collective expectations of those involved in developing a technology with respect to the profitability of attempting further developments.[29] The de-maturation that has occurred in some industries after economic changes like the oil shocks of the 1970s and also with the effect of pervasive new technologies such as microelectronics illustrates the fact that both technological and socioeconomic aspects are at the basis of the phenomenon of maturity.

4.3.3 The dominant design hypothesis

The emergence of a dominant design is a theme intimately related to the

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[26] Sahal (1985).

[27] See Iwai (1984a, 1984b), Abernathy and Clark (1985), Nelson (1992), Durand (1992).

[28] See, for instance, Sahal's (1981a, 1985) discussion on the fact that increases in the size of an object require, after a certain point, if it is to remain functional, a qualitative change that alters its morphology and structural properties.

[29] Georghiou, et. al. (1986).

life cycle idea.[30] According to the dominant design hypothesis, the fluid period in the development of a technology, characterized by active experimentation in product technology, comes to an end with the emergence of a dominant design. This dominant design incorporates a number of basic choices that are not reviewed any more in subsequent designs but are only further refined and elaborated upon.[31] Following Clark, the emergence of a dominant design can be characterized as the introduction of a well fitting design that receives market ratification and clarifies aspects of the consumer environment. As a result, items of the research agenda once opened become closed and development follows along narrowing lines.[32] As presented above, the image created by this story is one of superiority of the dominant design which imposes over competing alternatives. However, as Nelson has noted, there are other stories about the way in which a dominant design becomes established.[33] There is the possibility of "locked-in" phenomena, brought about either by the concentration of resources on a design that leads to increasing returns or, in technology systems, by early starts that create switching costs derived from interrelatedness and networking with other technologies.[34] This gives room for factors different to strict technological merit, such as small events and chance, to play a role in the establishment of a dominant design.[35]

The dominant design hypothesis has received confirmation by a number of case studies which, as Utterback and Suárez note, have been limited to assembly products.[36] Studies of industries like automobiles, tractors and aviation illustrate the convergence of different manufacturers towards a number of basic design concepts, which leads to the standardization of the product and to the passage to a new stage in the life cycle of the technology.

The dominant design hypothesis is a source of valuable insights;

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[30] Abernathy and Utterback (1978).

[31] Henderson and Clark (1990), p.14.

[32] Clark (1985), p. 246.

[33] See Nelson (1992).

[34] See Arthur (1988) and David (1985).

[35] See for instance David and Bunn (1990).

[36] Utterback and Suárez (1993), p. 2.

however, its universality is still open to question,[37] at least as it is applied to the typical cases mentioned above. Part of the problem lies in the fact that the hypothesis has been stated, in most cases, in terms of the product or the industry rather than as the technology life cycle idea that we have presented here. In technologies such as chemical processing, it is often the case that the innovations do not rest so much in the product itself but in the process. A good example of this is the Haber-Bosh process for the synthesis of ammonia.[38] Another example is polyethylene, which had been synthesized long before the introduction of ICI's high pressure process. In the chemical industries, the search for processes with high yields and based on cheap and relatively abundant raw materials have been central to innovation. This suggests that, if the dominant design idea were to apply at all in such cases, it would have to focus more on process rather than on product design. A second consideration is the fact that scaling up in these industries is a process that is central from the outset. Thus, the idea that the emergence of a dominant design precedes the stage in which innovative emphasis is put on achieving economies of scale does not follow in the way it does for assembled products.

Independently of the question of the universality of its applicability, the concept of dominant design offers useful guides for the analysis of the development of technology. This idea can be directly related to the concept of design configuration of the theoretical framework presented earlier in this chapter. There may be different designs coexisting in an industry. A single dominant design may emerge in some cases with complete or virtual elimination of others, but this will not necessarily happen in every industry. One reason for this is that markets are not homogeneous and different configurations may enjoy advantages in different niches. Another reason is the diversity that is inherent to the industry. Nonetheless, independently of whether a single design imposes itself or more than one coexist, the general idea of some configurations being abandoned while elements of design become firmly established with the development of a technological regime seems to be a plausible

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37 See Nelson (1992).

38 See Haber (1971), pp.85-97.

generalization.[39]

4.3.4 The parallel development of the technology and the industry

A first aspect of the relationship between the development of a technology and that of its industry is the connection of innovation and diffusion with the phenomena of industrial growth and decay. This aspect was identified long ago by Kuznets and Burns in their work on industrial development.[40]

A second issue is the relationship between technological change and industry structure. Most of the literature addressing this issue has focused on the influence of market structure on innovation taking the former as given, in order to explore the validity of the so called Schumpeterian trade-off.[41] Here we will focus on the opposite line of causation, which is more relevant for our present enquiry. The life cycle approach to technological change has thrown some light on this issue. In most industries, the trend in the early years of its existence is one of active entry which, as the life cycle hypothesis suggests, is also one of intense experimentation with the technology. There is some evidence that the emergence of a dominant design has a noticeable impact on the number of firms in the industry. Utterback and Suárez have found that, in a number of industries, this entry was followed by a decline in the number of participants, which appears to be associated with the changes in their respective technologies.[42] After the appearance of the dominant design, it is sound to expect this effect: first, because those firms strongly attached to unsuccessful configurations by sunk investment in knowledge and physical and managerial capital will, in general, find it difficult to switch to the dominant design; second, because the change toward more emphasis in cost reduction suggests that the new stage of the cycle will require different firm capabilities than those of the early stage, and not

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[39] These elements of design which become established relate to Sahal's concept of technological guide posts. Sahal (1981a, 1981b). In the present context, the concept will be applicable in some cases to the technological regime as a whole, while in others it will be specific to some design configurations.

[40] Burns (1934), Kuznets (1954).

[41] A survey of this literature can be found in Kamien and Schwartz (1975, 1982); for a critical discussion of this literature, see Nelson and Winter (1982b).

[42] Utterback and Suárez (1993).

all firms will be able to develop them. The same argument will apply in a more general scenario in which the new stage in the development of the industry is marked only by a reduction in the number of competing designs but a similar trend in other aspects of the process. Thus, concentration and market growth tend to generate an oligopolistic market structure as the industry moves towards maturity. However, the picture of a secular trend towards oligopoly is inaccurate. Firstly, because it will not necessarily apply to all industries: considerations on the relationship between plant scale and market size, which will not be pursued here, have an important bearing on this. Secondly, because, as we mentioned above, the innovation that follows the introduction of a new technology is an important part of its development and may have a significant impact on market structure. Swan and Gill, in their study of various industries experiencing rapid innovation, have found evidence in the sense that significant innovations within an industry may have concentrating or de-concentrating effects depending on whether they show continuity or they break with the widespread views held in the industry about the future development of the technology.[43]

4.3.5 Competition, selection and the co-evolution of technology and industry

The evolutionary approach (see 3.2 in chapter 3), offers a rich theoretical framework to integrate the ideas presented above. The emergence and evolution of a technology and of its associated industry are shaped in a competitive process in which the driving forces are selection and the generation of variety. In this context, the ability of competitors to adapt, to anticipate to the conditions of the market and to exploit the development potential of their design configurations that they champion is the key aspect for their competitive performance, rather than their static allocative efficiency. Firms search for competitive advantages by, among other things, introducing technological improvements. At each point in time, market demand and price structure act both as devices that guide innovative activity and that exert selective pressure. In this way, they favour some routes of technological development and hamper others. The routine dimension of technology and the elements of inertia in them play

[43] Swan and Gill (1993).

an important role. In the competitive process, some design configurations are eliminated; firms that, by chance or judgment, had stuck to successful designs tend to be in a more favourable competitive position. The different success of competing firms translates in different profitability and growth. For some firms, repeated failure will eventually lead to bankruptcy. For others, there will be scope for adaptation and they will be able to survive. Seen under this light, the size and number of firms in an industry and the diffusion of different routines among them are all outcomes of the same evolutionary process that drives technological development.

Not only technology and market structure change; the selection environment is not immutable: innovation and diffusion redefine the conditions under which subsequent market selection will take place. Moreover, those changes are not always unintended and in some cases they are deliberately promoted by firms participating in the industry. To some extent, the development of a technology is also a process of creation of its environment.[44] Firms and customers learn, and the concept of product and user needs are formed and reshaped.[45] There is, thus, the broader issue of the formation of the industry and its context. The co-evolution of the institutions relative to an industry is a complex process that involves not only the firms, but institutions such as governmental agencies, universities, engineering associations, regulations.[46]

4.4 The measurement and assessment of technological change

It is at the level of artifacts where technological change is more apparent, and this is the natural place to look at when one is searching for measures of its pace and direction. On the other hand, the knowledge and routines dimensions are crucial for the assessment of technological change. They can serve to build taxonomies which bring to light different aspects of the process of technological change.

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[44] Amendola and Gaffard (1988), p. 14.

[45] See Clark (1985) and Durand (1992).

[46] Pérez (1983).

4.4.1 Measurement of innovation and diffusion

The distinction between the innovation and the diffusion aspects of technological change is useful for measurement purposes. The characteristics space framework described in section 4.2.2 can be used to describe the changes experienced by a technology and to register the emergence of new characteristics that may appear during its development. The way in which this can be done has been suggested by Hagerdoorn: by selecting generations of key elements of the technology, it is possible to make operational concepts like that of technological trajectory.[47] This way of proceeding can be useful in the construction of diagrammatic representations of the evolution of a technology.[48]

Regarding diffusion, on a first approximation, it can be measured by indicators such as number of firms, output, capacity or employment associated with the technology. It is more problematic, however, to construct analytical indicators which relate actual to potential penetration of the technology. As Nasbeth and Ray note, it is practically impossible to define unambiguously the denominator of this type of measures.[49] The potential number of adopters and the notional point of saturation are not only difficult to identify, but will change with the evolution of the technology.

Indirect measures of technological change based on input indicators such as R&D expenditure or on output indicators like patents or publications of scientific papers have also been widely used in inter-sectoral comparisons. When referred to specific industries within a sector, they have been used to give an indication of the pattern followed by the rate of growth in the knowledge associated with that industry. This can be extremely useful to identify the trends in the technology side of the life cycle. Walsh, for instance, analyses the different stages in the cycle of a number of chemical industries on the basis of such type of indicators.[50] The use of expert opinion about which have been the most significant additions to a technology has also been used for a more

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47 Hagerdoorn (1989).

48 See for, instance, Abernathy and Clark (1985) and Durand (1992).

49 Nasbeth and Ray (1974), p. 297.

50 Walsh (1984).

qualitative follow-up of the evolution of a technology.[51]

4.4.2 Assessing the significance of innovations

Radical innovations

In our analysis we have proceeded by assuming an initial radical innovation and the birth of an industry. One of the objectives here is to determine when we can say that this kind of innovation has taken place. In the XIX century and early XX century, it was relatively common to see new industries starting virtually from nothing under the impulse of innovators-entrepreneurs.[52] However, in the modern times of large corporations with R&D facilities, innovation is more and more the result of the activity of these firms.[53] Increasingly, what we have called "new industries" emerge from established firms. Thus, it is not always easy to distinguish between a new technology and the mere launching of a new product in an already established industry.[54]

In our framework, independently of issues related to the impact of the innovation in the market, the critical question is whether the innovation breaks with existing technological regimes. It is existing technologies that can provide the point of reference to judge whether or not an innovation qualifies as radical. Thus, a clear definition of the principles and core elements of design that define a regime is essential. There is not a clear-cut rule on this issue; the definition of a regime rests to a great extent on technical judgment about what is the heart of a technology. A focus on the three dimensions of technology can help in this endeavour. As a first approximation, the main clues on what defines a regime can be found in the generic descriptions, in the literature of a specific technology, about what the product is, its applications and how it is produced. As we have repeatedly emphasized, changes at the level of artifacts will be associated with corresponding changes in the other dimensions of the technology. New artifacts will also involve new

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[51] A study of chemical industries that combines both approaches is that of Achilladelis et. al. (1990).

[52] See Jewkes, et. al. (1958).

[53] See Freeman (1982).

[54] See Nelson (1992), pp. 8-9.

technological knowledge which will often be noticeable as a new entry in the description of technologies within the broader field to which they belong.

Innovation and the competitive process

As it stands, the discussion above about whether an innovation qualifies or not as radical is relevant mainly in relation to the consistency of our framework. Taxonomies of innovations, however, can be analytically useful and different criteria will shed light on different issues. Sahal, for instance, classifies innovations from the point of view of their relationship with the technological constraints associated with the design as structural, material or system innovations.[55]

Technological change, we have argued, is shaped in the competition between firms that innovate, not only developing their own design configuration but, more generally, searching for new technology and market opportunities. A focus on how innovations relate to the actors that participate in this process is essential for an understanding of technological change. This directs our attention to the knowledge and routine dimensions of technology.

A number of scholars have converged in recent years in placing the competence of the firm as the point of reference to define criteria for the classification of different kinds of innovation.[56] The concept of competencies incorporates the three dimensions of technology as they exist in the physical and human resources of a specific firm. Other non-technological capabilities, which are relevant for the competitive position of the firm, such as marketing and financial capabilities, are also contemplated in the concept of competence. However, technology occupies a central place. Abernathy and Clark, and Tushman and Anderson have proposed to distinguish between innovations according to whether they are competence enhancing or competence destroying. As these authors have shown, enquiring about the effects of an innovation on different competencies can enhance considerably our understanding of the significance

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[55] Sahal (1985), p. 64.

[56] Among the recent literature that focuses on firms competencies or capabilities see Tushman and Anderson (1986), Dosi, Teece and Winter (1992), Henderson and Clark (1990), Prahalad and Hamel (1990).

of an innovation in relation to the competitive process.[57] Along these lines. Henderson and Clark, in particular, have introduced the concept of architectural innovation. This concept is applied to those innovations that, without necessarily changing the components of a product, modify the way in which they are integrated into the system. Architectural innovations according to them have a destructive effect on the knowledge and communication channels of firms and have significant competitive implications.[58]

In general, the advantages of a competence based appraisal of changes in technology are, first, that it highlights elements associated with the impact that they are likely to have for competition within the industry; and second, that they bring into focus the knowledge and routine aspects of technology which tend to be hidden and, in doing so, they inform us about the new conditions, the possible sources and directions of subsequent technological change.

Moving further in this direction, Metcalfe and Boden have introduced the concept of strategic paradigm.[59] This concept directs our attention to the active role of firms in changing their selective advantages. In particular, it expresses how in each firm the synthesis between the prescriptive content of the technological regime, the firm assessment of its own competencies and its objectives, is articulated to produce the firm's technology strategy. This concept of strategic paradigm brings us closer to an understanding of the factors that guide the innovative and growth efforts of the firms. Along this line, Swan and Gill emphasize the presumptions of the firms with respect to the future tendencies in the technological regime and how they relate to the firms' competencies. They introduce the notion of "visions of the future" which is seen as defining "the range of technological and market outcomes for which the organization can be prepared."[60] The impact of an innovation on the competitiveness of the firms in the industry will depend on the degree in which that innovation departs from those firms' visions.

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[57] Abernathy and Clark (1985), Tushman and Anderson (1986).

[58] Henderson and Clark (1990).

[59] Metcalfe and Boden (1991).

[60] Swan and Gill (1993), p.24.

Technological change and the pervasiveness of a technology

An important dimension of technological change is its overall economic impact. This, we have argued, materializes through the process of diffusion and post-innovation. Although, the pattern that a technology will follow in its evolution cannot be predicted in advance, nor can the size of its market niche be anticipated with precision, the position of a technology with respect to other technologies and its relationship with them is a source of valuable indications of its economic potential. Firstly, because an innovation will compete with technologies with similar performance characteristics. Thus, this can give us an idea of the magnitude of its prospective market niche. Secondly, because the position of a technology in the economic system and the degree to which key elements of its knowledge base are shared with other technologies is fundamental for its impact on the economy. In this context, Freeman and Pérez have proposed a taxonomy that distinguishes between four different levels of pervasiveness in technological change: incremental innovation, radical innovation, new technology systems and changes in techno-economic paradigm.[61] In the context of the foregoing argument, incremental innovations would be equivalent to the changes within existing regimes which we have been analysing. The term radical innovation has basically the same meaning that we have given to it here. It is the other two concepts that are of interest to our present discussion. New technology systems refer to constellations of technological and economically interrelated innovations. The synthetic materials, petrochemicals and plastics industries are some examples.[62] The concept of techno-economic paradigm is associated with changes that affect almost every branch of the economy. Such a paradigm consists of many clusters of radical and incremental innovations and may embody several new technology systems. Following Schumpeter, Freeman and Pérez associate these changes with the long waves observed in economic development.[63]

Although the scope of the present work is limited to the analysis of individual technologies, the taxonomy mentioned above calls our attention

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[61] Freeman and Pérez (1988), see also Pérez (1983) and Freeman (1988a).

[62] Freeman and Pérez (1988).

[63] Freeman and Pérez (1988).

to the fact that the position of an innovation with respect to wider changes in technology is an important aspect to be considered when assessing their potential significance. Thus, in the analysis of individual technologies, considerations of interrelatedness may be of great importance. A good example is found in David and Bunn study of the development of the electricity supply industry. There, the authors analyse innovations within network technologies. In this type of innovations, interrelatedness is all important, as David and Bunn illustrate very neatly with the case of the rotary converter.[64]

A final useful conceptualization related to the relationship between technologies is the notion of fusion and fission of technologies.[65] The former captures the idea that sometimes new technologies result from the confluence of existing technologies. The notion of fission refers to new technologies that emerge in the course of the development of a technological regime, which draw heavily on its knowledge base, but split from that regime.

4.5 On the empirical analysis of technological change

The foregoing argument has been focused on putting together a series of ideas from the literature on technological change within a framework that is useful for the analysis of specific technologies. This section will serve as an introduction to the case studies of the next two chapters. It gives a brief account of the way in which the concepts introduced earlier in this chapter have been applied to two innovations: indirect electrostatic photocopying (IEP) and linear low density polyethylene (LLDPE). The analysis and a detailed description of these innovations is made in the next two chapters. Here, we will limit ourselves to highlight some of the differences and similarities between them.

4.5.1 Technological regimes and design configurations

In section 4.2 we stressed the importance of looking at the three dimensions of technology. It is at the level of artifacts that the main characteristics of a technology can be identified. However, it is

[64] David and Bunn (1990).

[65] See Sahal (1985) and Kodama (1986, 1992).

necessary to look at the knowledge and routine dimensions of the technology to understand the process of its creation and development.

A first difference between IEP and LLDPE relates to the type of productive processes associated with them. IEP equipment is made in a assembly type of process that delivers a working system made of a number of components and subsystems. In the case of LLDPE, what we have is a material that is produced in a chemical process. This difference is not trivial. IEP corresponds to a type of industry in which the heart of the innovation is found in the design of an artifact that performs a particular function. In chemicals, although the purpose of the product is not irrelevant, it is the process that is central to the innovative process. The cases of many synthetic materials like Nylon, Teflon and polyethylene itself, in which the material was first discovered and its possible applications explored afterwards, illustrate this point.

We do not deny the importance of activities like material engineering in which the purpose of the innovation is to obtain a product with very specific characteristic. Neither do we ignore the fact that there are many assembled artifact for which many uses have been found after their introduction. However, the recognition of the preeminence of the product in assembly and of the process in chemicals is useful when trying to identify the technological regimes and design configurations in this type of industries. The fact that, as Nelson and Rosenberg have noted, the pilot plant plays, in the chemical industry, the equivalent role that the prototype plays in assembly manufactures,[66] is an important clue on the qualitative difference that exists between these industries. It also embodies a suggestion about where one ought to look in the search for the core aspects of these technologies.

In IEP, the core of the technology is found in two basic subsystems: the photoconductor and the development subsystems. The different design configurations in this technology can be defined on the basis of the different technological solutions that have been implemented at the level of those subsystems. LLDPE is a material with different characteristics to those of other polyethylene resins. However, it is not the characteristics of the product, but those of the process (the type of catalysts, reactor design and polymerization conditions), which allows us

[66] Nelson and Rosenberg (1993), pp. 6-8.

to distinguish the different design configurations in this technology. Having said that, it ought to be stressed that the distinction between product and process should not be made too sharply. As we noted in section 4.2 the process, technical and service characteristics of the product of a technology map into each other.

Although the artifact dimension of the technology is the one more readily observable, it is important to look at the knowledge (the principles and concept of design) associated with them. It is on that basis that IEP can be identified as a technological regime different from other reprographic technologies. In the case of LLDPE, the fact that it shares most of the knowledge base of the low pressure technology for the production of high density polyethylene (HDPE) defines it as an innovation within that regime.

The definition of industry in section 4.2 is that of a population of business units operating within the same technological regime. In practice, the firms that enter a new industry are often already established in other business areas. The financial, organizational and technological competencies required by the business unit, more often than not, build on the competencies of an existing organization. These are firms that either diversify or reorient their activities to the new business opportunity. A common characteristic of our two cases is that there was a proximity between the markets to which the innovation was directed and the markets in which most of the firms that adopted the technology were operating. This implies that they were familiar, if not with the new technology itself, with the techno-economic aspects associated with the satisfaction of similar needs to the ones to which the innovation was addressed.

In the IEP case, the majority of firms that entered the industry had a background in reprography, either in copying or in duplicating. Some of them were equipment manufacturers and others suppliers of dyes, chemicals and papers for reprographics.

In the case of LLDPE, rather than entry into a new industry, the question is about which were the firms that entered the production of LLDPE. It is of interest to ask whether they were operating in the regime to which the innovation belongs or in a different one. The LLDPE innovation competed mainly in the markets of the conventional low density polyethylene (LDPE), which is produced with a different, high pressure, technology. The evidence from the US and West European industries indicates that the majority of the entrants to LLDPE production were producers of LDPE and most of them were also HDPE producers. However, firms that only operate HDPE technology have not shown a tendency to produce LLDPE. The market overlap of the innovation with the activities of the firms seems to be a major consideration in the decision to enter the production of LLDPE.[67]

4.5.2 The development of an innovation

In both IEP and LLDPE, an important aspect of the development that followed the initial innovations was a proliferation of design configurations. In the IEP case, being a new regime, these were entirely new. In the case of LLDPE, in contrast, they were mostly based on designs that already existed and were used in the production of HDPE. As we said earlier, LLDPE was not a new regime. It rather represented a widening of the trajectory of development of the low pressure technology for the polymerization of ethylene based on organo-metallic catalysts.

The fact that IEP was a new regime while LLDPE emerged from a technology that have been developing for many years was also a crucial difference for other aspect of the subsequent development of the technologies and their industries. In IEP, there were periods of market creation and fast growth in which there were numerous entries and exits. The emergence of new designs and the expansion of markets was part of a competitive struggle from which the major competitors that we observe today in the industry also emerged. In LLDPE, there was a similar proliferation of designs but, as we saw, they derived from those for HDPE. The innovation was of a market stealing type and the potential niches for the innovation were relatively clear from the start. The changes in the technology and in the firms participating in it have been largely driven by the state of development of the polyethylene industries and technologies that already existed.

The coexistence of different design configurations and the fact that firms tend to champion different designs is another aspect that is clearly illustrated by the case studies. The coexistence of different designs rest

[67] There are, however, other considerations related to the different design configurations under which HDPE operates which may also have contributed to this event. Most HDPE producers operate slurry processes that have a limited flexibility for the production of LLDPE.

partly on the diversity of firms but also on the fact that they perform differently in different segments of the market. This appears particularly clear in polyethylene technologies. The different processes are better for the production of some grades but no process is the best for all of them. Furthermore, there are grades that are unique to a specific type of process. In the IEP industry, we find that different configurations in the photoconductor and the development subsystems give a different price performance relationship in terms of characteristics like speed reliability and copy quality. This makes some designs more adequate for some segments of the market (say slow and low cost machines) than for others.

Finally, another phenomenon that emerges in the case studies in relation to the competition between design configurations is the fact that often companies compete on the basis of more than one configuration. In the same way that a corporation diversifies and participates in different industries, a firm deploys different technologies in order to position itself better in different segments of the market. In the polyethylene industries, in particular, we find that licensing and plant takeovers contribute to this situation. In the IEP industry, we also find firms using different photoconductor materials in different segments of the market. Nevertheless, although a firm may compete on the basis of more than one design, it tends to be a limited number of them. In the case of firms with proprietary technology that falls in one design configuration, it is that technology on which the firm bases its technological competition.

4.6 The rate and direction of technological change

In this section, we bring together the ideas presented earlier in the chapter in order to outline the main elements of an evolutionary perspective of technological change.

The analysis of innovation and diffusion has traditionally been based implicitly or explicitly on a supply-demand perspective. Thus, the factors that affect technological change have been grouped according to whether they correspond to the demand or the supply forces of the market. This way of proceeding has produced many valuable insights. It is a useful way of analysing the different factors that affect innovation and diffusion in terms of how they impinge on the behaviour of producers and buyers.

However, it has a major shortcoming: it tends to make us look at the process as if it were the outcome of the interplay between two forces of the market acting relatively independently from each other. The evolutionary approach, in contrast, looks at the factors that influence technological change as relative to the technology itself, to the population of firms, and to the selection environment. This way of proceeding has the advantage that it unveils another dimension of the way in which these factors operate, namely, through the mechanisms that generate variety and through the mechanism of selection.

4.6.1 A Supply-demand approximation to technological change

A supply-demand framework centres our attention on two fundamental questions: first, the willingness and capacity to pay for the products of a technology, and, second, the profitability of producing them. In that context, innovation will be determined, on the demand side, by those factors affecting customer needs and their valuation of the different characteristics of the product. On the supply side, what is relevant for innovation are the constraints and opportunities associated with the technology and the cost and uncertainty of undertaking innovative activity.

Regarding diffusion, demand factors relate basically to the creation and growth of the market niche; questions of information and learning by users are all important. Clearly, specific considerations will change depending on whether the potential user is a final consumer or another firm that would use the innovation in its own production process. The first case is one where subjective valuation and purchasing power will determine whether or not to buy the commodity and how much of it is bought. The second case depends on profitability considerations, which affect the adoption decisions of the different firms concerned; subjective consumer consideration only enter indirectly in this second case. Supply factors, in turn, also involve questions of profitability, which affect the decisions of the firms about pricing, quantities to be produced and capacity expansions. Factors affecting entry considerations will also be relevant for supply and diffusion.

Curiously, in early research on both innovation and diffusion, the role of supply factors tended to be neglected, leading to a "demand pull" perspective of innovation and to models of diffusion, which looked only at the behaviour of adopters. Recent research on both fronts has vindicated the equally important role of supply.[68]

4.6.2 An evolutionary perspective of technological change

The supply-demand scheme, as used above, offers a convenient way of analysing the factors that affect innovation and diffusion in terms of how they affect the behaviour of producers and buyers, and is quite illuminating. Our purpose, however, is to analyse the role of those factors in the context of the competitive process that shapes the development of technology. Diversity, the mechanisms that generate it and market selection are central to that process. From that point of view, a supply-demand perspective, which focuses on representative agents and equilibrium outcomes resulting from the interplay of supply and demand forces, is not the most adequate. Thus, we will proceed by analysing the factors that affect innovation and diffusion in relation to the technology, the industry and the environment.

The technology

At any point in time, the technological regime that defines an industry consists of a body of knowledge not only about the properties of the artifacts and their design, but also about puzzles that remain to be solved, and notions of which improvements and directions of research seem promising and worth attempting and which do not. Each design configuration defines a more specific agenda of its own according to the particular solutions to design problems that it represents. These notions about the possible routes for the development of the technology are product of its past trajectory. During the development of a technology, design configurations emerge and are abandoned and guide posts are left for subsequent development.[69] These guide posts take the form of design principles about how sets of process and product characteristics can be

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[68] The most influential work leading to the 'demand pull' perspective of innovation was that of Schmookler (1966). For a critical view of this perspective, see Mowery and Rosenberg (1979). Among the early demand oriented studies to which we make reference are those of Griliches (1957) and Mansfield (1961). On the more recent work which emphasizes the role of supply factors, see Metcalfe (1981) and Stoneman and Ireland (1983).

[69] Sahal (1981a, 1981b)

delivered. They involve a perception of what can be improved and at what costs, and of what trade-offs are likely to emerge among the multiple characteristics of the technology.

Inherent to the concept of design is the fulfilment of some needs. At any point in time there will be a lower and an upper bound of performance characteristics delivered by the technology. The concept of technological corridor has been proposed by Georghiou et. al. to refer to the trajectory in time of this band. The corridor also plays a role in guiding the development of the technology in terms of the range of performance that is expected across the different characteristics that define the technology.[70]

Thus, regime, designs and corridor, together, point to the broad direction which the development of a technology may follow. Dosi has used the metaphor of a tunnel, rather than a line, to convey the idea of the large number of possibilities defined by the prospective technological trajectory.[71]

The state of development of the technology is not only relevant for the direction but also for the rate at which change is likely to take place. The state of knowledge and the extent to which the possibilities opened by the regime in its development have been explored, will have an important impact on the magnitude and frequency with which innovations are likely to take place. Particular attention has been drawn to the fact that, eventually, decreasing returns will appear in the innovative effort: the advance of a regime will become more difficult as the limits of its potential are approached. This phenomenon is referred to, in the literature, as "Wolf's law".[72] Of course, there will also be exogenous factors such as relevant scientific discoveries and advances in related technologies, which may have an impact on the technology and relax some of the difficulties, making it easier, for some time, to achieve further advance in the regime.

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70 Georghiou et. al. (1986).

71 Dosi (1982).

72 See Georghiou et. al. (1986), p.25.

The firms and competition within the industry

A key characteristic of industries is diversity. Firms differ not only in the design configurations that they promote, but in a number of other things such as their size, being (or not) part of a larger organization and, of fundamental importance, in their competencies. The competitive behaviour of firms rests on a series of competencies: technological, financial and marketing, which are at the heart of their different market performance. The differences in the technological competence of the firms are of particular interest to us. This competence is defined by the specific way in which the technology exists within the firm, that is, the collective knowledge and skills that are articulated in its technological routine. The differences in technological competence are at the basis of the different capacity of firms in identifying and exploiting technological opportunities. The routines and accumulated knowledge of firms are both an asset and a liability: they are the foundation for the effectiveness of their performance but may also operate as barriers, limiting the opportunities that are perceived and the capacity to change in certain directions.

Therefore, the design configuration in which a firm operates and its technological competence will exert a major influence on both the direction and effectiveness of its efforts to develop the technology. Clearly, there are a number of other factors that also intervene, such as other non-technological competencies, business objectives, financial position, the perception of the intensity and the main areas of competition (including threats of entry) and the overall perception of the market environment. In each firm, the impulse to innovate, imitate and grow responds to the elaboration of the firm's technology and growth strategies, which will involve an assessment of all the different aspects just mentioned. Central to the elaboration of that strategy will be the possibilities opened by the technology. These will set the alternatives from which, on a broader assessment, the strategy of the firm will emerge to guide the magnitude and direction of the innovative efforts and its capacity expansion.[73]

The distribution of firms according to their size and to the design configurations that they promote, the specific strategies that the firms

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[73] This relates to the Metcalfe and Boden's notion of strategic paradigm discussed in section 4.4.2.

follow and their ability to carry them affect the rate and direction of technological change. They influence the distribution of innovative efforts and the relative economic weight acquired by the different designs, and give shape to the process of diffusion.

Two additional remarks are in order. First, that other factors such as non-programmed creativity, contingencies and the influence of small events may have a significant influence on the outcome of firms' behaviour and, thus, have an unsuspected effect on the course of technological development. Second, it is important to keep in mind that, while developing the technology, firms develop themselves: some competencies are enhanced, knowledge accumulates, skills and overall routines are modified. At the same time, other possible courses of development are abandoned. In this way, the new conditions for further technological development are set.

The selection environment

The environment plays two fundamental roles in the development of a technology: it acts as the mechanism of selection and also a source of inducement. Ultimately, it is the selection environment that determines the relative success of firm's diverse behaviours. The way in which the mechanism operates has already been described elsewhere (see Chapter 3). The artifacts (the goods and services produced) are the direct objects of selection. This determines the differential profitability of firms and, through it, their growth. It is through the effect on the development of the firms in the industry that the mechanism selects indirectly over the knowledge and routine dimensions of technology, which are, in evolutionary terms, the "replicators". In this way, the economic significance of the technology and, in particular, that of the different design configurations is altered.

Two basic elements of the selection environment are the overall growth of the market and the users valuation of the different performance characteristics of the products of the different designs in the industry, not only relative to each other but also with respect to substitutes from other industries. Here, the considerations made earlier about whether buyers are consumers or other firms, apply. It is important to emphasize that these valuations will be influenced by the current state of both competing and complementary technologies.

Not only the objective characteristics of the products are important for the process of diffusion. Equally important are the questions related to information and learning by potential users and to the different factors that may create inertia and lead buyers to stick to other technologies.

A third aspect of the selection environment relates to the quality, price and availability of inputs. This will affect the cost of the firms and the price and performance that the firms themselves will be able to deliver. It is worth mentioning, in passing, that the fact that, as Sraffa's famous book reminds us, commodities are produce by means of commodities,[74] adds complexity to the problem of analysing technological change. In the development of an industry, division of labour will often break a technology into subsystems, redefining the industry and giving way to associated sub-industries. In a way, this is as if firms where able to buy competencies in the market. These considerations have to be kept in mind in empirical analysis.

Needless to say, the environment consists also of other institutions: government agencies, legislation, professional groups and other institutions relevant to the industry being analysed. These may also have a direct influence on the rate and direction of technological change.

Another important characteristic of the selection environment is its myopia: it selects on what exists. This, as we have already mentioned, may lead to lock-in phenomena in which design configurations, which are seen as technically inferior to other alternatives, become the dominant ones. Because of increasing returns or networking considerations, a technology can become dominant by getting an early foothold in the market.

The second role of the selection environment is that of inducing technological change. This inducement role is grounded on the same aspects that its selective role. The different sources of selective pressure are taken into account by the firms in their decisions concerning innovative efforts, pricing, production and capacity expansions. Firms try to adapt to the environment and to anticipate its changes. Moreover, to the extent that they are able to do so, they try to modify the environment in their favour. Thus, the boundaries between firms and their environment are not clear-cut. This, as Metcalfe and Boden have noted, rather than weakening

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[74] Sraffa (1960).

the evolutionary argument gives ground for an enriched discussion.[75]

Three final comments are in order before closing our discussion on the selection environment. First, that the environment is not immutable: it is changed by the development of the technology. Prices, the information that buyers have of the product and their valuations change and create the new conditions in which further development can take place. Second, that the environment relevant to the industry will be subject to shocks that may have profound effects on the rate and direction of change of the technology. Finally, regarding international trade, the national characteristics of the environments and their implications for the capacity of firms to compete internationally will be central for the geographical diffusion of technology and for patterns of international trade.

4.7 Concluding remarks

The main purpose of this chapter has been to put together a series of contributions from the literature on technological change, in a conceptual framework that can be applied to the empirical analysis of specific technologies. In the following chapters we will apply such a framework to two case studies: polyethylene and indirect electrostatic photocopying equipment. The starting point of the case studies will be to try to distinguish the key elements that define their respective technological regimes, and to identify the different design configurations that compete in the market. Another important step in the analysis will be to look at the histories of the technologies in order to identify the main factors that have shaped the course of their development. In order to explain such development, we will analyse those factors in the context of an evolutionary process.

Regarding international trade, it will be conceived, essentially, as an aspect of the spatial dimension of the process of diffusion. It is worth stressing that we do not argue that technological change is a factor that "explains" the patterns of international trade. Our claim is of a different kind. We hold that, by analysing the factors that shape those patterns from an evolutionary perspective, it is possible to derive insights that deepen our understanding of international trade.

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[75] Metcalfe and Boden (1991), p. 710.

5 Diffusion of innovation and international trade in indirect electrostatic photocopying equipment

5.1 Introduction

In this chapter, we will study the relationships between the diffusion of the technology, the development of the industry and the shaping of the patterns of trade in the indirect electrostatic photocopying (IEP) equipment industry.

The case study centres its attention on two questions: First, on giving an account of the development of IEP technology and of its relationship with the evolution of its associated industry. Second, on tracing the implications of these processes for the patterns of international trade in IEP equipment. The case study seeks to establish how patterns of international trade are created and shaped by the emergence of a technology and its subsequent development and diffusion at an international level.

In section 5.2, we characterize the IEP technological regime and compare it with other reprographic technologies that existed at the time when it was introduced. Section 5.3 gives a brief account of the innovative process that led to the introduction of the first automatic plain paper copier. We also describe there the characteristics of the market during the period in which Xerox Corp. monopolized the technology. In section 5.4, we look at the changes that occurred in terms of both the development of the technology and the functioning of the market during the early 1970s, when the basic patents held by Xerox expired and competitors entered the industry. Section 5.5 is an analysis of the major changes that have taken place in the technology and in the industry. Section 5.6 focuses on the patterns of location of production and international trade that have been associated with the diffusion of IEP technology. Finally, section 5.7 looks at the insights provided by the case study on the relationship between technological change and trade.

5.2 Reprography: markets and technologies

5.2.1 Copying and duplicating processes

In order to understand the nature of the IEP innovation, it is necessary to make a brief review of the main reprographic technologies that existed at the time when IEP was introduced and of the main characteristics of the markets relevant to innovation. The reproduction application on which IEP competed with other technologies when it was introduced was the convenience copying of documents in black and white. Thus, in this section, we will be looking at other reprographic technologies from the point of view of this application. The first indirect electrostatic full colour copier appeared in the market in 1973 and it has not been but until the 1990s that full colour copying has started to gain importance.[1]

It is convenient to distinguish between two groups of reprographic processes: copying and duplicating. The basic distinction between the two groups relates to the way in which the reproduction is made. Copying processes make the reproduction directly from the original to the copy. Although making a copy was relatively simple in most of the technologies that preceded IEP, each copy required exposure to the original and this was time consuming. Copying processes were usually employed for relatively low volume applications. Duplicating, on the other hand, requires an intermediate step in which a master is prepared. Afterwards, the master is placed in the duplicating equipment and multiple reproductions can be obtained in a short time. Duplicating is more complex than copying since it involves making the master and mounting it in the duplicator. However, these processes are faster than copying when many copies of one original are required. Thus, duplicating tends to be used in high volume applications.

As it occurs with most classifications, a clear-cut division between copying and duplicating is problematic and some processes may not fit well in the classification presented above. Furthermore, with the development of technology, new processes and hybrid technologies have appeared, which tend to blur the boundaries between the two groups. Nevertheless, the

[1] Some of the technologies reviewed in this section are also used for colour reproduction. Full colour copying will be commented upon in section 5.5.2.

classification will help us to understand the place of the IEP innovation in the markets for reprographic equipment.[2]

At the time of the introduction of IEP, the dominant copying technologies in the market were contact processes such as diazo, thermocopying, dual spectrum, diffusion transfer, reflex and gelatine transfer. However, the direct electrostatic photocopying process (DEP), introduced a few years before the IEP, was gaining increasing acceptance in the market during the late 1950s.

A common characteristic of the copying processes available in those years, DEP included, was the use of coated paper. Most contact processes used paper coated with light sensitive chemicals and required a developing step in which the final copy was obtained by a chemical process. Most of these technologies found their antecedents in photography. Electrostatic technology is different in this respect since it does not rely on chemical principles but on photoconductivity and electrostatics. In electrostatic processes, the final image is obtained by application of toner, which is fused into the paper through heat and pressure. These differences gave the DEP process an advantage since the paper that it used was not sensitive to light unless electrostatically charged and chemical reactions were not necessary. However, the IEP process would offer further advantages. One of the main reasons why it was considered technically superior is that it made possible to make copies in plain paper. In fact, IEP machines became known as plain paper copiers (PPCs).[3]

It is of interest to look briefly at the main reprographic technologies that existed in the 1950s and at the firms responsible for their introduction in the market. Firstly, because this will allow us to see more clearly the distinctive nature of the IEP regime. Secondly, because the champions of other precursor reprographic technologies were among the firms that were threatened by the new technology. As we will see later, several of these firms entered the IEP industry, although not all of them were equally successful.

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[2] The dual spectrum process, to which we will refer later, for instance, is considered a copying process. However, it requires an intermediate copy to produce the final reproduction.

[3] Throughout the study, we will be referring to this equipment without distinction as Plain Paper Copiers (PPCs) or as Indirect Electrostatic Photocopiers (IEPs). It is worth mentioning, however, that other copying techniques such as Indirect Electrostatic Digital copiers have been developed which also make copies in plain paper. See section 5.5.2.

Contact copying[4]

The most common copying technologies in the late 1950s were contact processes such as diazo, thermocopying and transfer processes.[5] The diazo process was patented in 1929 by the German firm Kalle, which became producer of Diazo machinery and materials traded under the name "Ozalid". The process is based on a compound which is a mixture of diazo salts that are sensitive to ultraviolet light and azo dyestuff. In this process, a translucent original and a diazo coated paper are exposed to ultraviolet light. The light destroys the salts in that parts of the copy paper not protected by the opaque image in the original and deactivate the dye. The latent image is developed using ammonia vapours and the copy that emerges is a facsimile of the original.

Thermocopying was introduced by 3M in the US in 1950 under the trade name "Thermofax". In this technology, the image is exposed to infrared radiation. The dark parts of the original turn the infra-red rays into heat, which acts on a thermosensitive sheet that is placed in contact with the original. A positive copy is created through liquefaction of crystallization on the thermosensitive layer of the paper. A variant of the process, called dual spectrum, which involves the creation of an intermediate copy, was also introduced by 3M in the 1950s.

The two other main contact technologies were the diffusion transfer and the gelatine transfer processes. Like photography, both are based on the use of silver to produce the copy. Diffusion transfer was introduced by the Belgian firm Agfa-Gaevert. The main patents of the process known by the trade name "Copy Rapid" date from 1941 and 1949. The process is based on the use of a silver chloride emulsion. Light sensitive negative paper is exposed to light together with the original. Afterwards, the negative is matched with positive coated paper and they are processed together in a chemical bath. The unexposed areas of the negative transfer the unused silver salts to the positive paper forming in it a black image.

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[4] The following description of copying and duplication processes has drawn on various sources: IFD (1953-1961), McGraw Hill Encyclopedia of Science and Technology (1977, 1987), Ghazanfar (1984) and Datapro (1981, 1984).

[5] The generic name of contact processes stems from the fact that, at some stage of the reproduction process, the original and the material to which the image is transferred are brought into close contact.

The gelatine transfer process was introduced by the US firm Kodak in 1952 under the name "Verifax". In this process, the image from the original is impressed on a master paper using a carbon ribbon, hectograph pencil or ink. The image from the master is then pressed into the Verifax matrix, which is a gelatine mass or pad. The matrix consists of an emulsion containing silver halide, a dye forming component and a hardening agent. The matrix is processed in a chemical bath and the copies are made by pressing it against plain paper. Between two and nine copies can be made, although each is fainter than the preceding one.

A report by the IFD identified, in 1958, 25 firms that produced contact copying equipment in the US and 43 in Western Europe. Germany was the European country with the largest number of producers, with 19 manufacturers of contact copying equipment.[6]

Duplicators

With respect to duplicating technology, the main processes were spirit hectography, stencil and offset lithography. In these three reprographic technologies, ordinary paper was used. Nevertheless, since they rely on the application of dyes or inks on paper, the quality of the paper in terms of its absorbency was important. In the case of offset lithography, it was also required to use acid-free paper since the process is based on the principle that grease and water do not mix.

Regarding hectography, some antecedents of the modern version of the process were used in the XIX century. The most significant contribution to the modern process was by the German W. Ritzerfeld in 1923, who introduced the use of spirit or alcohol, bringing the process to its present form. In spirit hectography, blank sheets of paper are moistened usually with methyl alcohol and passed against a negative master that contains a carbon dye in its back. The moistened sheet absorbs a small proportion of the dye to form a positive print. Each master delivers a limited number of copies, in the range of 50 to 500, depending on the quality of the master. In 1959, the IFD identified 18 manufacturers in the US and 34 in Europe with France leading in Europe with 11 manufacturers.

[6] IFD (International Federation for Documentation) (1953-1961).

Stencil duplicators where developed in the 1880s independently by Edison and Dick in the US and D. Gestetner in the UK. The process is ink based. It uses a stencil master made of a fibrous base permeable to ink and a plastic overcoating. There are various ways of preparing the master; basically, what is done is to cut the pattern to be reproduced on the master. After preparation, the master is mounted on a cylinder that contains an ink device, which passes ink through the stencil onto the paper as sheets are pressed against the master. Stencils are a relatively fast means of reproduction, once the master has been prepared, and they can produce between 100 and 200 copies per minute. Repeated use of the master is possible although quality is gradually lost. The IFD identified, in 1957, 17 manufacturers of stencils in the U.S, 48 in Europe, 1 in Japan and 1 in India. France, with 19 manufacturers, was the country with the largest number of producers.

Offset lithography was patented in England in 1853 and is one of the most popular printing methods. Offset duplicators use masters with ink receptive image areas and water receptive clear backgrounds. An aqueous solution is applied to the plate, which is repelled by the grease receptive image but accepted by the non image area. Ink, on the other hand, adheres to the image area. The image is transferred from the master plate to a cylinder on which a rubber blanket is mounted. An impression cylinder brings the paper into contact with the blanket cylinder transferring the image from the blanket to the paper. The IFD identified, in 1955, 2 manufacturers of offset equipment in the US and 7 in Europe, of which 3 were located in the UK.

5.2.2 The IEP innovation

Each of the various processes reviewed above had advantages and disadvantages, which made them particularly suitable for some applications and not for others. For the particular type of applications with which we are concerned here (reproduction of documents in black and white), the choice of process would depend on the quality of the reproduction required and on the number of copies wanted from each original. In addition, various cost elements such as the price of equipment and materials and the cost of an operator (if needed), would also have to be evaluated to choose between competing alternatives. The IEP process that we will describe below offered technical advantages over existing processes. The development of IEP technology led to a widening of the segment of the reprographic market in which it could successfully compete.

The first automatic IEP machine was introduced by Xerox in the US in 1959. It was named the 914 copier because it could copy pages as large as 9 by 14 inches. In the original Xerox process, a photoconductor, consisting of a selenium drum, is given a positive static charge by exposing it to high voltage through a corona discharge mechanism. The positive charged photoconductor becomes sensitive to light. By means of light and an optical system, the image of the document to be copied is reflected on the photoconductor. The white parts of the document reflect light on the photoconductor, which looses its charge in the corresponding areas. On the other hand, the areas corresponding to the black parts of the document are not exposed to light and remain charged. Thus, after exposure, a latent electrostatic image of the document remains on the drum. The next step of the process consists of applying negative charged particles of toner (a black thermoplastic powder) to the drum. The particles are attracted by the positively charged parts, making the image visible. Finally, the image is transferred to paper by giving it a higher positive charge and placing it around the drum. The paper attracts the particles of toner and the image is fixed by fusing these particles on the paper through heat and pressure. According to its characteristics, the IEP process is in the copying group of reprographic technologies. However, it is considerably different to other reprographic processes with the exception of DEP, to which it is closely related.

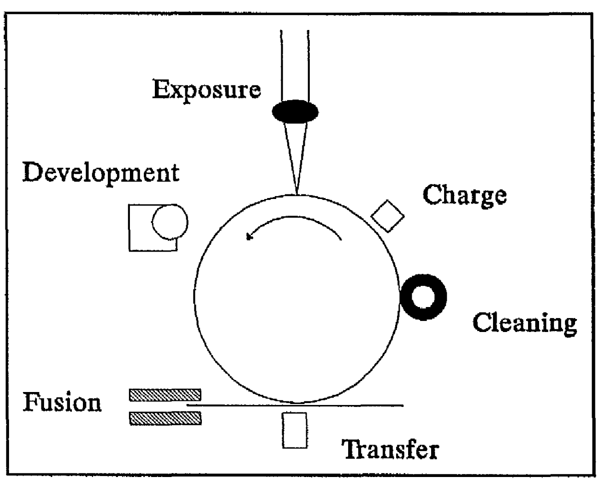

Figure 5.1 Indirect Electrostatic Photocopying

The use of electrostatic technology in photocopying was a major breakthrough, which inaugurated, in the terminology of chapter four, a new technological regime. Electrostatic photocopying relied on an entirely different knowledge base and skills than those underlying the copying and duplicating technologies reviewed earlier. It introduced an entirely new approach in copying technology. The use of light and the reliance on photosensitivity are the only important elements in common with the technological paradigm that guided the development of copying technologies. The path breaking nature of this technology allowed it to penetrate markets traditionally reserved to duplicating, where other copying processes could not compete.

Most of the copying processes reviewed above were based on the chemical decomposition caused by exposure of some materials to light and used chemical reactions to obtain their images. There were some exceptions, like thermocopying, in which it is infrared radiation and the use of heat (or infrared) sensitive paper that is used to produce the copy. However, thermocopying shared a common characteristic of all copying technologies previous to IEP, namely the use of special papers to make the copy.

The first successful commercial application of electro-photography to document reproduction was introduced by RCA. In 1955, RCA developed the DEP process based on technology licensed from Xerox, which was marketed under the trade mark "Electrofax".

DEP used the same electrostatic principles that IEP; however, it still inherited from previous processes the idea of using a specially coated paper to make the copy. It relied on the use of paper coated with zinc oxide, which had photoconductive properties. It was not until the introduction of IEP that the break with the technological paradigm that prevailed in the copying industry was completed. With IEP, the essence of the copying process passed from being in the material in which the copy was made to the equipment used, and chemistry was deprived of the central place it had occupied in copying technology.

Figure 5.2 illustrates the significant change in the knowledge base that was associated with electrostatic photocopying technology. However, when looking at the diagram, it ought to be kept in mind that scientific and technological research are interdisciplinary activities and that the same phenomena are studied by people from different backgrounds from a different point of view.[7]

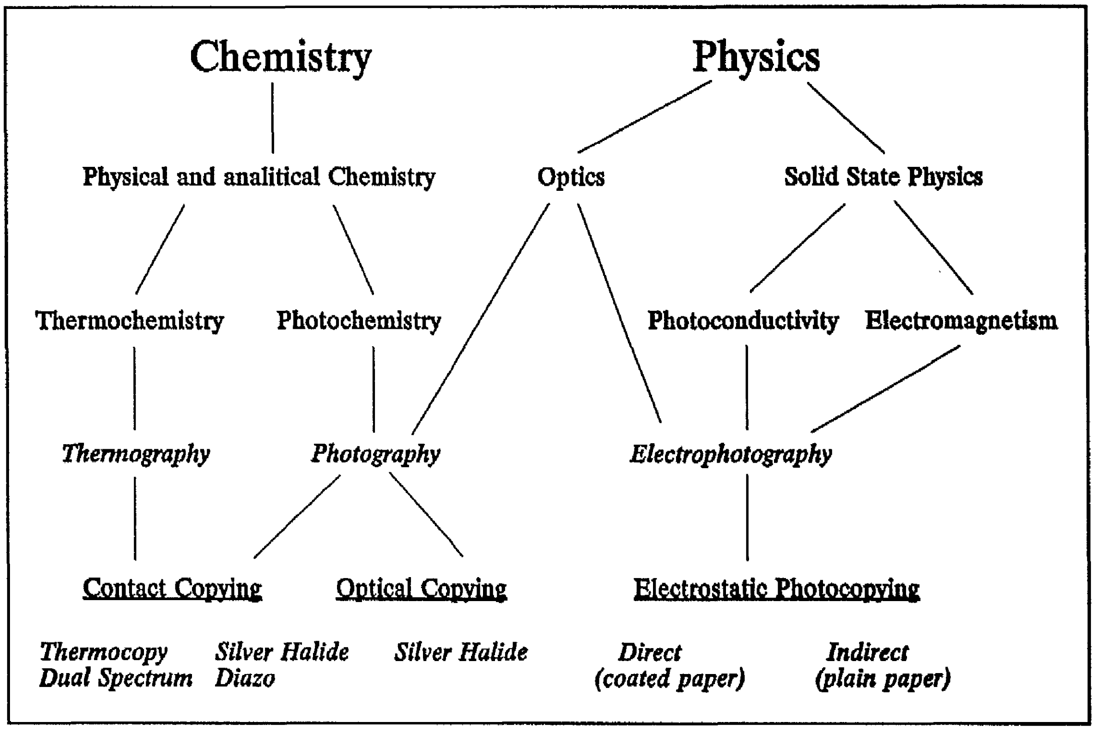

Figure 5.2 Knowledge base of various copying technologies

Finally, although it is useful to identify the relationship between technologies and branches of scientific knowledge, it would be misleading to think of technology as a derivative of scientific research. In fact, IEP is an example of a technology that was widely applied before many of the principles that make it possible were systematically studied and understood.[8] Furthermore, the invention of electrophotography provided the basis for the subsequent advance of neglected areas in solid state physics.[9]

5.2.3 The IEP process in the reprographic markets

IEP offered a number of technical advantages that enabled it to compete with, both, copying and duplicating processes. However, the specific needs of different applications vary considerably. IEP technology had to develop

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[7] The functioning of an organic photoconductor, for example, would be described by a chemist as a reversible redox reaction, while a solid state physicist would consider charge transport in a disordered amorphous system. (We owe this example to a research fellow from Xerox).

[8] See Schein (1992) and Mort (1989).

[9] See Mort (1994), pp. 34-35.

to gradually occupy segments served by other processes and also to create new markets. This last aspect was very relevant: IEP contributed considerably to the expansion of the convenience copying market.

The competition between different technologies is a complex issue. Various factors enter in the choice of process by the user and the conditions are continuously modified with the development of the technologies and changes in economic conditions, which affect the performance of the processes and their relative costs. A new "superior" technology like IEP may overlap with others in its application. However, more often than not, the old technologies keep some segments of the market for which they are more adequate and continue developing for considerable periods of time. This is illustrated by the fact that, to date, more than thirty years after the introduction of the first IEP, other copying processes like diazo, thermocopying and other contact type processes are still used for the reproduction of documents. Diazo, for instance, is still widely applied for the reproduction of blueprints. Thermography is used in the preparation of masters for duplication processes and both thermography and dual spectrum are still applied to copying at very low volumes. Here, we will limit ourselves to mention some of the major elements in which IEP compared favourably with other reprographic processes.

In general, the special coated and thermal papers used in other copying processes are more expensive than ordinary paper. The life of the print made by these processes varied. In the case of diazo and thermal copies, print life was relatively short. Copies in silver halide paper had a longer life. Contact processes, which required a chemical development of the image, were slow. The diazo process, for instance, which was one of the fastest, took one minute to deliver a copy. The first automatic IEP machine, in contrast, produced the first copy in twenty five seconds and subsequent copies in seven seconds. The DEP process did not have that speed disadvantage, but it required heavier and more expensive paper that left a coated-like feel in the copy. The copy was also of lower quality and was susceptible to marking from metal objects.

Despite its advantages, the complexity of the IEP process also meant a more expensive machine. Therefore, traditional copying processes were economically more sound for users that required a low volume of copies. The DEP process, in particular, continued experiencing considerable development well after the introduction of IEP. In relation to duplicating technologies, the major advantage of IEP was that it did not require the production of an intermediate master. The use of IEPs would be preferred in the reproduction of pre-printed material for which a limited number of copies per original was required. However, little can be said in general, given the wide range of equipment prices and capacity in the different types of duplicating machines.

A report for the UK by the Monopolies and Mergers Commission estimated that, in 1975, the IEP had an advantage over other reprographic methods for copy volumes in the range of 5,000 to 50,000 copies per month. The major handicap at lower volumes was considered to be the price of the machine. At more than 50,000, the costs of making masters for an offset duplicator were more than compensated by the low costs of running the process.[10]

The development of IEP technology and its relationship with other technologies will be discussed in more detail in section 5.5. It is important at this point to stress, however, that the conditions have not remained static. The importance of the progress in the technologies can hardly be over-stressed. The introduction of cheap personal IEPs has undermined the advantage of DEP and other processes in low volume segments.[11] In the other end of the market, that of high volume reproduction, the introduction of faster IEPs with features which augment productivity has increased the competitiveness of copiers versus duplicators. High volume copiers now incorporate automatic document feeders, collators and binders, large capacity suppliers and memory for programable tasks. However, competing technologies have also experienced considerable technological development. Offset lithographic equipment, for instance, has incorporated microprocessors and electronic controls similar to those found in photocopiers. There are, in the market, modern offset duplicating systems that compete successfully in the 40,000 to 150,000 copies per month markets, which are also catered by high speed IEPs. For higher volumes, however, electrostatic copying/duplicating systems have

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[10] Monopolies and Mergers Commission (1976).

[11] Around 1984, for instance, two years after the introduction of the personal copier, thermal and dual-spectrum copying were considered a sound option versus IEP for copy volumes as small as 500 copies per month. Datapro (1984).

been developed that are regarded as superior for volumes above the 150,000 per month.[12]

Technological change tends to blur the boundaries between different technologies. Technological fusion has lead to the emergence of hybrid technologies in reprography, that is, they combine elements of different processes.[13] Furthermore, electrostatic principles are being used not only in reprography, but in laser printers that operate with digital technology. IEP, on the other hand, is increasingly becoming integrated with modern information technology. These and other related issues will be discussed in section 5.5.

5.3 Xerox and the development of electrostatic copying

In this section we will describe, first, how IEP was taken from its invention to a successful innovation. Afterwards, we will look at the history of Xerox, which monopolized the process during the first ten years of its economic life.[14]

5.3.1 From discovery to commercial introduction

The electrophotographic reproduction of documents was invented by Chester Carlson in the late 1930s.[15] Carlson had a degree in physics and worked as patent attorney, first at the Bell Laboratories and later at P.R. Mallory. In his job as patent attorney, he could appreciate the need that existed for copies of documents and also how costly and laborious were the copying methods available and decided to work on the development of a simpler and inexpensive process for convenience copying.

Carlson was convinced that, for the process to have widespread application, it would have to be based on the effect of light. From the outset, he decided to avoid working on silver halide and other chemical

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[12] Datapro (1984).

[13] See Sahal (1985) and Kodama (1992).

[14] Throughout the essay we will be using Xerox to denote the group formed by Xerox Corp. and all its associates and subsidiaries worldwide. When necessary, we will make the distinction between the group and the individual firms within it.

[15] The following account of Carlson's discovery draws mainly on Jewkes et. al. (1958), Dessauer (1971), Monopolies and Mergers Commission (1976), Mort (1989) and Schein (1992).

processes since he knew that these had been thoroughly explored by the big companies in the reprographic business.[16] He engaged in an extensive literature research on the work of other inventors. Initially, he considered the possibility of an electrochemical process, but this option was soon discarded because of the high currents required.

In the course of his search, Carlson became acquainted with previous work on electrostatic recording of images that dated from 1777, when this possibility was discovered by the German physicist Litchenberg. Carlson found inspiration in the work of the hungarian physicist Selenyi who demonstrated in 1936 an electrographic recording system in which a charged pattern was written in an insulator and the image was developed using an insulating powder. Carlson had explored the potential of the photoelectric effect in imaging and arrived to the idea of using an electrostatic light sensitive plate. This concept, combined with Selenyi's idea of using an insulating powder to develop an electrostatic image, led Carlson to conceive for the basic principles of what he called Electrophotography in 1937. With the help of O. Kornai, a German engineer, Carlson put those ideas in practice and filed the first patent on this process in 1939. A year later he filed a patent on an automatic copying machine.[17]

Carlson unsuccessfully approached more than twenty companies trying to persuade them to support the commercialization of his invention. In 1944, the Batelle Memorial Institute, a non-profit research organization, became interested in the electrophotographic process and signed a royalty-sharing contract with Carlson. Development work started at Batelle, while Carlson continued trying to interest a company in the process in order to get the necessary support to further develop the technology. In 1946, it was Batelle which was itself approached by Haloid, a small photographic paper company in Rochester, New York. Haloid provided funding and participated in the research in exchange for an exclusive license of Batelle patents. They continued developing the process, which was named Xerography from the greek words "xerox" (dry) and "graphien" (writing). The first machine using the electrophotographic process to be marketed was Xerox model A produced in 1949. The machine was field-tested by lending it to four large companies, but they found it of little use: it was slow

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[16] Jewkes et. al. (1958), p. 406.

[17] See Schein (1992), pp. 5-6.

and complicated to use. Nevertheless, Model A found commercial application in the preparation of lithographic masters. This was followed in 1955 by the Xerox Copyflo, a continuous printer used to make copies of microfilms, microfiches and opaque cards.[18]

In the mid 1950s, Haloid tried to interest other companies in its process. Its purpose was twofold: to obtain more financial resources and to establish international operations. In 1956, Haloid established Rank Xerox in the UK, a 50-50 joint venture with the Rank Organisation, a company incorporated in England. From this venture, Xerox not only obtained financial resources, but also the organisational basis for mounting international operations. In that same year, it purchased the basic patents of Xerography from Batelle. In 1958, Haloid changed its name to Haloid-Xerox and announced the first dependable easy to use copier, which started to be marketed a year later. In 1961, Haloid-Xerox took its actual name, Xerox Corporation.

The first automatic plain paper copier was the Xerox model 914 introduced in 1959. Although based on the principles of the automatic copier patented by Carlson 19 years earlier, it incorporated a series of developments product of all the years of research at Batelle and Haloid. Instead of Sulphur or Anthracene, the photoreceptor was a metallic drum covered by amorphous Selenium (αSe) layers, which were prepared by a vapour evaporation technique developed at Batelle. The rubbing techniques used to charge the photoreceptor in the original design were replaced by the application of voltage by means of a Corona device. A cascade development system based on dual dry toner (a mixture of toner and carrier particles), and an electrostatic transfer process were also introduced. These improved considerably the quality of the copy relative to Carlson's original method in which toner was sprinkled on the charged photoreceptor, loose powder was simply blown off and the image was transferred to paper by pressing it on the photoreceptor carrying the dusted image.[19] The 914 model was the cornerstone in the development of the IEP technology. Most of the key elements of its design became the foundation on which subsequent models were made and the technology was developed.

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[18] See Mort (1989), pp. 62-5.

[19] See Schein (1992), p.6.

5.3.2 The IEP market under Xerox

The Xerox 914 was an automatic copier able to produce seven copies per minute on plain paper. The copier was not offered for sale but on a rental basis, which consisted on a fixed rent plus a charge per copy with a minimum copy volume.[20]

The introduction of the first plain paper copier was a great commercial success. As a result, Xerox experienced an enormous growth, which continued for many years. Between 1959 and 1974 Xerox sales increased from 33 million to 3.6 billion US dollars, its profits increased from 2 million to 331 million, and the price of its stock passed from 2 to 174 dollars a share.[21] Internationally, Xerox expanded, forming a network of associated companies and subsidiaries for the distribution and, in some countries (like Netherlands and Japan), also for the manufacture of Xerox products.

In spite of its many virtues, a major drawback of the Xerox machine was its complexity and the fact that it was a relatively expensive piece of equipment when compared to other copying machines.[22] Other types of copy equipment were sold relatively cheaply and a substantial part of the revenues were generated by the supply of consumables: chemicals and coated paper. The machine introduced by Xerox was not only more complex and expensive than existing copying equipment, but it also required more specialized servicing. As we mentioned above, instead of outright sale, Xerox adopted a leasing practice, which would adopt the form of a two tier price structure: a base lease price was charged, which covered a given number of copies per month, and a metering price was applied to copies in excess of that number.[23] The fees covered service and the supply of consumables, excluding paper. The approach chosen by Xerox allowed it to penetrate more rapidly into the market. It helped to overcome the reticence that potential buyers could feel about acquiring an expensive

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[20] In 1961, for instance, the charge was of 25 U.S dollars per month plus 3.5 cents per copy with a minimum copy volume of 2000 copies per month. Blackstone (1975), p. 191.

[21] Hunger et. al. (1986), p. 448.

[22] The reported manufacturing cost of a IEP copier was of 2,500 U.S dollars. against a manufacturing cost between 250 and 300 U.S. dollars for a DEP copier. Blackstone (1975), pp. 191-192.

[23] Mort (1989), p. 66.

piece of equipment. Thus, it was the photocopying service, and not the equipment, that Xerox commercialized. The more important aspect of this practice, however, is that it allowed Xerox to maintain the control of the technology and to exploit its monopolistic position in the supply of IEP equipment. With the rental plan introduced by Xerox, it reserved for itself the provision of supplies and servicing. If a IEP was allocated to a high-copy-volume user, the cost of the machine was very soon payed for and a highly profitable stream of revenue could be obtained during the rest of the life of the machine. Another advantage of the rental scheme is that, by retaining the ownership of the equipment, Xerox derived significant tax advantages from depreciation.[24] The initial resistance of Xerox to sell its copier and the very high figure at which they were finally priced in 1962 is indicative of the profitability of the rental scheme.[25]

On the technology side, Xerox continued developing its product. During the 1960s, while new versions of its 914 model were introduced, it also launched new products directed to serve the low and high volume segments of the market. In 1964, Xerox introduced a machine slower than the 914, aimed at the low end of the market. Three years later, it introduced its 3600 copier that, with a speed of 3600 copies per hour (nearly four times faster than its fastest model), was directed to high-copy-volume users. In parallel to the introduction of its new products, Xerox advanced new pricing plans aimed to increasing the attractiveness of its product. The high profitability of the high volume market led Xerox to concentrate its efforts at this end of the market. IEP gradually penetrated applications traditionally reserved to hectographic and stencil duplicating technologies and, eventually, it also entered into competition with some segments served by offset lithography.

At the low end of the market, DEP, its cousin technology, had considerable success placing itself above the contact processes that had dominated during the 1950s. DEP experienced considerable growth during the period that Xerox held the monopoly of plain paper copiers. In the DEP

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[24] Mort (1989), p.65.

[25] The reported costs of a Xerox machine were 2,500 U.S. dollars. It was, however, priced in 1962 at 29,500 U.S. dollars. As Blackstone suggests, such a price was set to discourage purchase. See Blackstone (1975) p. 190-2.

industry, where the technology had been widely licensed, equipment and consumables suppliers proliferated. In the US, for instance, between 1962 and 1967, the number of firms selling DEP machines passed from 3 to 26.[26] Increased competition decreased prices of the DEP process and it started to become and increasingly attractive option for IEP users. As Blackstone suggests, this may well have been a factor contributing to the Xerox decision to reduce the list price of its standard copier, which in 1969 was priced at nearly a quarter of the price set in 1962.[27] Throughout the 1960s, the DEP remained as a strong contestant in the photocopying market. However, according to Blackstone, by 1968, Xerox alone received 60% of the total revenues of the copying machine industry while only 20% accrued to all the DEP industry.[28]

5.3.3 The diffusion of IEP

The international diffusion of IEP technology during its first twelve years in the market went in parallel with the international expansion of Xerox. A detailed break down of the production sales and exports of the different firms within the Xerox Group is not available. However, there are some estimates of sales and placements for some major markets, which can help us form an idea of the degree of penetration reached by electrostatic photocopying relative to the size of the market of copiers in the last years of the Xerox monopoly.

Table 5.1 Copying machines installed in the UK and Japan in 1968 (units)

	UK	Japan
Total of copying machines	135,500	201,677
Electrostatic Transfer	23,500	80,263
Direct process	18,000	na
Indirect process	5,500	na

SOURCE: Ghazanfar (1984).

These indicators show clearly that the IEP process had gained a significant share of the markets in question by the end of the 1960s. This

[26] Blackstone (1975).

[27] In 1969, Xerox set the list price of its copier at 8,000 U.S. dollars. against a price of 29,500 in 1962. Blackstone (1975), pp. 191, 201.

[28] Blackstone (1975), p. 190.

Table 5.2 US copier markets, 1960-1967. Shares of different processes in total sales (%)

	1960	1963	1967
Electrostatic			
Direct	-	10	20
Indirect	2	38	63
Contact			
Diazo (dyeline)	5	2	1
Transfer (a)	47	25	5
Thermography (b)	45	25	11
Total (mil. US dlls.)	200	350	850

SOURCE: Ghazanfar (1984), p.203.
Notes: (a) includes gelatine transfer and diffusion transfer.
(b) Includes dual spectrum.

was partly at the expense of other reprographic technologies, but it was also largely due to the expansion of the market that stem from the innovation.

5.4 Entry, diffusion of innovation and competition in the IEP industry

The IEP industry provides a remarkable example of the fact that important qualitative changes often result from the entry of new firms into an industry. These changes go far beyond the simple increase in the supply and the change in the pricing and production behaviour associated with the presence of a larger number of participants. Entry into the IEP industry had significant effects, both in terms of innovations that affected the course of technological development and in the introduction of strategies and institutional arrangements, which also represented important innovations that modified the functioning of the IEP market.

5.4.1 Entrants into IEP manufacturing in the early 1970s

Even before the introduction of the coated paper based DEP, the great potential of xerography was recognized in the reprographic industry.[29] As we mentioned above, while the Xerox monopoly prevailed in IEP, competition concentrated on DEP, and the coated paper process rapidly gained a place in the copying market as a fast, inexpensive and easy method of convenience copying. The superiority of the IEP process, however, was also widely recognized by the end of the 1960s, as were also well known the

[29] See IFD (1953) p.221 E1.

extraordinary market performance and high profits enjoyed by the innovative firm. In the early 1970s, most of the basic patents held by Xerox expired and other companies, which had been developing their own IEP machines, entered the market.

The first firm to enter the US market was IBM in 1970 with its "Copier I". The photocopier used an organic photoconductor instead of the selenium drum used in Xerox machines. In terms of performance, it was comparable to the latest version of Xerox 914 family of copiers. A faster model, Copier II, was introduced two years later. Shortly after IBM, other manufacturers entered the market. Between 1970 and 1975, at least seven new manufacturers of IEP entered the US market. Among them were VanDick, 3M, Saxon, Kodak, Pitney Bowes and Adressograph-Multigraph. With the exception of the information technology giant IBM, which had no former presence in reprographics, all the other companies mentioned above were already participating in this market. Kodak and 3M had introduced their own proprietary contact copying technologies, which were being displaced by the new technology. 3M, VanDick, Pitney Bowes and Saxon had already been participating in the DEP market, while Adressograph-Multigraph was a producer of small offset equipment. A common characteristic of most of the machines introduced by the U.S manufacturers in this period was that they were aimed at average copy volumes of around 10,000 copies per month and directed to the market served by Xerox medium volume copiers. In addition to these manufacturers, in the mid 1970s, a number of companies became distributers of photocopiers manufactured overseas, particularly in Japan.

In Japan, where Fuji-Xerox had dominated the IEP market, as many as 10 firms began to manufacture IEP equipment between 1970 and 1975. The first entrant was Canon in 1970. The company had entered the copying machine business in 1965 and had launched a research programme aimed at circumventing Xerox patents in IEP equipment. Canon developed an alternative electrostatic method based on a cadmium sulphide drum, instead of the selenium one used by Xerox. The research effort culminated in 1972 when its "new process" was perfected with the development of a liquid toner. Its NP copiers series (NP for new process) where introduced in the European market in 1973 and in the US in 1974. The copiers produced by Canon had two major characteristics, which distinguished them from those of the US manufacturers: they were aimed at the low volume market traditionally served by the smaller of Xerox copiers, and they were priced considerably below the price of the Xerox machine.[30] Canon's technology was licensed to twenty firms in Japan and three in the US. Other Japanese manufacturers which entered the market in this period where Konishiroku (Konica), Ricoh, Iwatsu, Tokyo Aero Keichi, Copyer, Sharp, Toshiba, Minolta and Mita Kogyo.[31] Two US companies, IBM and 3M, also attempted to enter the Japanese market but soon dropped out.[32] Tokyo Aero Keichi presence in the market was also short lived. Japanese producers came in their majority from three different industries: reprography, photography and electric and electronic equipment. Canon, Minolta and Konishiroku (Konica) were established manufacturers of photographic equipment; however, Minolta was already producing DEP equipment, and Canon, as we mentioned, had entered the photocopy business in 1965, Konishiroku's major business was the production of photographic film. Ricoh, the other major Japanese entrant, was the largest supplier of reprographic products in Japan and Mita Kogyo was also specialized in reprographics, mainly diazo. Finally, Matsuchita (Panasonic), Sharp and Toshiba were manufacturers of consumer and industry electric and electronic equipment. Like Canon, Japanese producers concentrated their efforts on products aimed at the low volume segment of the copying market.

Also in Europe various companies entered the industry to challenge the Rank-Xerox monopoly. Practically all of them where already participating in the reprographic industry. Gestetner, a UK based manufacturer of stencil equipment and a forerunner of this technology introduced a copier in 1971. It was followed by the Belgian company Agfa-Gaevert, which, although better known by its photographic products, was also producing DEP equipment and offset materials. Agfa-Gaevert's machine, however, was produced in Germany. Various German companies also entered the industry: Develop, which had been a producer of contact copiers, Pelikan, a manufacturer of office products and stencil equipment, and AEG Olympia, producer of typewriters and business machines. Other European manufacturers were the German-Italian firm APECO, which produced contact

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[30] In 1975, for instance, Thorn, Canon's distributer in the U.K. priced Canon's NP 70 and NP 1100 machines at £2,600. In that same year, the price of Xerox equivalent machine, the model 3100, was of £ 5,500. Monopolies and Mergers Commission (1976).

[31] Information provided by the Japanese Business Machine Association.

[32] See Ghazanfar (1984).

copying and DEP equipment, the Italian typewriter producer Olivetti and, in Denmark, Rex-Rotary, a producer of hectographic equipment.

As in the US, in the 1970s, a number of European companies opted for distributing or marketing rebadged models of photocopiers manufactured in Japan. They were soon followed by the manufacturers of photocopiers themselves. Both in Western Europe and the US, the low-volume, low-priced copiers made in Japan had and excellent market penetration and as we will see later, in a short period of time Japanese producers became a dominant force in the IEP industry.

5.4.2 Indirect electrostatic photocopying: imitation, innovation and changes in the market

With the introduction of IEP, Xerox revolutionized copying technology and created a new industry. To a great extent, entry into this industry involved the imitation of Xerox technology and practices. However, there were, in different degree depending on the firm, important elements of creativity by some of the new entrants. From the outset, there were companies which innovated not only in technology, but in the ways in which their product was marketed. The diversity of new competitors brought along new approaches to the IEP process and also introduced a great deal of product differentiation.

Post innovation performance: new design configurations and product differentiation

During the first half of the 1970s, in response to the entries into IEP, Xerox undertook legal action for patent infringement against a number of firms. Among the firms sued where IBM, VanDick, SCM, Gestetner, Kodak and Agfa-Gaevert. Some of these companies, in turn, filed suits against Xerox, charging the company for restrictive business practices. The course of these disputes was, to some extent, decided in 1975. Following antitrust action against Xerox Corp. in the U.S, in 1975, Xerox Corp. signed a Federal Trade Commission consent order in which the firm committed itself to license its technology worldwide. The consent order also imposed restrictions on Xerox's pricing plans and required it to fix a selling price on its machines at the same time that they were offered for lease. In addition, Xerox Corp. had it forbidden to acquire further interests in other copier supplies.[33] This event contributed to the opening of the market and most legal undertakings were settled through licensing and cross licensing agreements between the firms in conflict.

It is true that the new entrants were using the basic elements of the Xerox process and that many entrants used essentially the same technology as Xerox. However, there were others which had been devising ways to circumvent Xerox patents and, with varying degree of success, had generated innovations in key elements of the IEP process. Some of these innovations, in core elements of the process, were the foundation of the emergence of alternative design configurations in IEP technology. IBM machines, for instance, used an organic photoconductor instead of selenium. The German company Kalle-Infotec also marketed machines that used an organic photoconductor developed by its parent company Hoechst. These machines were designed and manufactured in Japan by Ricoh, but used Hoechst photoreceptor technology.[34] 3M also produced copiers based on a different photoconductor technology. The photoreceptor was based on a coat of Zinc Oxide, the same material that was used in coated paper for the DEP process.[35] 3M's machine also incorporated a different toning system based on monocomponent magnetic toner.

Another innovative approach to the IEP process was the technology developed by Canon. As 3M, Canon not only incorporated changes in the photoconductor system, but also in other key aspects. In the late 1960s, Canon developed a copier drum with an insulating material, which allowed it to use cadmium sulphide (CdS), a material with a light sensitivity comparable to αSe. This was complemented with the use of its "liquid-dry" system in which toner particles were suspended in a liquid medium instead of being used as a dry powder. In this system, the toner was dried naturally as the solvents evaporated, instead of using heat as it was traditionally done. Other machines that also incorporated the liquid development system were the ones manufactured by Ricoh for the US company Savin. The liquid toning system was slower but delivered good copy quality and also made the process cheaper; therefore, it was better suited for slow low-volume copiers, and it was very successfully applied in these machines

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[33] See Monopolies and Mergers Commission (1976), pp. 37-9.

[34] See, Monopolies and Mergers Commission (1976).

[35] Schaffert (1975).

during the 1970s. For faster machines, the dry toner system continued being a better alternative.

In addition to those aspects of technical progress, which relate to higher productivity and lower manufacturing costs, the other important dimension of technological change in IEP has been the gradual incorporation of new features to the design. Manufacturers change their design and incorporate novelties, which improve the performance of their products and help to differentiate them in order to capture market niches. However, with the passage of time, many of them have become standard elements in photocopiers. That is the case of the introduction of reduction capabilities, productivity enhancing features and the use of microprocessors to automate many functions of the copiers. These new features, independently of their degree of novelty and ingenuity, to the extent that they are external to the core of the technology, ought to be distinguished from the type of innovations mentioned above. These elements of product differentiation do not define a new design configuration and may be incorporated in the different competing designs.

The development of IEP technology and its relationship with other aspects of the evolution of the industry will be discussed further in section 5.5. What we wish to emphasize at this point is the fact that the entry of new competitors brought with it innovation and technological diversity to the IEP industry.

The effects of entry in the functioning of the market

The presence of new competitors in the IEP industry not only brought along changes in technology, but also noticeable changes in the market place. Some entrants like IBM and Kodak competed with Xerox using a similar strategy to the one used by the latter. They produced equipment, focused on the high volume segment in which Xerox had concentrated its major technological efforts and used a similar scheme of commercialisation based on the lease or rent of the equipment. There were others, however, that adopted a more innovative approach.

After Canon's introduction of low-volume low-price PPCs, various manufacturers, mainly Japanese, focused on this segment of the market. Many companies in the US and Western Europe found it more profitable to compete in these markets by commercialising equipment produced overseas.

Besides attacking the low end of the market, another innovative element of these competitors was the shift towards an emphasis on sales of equipment, instead of the traditional renting or leasing schemes. Low-priced low-volume machines made it possible to enter the market competing on an entirely new basis. In contrast to leasing, the practice established by Xerox, copiers were sold. The change was significant; firms were able to enter into the market without having to undertake the huge investment involved in building the organization required to compete with Xerox on its own terms.

In the US and Western Europe, the formula was in most cases a combination between a Japanese manufacturer and a local firm, which distributed the product, either directly or through a network of dealers. A symbiotic relationship developed, in which Japanese manufacturers benefited from the marketing capabilities of firms in foreign markets, while the latter profited from being able to sell a very competitive product in a new segment of the market. The agreements of the Japanese manufacturer Ricoh with Savin in the US and with the German company Kalle-Infotec are the best example of this kind of situation. The first agreement was that Ricoh would produce copiers using the designs of Savin, and Savin would commercialise them in the US. In the case of Kalle-Infotec, Ricoh would develop and manufacture a copier that incorporated an organic photoconductor patented by Hoechst (Kalle-Infotec's parent company). The equipment would be sold in Europe by Kalle-Infotec. Other commercialisation agreements were also reached by Ricoh with Nashua and Oceania. Ricoh reserved for itself the distribution of its copiers in the Far East. These deals proved to be very successful. In the case of Savin, for instance, by 1981, the firm was the second in market share after Xerox in the convenience copying segment of the US reprographics market.[36] The scheme has of course evolved with time and changed from company to company. Once established in the market, Japanese manufacturers have tended to distribute the product through their own subsidiaries and to develop their own network of dealers. Nevertheless, badging (that is, a firm marketing equipment from another manufacturer under its own label), has become a very

[36] According to estimates by Modern Office Procedures in 1981, Savin had a market share of 13% in the US convenience copying market. (quoted in Appliance, September (1982)).

extended practice. Even firms that produce their own copiers resort to this scheme to complete their product line.

5.4.3 The diffusion of IEP during the 1970s: some indicators

The entry of new firms and the diffusion of the IEP technology made a significant contribution to the overall expansion of the copying market. Demand for copying equipment and the output of IEPs grew at high rates during the 1970s. Not all the expansion of the market can be attributed to the diffusion of IEP technology; there were other processes like DEP that also grew at high rates in the 1970s. However, the data available on output growth and on the shares of different reprographic processes indicate that IEP diffusion was a major factor behind that growth.

One of the main difficulties in analysing the copying industry is the lack of systematically collected official data at the level of disaggregation that is required. Most of the data on the technology and industry that we present in this chapter is information generated by two private agencies: Dataquest and Datapro, which are two of the longer established companies that report on the industry. Part of the information has been obtained directly from those agencies and part has been collected from various sources, such as trade journals, monographs from other authors and newspapers. The data are not official, but estimates produced by different private agencies; thus, they have to be taken with care. However, this information helps us form an idea of the expansion experienced by the IEP industry.

There are various possible measures of the size of the market, such as copy volume, revenue, units installed and placements, each showing a different aspect of it. The fact that participants in the IEP industry operate both by selling and by leasing equipment complicates the problem of measurement. This makes it difficult not only to estimate the size of the market, but to compare the IEP market with that of other processes and to assess the relative performance of different producers.

Table 5.3 presents data on the total revenue for all copying and duplicating markets in 1970 and 1975 and for plain paper copiers. This table helps us form an idea of the size that this industry had reached with respect to the reprographics market.

Table 5.3 Plain paper copier markets in 1976

Region	Copy Volume (billion copies)	Total revenue (mil. US dlls.)	Placements (000 units)
North America	74.7	3,104	107
Europe	43.8	2,159	80
Japan	13.3	767	64
Rest of world	9.3	721	31
Total	141.1	6,751	286

SOURCE: Dataquest, in Ishikura (1983a).

The data on copying and duplicating are for 1975, and, on plain paper copying, for 1976; thus, they are not strictly comparable. However, they suggest that, by the mid 1970s, plain paper copying had acquired a large share of the reprographics market, in terms of revenues.

There are also some indicators, collected from various sources, of the rate of growth experienced by IEP and other reprographic processes in the early 1970s. Table 5.4, on the rate of growth of the copying and duplicating markets, will serve as benchmark to the tables presented below.

Table 5.4 World copying and duplicating market. Compound annual rate of growth, 1970-1975 (%)

Region	Copy volume	Total revenue	Units installed
North America	2.6	13.4	8.7
Europe	8.1	17.6	6.9
Japan	6.0	16.6	9.0
Other	17.4	32.2	14.5
Total	5.2	16.3	8.6

SOURCE: Dataquest, in *Financial Times*, 27 November (1976).

Tables 5.5 to 5.7 present data that help us form an idea of the relative contribution of IEP to the rate of growth that the reprographics industries enjoyed in the early 1970s in the US, Western Europe and Japan.

Table 5.5 US plain paper copier market, 1970, 1976 (mil. US dlls.)

Concept	1970	1976	Compound annual rate of growth (%) 1970-76
Revenue from hardware	852	2,465	19.4
Units in place	269	654	16.0

SOURCE: Dataquest, in *Financial Times*, 27 November (1976).

By comparing Tables 5.4 and 5.5, we can see that the rate of growth of PPCs in place in the US is considerably higher than that for North America's reprographics. The rate of growth in the US of revenue from hardware is also high. This concept, however, is not entirely comparable with the concept of total revenue, which includes revenues from services and supplies. In addition, since outright sales gained importance in this period, that indicator may tend to overestimate the expansion of the market.

Table 5.6 on Western Europe gives us a good picture of the high growth experienced by IEP relative to the other processes. IEP was the reprographics technology whose market experienced the highest rate of growth between 1970 and 1975.

Table 5.6 Reprographic market in Western Europe. Compound annual rate of growth, 1970-1975 (%)

Process	number of copies	number of machines
Indirect electrostatic	31	26
Direct electrostatic	8	19
Other coated paper	-6	9
Offset	6	10
Stencil	0.4	1
Spirit	2	-

SOURCE: Monopolies and Mergers Commission (1976), p. 8.

A break down of the Japanese market by process is not available; thus, we have resorted to data on production to have some idea of the size and relative growth of the industry in this country. Table 5.7 shows the great importance that IEP had reached in Japanese production of reprographics equipment and the fast growth of the electrostatic copying industry, which contrasts with the decline of other reprographics industries.

Table 5.7 Japan copying and duplicating equipment production, 1973, 1977 (000 units)

	1973	1977	Compound annual rate of growth (%) 1970-77
Duplicators	40	38	-1.3
Electrostatic copiers	319	622	18.3
Direct process	na	439	na
Indirect process	na	117	na
Other copiers	181	117	-10.3

SOURCE: MITI, in *Office Equipment and Products*, February (1979).

5.5 The development of indirect electrostatic photocopying technology and the evolution of the industry, 1960-1990

One of the most significant facts that emerged in our account of the evolution of the IEP industry during the first half of the 1970s (section 5.4.1) is that the entry of new competitors also brought important contributions to the technology. These contributions were not simply improvements in Xerox's process but represented a widening of the trajectory along which the technology was developing. In this section, we will look in more detail at the major developments in IEP technology that have run in parallel to the evolution of the industry.

It is important to distinguish between those elements of design that are at the heart of the IEP process from other features that, although important for the performance of the equipment, are not central to the technology. It is the former group of basic elements of design that defines the technological regime. It is also the different specific solutions given to the problems defined by those design parameters that define the different design configurations within the regime.

We will be referring to those basic elements of the technological regime that are relevant for the definition of different design configurations as the core aspects of the technology. Other elements will be referred to as features. The latter can, in principle, be shared by equipment of the different design configurations.

The core of the technology occupies (in Clark's terminology), a higher hierarchy in design.[37] The knowledge associated with the core aspects of the technology is central to the competencies of firms in the industry. Clearly, other aspects affect firms' competitive performance, but strong capabilities in the core of the technology are essential for success in the industry. Only on that basis, the service and marketing strategies, the introduction of innovative features in the equipment and the like, can give a competitive edge. But no amount of the latter can sustain a manufacturer whose basic technology is lagging behind, since it is this basic technology that is fundamental for the main performance characteristics of the equipment, such as copy quality, equipment reliability, speed and price.

5.5.1 The core of the technology

The IEP technological regime can be characterized by the six basic steps of the IEP process shown in figure 5.3.

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[37] Clark (1985).

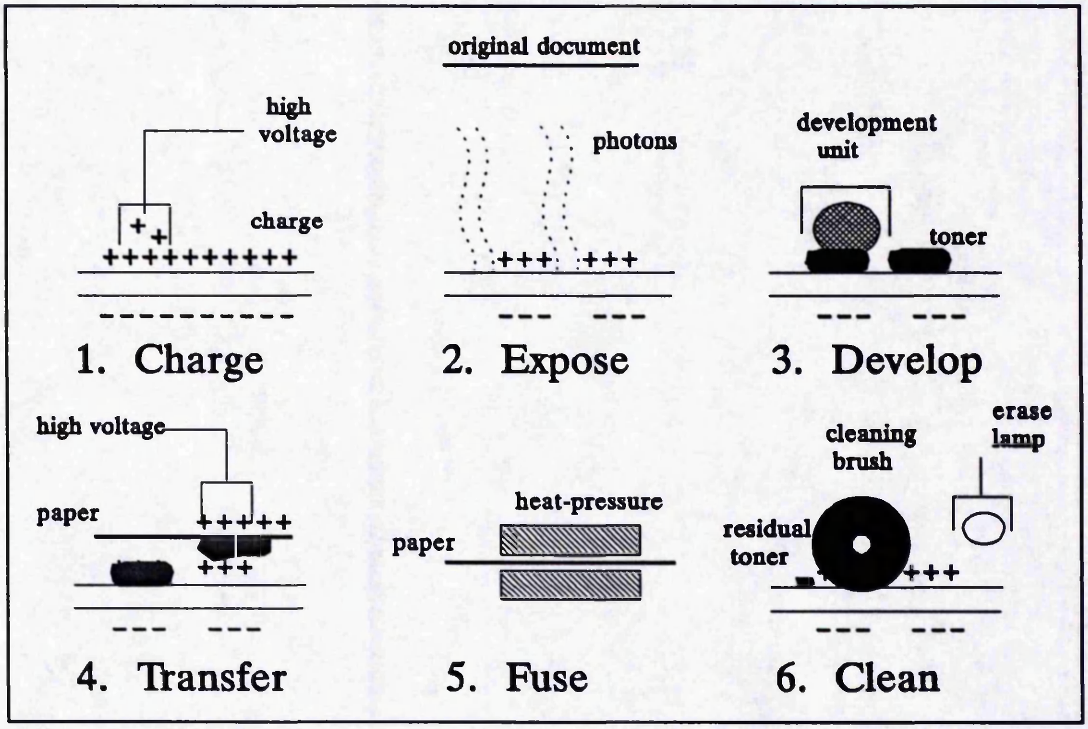

Figure 5.3 Steps of the IEP process

As IEP technology has been developed, different solutions have been given to the problems posed by these steps and to the way in which they are articulated in an operating system. In each of these different steps, a variety of designs have been implemented by different firms in the industry. This has been partly in search of improved performance over existing designs, but it has also been the result of an effort to develop an alternative to the proprietary technology of their competitors.

Since the introduction of the model 914 by Xerox, corona devices have been generally used to charge the photoreceptor. Numerous improvements have been continuously introduced to eliminate shortcomings of previous designs, such as overcharging, which could damage the photoreceptor, and susceptibility to contamination, which induces non-uniform charge.

For exposure, the light sources more commonly used are neon lights, belt scanners and flash lights. Lenses and mirrors or fibre optics are used to take the input image of the original being reproduced to the photoreceptor.

Regarding the photoreceptor, a diversity of both organic and inorganic photoconductive materials are used. Amorphous Selenium, which was used in the 914 model, is still widely used in alloys with other materials. Organic materials have been increasingly gaining importance.

The most common physical configurations of the photoreceptor are as a drum or as a belt.

With respect to image development, different types of dry and liquid toner have been used in a variety of development systems. The design of the system is intimately related to the characteristics of the toner used. The most widespread type of toner is the dual dry toner introduced by Xerox, which was already present in the 914 model. Other alternatives to the use of dual dry toner are liquid toners and dry monocomponent systems.

With few exceptions, the generalized mechanism to transfer the image from the photoreceptor to the paper is electrostatic transfer, introduced by Xerox and already present in the 914. In this system, an electrostatic charge is applied to the back of the paper and the toner is transferred from the photoreceptor to the paper.

The fusion method depends to some extent on the type of toner used. The majority of the fusion methods use heat and pressure to fuse the toner on the surface of the paper. Other alternatives are radiant heat, cold pressure and the use of flash lights. Different methods have their own advantages and shortcomings. Cold pressure fusing, for instance, saves electricity consumption, reduces risk of overheating and, in most machines, eliminates the need for a warm up time. On the other hand, the high pressure applied to the paper in this method affects the texture of the paper and can even produce deformations.

Finally, regarding the cleaning of residual toner from the photoreceptor, blades or brushes are often used. Blades are a cheaper and simpler mechanism but are, in general, more abrasive and tend to be used in the lower end of the market or with a photoreceptor of outstanding hardness. Brush mechanisms (non magnetic and magnetic) are more expensive but also more gentle ways of cleaning the photoreceptor, which lengthens its life.

The systemic nature of a photocopier is apparent from the above description of the different parts and steps involved in the IEP process. The design decisions adopted in different components of the system, notably the photoreceptor and the development subsystems, are important determining factors of the requirements that are imposed on other components. These are illustrated in Figure 5.4 below, adapted from Scharfe (1984). Scharfe distinguishes between three basic subsystems, which are central for design:

exposure, photoconductor and development. These subsystems interact with each other to produce a practical IEP system.

The exposure subsystem transfers the optical input image into an input exposure image on the surface of the photoreceptor. The photoconductor subsystem transforms this input exposure into an electrostatic latent image. Finally, the development subsystem transforms the latent image into a developed real image into the photoconductor. Clearly, the input received by a subsystem from the preceding one is fundamental for the output that the former will deliver. Quadrant I of figure 5.4 shows the tone reproduction curves for one hypothetical design by using lines and solid areas . These curves show the relationship that exists between input image and output image for the system as a whole. The other three quadrants show the relationship between the different subsystems. Changes in the configuration in one of the subsystem will affect these relationships and the final input output reproduction curves.

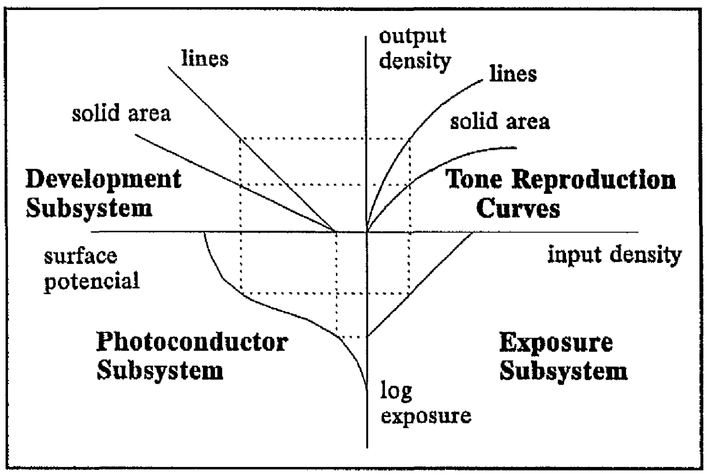

Figure 5.4 Subsystems interaction in the IEP photocopying process
SOURCE: adapted from Scharfe (1984).

The question of subsystems interaction is pervasive in IEP design. Depending on the importance that is given to variables such as cost, copy quality, speed and reliability, different choices are made on the configurations of basic elements of the design, which have immediate implications on the possibilities that are open for other parts of the system. In this context, Clark's concept of hierarchy is particularly relevant: in IEP technology, it is the photoreceptor and the development subsystems that occupy the top level in that hierarchy.[38] It is also on the basis of these subsystems that the different design configurations that characterize IEP technology can be identified.

The photoconductor system[39]

The type of material used is photoreceptor at the centre of the photoconductor system. Three main types of materials are used commercially: Selenium-based materials (also known as chalcogenide glasses), organic materials and amorphous hydrogenated silicon (αH-Si). Amorphous selenium and other chalcogenide glasses are rigid and more suitable to be used in a drum configuration. The same applies to photoreceptor made of (αH-Si). Organic materials offer greater flexibility and can also be used in belts.

A drum configuration requires that the image is gradually transferred as the drum rotates and, thus, requires a scan type of exposure system. Belts and masters, on the other hand, allow a full image to be transferred by means of a flash light. The mechanical properties of the photoconductor material also have an influence on the cleaning devices that are used: organic materials, for instance, are less hard than the other two types of materials and their life can be lengthened with the use of gentle cleaning systems.[40]

To the extent that the different materials are bound to be used to perform the same function within the photoconductor system of a photocopier, there is a common set of characteristics relevant for their performance. Table 5.8 lists some of the more important dimensions across which photoconductor technology has been developed.

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[38] It is worth noting that, although valid, in general, this statement is not always true. The use of solid state lasers in digital copiers, for instance, has conditioned the design of the photoconductor system.

[39] Our description of the photoconductor and the development subsystems draws mainly on Borsenberg and Weiss (1993) Schein (1992) and Mort (1989), where more detailed descriptions of these subsystems can be found.

[40] Cost considerations, however, have led to the use of blades in low priced machines which use single layer organic photoreceptor. This makes the already short life of the photoreceptor even shorter, but the machines are designed for frequent simple replacement of the photoreceptor, development and cleaning systems. Thus, the short life is compensated with a low price of this replacement, relative to better quality ones.

Table 5.8 Relevant characteristics for photoreceptor performance

Characteristic	Desirable	Reason
hardness (trade-off)	high	larger life
	low	flexibility to use in belts
photosensitivity	high	less exposure needed, better image quality
trap density	low	avoid distortion of subsequent images
mobility of charge carrier	high	reduce process time
spectral response	wide	sensitive to all colours
residual potential	low	contrast obtainable
acceptance potential	high	contrast obtainable
retentivity	high	be able to store image
thermal generation rate	low	avoid operation problems due to heat
toxicity	low	health, environment
manufacturing costs	low	economic

In spite of the common set of characteristics by which photoconductors are evaluated, different types of material vary considerably in their properties. Because of these differences, each material poses different problems and the solutions to them are specific to the material in question. The choice of the particular type of photoconductive material to be used also determines the characteristics of manufacturing process of the photoreceptor. In short, the practical application of a particular type of material to the production of a photoreceptor requires the development of a knowledge base specific to it. Therefore, the three types of materials mentioned above define three different design configurations at the level of the photoconductor subsystem of IEP technology.

In relation to the various characteristics of photoconductive materials, the sensitivity of the photoreceptor and its range of spectral response are particularly important properties for the commercial application of a material. There has been a considerable increase in photoreceptor sensitivity relative to that of the materials initially used by Carlson in its experiments: Modern photoreceptor are 10^4 more sensitive than the most pure anthracene, which was the material used by Carlson.[41]

Table 5.9 shows the photosensitivity of some of the main photoconductive materials that were used by 1975 relative to that of sulphur. The high sensitivity to light of amorphous selenium was one of the major considerations that made this material to be preferred for the first commercial applications of xerography. However, as the table shows,

41 Schein (1992), p. 4.

Table 5.9 Relative photosensitivity of various materials

Sulphur	1
Anthracene	4
Polyvinyl carbazole	7
Zinc oxide mixture (dry sensitized)	500-1000
Z-CdS resine mixture (70% CdS)	900
PVK-TNF	900
Amorphous Se	1000
Se alloys	
-arsenic	3000
-antimony	12000
-tellurium	10000
-Se-arsenic-antimony (iodine doped)	12000-18000

SOURCE: Schaffert (1975), p.62.

it was later considerably increased by making alloys with other materials.

The range of spectral response is also important since it determines the sensitivity of the photoreceptor to different colours. One limitation of αSe is its low photoconductivity in the long wave range of the visible spectrum. This has been solved to some extent by making Selenium alloys, which incorporate tellurium or arsenic in high concentrations. A further advantage of these alloys is that they improve the mechanical properties of the material.

As we pointed out in section 5.4.2, the entry of new competitors to the industry was accompanied by the introduction of significant innovations in IEP technology. In the area of the photoconductor system, from the outset, alternatives to Xerox's αSe drum configuration were introduced. IBM was the first company to use an organic photoreceptor; IBM's "Copier I" was based on a layer of PVK and TFN.[42] A major limitation of this material was its shorter life. It was a softer organic material that wears out more quickly and builds up trapped charge. On the other hand, the photoconductor was less expensive to manufacture so, in itself, its shorter life is not a major problem. The real problem, which was the need of frequent replacement, was solved by IBM by coating the photoconductor material onto webs of aluminized Mylar, which were rolled inside a drum. When new photoconductor was needed it could be released by pushing a button. In this way, the rolled up photoreceptor had an overall longer life than the Se drum.[43] In 1975, Kodak also entered the market with an

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[42] PVK stands for poly-(N-vinylcarbazole) and TFN for 2,4,7-trinitro-9 fluorenane.

[43] See Borsenberg and Weiss (1993), p. 383 and Schein (1992), pp. 8, 40.

organic photoreceptor but adopted instead a belt configuration. This allowed Kodak to use a flash exposure system that exposed the photoreceptor to a full image and eliminated the recovery time of the light belt system required in machines that used a cylindrical photoreceptor. An additional advantage of the belt was that it permitted improved paper handling, which is important for reliability, particularly in high speed-high volume applications.

Organic materials exhibit comparable levels of photosensitivity than chalcogenide glasses. Their relative softness allows them to be used in a belt configuration; however, it is also the source of poor mechanical properties, which lead to a shorter life. Another shortcoming of most organic photoreceptors is that there is either mobility of wholes or of electrons but not of both, which creates problems of image hysteresis. These problems have been solved by adopting a two layer configuration in the photoreceptor structure, which not only reduces the image hysteresis problem, but makes the photoreceptor more resistant to wear and damage.

Although the two layer structure increases the complexity and cost of producing an organic photoreceptor, this cost is still lower than that of photoreceptors made of Selenium. Organic photoreceptors are produced with a solvent coating process, while Se drums use a vapour depositation technique that is more expensive. In addition to their fabrication costs disadvantage, the production of Se photoreceptors involves the use of hazardous materials with the related health and environmental problems. In the case of organics, the use of solvents and their emission to the atmosphere is also a problem, but it is comparatively less severe.

Other photoconductive materials like Zinc Oxide and Cadmium Sulphide dispersed in a polymer host have been used in the production of photoreceptors. Nowadays, the Dutch manufacturer Océ is the only major producer that still uses this material. The main limitations of Zinc Oxide are short life and charge transfer problems. The Cadmium sulphide photoreceptor was introduced by Canon in 1972, and was used by the company until the mid 1980s. The technology was widely licensed and became relatively common in Japanese copiers. However, it has been phased out, mainly because of the great toxicity of the materials used and the associated environmental problems.

In 1985, amorphous hydrogenated Silicon (αH-Si), a photoconductive material initially used in photovaltics technology,[44] was introduced by Canon in its NP-7000 model.[45] The main advantage of this material is its hardness. To the extent that the life of a photoreceptor depends on wear and abrasion, the life of αH-Si photoreceptor is longer. Table 5.10 compares the hardness of various materials.

Table 5.10 Hardness of different types of photoconductive material

	Vickers hardness (Km/mm2)
Organic materials	20-30
Amorphous Se	30-50
Se-Tellurium alloy	30-50
Se-arsenic alloy	150-200
Amorphous silicon	1500-2000

SOURCE: Borsenberg and Weiss (1993), p.32.

The life of the αH-Si photoreceptor is estimated to exceed 10^6 copies, which is ten times more than the life of a conventional Selenium based photoreceptor. Another advantage of the new material is the high mobility of its charge carriers, which permits the reduction of the process time between exposure and development. The major limitation for the use of αH-Si photoreceptors is their high manufacturing cost. They are produced by plasma induced dissociation of gaseous silene that requires several hours of expensive equipment. Another problem is that the process involves the use of highly toxic and flammable materials. Finally, due to its hardness, the new material can only be used in a drum configuration.[46]

It is clear from the foregoing description of photoconductor technologies that there are different combinations of performance characteristics associated with the different design configurations of the photoconductor. The specificity of each configuration also implies a different potential of improvement across the various performance characteristics that are relevant. One important implication of this diversity is that, at any particular point in time, the strength of the different configurations may vary for different segments of the market. From the point of view of market dynamics, the relative shares of the

[44] See Mort (1989, 1994).

[45] Schein (1992), p. 11.

[46] Borsenberg and Weiss (1993), pp. 31-34.

various configurations will depend, on the one hand, on the degree of development of each configuration and, on the other hand, on changes in the environment, which may change the social valuation of the different performance characteristics. Table 5.11 below uses data on the US market for 1984 and 1993 to illustrate the tendency of certain configurations to prevail in some segments of the market. For simplicity, the market has been divided in three segments according to the speed of the machines. The low speed segment includes machines with a multicopy speed up to 30 copiers per minute (cpm), the medium speed segment refers to machines in the range of 31 to 69 cpm, and the high speed segment is that of machines of 70 cpm or more. The intertemporal comparison also shows the changes in the shares of the different design configurations that stem from the development of the technological regime and from the competition between different regimes in the market place.

Table 5.11 IEP models sold in the U.S. market 1984-1993. Photoconductor configurations: shares by segment of the market (%)

	1984				1993			
	ALL	SEGMENT			ALL	SEGMENT		
Material	MODELS	Low	Medium	High	MODELS	Low	Medium	High
Selenium based	69	73	81	36	36	18	54	48
Organic	14	8	0	64	56	80	34	35
Cadmium sulfide based	15	15	19	0	0	0	0	0
Amorphous silicon	0	0	0	0	5	2	6	10
Zinc oxide	2	3	0	0	3	0	6	3
% of models	100	100	97	100	87	83	94	87
Physical Configuration								
Drum	80	91	97	0	84	85	92	59
Belt or loop	15	2	3	100	10	1	8	41
Cartridge	1	2	0	0	6	14	0	0
Master	4	5	0	0	0	0	0	0
% of models	100	100	97	100	84	79	92	80
Total number of models	212	149	32	28	301	147	106	46

SOURCE: elaboration on data supplied by Datapro and Rank-Xerox.
Notes: for 1984, a small proportion of the models included in the "Se based" group were refered to as "inorganic" in the original sources.

Table 5.11 shows that there has been a significant change in the penetration of the different designs in different segments of the market. A major change in photoconductor technology has been associated with the type of material used. Se based photoreceptors have lost their dominant place and, as noted earlier, CdS has been abandoned, while the use of Zinc Oxide remains marginal. Organic materials have become the most used materials in the photoconductor system. In the low speed segment of the market, organic mono-layer photoreceptors tend to be preferred mainly due to costs considerations. At the highest end of the market, organic multilayered photoreceptor are attractive because they can be used in a belt configuration, which confers advantages when working at high speeds. Curiously, however, in this segment of the market, where organic materials and a belt or loop physical configuration were already dominant in 1984, there has been a move in the opposite direction and this type of configuration has lost ground. A higher proportion of models now use Selenium. Silicon drums have also been introduced and there are even some machines which use Zinc Oxide. The main explanation for these changes lies in the fact that, in 1984, there were only three, US based, manufacturers in this segment of the market and that two of them, Kodak and IBM, had adopted the Organic belt/loop configuration. The other manufacturer, Xerox, had also adopted a belt configuration for its machines in this segment. By 1993, however, other firms, many of them using Selenium based materials and a drum configuration, have penetrated the high speed segment of the market (particularly its lower end). This illustrates another important aspect of the technological diversity that we observe in the industry, namely, that there is also a significant degree of firm specificity in the technology used. Firms tend to concentrate on a particular design configuration and to acquire competencies on that technology as they develop it. This appears clearly in table 5.12, which shows the different configurations adopted by the major manufacturers in the models sold in the US market in 1984. As we noted earlier, the use of Selenium and Selenium alloys in a drum configuration was most common in that year, and it was present in the models of Xerox, Ricoh, Mita, Konica, Panasonic and Toshiba. Kodak and IBM relied on organic belt or loop configurations. Canon and Minolta, on the other hand, concentrated on Cadmium sulphide drums. We also note in the table that Canon and Sharp (which also used CdS in its fastest models) were already introducing organic photoreceptors in the lower end of the market.

In the last ten years, there has been a convergence towards the use of organic materials that is evident when we look at a the photoconductor technology in use in 1993 (see tables 5.11, 5.12). The shift towards organic photoreceptors has been more generalized in low speed machines than in any other segment of the market. If we look at the phenomena at the level of the firms, another important change that can be observed is that, although maintaining some degree of technological specificity, several firms have been widening their technological capabilities (see table A.1

Table 5.12 Photoreceptor configuration of the models of some major vendors in the U.S. market, 1984

cpm	Xerox	Kodak	IBM	Savin (Ricoh)	Ricoh	Canon	Mino-lta	Mita	Panas-onic	Royal (Konica)	Sharp	Tosh-iba
120	S-B											
		O-B										
			O-B									
70	S,O-B	O-B	O-B									
60	S-D											
50	ST-D					sC-D						
							S-D					
	S-D								ST-D	S-D		
				S-D								
40	S-D					sC-D					C-D	S-D
				ST-D								
	ST-D				S-D							
										S-D		
30	S-D		O-B	S,ST-D	S-D	sC-D	sC-D	S-D	ST-D	S-D		
				S-D								S-D
						sC-D						
	S-D											
25							sC-D		ST-D		C-D	
	S-D											
										Sa-D		S-D
						sC-D						
20	S,ST-D			S,ST-D	S-D			ST-D				
	S-D			S-D			C-D		ST-D			
										S-D		
15				S-D	S-D	O-D				Sa-D	O-D	S-D
									ST-D			
				ST-D		sC-D	C-D	S-D			O-M	S-D
	ST-D											
10	S-D				S-D			ST-D		ZO-D	O-M	
								ST-D				
	S-D					O-c						
6											Z-M	

SOURCE: elaboration on data provided by Datapro and Rank-Xerox.
KEYS: Material: C=CdS, sC=seamless CdS, O=Organic, S=Se, ST=Se-Tellurium, Sa=other Se alloys, Z=Zinc Oxide.
Physical Configuration: D=Drum, B=Belt, M=Master, c=cartridge.

in appendix A). The firms have tended to adopt, in different segments of the market, those configurations that are more advantageous.

The use of organic materials has introduced a great scope for material engineering. As a result, new and improved organic photoconductive materials are continuously added to the already large list of these materials.[47] The development of photoconductor technology that we have been describing follows a pattern that is reminiscent of that which has been suggested by paleontologist to describe the evolution of species and to explain the present diversity of living creatures.[48] A diversity of photoconductor materials have been appearing from the development of

[47] See Borsenberg and Weiss (1993).

[48] See Gould (1989).

photoconductor technology. Some of the different configurations that have emerged have become dominant, while others have been abandoned.

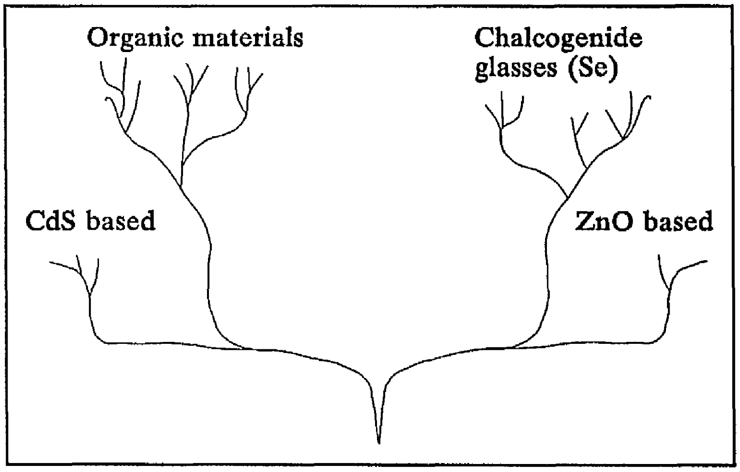

Figure 5.5 Diversity in photoconductor materials

The development system

The development subsystem is the second core aspect of IEP technology. Also here, different design configurations can be clearly identified. Each configuration represents a different technological solution to the problem of transforming the latent image in a real image susceptible of being transferred to paper.

The basic components of the development system are the toner and the devices and process used to bring the toner in contact with the charged photoreceptor. The most widespread type of systems are those which rely on dry dual component toner. This type of toner consists of the toner powder itself, usually powder of a polymer charged with carbon black of an average diameter of 10 μm, and of other larger particles, called carriers, of an approximate diameter of 200 μm, which carry the toner to the photoreceptor.

The Xerox 914 model used dry dual toner and a cascade development system in which gravity is used to bring in contact carriers and toner with the charged drum. This system has been superseded by others which give a better copy quality. The more widespread configurations are the systems based on a magnetic brush (developed by RCA in the 1950s). In these systems, the carriers with the toner are attracted by magnetic forces to the brush, which is used to bring them in contact with the photoreceptor. In 1975, Kodak entered the industry and introduced and improved system based in dual dry toner. This system, called conductive magnetic brush, uses irregular carriers instead of the conventional spherical ones. The innovation increased considerably the quality of the copy.

Other systems, introduced by early entrants to the industry, were monocomponent toner, by 3M, and the "liquid-dry" development system by Canon. The monocomponent system, as it was developed by 3M, had major flaws, which led to its abandonment.[49] However, in 1979, Canon introduced a very successful model that incorporated a toner projection development system based on dry monocomponent toner. Monocomponent systems have continued being developed and are used by several companies. Canon, for instance, has introduced a system based on insulative toner and non-contact development, which eliminates the drawbacks of earlier conductive monocomponent toners. A different approach, which relies on non magnetic toner, was introduced in 1985 by Ricoh.[50] The advantage of this type of toner is that it is potentially cheaper and more easy to produce in different colours.

Liquid development systems were widely used in DEP, and were subsequently adopted in IEP by some Japanese producers. This system was very successfully applied during the late 1970s and early 1980s in the low end of the market by Savin and Ricoh. Liquid development eliminated the need of a fuser to fix the toner to the paper, saving energy. In addition, the system used a simpler mechanism with less parts, which lowered the cost and increased reliability. A major drawback, however, is that these systems require the use of organic solvents, such as kerosene. These tend to be retained in the paper and slowly released into the environment.

An advantage of both dry monocomponent and liquid toner development systems is that, in general, they involve lower costs than dual dry ones. Monocomponent toner eliminates all the hardware complications associated with having to deal with two components and to maintain a proper balance between the two. Liquid development systems are also more simple than dual component ones. It is for this reason that they tended to be applied at the low end of the market, where a low machine price is particularly important in competition. However, Canon has been extremely successful in using its monocomponent development system across the full range of its

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[49] The main problems were, first, that the development consisted of only one layer of toner, which gave grey copies, and, second, that transfer was sensitive to humidity.

[50] Schein (1992), pp. 11-12.

machines. Table 5.13 shows the type of development systems used in some of the main models sold in the US around 1985.

Table 5.13 Development technology of the models of some major vendors in the U.S. market

cpm	Xerox	Kodak	IBM	Oce	Savin (Ricoh)	Ricoh	Canon	Minolta	Mita	Panasonic	Konika (Royal)	Sanyo	Sharp	Toshiba
120	DI													
90	DC	DC												
70	DC	DC	DI				MIM							
60	DI												DI	
				MCM										
											DI			
50	DI				L	DI	MIM		DI		DI		DI	
	DI			MCM				DIm		DI				
40	DI						MIM				DI			
								DIm						
	DI				L	DI								
							MIM						DI	
												DI		
													DI	
30					L	DI		DIm	DI	DI				DI
							MIM	DIm		DI	DI			
25	DI						MIM	DIm						
	DI													
	DI					DI								DI
									DI					
20													DI	
											DI	DI		
									DI					
						MIM	MIM	DIm						
15										DI				
											DI			DI
	DI						MIM			DI	DI	DI	DI	
	DI					MIM			DI					
10								DIm					DI	DI
8						MIM	MIM					DI	DI	
						MIN								
6							MIM							

SOURCE: Schein (1992), p. 18.
KEYS: D=dual, for which I=insulating, C=conducting, m=microcarrier.
M=monocomponent, for which I=insulating, C= conductive, M=magnetic, N=non magnetic.
L=liquid.

From table 5.13, it can be seen that the more widespread development system configurations is the one based on dual dry insulative toner, like the one that was used in the first automatic copier launched by Xerox. It also reveals that firms tend to concentrate in one configuration. Most firms use dual dry insulating toning systems.[51] Three companies, Canon, Ricoh and Océ, have adopted monocomponent magnetic toning systems (the former two of insulative type and the latter of a conductive type). The conductive dual toning system is used by Kodak and is also present in some

[51] Minolta's micro carrier toning system is a version of the dual insulating system that uses carriers of a smaller size than the conventional ones.

of Xerox high speed models. Ricoh introduced in 1985 a nonmagnetic monocomponent toning system for multi-colour copying at the low end of the market. Finally, Savin, which commercializes machines manufactured by Kodak, is the only one using a liquid toner system. Table 5.14 compares the situation in relation to development systems in the US market in 1984 and 1993.

Table 5.14 IEP models sold in the US market 1984, 1993. Development system configurations: shares by segment of the market (%)

	1984				1993			
	ALL	SEGMENT			ALL	SEGMENT		
Toner type	**MODELS**	**Low**	**Medium**	**High**	**MODELS**	**Low**	**Medium**	**High**
Dual dry	77	74	74	100	83	83	81	87
micro carrier	0	0	0	0	3	4	3	0
Mono dry	14	15	16	0	17	17	17	13
Liquid	9	11	10	0	1	0	2	0
% of models	99	99	97	100	97	97	97	100
Toner application method								
Magnetic brush	80	79	69	100	78	81	74	80
Magnetic roller	0	0	0	0	3	1	3	9
Toner project.	9	9	13	0	10	11	7	11
Toner transfer	0	0	0	0	4	3	7	0
Cascade	2	1	9	0	0	0	0	0
Liquid/Landa	9	11	9	0	1	0	2	0
Ink/Injection	0	0	0	0	4	4	6	0
% of models	100	100	100	100	94	93	92	100
Total number of models	212	149	32	28	301	147	106	46

SOURCE: elaboration on data supplied by Datapro and Rank-Xerox.

Table 5.14 illustrates the fact that the development system based on dual dry toner and a magnetic brush has established as the dominant design in IEP equipment. Although this table does not provide the same detail of table 5.13 on the toning systems, it indicates that the proportion in which different development systems are used in the industry has not changed significantly in the last ten years. Only at the high end of the market one observes that monocomponent toner development systems have gained importance. This is mainly the result of the fact that Japanese firms like Ricoh and Canon, which have adopted this type of configuration, have been penetrating that segment of the market during the period in question.

In summary, in the development subsystem, the dual dry-magnetic brush has become the dominant configuration, but there are firms that champion other designs. Thus, changes in the market shares of the different firms can lead to changes in the market shares of different design configurations.

5.5.2 Market segments, innovation and product differentiation

The core of the IEP technology defines the basic performance of the copier. Different configurations convey different sets of advantages and trade-offs, which impinge directly on performance characteristics such as the quality of the copy, the speed at which copies are made, the price of the equipment and its reliability.

A key variable that is used to identify the different segments of the market is the multicopy speed of a machine, measured by the number of copies of the same original that it can produce in a minute. Multicopy speed is related to the copy volume that a machine is designed to handel and is indicative of the type of copying needs of the user. Clearly, this is only one rough indicator of the different segments of the market. There are many other characteristics such as the size of the copies that a piece of equipment can handle, the capabilities to reduce, enlarge or edit the copy that it offers, whether it allows to make copies in different colours or full colour copying and so on.

Manufacturers compete not only by improving the core of the technology but also by introducing features and devices that enlarge the capabilities of copiers and enhance their performance across the multiple dimensions that are relevant to the users. This is also an area that has been intensively developed. Since the first competitors entered the market to challenge the Xerox monopoly, the introduction of new features has been exploited to try to differentiate the product and get hold of different market niches. In 1973, 3M introduced its second IEP model, the VHSR, which was the first copier to incorporate reduction capabilities. This feature, which for many years was the basis of product differentiation, is nowadays present in virtually all copiers. This, as many other features, has been the focus of numerous improvements: a fixed reduction choice was followed by multiple options and by the inclusion of enlargement capabilities. These were followed by the introduction of zoom lenses. Nowadays, many models come with microprocessors that determine automatically the required reduction or enlargement ratios depending on the sizes of the original and of the copy paper.

Another example of the incorporation of devices to improve the performance of a copier is the introduction of document feeders and sorters to increase productivity. The use of paper feeders was pioneered by Kodak, which entered the market in 1975, with the Ektaprint 100, which incorporated a recirculating document feeder. This device, coupled with other more basic innovations in the exposure, photoconductor and development subsystems, gave the company an edge over its competitors at the high end of the market. However, other firms followed its lead and the use of document feeders has also become widespread. Document feeders have increased in speed and capacity and many of the feeders now in use can handle documents for two side copying. Table 5.15 below, based on data on the US market, illustrates the considerable improvements and diffusion of various features that has taken place in the last ten years.

Table 5.15 IEP models sold in the US, 1984, 1993. Features present in the models: shares by segment of the market (%) (a)

	1984				1993			
	ALL MODELS	SEGMENT Low	SEGMENT Medium	SEGMENT High	ALL MODELS	SEGMENT Low	SEGMENT Medium	SEGMENT High
Reduction								
1-4 Ratios	50	43	69	71	60	59	59	67
5-10 Ratios	0	0	0	0	22	11	38	23
None	50	57	31	29	18	31	3	9
% models	100	99	100	100	90	89	92	93
Enlargement								
1-3 Ratios	22	23	42	0	52	52	51	56
4-8 Ratios	0	0	0	0	28	18	44	19
None	78	77	58	100	21	30	5	26
% models	99	99	97	100	90	88	92	93
Zoom								
50-200/more	0	0	0	0	44	43	56	24
Less/50-200	4	2	6	11	37	22	41	74
None	96	98	94	89	19	35	4	2
% models	100	100	100	100	99	97	100	100
Duplexing								
Auto 2 side	0	0	0	0	24	10	36	41
Automatic	8	1	19	32	26	4	43	59
Manual	82	89	66	68	50	86	21	0
None/not rec.	11	10	16	0	0	0	0	0
% models	100	100	100	100	91	90	90	96
Document Feeder								
Auto/Recirc.	32	20	56	64	76	54	99	100
Semiautomatic	22	22	22	29	2	4	0	0
None	46	58	22	7	22	42	1	0
% models	95	93	100	100	97	99	99	87
Multiple colour (a)								
3 to 6 colours	2	3	0	0	47	72	26	16
Black only	98	97	100	100	53	28	74	84
% models	100	100	100	100	98	99	99	98
Total number of models	212	149	32	28	301	147	106	46

SOURCE: elaboration on data supplied by Datapro.
Notes: (a) we have consider a feature as present in the model, both if it is offered as a standard feature or as an optional one.
(b) refers to copy in more than one colour which should be distinguished from full colur copying. In 1984, the data base did not have an entry for colour. For 1984 we have included the models which reported it as a special feature.

As Table 5.15 shows, there has been an increase, not only in reduction-enlargement and document feeder capabilities, but in the automation of functions and in the possibility of copying in different colours. These improvements spread across the different segments of the market.

These examples illustrate the continuous interplay between the efforts of manufacturers to differentiate their product and outperform those of their competitors. Table 5.15 only provides two snap shots of some aspects of the characteristics of IEP equipment at two points in time. As the technology evolves, features are added incrementally, existing ones are modified and standards are changed. In 1984, for instance, the use of zoom lenses was infrequent. They have now become widespread in all segments of the market. Another important element introduced in the early eighties by Canon was the use of replaceable cartridges containing the photoconductor and the development systems. These made it easier to use toner of different colours. Nowadays, the option of multiple colour copying is very common, particularly in the low speed segment of the market. Needless to say, not all features gain acceptance in the market. In 1984, for instance, some Sanyo models had the option of a synthesized voice that gave instructions to the operator. This device did not find an echo in other manufacturers.

Market success is, no doubt, an important aspect of an innovation; but, as we pointed out in chapter four, a crucial element for its competitive impact relates to the ease or difficulty with which other firms can adapt or imitate. This, in turn, depends on the extent to which an innovation departs from the firms' technological knowledge. There are more dimensions to technological development than those suggested by the simple distinction between radical and incremental innovations. IEP constituted a radical innovation that created a new industry; but the development of this technology has followed different routes, as it was illustrated in the sections on the photoconductor and development systems. This branching in the development of a technology is not well reflected with the concept of incremental innovation, which suggests gradual additions along a trend. There have also been revolutionary changes within IEP technology whose understanding requires a richer conceptualization. Canon's personal copier provides a good example of this type of changes.

Canon's personal copier: a case of architectural innovation

In 1982, Canon introduced the first personal copier (PC), which represented a significant breakthrough from both a market and a technological perspective. The PC was a very light and compact low volume copier, which was priced at less than fifty percent of the price of the cheapest copier available in the market at that time. The PC integrated the key subsystems of the IEP process (the photoreceptor, the development mechanism and the toner) in a cartridge. This eliminated the need of servicing and increased real and perceived reliability. The PC was the result of a three year development programme. According to Yamanouchi's (1989) account of the innovative process at Canon, the PC project stem from the perception of a market segment (that of small offices of one to four employees), which was not served yet by the IEP equipment available with the current technology.[52] The key limitations on serving that market were considered to be the cost of the product and its servicing. A development programme was launched having as target a product that would be sold at less than 1000 US dollars, with exchangeable disposable parts that would free it from service and increase the perceived reliability. Other objectives where to make it compact and easy to operate. The programme was very similar to that which gave rise to Canon's AE-1 camera in 1978, the most successful innovation in the 35mm. segment of the market since the introduction of the famous "Leica", in 1925. In fact, the expertise gained in the development of the AE-1 was put to the service of the PC in the product design and redesign of the production line. This expertise was the basis of the design of a 'non-adjust' automatic assembly line and an automatic inspection production process, which were crucial for the required cost reduction that enabled Canon to meet its costs target.

The major technological innovation was the cartridge system. In terms of the core aspects of the technology and the design configuration of the various subsystems reviewed in the previous sections, there was nothing significantly new. The photoconductor used an organic drum configuration and the main change was a reduction in the diameter of the drum. The development system used monocomponent magnetic toner and Canon's "jump" development method, which were already present in other Canon's copiers. The revolutionary concept was the new architecture, which put the photoconductor, the development and the cleaning subsystem together in a disposable cartridge that could be replaced by the user himself, freeing the copier from servicing requirements. As Clark has noted, Canon's PC constituted what this author and Henderson call an architectural

[52] See Yamanouchi (1989).

innovation.[53] Changes in materials, in systems design and in the production process involved the accumulation of new technological knowledge, organizational changes within the firm, and the creation of new routines and communication channels. From the market point of view, the PC was also a niche creating innovation that opened a segment at the low end of the market.

Other firms have followed Canon and introduced their own PCs and larger copiers that use cartridge technology. However, Canon's head start in this technology gave it a leadership in this segment of the market that it preserves. In 1989, for instance, the share of Canon's direct placement in the PC market was of 62% in the US and 52% in Western Europe.[54]

The impact of Canon's cartridge technology has not been limited to the photocopy industry, it has also been incorporated in laser printers, a closely related technology. This takes us into the next topic: the relationship between IEP and other technologies and how this relates to the competencies of firms.

Firms' competencies: IEP and related technologies

Throughout the essay, we have been keeping a very narrow focus and we have concentrated on IEP and the business unit that deploys the technology. However, in most cases, the business unit is part of a larger firm and the competencies of the unit are immersed and contribute to the general competencies of the firm. Our example of Canon's PC illustrated the relevance of this fact: Canon's product engineering centre, which had acquired important know how in the production of cameras, played a major role in the rationalization of production of the PC. Yet, another example is the introduction by Canon in 1985 of α-H:Si photoreceptors. This material discovered in 1965 had its first commercial applications in photovaltics.[55] Canon was active in this area in a joint venture with ECD (Energy Conversion Devices), a US company that had been in photovaltics

[53] Clark (1987) and Henderson and Clark (1990).

[54] These estimates, based on data from Dataquest, refer only to placements by Canon. If machines badged by other vendors were added, these shares would be bigger.

[55] See Mort (1989).

technology since the 1960s.[56]

Firms tend to diversify in industries that have technological and/or market linkages with each other. In this way, technological expertise and other competencies within the corresponding business units reinforce each other and increase the capacity of the firm to move in different directions and the chances of being able to respond to innovations from competitors.

We have mentioned in section 5.4 that many of the entrants to the IEP industry had a background in reprographics technology and others in cameras and business machines. All these were related to a greater or lesser extent to the market at which IEP was aimed. In addition, as table 5.16 shows, most major manufacturers of IEP equipment were also involved in the commercialization of other office automation products in the early 1980s.

Table 5.16 Office automation products marketed by major competitors

	PPC	Micrographics	Facsimile	Electronic Typewritter	Word Processor	Personal Computer
Xerox	X	X	X	X	X	X
Canon	X	X	X	X	X(J)	X
Savin	X		X		X	X
Ricoh	X	X	X		X(J)	X
IBM	X		X	X	X	X
Minolta	X	X				X
Olivetti	X			X	X	X
Sharp	X		X	X	X(J)	X
3M	X	X	X	X		X
Toshiba	X		X		X(J)	X
Pitney Bowes	X				X	X
Matsushita	X		X			X

SOURCE: Ishikura (1983a), p.23.
Note: (J): Japanese word processing.

Microelectronics and its application in information technologies are particularly close to IEP. These technologies have become pervasive in the economy system as a whole. The use of microprocessors in photocopiers and the automation in their design and production are not different from the presence of these technologies in other manufacturing industries. However, in addition to these, there are other more specific links between IEP and those technologies. Firstly, because, as J. Mort has stressed, both technologies share a common root in solid state physics.[57] Secondly, because IEP, being a technology for document reproduction, falls at the boundaries of several information technologies.

The relationship between IEP and laser printers is an example of a

56 The Economist, 28 March (1994).

57 Mort (1989).

case in which IEP fused with another technology (laser technology) to give birth to a computer peripheral. In essence, a laser printer is a IEP in which the exposure system has been replaced by digital input and a laser beam. The laser beam is scanned across the photoreceptor surface to create the latent image.

The first electrophotographic printer was introduced by Xerox in 1973. The copier optics were replaced by a Xenon flash lamp. However, the real commercial success would be the laser printer, introduced by IBM in 1975. The technological proximity between laser printers and IEP copiers helps to explain the fact that several of the major IEP producers such as Xerox, IBM, Canon, Ricoh, Minolta, Sharp and Kodak are also manufacturers of laser printers.[58]

In 1983, Canon profited from its technological lead in the low end of the IEP market and opened the low speed-low cost segment of the laser printer market. The company introduced a printer that was in essence its PC with a semiconductor laser. As table 5.17 shows, this segment has experienced an enormous growth and, by 1990, it had become the segment with the largest share in the US laser printer market.

Table 5.17 US printer market (mil. US dlls.)

Segment Speed(ppm)	1986	1990	Compound annual Rate of growth
up to 10	1,220	5,573	46.2
11-20	379	785	20.0
21-30	106	256	24.7
31-50	387	240	-11.3
51-80	432	290	-9.5
81-150	583	1,068	16.3
151+	1,220	851	-8.6
Total	4,325	9,063	20.3

SOURCE: Dataquest, in Schein (1992), pp. 19, 227.

In the path of their development, technologies experience fissions that give origin to new technologies; in other cases, it is the fusion with other technologies the source of a new technology or of a revolution in an old one.[59] The relationship between laser printing and IEP technologies, and between IEP and information technologies in general, illustrate these patterns of technological development. As we noted above, laser printers emerged from a fusion of IEP laser technology in the mid 1970s. A decade

[58] See Schein (1992), pp 17-19.

[59] See Sahal (1985) and Kodama (1992).

later, the technology used in laser printers, in turn, has combined with that of optical scanning to give birth to the digital copiers.[60]

A major advantage of digital copiers with respect to analog ones is that they allow to store the image digitally and manipulate it. Another crucial advantage is that, in principle, they can be connected to computer networks as another computer peripheral. Although digital copiers occupy still a small proportion of the market, they are expected to grow in importance, given their connectivity potential. There are already machines in the market which operate both as a copier and as laser printer and that can be connected to PC's, fax and other digital equipment.

The development of information technology and the digitalization of electrostatic copying has been particularly significant for the evolution of electrostatic colour copying, both from the technological and the market points of view. The first full colour copier, an analog machine introduced by Xerox in 1973, had limited success. In 1978, Canon also introduced a full colour analog copier with similar results. Throughout most of the 1980s, the evolution of the full colour copying market was one of slow growth.

The main limitations of the full colour copying market were a low print quality relative to printing technologies like offset, the high cost of the machine and the slowness of the process. A colour copier requires at least three exposures and their respective development steps to achieve the superimposition of basic tones that produces the full colour image. In addition, the reduced need to reproduce colour originals relative to, for instance, black and white ones limited the size of the market. Digital technology has improved image quality and during the 1990s, analog full colour copiers have been displaced by digital ones. In 1984, only three models (one by Xerox and two by Canon) of electrostatic full colour copiers were offered in the US and the three were analog. By 1992, nine models were being offered, of which seven where digital.[61]

As we noted above, one of the limits for the growth of full colour copying has been the absence of a large market for colour reproduction.

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[60] In these copiers the photographic exposure system has been replaced by a optical scanning device which transforms the image into digital signals and a laser beam is used to create the latent image on the surface of the photoreceptor.

[61] For a detailed description of various models see Schein (1992) and Datapro (1993b)

There is consensus among industry analysts in pointing out that, given the popularity that colour has reached in computer applications, the need for producing and reproducing colour originals is increasing.[62] Thus, an important synergy is emerging for a parallel development of the full colour electrostatic printing and copying markets. Full colour copying has predated colour laser printing and, by mid 1993, full colour laser printers were not yet available in the market. However, Xerox and Canon offer models of full colour copiers that can be upgraded to function also as a laser printers by adding a fiery controller. The interrelation and mutual influence between electrostatic copying and printing is shown in the following figure. These developments are an expression of the fact that IEP is experiencing a transition to become part of the document production technology fully integrated into digital information technologies.[63] A transition that, as table 5.16 illustrated, was anticipated by the major competitors in the industry which diversified to other office automation technologies.

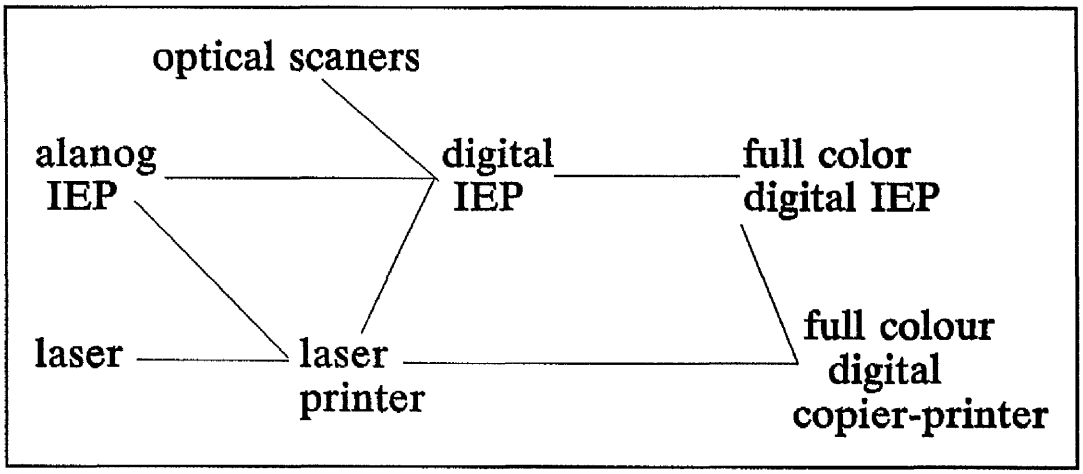

Figure 5.6 Technological fusion in electrostatic copying and printing

5.5.3 The evolution of the industry

The list of the major manufacturers that compete in today's IEP industry was basically complete by the end of the 1970s. The entry of Japanese firms as large scale producers was accompanied by a gradual withdrawal of US and European based firms, which reduced or completely abandoned

[62] Datapro (1993b), Schein (1992) and interviews.

[63] Mort (1989).

manufacture. Several of these firms opted to become distributers and entered arrangements that allowed them to sell, under their own brand, copiers made by Japanese firms. Most exits occurred in the late 1970s and early 1980s; the only recent major exit was that of IBM, whose copier business was taken over by Kodak. There have been no major entries. As we saw earlier, by the mid 1970s, the main design configurations in photoreceptor and developed subsystems had already emerged. The 1980s has also been a period of consolidation of the dominant designs in different segments of the market. The development of the IEP industry is in line with the findings of Utterback and Suárez in assembly type industries.[64] These authors found that the introduction of innovations tended to be accompanied by entry of firms and that this was followed by a consolidation of the industry that goes in parallel with that of the dominant designs.

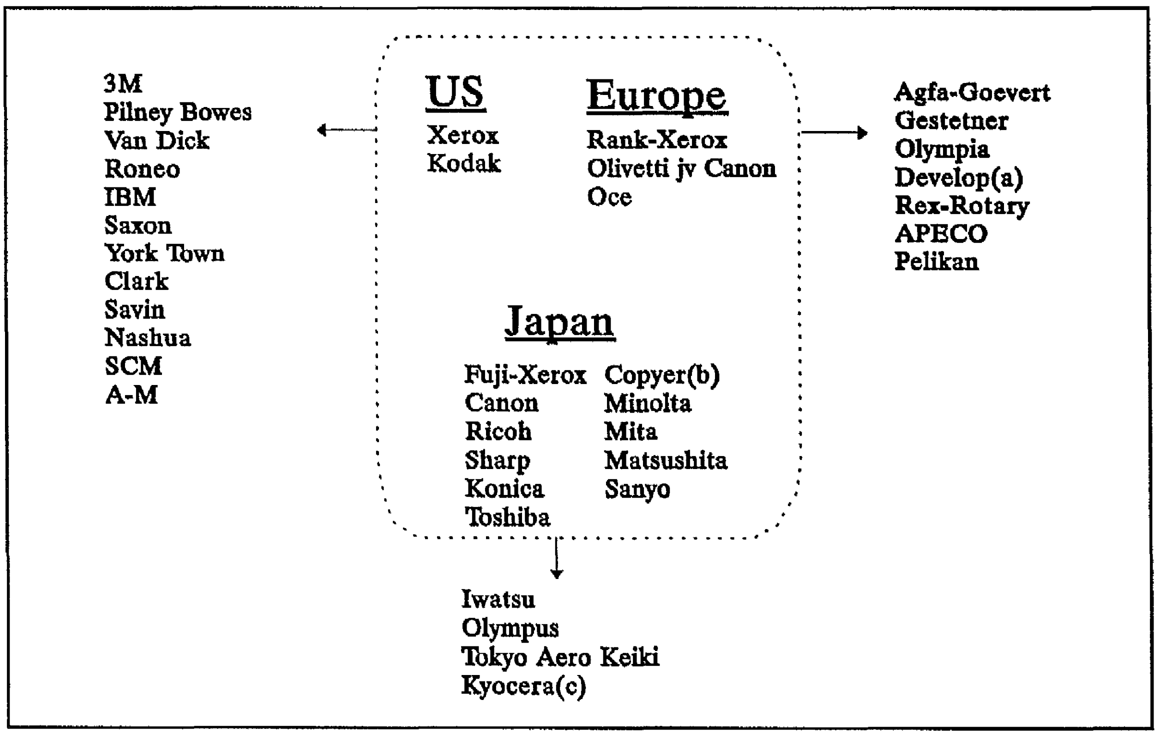

Figure 5.7 IEP manufacturers and firms that have abandoned production
Notes: (a) Devolop was taken over by Minolta.
(b) Canon has 44% of participation in Copyer.
(c) Kyocera has announced that will restart production of IEP.

Figure 5.7 shows, in the centre, the main US, West European and Japanese manufacturers of equipment. The firms outside the doted area are firms that, at some point in time, produced copiers and nowadays have either completely abandoned the business, been taken over, or have limited

64 Utterback and Suárez (1993).

themselves to distribute equipment produced by Japanese manufacturers.

Table 5.18, elaborated on data from Dataquest, shows the evolution of the shares of different vendors in the US, West European and Japanese markets. In some cases, the names of the sellers have changed during the period covered. This may relate to different reasons: from reorganizations within corporations, to takeovers and mergers between firms. Not only have companies reorganized, but distribution arrangements have also changed: vendors move from one original equipment manufacturer to another or to distributing equipment from various producers. 3M, for instance, initially passed from selling its own models to selling also some copiers made by Toshiba. Years later, what was 3M copier business became Harris-3M and is now Lanier. The company commercializes models from a variety of Japanese manufacturers. Thus, in many cases, it is not possible to identify with precision the manufacturers of the copiers placed by a particular vendor. The table shows the number of copiers placed in the US, Western Europe and Japan by different vendors (which in some cases are also manufacturers) in two different years.

Table 5.18 Western Europe, US and Japan. shares of Vendors in PPC placements (%) and total placements, 1979, 1989 (000 units)

Western Europe			United States			Japan		
	1979	1989		1979	1989		1979	1989
Canon	10.4	23.2	Canon	8.0	23.0	Canon	24.6	29.2
Ricoh	0.0	6.0	Mita	1.5	8.4	Fuji-Xerox	20.0	20.8
Olivetti	3.3	6.1	Ricoh	0.0	5.7	Sharp	5.2	5.7
Minolta	3.5	6.0	Konica	-	5.3	Konica	4.5	4.2
Panasonic(c)	0.0	1.9	Panasonic(c)	0.0	2.7	Matsushita	1.2	0.8
Mita	3.1	4.5	Minolta	3.4	5.1	Mita	3.7	2.9
Triumph-Adler	0.4	1.4	Sharp	13.0	14.6	Ricoh	31.7	30.6
Toshiba	5.4	6.4	Pitney B.	1.1	2.4	Minolta	4.3	2.8
Oce	1.4	1.7	Adler/Royal	-	1.3	Toshiba	4.8	2.9
Kodak	0.0	0.3	Monroe	0.0	1.1			
Konica/U-Bix	5.0	5.2	Toshiba	3.0	3.7	Total	5561	725
Gestetner(a)	3.5	3.0	Gestetner	0.2	0.9	Herfindhal	.2114	.2297
Copyer	0.8	0.2	Selex	-	0.3			
3M/Lanier	4.6	4.0	Sanyo	-	0.3			
Develop	1.5	0.8	AEG Olympia	-	0.2			
CPF	0.8	-	Oce	-	0.2			
Agfa-Gevaert	3.3	2.2	Silver Reed	-	0.1			
IBM (b)	1.2	-	Swintec	-	0.0			
Rank-Xerox	14.9	11.8	3M/Lanier	4.8	4.4			
Sharp	9.6	6.5	Kodak	1.9	1.1			
Hoechst/Kalle	5.8	1.8	A.B. Dick	2.5	0.8			
Nashua	11.2	4.0	IBM	1.9	-			
Other	10.4	2.9	Olivetti	2.5	-			
			Xerox	18.6	15.2			
Total	259.1	1198.6	Saxon	5.0	-			
Herfindhal	.0720	.0976	Royal	9.3	-			
			Savin	20.9	3.2			
			Other	2.6	-			
			Total	68.2	1175.8			
			Herfindhal	.1192	.1190			

SOURCE: elaboration on data provided by Dataquest.
Notes: (a) in 1989 Gestetner includes Rex.
(b) IBM's PPC business was taken over by Kodak in 1988.
(c) Panasonic is subsidiary of Matsushita.

The companies have been listed in decreasing order according to their gains in market share. The Japanese firms not only hold large shares of the market, but have enjoyed the greater gains. It should be pointed out, however, that in the case of companies like Ricoh and Konica, these gains are mainly due to the fact that they have been taking on the direct distribution of their copiers in foreign markets. Thus, the counterpart of the increased shares of those companies is the loss of share of the traditional distributers of Japanese copiers, such as Savin, Nashua, Kalle, and Royal. From the point of view of market share, a focus on units placed may overestimate the weight of Japanese producers since the high volume machines, which are also the most expensive ones, are produced mainly by Xerox, Kodak, IBM and Océ. Far more important, however, is the fact that a large proportion of the placements of non-Japanese vendors are badged machines made in Japan. Thus, the table sub-estimates considerably the share of the market of the equipment made by Japanese producers. In any case, the domination of Japanese manufacturers as a group is evident. The placements that can be directly attributed to Japanese companies and to their traditional distributers, for any of the years considered, is always superior to 50%. If we look at the detail of the shares in different segments (not included in the table), it is only at the very high speed segment, in high volume machines of a speed above 90 cpm, that non-Japanese firms, such as Xerox, Kodak and Océ, dominate. One reason for this may lie in the fact that this type of machines have never had and important market in Japan. Another explanation is that the very high-speed, high-volume segment is mainly a rental business built on contracts with high volume users. This type of business is different from the one on which the Japanese based their success. As we mentioned in section 5.5.3, the approach on which Japanese firms based their success was the production of low volume copiers in large scale and at low price, which were often sold rather than rented.

Innovation and competition

The contributions to the development of the technology tend to be linked to the requirements of the design configurations that they champion and the needs of the segments of the market where those configurations are more competitive. The examples of the innovations by Canon and Kodak that we considered earlier illustrate clearly the case. Canon's cartridge system is particularly advantageous for low volume, compact, low price machines.

The same is true about Minolta's fibre optics based exposure system. Kodak's conductive magnetic brush and document feeders are relevant for a segment of the market in which quality and productivity are more relevant than the size and price of the machine. It is natural to expect that the innovations of a producer will be aimed at the segments where it competes. This diversity in the focus of the innovative activities of the firms is at the basis of their different technological competencies. These differences, in turn, are major factors behind the evolution of the market shares of the firms in the different segments of the market.

The market performance of a firm responds, to some extent, to the potential of the design configuration on the basis of which it competes and on its ability to exploit it; the market acceptance achieved by the innovative features introduced by a producer is also important. However, as our brief overview of the evolution of IEP has illustrated, this is not a rule. From the technology point of view, what really matters is the overall technological capabilities of a firm and its capacity to innovate and to adapt to change. In addition, there are other factors such as marketing, financial situation, commitment to the business, and country specific factors, which can be decisive for the performance of the firm. The two main Japanese competitors, Ricoh and Canon, for instance, have moved away from the basic photoconductor and development subsystems on which they based their challenge of the market. Cadmium Sulphide has been abandoned and liquid development systems have practically disappeared. The two firms have moved to other configurations and managed to contribute to their development and maintain a good market performance. On the other hand, several of the firms that abandoned manufacturing had followed, from the start, the photoconductor and development configurations that were dominant. There are also companies that have left which were the first to introduce successful elements of design, such as IBM's organic photoreceptors in a flexible configuration, or 3M's copier with reduction capabilities. Not only the technological competence of each individual firm ought to be taken into account to understand the different performance of firms that compete at a worldwide level. Other characteristics and the elements of the environment that affect firms' performance, such as the national environment, are also relevant.

5.6 International diffusion of IEP technology: location of production and patterns of international trade

There are two dimensions of the diffusion of IEP technology that are particularly relevant for international trade, namely the market performance of the individual firms in the industry and the patterns followed by the location of supply at an international level. The relationship between these two aspects and their importance for international trade are very well exemplified in the case of the IEP industry. The competitive process in this industry has led to a situation in which the industry is dominated by a reduced number of companies, most of them of Japanese origin. The production of IEP equipment has concentrated in a few countries with Japan holding the largest share of both world production and exports of photocopying equipment.

5.6.1 The emergence of Japanese producers as mayor players in the IEP industry

The opening of the IEP market had the natural effect of provoking a decline in the market share of Xerox in world markets. As table 5.19 shows, eleven years after the opening of the IEP market, Xerox passed from its monopolistic position to having less than fifty percent share of the revenue generated by plain paper copiers in the major markets.

Table 5.19 Xerox: estimated revenue and market shares in the plain paper copier market, 1981

	Market size mil. US dlls.	Xerox revenues mil. US dlls.	Xerox market share (%)
US	7,350	3,160	43
Europe	4,900	2,200	45
Japan	1,510	620	41
Canada	725	410	56
Other	na	525	na

SOURCE: Northern Business Information Inc., in Hunger et. al.(1986).

Initially, competition from new manufacturers emerged in the US, Japan and in Western Europe. During the late 1970s and early 1980s, Japanese firms turned into the strongest competitors of Xerox and, although US and Western Europe are still important producers, Japan has become the largest manufacturer of photocopying equipment. As we pointed out in section 5.5, the majority of the US and Western European firms that entered in the 1970s and are still in the IEP business have abandoned production and have shifted to the sale or lease of equipment manufactured by Japanese firms. There are no published data on world production or world capacity for IEP's. However, there are some data for the two major producers: Japan and the US (see table 5.20).

Table 5.20 Japan production and US shipment of indirect electrostatic photocopiers (000 units)

	1970	1975	1980	1986	1991
US shipments	218	364	617	1,285	1,401
Japan output	na	131	964	2,393	2,542
US/Japan	na	2.78	0.64	0.54	0.55

SOURCES: US: Computer and Business Equipment Manufacturers Association, in Wolfman (1992, 1993); Japan: MITI (1990, 1993).

Japanese production experienced an enormous growth between 1975 and 1986. In the late 1970s, Japanese output of IEP's surpassed United States shipments, and, although Japan's production has stagnated since 1986, this country remains as the largest producer of this type of equipment. The comparison in table 5.20 is between Japanese output and US shipments and to make the figures strictly comparable we would have to either deduct the changes in Japanese inventories from its production data, or to add the changes in US inventories to the shipments of the latter. Data on inventory changes is available only for Japan from 1983 onwards and the change in inventories never exceeds 4% of the volume of Japanese production. Therefore, the possible distortion that this difference may introduce is minor and does not affect our conclusions.[65] The fact that Japanese producers are more concentrated on low volume copiers, which have a lower value, is far more important. A comparison of the production of the two countries in value terms, which to some extent takes into account the qualitative differences in the equipment, would reflect better the relative importance of the two producers. One would expect that such a comparison would show a smaller difference between US and Japanese production. In any case, Japanese production is considerably larger than the domestic demand for copiers and, as it is shown in table 5.21, this industry is heavily export oriented, much more than that of the US.

The large share that firms of Japanese origin hold in the world market of IEP is behind the Japanese large IEP output and high export

[65] We have used these series because they were the more complete and reliable. A comparison of US and Japanese shipments for the late 1970s (for which some estimates of Japanese shipments were available) gave a similar picture to that provided by table 5.20.

Table 5.21 Japan and US trade in indirect electrostatic photocopiers (000 units)

	Japan			US		
	1980	1986	1991	1981	1986	1991
Exports	676	1,974	1,786	10	13	19
Imports	NA	NA	4	375	943	927
Export/Production (%)(a)	71.5	82.5	70.3	1.4	1	1.4

SOURCES: US Department of Commerce; Japan Tariff Association.
Notes: (a) For the US the denominator are shipments

ratio. As it can be seen in table 5.22, the other side of the fall in the market share of the Xerox Group has been the strengthening of the market position of Japanese firms. In 1979 the placements by Japanese manufacturers and by firms that have traditionally been distributers of Japanese copiers accounted already for more than 50% of the placements in the US and Western Europe. During the 1980s some firms like Ricoh and Konica tended to take on the distribution of their copiers, which reflects in the fall of the share of the traditional distributers. The table also shows that there has been an increase in the aggregate share of Japanese vendors and their traditional badgers at the expense of the other vendors. As we mentioned in section 5.5, the focus on placements by vendor underestimates the weight of Japanese producers. There has been a tendency of manufacturers, both in the US and Western Europe, to abandon production and shift to the badging of copiers made in Japan, which is not reflected in the table. During the late 1970s and early 1980s, firms like Pitney Bowes, 3M, Agfa-Gaevert and Gestetner were still marketing machines manufactured by them, together with some Japanese models. Nowadays, all these companies have abandoned production completely and they only sell copiers manufactured by Japanese firms. Thus, the share of Japanese made copiers in total placements is larger than the one suggested by table 5.22.

Table 5.22 Shares in placements by type of vendor in the US and Western Europe, 1979, 1989 (%)

	Western Europe		United States	
	1979	1989	1979	1989
Japanese manufacturers	37.8	59.9	29.0	69.6
Badgers of Japanese equipment	17.4	7.2	32.7	6.8
Other manufacturers/badgers	33.6	29.9	35.7	23.6
Other not identified	11.2	2.9	2.6	0.0

SOURCE: elaboration on data provided by Dataquest (see table 5.18)
Notes: (a) Other manuf./badgers are firms that at some stage marketed mainly their own copiers or non-Japanes copiers. This group includes: Xerox, Rank Xerox, IBM, 3M/Lanier, Kodak, Agfa-Geaevert, Gestetner, Oce, Develop, Olivetti, AEG-Olympia, Pitney Bowes and Saxon.

(b) Badgers of Japanese equip. are firms that have always been mainly re-sellers of Japanese copiers (athough at some stage they may have produced some equipment). This group includes: Nashua, Kalle, Savin, Royal, Monroe, AB Dick, Selex, Adler Royal, Triumph Adler, Silver Reed and Swintec.

5.6.2 Explaining the success of Japanese producers

The factors behind the strong position achieved by Japanese firms in the world photocopy industry are of central concern to us. A first question that one ought to have in mind is that, since the years of the Xerox monopoly, the technology had already diffused beyond the US, and that this included Japan. As A. Ghazanfar (1984) has reported, Japan already had a significant copying and duplicating market in the late 1960s. In fact, the market for copiers, and in particular for those that used the electrostatic transfer process (to which PPCs belong), was larger in Japan than in the UK (see table 5.1).

Japan offered an attractive market for the new firms that entered the industry as Xerox key patents expired and its monopolistic position weakened. The complexity of Japanese writing, based on Kanji characters, has been suggested as an element that contributed to promote the development of the IEP market in Japan.[66] Manual copying of documents in this type of writing is very time consuming. In that context, the need of efficient methods of copying is particularly pressing. This particularity of the Japanese market gave a strong market base to Japanese manufacturers. It may also have contributed to their perception of the potential of the low volume copier and of the possibilities of outright sale instead of rental. Concepts like that of the personal and the family copier promoted by Japanese producers were particularly suitable to that environment. Thus, the experience of their own market is likely to have influenced the decision of Japanese manufacturers to enter the production of low volume machines in large scale. Most of these producers moved towards the export market to exploit the advantages that they developed in the production of low volume copiers.

A major factor behind the success of Japanese firms in foreign markets was their ability to produce equipment that had a very good performance and was produced at a lower cost than that of their competitors in other countries. Two main elements contributed to the Japanese advantage. First, the fact that, at the time when the firms entered the industry, labour costs in Japan were low relative to those of the major competitors. This was particularly important at that time, when assembly

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[66] The relevance of this element was pointed out to us by a Rank-Xerox executive.

had not reached the levels of automation that it has now. A second factor was the very efficient methods of production developed by Japanese producers, which have been the basis of their success in other assembly industries like automobiles and consumer electronics.

Let us consider, briefly, the labour costs issue. Table 5.23, based on data from the International Labour Office, provides some evidence on Japanese low wage advantage. We present data on both wages and labour costs. The former are data on wage earnings and the latter is a more comprehensive measure of the remuneration that is given to employees. However, this international comparison ought to be taken with reservations. The concepts used in the statistics provided by the different countries are not identical. In addition, the data reported by Japan are monthly wages, while other countries' data are in an hourly basic. Thus, we have transformed Japanese data to an hourly basis assuming a month of 4.33 weeks and weeks of 40 hours. ILO statistics of hours worked per week suggest that our 40 hours per week assumption is plausible. Data for all countries have been transformed to US dollars using yearly average exchange rates. All these adjustments may introduce some distortions, which add to those derived from national differences in the concepts used. Therefore the comparisons made in the table, need to be taken with caution and are intended to serve as a rough indicator.

With the reservations mentioned above, table 5.23 suggests that, in the mid 1970s, the remuneration to labour in manufacturing was lower in Japan than those in the US and in the major European countries with the exception of the UK. Ghazanfar has also found some evidence of lower labour costs, which rested on the use of a high proportion of low waged female workers.[67] The table also indicates that the Japanese advantage in the manufacturing sector derived from low wages has gradually disappeared.[68] One factor that has contributed to this trend is the strengthening of the Yen relative to the dollar and to the ECU, which is illustrated in figure 5.8.

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[67] Ghazanfar A. (1984).

[68] Similar tables based on wages point in the same direction.

Table 5.23 Wages and labour costs in manufacturing 1975-1988. Major exporters of photo and thermocopy apparatus. (dollars/hour) (a)

Wages(b)	1975	1978	1981	1984	1988
United States	4.83	6.17	7.99	8.83	10.19
Japan	3.18	5.88	6.79	7.10	14.35
France	2.80	3.88	4.81	4.08	7.02
Germany, Fed. Rep.	3.94	5.84	6.16	5.44	10.44
Netherlands	3.93	5.77	5.84	5.04	8.94
United Kingdom(c)	3.10	3.74	5.90	4.78	8.34
Labour costs	**1975**	**1978**	**1981**	**1984**	**1988**
United States(d)	6.36	8.28	10.79	12.55	13.91
Japan	3.80	7.18	8.16	8.64	17.89
France	5.82	8.28	10.91	9.81	18.05
Germany, Fed. Rep.	7.13	10.83	12.19	11.15	21.64
Netherlands	8.00	11.66	11.98	10.70	19.41
United Kingdom	3.67	4.81	7.64	6.95	12.27

SOURCES: elaboration on ILO, *Yearbook of labour statistics* (various years). Conversion factors from IBRD *World Tables* (1992).
Notes: (a) The original data for Japan for both wages and labour costs are monthly payments. They have been converted to hourly payments by assuming that monthly payment are for 173.33 hours.

(b) For all countries the wage figures are earnings.
(c) For UK 1975-1981 wage data are earnings of male workers.
(d) For the US labour costs data are compensation to employees.

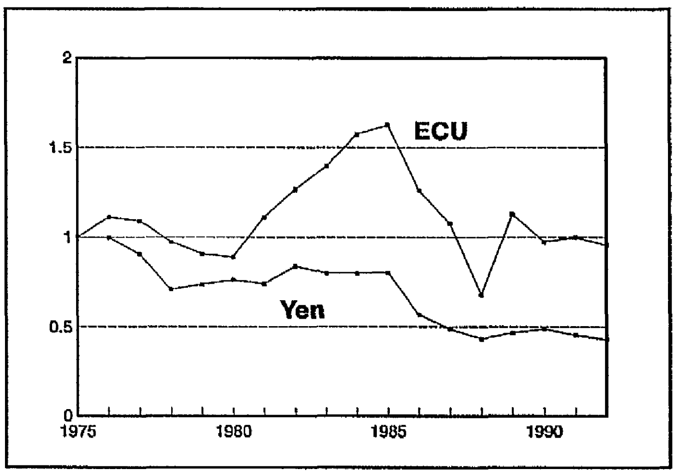

Figure 5.8 Evolution of the exhange rate of the Yen and the ECU against the US dollar (Index: 1975=1)
SOURCE: elaboration on OECD Economic Outlook; Eurostat, Basic statistics of the community.

Regarding the efficiency of Japanese manufacturing methods, most Japanese entrants came from industries in which they had a long experience in the assembly of equipment. Some firms diversified from businesses like camera and business equipment manufacturing; others were already in the reprographics industry. Japanese success in the production of low cost copiers combined innovative product design with highly efficient forms of organization of production, which were the basis of the success of Japanese producers in other assembly industries such as automobiles, consumer electronics and home appliances.[69] Ishikura's (1983) description of the functioning of Canon's factory at Toride provides an illustration of the kind of practices adopted by Japanese firms.[70] Some of these are: daily programming of type and number of copiers to be produced; flexible manufacturing systems to accommodate different models and electrical specifications; stop and fix systems, which made it possible to solve problems in the spot; continuous delivery of parts and subassemblies. All parts to be assembled were placed on a cart and taken to the assembly point, which reduced inventories, reduced problems of parts mismatching and economized space. There were frequent meetings of workers to discuss improvements to assembly. A thorough analysis of the assembly process was carried out after the start-up of a new product to reduce inspection and fine tuning and to economize in the assembly process itself. All these practices not only reduced considerably manufacturing costs. They contributed to increase the quality of the copiers produced.[71]

Innovation in IEP technology was also central for the success of Japanese firms. The leading Japanese producer Canon provides a very good example of the role of innovation as a competitive weapon in this industry. Canon entered the copying market with its "new process", an alternative design configuration for photocopy equipment. The process was widely licensed, and Canon technology was incorporated into the low volume copiers of other Japanese producers that entered the industry in the mid 1970s. One of the major innovations of Canon was the introduction of its desktop personal copier, which opened a new segment in the IEP market. Although Canon is perhaps the most innovative of the Japanese copier manufacturers, other Japanese producers have also contributed with significant innovations. Minolta, for instance, was the first to introduce fibre optics instead of lenses and mirrors in the exposure system in order to economize in costs and machine size; it also introduced a micro-carrier toner development system that produces very good copy quality. Ricoh and Toshiba introduced non-magnetic monocomponent toning systems that reduce

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[69] A well known and thoroughly studied case is that of the Japanese automotive industry. See, Altschuler et. al. (1984), and Hoffman and Kaplinsky (1988).

[70] Ishikura (1983b).

[71] It is worth mentioning that in 1982, which is the year that corresponds to Ishikura's description, many stages of the process had been automatized. See Ishikura (1983b) pp. 8-9.

costs and can be produced more easily and cheaply in different colours.

Some of the initial advantages of Japanese producers have been offset since the mid 1980s due to the strength of the yen and the increase in the relative wages of Japanese workers. In any case, the increased automation of production has reduced the importance of direct labour costs for assembly. However, through their presence in the market, Japanese producers have developed competencies that allow them to remain in a leading position in the world photocopying industry.

5.6.3 International trade in photocopying equipment

A generalized problem when studying trade flows of a new product is that it takes time for data to appear in trade statistics, even at the highest level of disaggregation available. This is something to be expected because of the time that it takes before trade in that product is significant enough to merit separate coverage in trade accounts. This has been the case with IEP equipment. Photocopiers, as a group, started to be registered separately in major exporting countries in the mid 1970s and it has been only in the late 1980s that it has become a generalized practice to disaggregate this group of products and publish data on IEP equipment separately. Thus, in order to give a worldwide perspective of the trade in photocopy equipment and of how the shares of the major exporters have evolved, we rely on the more aggregate category of photo- and thermocopying apparatus, presented in table 5.24, for which data go back to 1978.

Table 5.24 reflects the dominant position of Japan in world trade of photo and thermocopying apparatus. The other fact that is immediately apparent is the high concentration of exports in a reduced number of countries: the seven countries in the table account for more than 90% of total trade in any of the years of the period covered in the table, and if we include other E.E.C countries, that share is always over 95%.

Table 5.25 shows a more striking result. Only three out of seven major exporters of photo and thermocopying equipment have a net surplus. When we look at a complete table of all exporting nations (not included here), the result is similar. Only Mexico joined the group of surplus countries in 1988. Thus, it is only these surplus countries that cater for the excess of demand over supply of the rest of the world.

Tables 5.26 to 5.28 show a more disaggregated picture of the trade

Table 5.24 World exports of photo- and thermocopying apparatus and share of major exporters (%), and total exports of market economies, 1978-1991

	1978	1980	1982	1984	1986	1988	1990	1991
Japan	42	43	56	61	62	49	43	42
US	6	6	7	8	4	5	6	7
EEC 12 (a)	49	48	33	28	30	39	44	44
West Germany	16	13	8	5	8	11	11	10
Netherlands	17	13	9	14	11	12	16	16
UK	10	15	11	5	5	8	6	6
France	2	3	2	1	4	4	7	8
Hong Kong	0	1	1	2	2	4	4	4
Total (mil. US dlls.)	1,633	2,314	2,306	2,917	3,692	4,769	5,709	6,208

SOURCE: UN *Yearbook of International Trade Statistics* (various years).
Note: (a) Data for Greece, Spain and Portugal have been added when necessary to have E.E.C. 12 trade balance for all years.

Table 5.25 Major exporters: trade balances of photo- and thermocopying apparatus, 1978-1991 (mil. US dlls.)

	1978	1980	1982	1984	1986	1988	1990	1991
Japan	667	950	1,269	1,761	2,276	2,309	2,388	2,593
US	(193)	(273)	(384)	(601)	(1,023)	(1,033)	(982)	(871)
EEC (12)(a)	43	4	(356)	(375)	(405)	(288)	(543)	(648)
West Germany	60	14	(78)	(152)	(65)	22	(79)	(274)
Netherlands	213	223	113	314	254	385	426	344
UK	12	181	51	(69)	(81)	36	(68)	(7)
France	(143)	(241)	(218)	(187)	(141)	(219)	(181)	(77)
Hong Kong	(5)	0	0	5	50	135	170	153

SOURCE: UN Yearbook of International Trade Statistics (various years).
Note: (a)Data for Greece, Spain and Portugal have been added when necessary to have EEC 12 trade balance for all years.

flows, which allows us to see the relative weight of IEP equipment in the more aggregate category. As it can be seen in the data for Japan in table 5.26, IEP equipment account for the bulk of the exports of Japan's trade in photo and thermocopying equipment (they represent more than 90% of the exports in any of the years reported in the table).

Table 5.26 Japan trade of copying equipment and duplicators

	(000 units)				(Mil. US dlls.)(c)			
Exports	1975	1980	1986	1991	1975	1980	1986	1991
Electrostatic	184.4	769.0	1989.1	1808.9	167.9	979.0	2225.9	2792.1
Direct	-	92.8	15.3	22.4	-	62.8	27.6	35.5
Indirect	-	676.2	1973.8	1786.4	-	916.2	2198.3	2756.6
Other (a)	3.6	2.3	109.3	34.6	2.3	3.9	67.1	33.9
Total copiers	188.0	771.4	2098.4	1843.4	170.2	982.9	2293.0	2826.0
Duplicators	5.6	16.9	14.3	28.8	1.3	4.5	6.4	34.8
Imports								
Photocopiers(b)	0.8	3.5	1.6	5.2	4.0	36.2	6.6	36.8
Duplicators	10.5	9.0	1.2	0.0	3.8	6.6	0.8	0.1

SOURCE: Japan Tariff Association; conversion factor: IBRD (1992).
Notes: (a) includes, diazo and other contact copiers, thermocopying apparatus, other copying apparaturs with optical system and copying apparatus N.E.S.
(b) for 1975-1986 contact copiers and other copiers: optical system N.E.S.; for 1991, electrostatic of direct and indirect type, thermocoppy apparatus, contact type copiers and copiers N.E.S.
(c) figures converted to dollars using yearly average exchange rate.

The domination of Japan in the trade of IEP equipment is evident when we compare the volume of its exports with those of the US and with the EEC exports of copiers with an optical system (which include IEP equipment), in tables 5.27 and 5.28. Both the US and the EEC are heavy importers of copiers. While the US has been in deficit in photocopy equipment throughout the period covered in the table, the EEC passed from having a surplus in 1975, to having a deficit.

Table 5.27 US trade of copying equipment and duplicators

	(000 units)				(mil. US Dlls.)			
Exports	1978	1980	1986	1991	1978	1980	1986	1991
Electrostatic	-	-	15.8	115.0	-	-	42.9	251.5
Direct	-	-	3.0	18.9	-	-	2.8	21.5
Indirect	-	-	12.8	96.1	-	-	40.1	230.1
Other (a)	-	-	50.2	44.7	-	-	76.1	88.3
Total copiers	64.9	47.1	66.0	155.3	87.5	94.0	119.1	336.5
Duplicators (b)	15.9	14.7	4.7	9.9	26.5	51.7	25.2	21.0
Imports								
Electrostatic	-	217.8	954.7	958.6	-	265.3	1,051.1	1,265.7
Direct	-	33.0	12.2	31.5	-	25.4	14.7	45.2
Indirect	-	184.8	942.5	927.1	-	239.9	1,036.5	1,220.5
Other (a)	-	114.6	189.6	43.5	-	145.9	278.1	42.6
Total copiers	241.8	332.4	1,144.3	973.1	309.7	411.2	1,329.3	1,296.5
Duplicators (c)	31.7	11.2	16.6	20.7	16.9	15.6	38.3	48.5

SOURCE: US Department of Commerce.

Notes: (a) in 1986, includes photocopiers excluding electrostatic and office copiers N.S.P.F. In 1991 includes thermocopying apparatus, other copiers of optical type and other copiers of a contact type.

(b) for 1978-1986, includes stencil, spirit and offset duplicators, for 1991 statistics presented as an aggregate are not comparable with those of earlier years.

(c) in 1978-1986, includes stencil spirit offset and other duplicators weighting less than 3,500 lb.

Table 5.28 EEC trade of copying equipment (extra EEC)(a)

	(000 units)				(mil. US dlls.)(e)			
Exports	1975	1980	1984	1989	1975	1980	1984	1989
Optical system (b)	74.2	101.6	130.9	148.5	166.3	349.5	306.4	418.8
Other (c)	43.5	160.2	45.8	18.0	21.4	40.7	38.2	57.1
Total copiers	117.7	261.8	176.8	166.5	187.8	390.2	344.5	475.9
Duplicators (d)	82.4	80.0	43.6	31.1	28.2	48.0	18.1	18.6
Imports								
Optical system (b)	55.4	208.7	499.3	449.4	72.0	350.2	605.6	783.8
Other (c)	32.7	51.4	15.4	21.3	19.4	31.1	24.4	33.8
Total copiers	88.1	260.1	514.7	470.6	91.4	381.3	629.9	817.5
Duplicators (d)	7.0	8.0	4.8	21.6	1.7	3.0	1.8	34.2

SOURCE: Eurostat; conversion factor: Eurostat.

Notes: (a) 1975 EUR 9; 1980 EUR 10; 1984 and 1989 EUR 12.

(b) 1975 to 1984 reported as aggregate; in 1986 includes elecrostatic copiers of direct and indirect type and other copiers incorporating an optical system.

(c) includes thermocopying apparatus, diazo and other copiers of a contact type.

(d) 1975 to 1984 includes hectograph and stencil duplicators, in 1989 reported as aggregate.

(e) figures converted to dollars using yearly average exchange rate.

In appendix A, we include similar tables for the trade of the four major EEC exporters and importers of photocopy equipment that were listed in table 5.24. The trade pattern of these countries in copiers incorporating an optical system is the same as the one for the more aggregate category used in tables 5.24 and 5.25: only the Netherlands, where Rank-Xerox largest production facilities are located, has been consistently a surplus country. Germany and the UK passed from having a surplus to being in deficit. France, despite the recent increase in its exports, has remained in deficit throughout the whole period for which statistics are available (See the tables in appendix A).

Before continuing with our discussion of the trade flows, a comment is in order in relation to our use of statistics for trade in copiers carrying an optical system instead of data on IEP equipment for the EEC and the major European exporters. A first reason for this is that, since separate statistics for IEP are only available from 1988 onwards, we cannot use that data to follow the change in the trade patterns over the longer time span that we are analysing here. In addition, the more recent statistics for the EEC and major EEC exporters, which disaggregate the trade data on copiers with an optical system into DEP, IEP and other photocopiers, attribute a high proportion of the trade to the last category. We have reasons to think that either part of the trade attributed to other copiers with and optical system corresponds, in fact, to electrostatic copiers, or that it corresponds to equipment that is not used in the convenience copying of documents. In an enquiry among major vendors and manufacturers of photocopy equipment, all coincided in pointing out that IEP takes almost the totality of the convenience copying market, which is the application being analysed here.[72] Thus, we have opted for using the more aggregate category of copiers incorporating and optical system under the assumption that the largest share of it corresponds to IEP equipment.

In the tables presented above and in those of appendix A, we have included data on the trade of other copying equipment, which includes diazo, thermography and other contact processes, and on trade in duplicators. This allows us to see the evolution of the trade patterns in this products in parallel to that of IEP equipment (and optical copiers in the case of the EEC). Although there are significant variations in trade flows from year to year, the magnitude of the changes in the trade of other copying apparatus and duplicators has been minor when compared with that of IEP (or optical copiers). Between 1980 and 1986, US imports and

[72] The apparent anomaly in EEC statistics is found in all member countries, the UK included. For the UK, the information provided by the major vendors has been corroborated by the Tariff and Statistical Office of HM Customs and Excise that deals with the trade statistics of this type of goods.

Japanese exports of IEP experienced an enormous increase. In DEP equipment, there has been a decline in Japanese exports, while US exports have increased and its imports have fallen. In the EEC, imports of copiers with an optical system between 1975 and 1984 also experienced considerable growth.

With respect to other copying equipment and duplicators, the overall picture is of stagnation or of modest growth. What is of interest to us is that the order of magnitude of the changes in the trade of DEP and other copying and duplicating machines is small relative to the growth of IEP.[73] This fits well with the observation made earlier in this chapter in the sense that IEP was, above all, a market creating innovation. It is true that IEP took a portion of the market of the other copying and duplicating technologies. However, most of its growth was due to the fact that it expanded considerably the market for convenience copying, while other reprographic technologies have retained a place in other market niches.

Another important aspect of the patterns of trade is the destination of exports and the origin of imports. It can be seen from table 5.29 that the US and the EEC absorb the largest proportion of Japanese exports of electrostatic copiers. These two regions also account for the largest share of Japan's imports of photocopiers; however, such imports are of a very small order of magnitude.

Table 5.29 Japan trade of copying equipment (000 units) and shares of main countries of destination and origin (%)

Exports	1975		1980		1986		1991
Electrostatic	184.4		769.0		1,989.1		1,808.9
Destination (%)							
US	50.2	US	44.4	US	46.9	US	41.0
Germany	9.7	Germany	15.4	Germany	9.8	Germany	14.6
Nether.	9.5	Nether.	7.9	Nether.	8.2	Nether.	8.1
EEC	30.0	EEC	35.1	EEC	32.2	EEC	29.1
Imports							
Photocopiers	0.8		3.5		1.6		5.2
Origin (%)							
US	52.7	US	50.2	US	58.7	US	67.2
EEC	45.7	EEC	28.3	EEC	40.1	EEC	7.5

SOURCE: Japan Tariff Association.

Similar tables for the US and the EEC reveal that, in both cases, Japan is the major source of their imports. These patterns of trade at the

[73] There has been, however, a sharp increase in EEC imports of duplicators in 1991 relative to the level of 1986. Some companies pointed out to us in phone interviews that, recently, ink duplicating processes have been experiencing a fast growth, but that the size of the market is still small relative to IEP.

level of nations are a reflection of the domination of Japanese firms in the photocopy industry that we described in our account of the evolution of the industry in previous sections of this chapter. Hong Kong appears to be gaining importance as a supplier of photocopy equipment. In particular, in 1989, the share of Hong Kong in EEC imports increased considerably at the expense of that of Japan.

Table 5.30 US trade of copying equipment (000 units) and shares of main countries of destination and origin (%)

Exports	1978		1980		1986		1991
Photocopiers	64.9		47.1		66.0		155.3
Destination (%)							
Canada	19.8	Canada	20.7	Canada	40.6	Nether.	25.3
Germany	19.1	Germany	10.4	Venez.	5.6	Canada	19.3
Nether.	9.2	Nether.	9.2	Nether.	3.7	Japan	12.9
Imports							
Photocopiers	241.8		332.4		1,144.3		973.1
Origin (%)							
Japan	83.1	Japan	90.1	Japan	93.9	Japan	90.2
Germany	7.8	Germany	4.9	Nether.	2.6	Hong Kong	6.7
Denmark	4.4	Denmark	0.7	Hong Kong	2.5	Nether.	2.4

SOURCE: US Department of Commerce.

Table 5.31 EEC extra-EEC trade of copying equipment(a) (000 units) and shares of main countries of destination and origin (%)

Exports	1975		1980		1984		1989
Optical system	74.2		101.6		130.9		148.5
Destination (%)							
US	17.6	US	20.8	US	44.0	US	30.6
Spain	11.8	Sweden	9.8	Spain	6.9	Japan	8.0
Sweden	8.0	Switzer.	9.6	Switzer.	4.8	Australia	3.7
Imports							
Optical system	55.4		208.7		499.3		449.4
Origin (%)							
Japan	71.6	Japan	90.4	Japan	97.3	Japan	71.4
US	23.0	US	6.4	US	2.0	Hong Kong	20.4
Sud Afr.	0.2	Hong Kong	1.0	Switzer.	0.2	US	4.4

SOURCE: Eurostat.
NOTES: (a) 1975 EUR 9; 1980 EUR 10; 1984 and 1989 EUR 12.

The table also shows that there is a significant share of intra-industry trade between the US and Europe: US is one of the major destinations of EEC exports and Netherlands, Europe's main exporter, figures among the three main destinations of US exports. The data also suggests that geographical proximity is an important factor affecting trade flows. This is revealed by the presence of Canada among the three main destinations of US trade while, in the EEC, Spain (before it joined the EEC), Sweden and Switzerland figure in the list of the major destinations of extra-EEC exports. In appendix A, we present tables with the trade data on the four main European exporters of photocopy equipment, which are also among the largest economies of Europe.[74] They reveal that the main destination of the exports of each of these countries is with other countries of the same group. The presence of a copier industry appears to combine with the large market size and proximity of these countries to create the substantial flows of intra-industry trade that we observe.[75]

The data show various signs of changes in the patterns of trade during the late 1980s. Japan's exports have stagnated and even show a slight decline and the same has occurred with the imports of the US and the EEC. Since the mid 1980s, there has been a decline in Japan's share of world exports and a parallel increase in the share of EEC countries. This is associated with the stagnation of Japan's exports in this period and to the increase in the EEC world exports (see figure 5.9). Table 5.32 shows that the volume of EEC trade in copiers with an optical system has increased. The share of intra-EEC trade has increased considerably while the participation of Japan in Extra-E.E.C imports has declined.

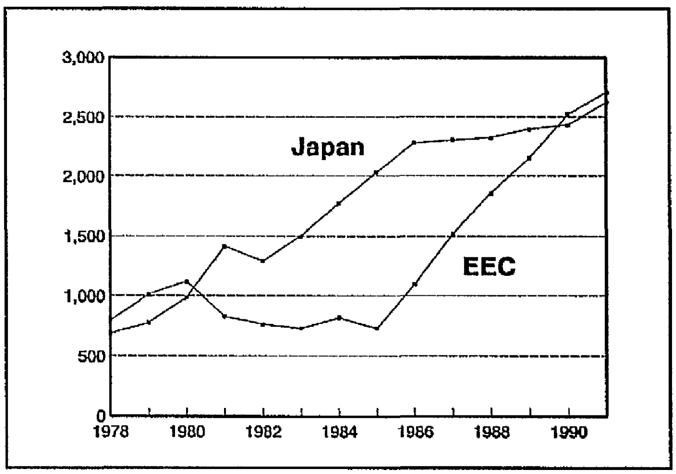

Figure 5.9 Exports of photo- and thermo-copying apparatus, Japan and EEC12 (mil. US dollars)
SOURCE: elaboration on UN Yearbook of International Trade Statistics (various years).

The trends shown in figure 5.9. and table 5.32 are mainly an expression of the fact that Japanese firms have been establishing subsidiaries in EEC countries and have increased production near the markets that they used to serve through exports. A consequence of these

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[74] Italy and Spain are the other large economies with a larger GDP than the Netherlands.

[75] The important role of proximity and market size in explaining bilateral trade has been confirmed in many cases by gravity models which, as Deardorff has noted, have been remarkably successful in empirical analysis. See Deardorff (1984), pp. 503-4.

Table 5.32 EEC trade of photocopy equipment carrying an optical system. Ratios of Intra-EEC to extra-EEC trade and ratio of Japanese trade to Extra-EEC trade (a)

	(ratios based on units)					(ratios based on values)				
Exports	1975	1980	1982	1984	1989	1975	1980	1982	1984	1989
Intra/Extra	1.30	1.98	2.50	1.67	5.40	1.68	1.93	2.41	1.47	3.62
World Total	170.3	302.8	292.8	349.1	950.9	359.2	736.0	710.7	959.8	1756.8
Imports										
Intra/Extra	1.44	1.10	1.55	0.64	1.94	3.39	1.93	1.17	0.79	2.01
Jap./Extra	0.72	0.90	0.95	0.97	0.71	0.57	0.89	0.85	0.77	0.69
Jap./World	0.29	0.43	0.37	0.59	0.24	0.13	0.30	0.39	0.43	0.23
World Total	135.1	438.9	833.0	817.0	1323.0	255.1	737.3	1017.6	1371.9	2141.9

SOURCE: Eurostat; conversion factor for value figures: Eurostat.
Note: (a) World total expressed in (000) units and in (mil. US dlls.)

has been an increase in intra-EEC trade and a decline of Japan's exports to this region. The anti-dumping duties that started to be imposed in 1986 by the EEC on imports of Japanese copiers are an important factor behind these developments. In 1986, Japanese copiers where estimated to be 85% of the European market, which imported 637 000 units from Japan in that year. There were allegations of dumping against the Japanese firms selling in EEC markets. Export prices by Japanese firms were found to be between 20% and 40% below their prices in the domestic market. As a result, duties of 15.8% were imposed by the EEC Commission on some categories of copiers imported from Japan.[76] These anti-dumping measures continue in force to date: a general duty of 20% is applied to low and medium volume copiers imported from Japan (although a few companies are charged smaller duties).[77]

The anti-dumping measures have contributed to promote production within EEC member countries by Japanese firms that, willingly or pressed by European governments, have installed production facilities in the region. By the end of 1992, there were 11 major manufacturers of photocopiers producing on different sites of Western Europe; of these, 7 firms are subsidiaries of Japanese companies. In spite of the decline in the participation of Japan in the imports of the EEC, Japanese firms have been able to retain their share of the West European market both by exporting from different locations and, to a greater extent, by increasing

[76] See, Appliance, November (1986) and Dempa Digest 22 June (1987).

[77] Provisional measures in 1986 were followed by EEC Council Resolution No. 535/87 in February 1987, in which a 20% tariff was imposed on imports of plain paper copiers incorporating an optical system that operate at a speed of up to 75 cpm. Lower duties of 7.2%, 12.5% and 10.0% were imposed to Copyer, Mita and Toshiba, respectively. See Monopolies and Mergers Commission (1991), pp. 64, 194-195.

their manufacturing facilities in the region.

Table 5.33 Japanese firms with manufacturing facilities for Plain paper copiers in Western Europe: year of entry to IEP, year of plants start up and estimated plant capacity (000 units/month)

	Italy		France		Germany		UK	
	Year	Capacity	Year	Capacpty	Year	Capacity	Year	Capacity
Canon (1971)	1987	10-12	1984	20	1973	4.5		
Ricoh(1975)			1988	5 - 6.5			1986	5
Konika(1971)					1986	3-3.5		
Sharp(1974)			1989	2.5 - 3			1988	1.5 - 2
Toshiba(1974)			1990	10				
Minolta(1974)					1986	10		
Matsushita(1979)					1987	3 - 4		
Total		10-12		37.5 - 39.5		20.5 - 22		6.5-7

SOURCES: Dataquest; Japanese Business Machine Association.

Figure 5.10 shows the share in placements of equipment produced by the eight major Japanese manufacturers of photocopiers. It includes their original equipment and that produced for other private labels.[78] As the figure shows, the share of the eight major Japanese firms that produce IEP equipment has not declined but increased since 1986, when the anti-dumping duties were established.

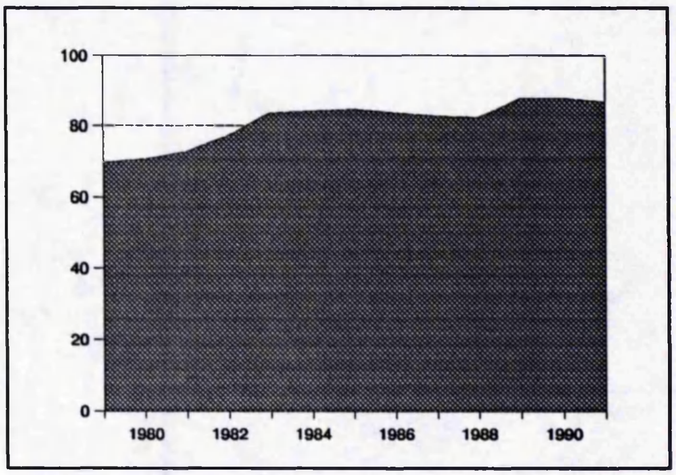

Figure 5.10 Share of Japanese manufacturers in West European placements of IEP equipment (%)
SOURCE: elaboration on data provided by Dataquest.
Note: (a) Placements of equipment manufactured by Canon-Olivetti joint venture is included in Japanese placements.

Also in the Unites States, Japanese uncertainty about tariffs on imported copiers and the strengthening of the Yen against the dollar gave

[78] The total share shown in the table corresponds to the placements of copiers manufactured by Canon (including its joint venture with Olivetti), Konica, Minolta (including its subsidiary Develop), Mita, Panasonic, Ricoh, Sharp and Toshiba.

incentives to Japanese manufacturers of copiers to establish facilities in the US: Canon has plants in California and in Virginia that produce copiers and laser printers (the latter started to operate in 1987). Ricoh also produces copiers in the US. It has three plants in California and one in Georgia, while Toshiba started to produce PPCs in California in 1989. In addition, Konica, Minolta and Mita have also plants in the US that produce toner for copiers.[79]

5.7 Concluding remarks:technology and trade

To conclude our discussion, let us look at the insights provided by the case study with respect to the relationship between the diffusion of technology and the changes in the patterns of trade.

IEP is the case of an innovation of which a substantial part of the productive capacity has concentrated in Japan, which is a different country from that in which the innovation emerged. This has resulted in a considerable trade surplus of Japan with the rest of the world and, in particular, with the US (were the innovation originated) and Western Europe. The deficit of the last two regions with Japan is not the result of a technology gap type of trade. The technology entered Japan later than those regions. Neither can it be seen as a corroboration of Vernon's product cycle hypothesis. The shift of productive capacity to Japan does not fit a pattern in which, once the technology offers little potential for further innovation and for the exploitation of economies of scale, the production migrates to a low wage location. A relatively low wage gave an advantage to Japanese producers; but significant innovation in product and process technology and the entry in large scale to a new segment of the market were also important factors behind the Japanese success. IEP technology was far from being mature when Japanese firms established their domination on the industry.

Although the particular hypotheses associated with the two main technology theories of trade do not apply to this particular case, the basic idea behind these theories is of direct relevance, namely, that the emergence of the trade flows described above is based on the diffusion of IEP technology. With this, we do not mean that diffusion is the factor

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[79] Datapro (1993a) and Dataquest.

that explains trade. The focus on the link between diffusion of innovation and trade emphasizes the time dimension of these phenomena and centres the attention on the competitive process that has shaped their evolution.

The changes in the location of IEP production occurred during the fluid period of the development of the technology. In this period new design configurations were introduced and the markets for the product were created. The course followed by the diffusion of IEP, and, in particular, its spatial dimension, was shaped in a competitive struggle. The outcome of this struggle depended both on the innovative performance of the firms in product, process and market practices and on the differences in the national environments where the firms were located. Thus, in order to understand the shift in trade patterns in favour of Japan, we have had to look at the different factors relative to the firms, the environment and the technology that contributed to a superior market performance of the Japanese firms during the period in which that shift occurred.

The superior performance of Japanese firms rested: first, on their ability to produce copiers of comparable quality to those of their competitors but at a much lower cost, and, second, on their perception of the potential of outright sale in the low speed-low price segment of the market. The entry of Japanese firms contributed to a considerable expansion of the low end of the photocopying market. The ability of the firms to either develop or acquire the technological knowledge associated with design configurations competitive in that segment of the market was an important element behind their success in the industry. The relatively low wage of Japan with respect to the US and West European competitors gave, no doubt, an important cost advantage to Japanese firms. Equally important were the particularly efficient combination of methods of production and product design that has been characteristic of the success of Japanese firms in other industries was equally important. This efficiency in manufacturing was largely related to conditions specific to the Japanese environment, which, as it has been documented in many studies, extend beyond the individual firm into the various companies participating in the production chain.[80] Other characteristics of the Japanese

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[80] See, for instance, Altschuler et.al. (1984) and Womack et. al. (1990) on the Japanese methods of production in the automotive industry, and Goto (1982) for a discussion on Japanese 'Kereitsu' groups. On the Japanese institutions that participate in the technology support system, see Freeman (1987) and Odagiri and Goto (1993).

environment, such as the complexity of their writing, have also been suggested as being likely to have influenced the ability of the firms to perceive the potential of the low end of the market and to focus on it on a large scale. Finally, it is also significant the wide licensing of Canon's proprietary technology to other Japanese producers and the entry of the state owned firm Copyer, which suggests a concerted action to focus on IEP as an export oriented industry.

The important role played by elements shared by Japanese firms should not obscure, however, the relevance of diversity. In spite of common national advantages, not all Japanese firms have performed equally: as in Europe and the US, some have left the market. In the case of successful firms, the key elements for success have been different. Canon and Ricoh, the two firms that have captured the largest market shares, illustrate this point. Canon's outstanding innovative performance was a distinctive characteristic from the outset. In the case of Ricoh, distribution agreements with North American and West European firms played and important role in the building up of the significant market share that the firm gained soon after its entry.

Some of the initial advantages enjoyed by Japanese firms have been affected by changes such as the strengthening of the yen and the increase in wages in Japan. However, through their presence in the industry, the firms have built technological competencies and a market position that have proven resilient to changes in the environment that contributed to their initial advantage. The response of Japanese firms with direct foreign investment to the imposition of anti-dumping duties in the EEC in 1985 is indicative of the importance of the advantages acquired by Japanese firms. It is significative that although the contribution of Japanese exports to the West European market has fallen, the share of Japanese firms in that market has not been weakened by the imposition of tariffs. This calls the attention to the need to adopt a wider perspective and look not only at the trade flows between countries, but at flows of capital and technology licensing agreements. These are additional ways in which the firms based in a country claim shares of the profits generated in the industry.

6 Linear low density polyethylene: diffusion of innovation and international trade in polyethylene

6.1 Introduction

In this chapter, we will study the development of LLDPE technology, and look at how the introduction of such an innovation relates to the evolution of the patterns of trade in polyethylene resins. The case study has two main purposes. The first is to analyse the different dimensions of the development of the LLDPE innovation and the factors that have affected the course of that development. The second is to see how patterns of trade emerge and are shaped by the introduction and the diffusion of new technologies.

The structure of the chapter is as follows: in section 6.2, we present an overview of the different polyethylene technologies and of their markets. This provides the basis for the analysis of the nature of the LLDPE innovation and of the main aspects that have shaped the development of this technology that is made in section 6.3. In order to look at the spatial dimension of the process of diffusion, we undertake a comparative study of the diffusion of LLDPE technology in North America and Western Europe. Section 6.4 focuses on the competitive process associated with the adoption and diffusion of LLDPE technology among the polyethylene producers of these two regions. In section 6.5, we have tried to identify the various factors that help to explain the different diffusion experienced by LLDPE in North America and Western Europe. In section 6.6, we focus on the trade dimension of the diffusion of polyethylene technologies. There, we analyse the factors that have shaped the evolution of the trade flows in polyethylene, including those in LLDPE. Finally, in section 6.7, we present the main conclusions on the relationship between technological change and trade that emerge from the case study.

6.2 Polyethylene markets and technologies

Polyethylene is a non-toxic and odourless thermoplastic solid. It offers good chemical resistance, excellent electrical insulating properties and it is relatively easy to process. Some of its limitations are poor rigidity, low tensile strength, susceptibility to oxidation and a low melting point.

Before the introduction of LLDPE, two types of polyethylene were used commercially: low density polyethylene (LDPE) and high density polyethylene (HDPE). The key difference between these materials lies in their molecular structure, which determines their crystallinity. The different degrees of crystallinity of the resins are responsible for differences in density and other physical properties.

A time span of approximately 20 years separated the main innovations that gave birth to the presence of these two types of polyethylene. LDPE was the first to be discovered, in 1933. It is produced by high pressure polymerization and, although initially it was used mainly for electrical insulation, nowadays it finds most of its market in film applications. The next development occurred in the mid 1950s and consisted of the production of polyethylene using sophisticated catalysts. This process delivered HDPE, a tougher and more rigid polymer, which is used mainly as a substitute for materials like glass and metals in containers and other rigid products. The two polymers are obtained by the polymerization of ethylene, but the molecular structure of polyethylene varies considerably depending on the process used. This, as we mentioned above, has important consequences for the characteristics and properties of the resins produced.

Therefore, the process, as in most chemical technologies, is the central aspect of polyethylene technology. As a material, what we know today as polyethylene had been synthesized in a laboratory since 1898.[1] However, the significant innovation was the discovery of a process that used a low cost raw material and could be scaled up to produce polyethylene in large quantities. Although at the level of the product we have distinguished two types of resins, it is with reference to the process that one can more readily identify and give empirical content to the concepts of technological regime and design configuration that were introduced in chapter 4.

In what follows, we give a brief introduction to the different types of polyethylene: their discovery, the basic processes used to produce them, their characteristics and their main markets and applications.

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[1] Candlin (1993).

6.2.1 Low density polyethylene

The first type of polyethylene discovered was the resin that we call low density polyethylene. The discovery took place in Britain while experimenting with ethylene at ICI laboratories. These experiments were part of a research programme devoted to study the effects of extremely high pressures on chain reactions. The synthesis of polyethylene was the unexpected result of taking pressures to levels without precedent. Serendipity played an important role, as it has occurred with numerous innovations: a leak that allowed oxygen into the pressure vessel provoked the reaction that led to the synthesis of polyethylene.[2] In spite of the accidental elements behind the discovery, there are two major streams of scientific and technological research that can claim parenthood over the innovation. It followed, on the one hand, from the research on high pressure chemistry, a technology that became established with the discovery of the Haber-Bosch process for the production of ammonia. The other main antecedent in the discovery of polyethylene is the work on macromolecules of the twenties and thirties, to which Staudinger and Carothers were two of the more outstanding contributors.

In terms of the conceptual framework of chapter 4, the discovery of the high pressure polymerization of ethylene constituted a radical innovation that inaugurated a technological regime and gave birth to a new industry. The first facilities for the commercial production of polyethylene were built by ICI in 1939. As a result of information exchanges between this company and DuPont in the United States, the latter developed its own process technology, in parallel to ICI. LDPE was initially used as an insulating material for underwater cables, but, after the war, the resin experienced a period of very rapid growth in numerous commercial applications. In the mid 1950s, as a result of anti-trust actions against ICI and DuPont in the United States, LDPE technology was widely licensed. Since then, different processes have been developed mainly by former ICI licensees like El Paso, Dow, Chevron, Union Carbide and USI.

LDPE processes are usually classified according to the kind of

[2] For an account of the discovery of polyethylene and a detailed analysis of the scientific and technological roots of the high pressure process for the production of ethylene, see Allen (1967).

reactor used: autoclave or tubular. The processes also differ in the kind of initiator used: usually benzoyl peroxide or gaseous oxygen. Autoclave and tubular are the two dominant designs in high pressure technology for the polymerization of ethylene. The specific designs on the basis of which the different companies operate can be readily identified as belonging to one or the other. In the early 1980s, approximately 45% of the world capacity was autoclave technology and 55% was tubular.[3]

The autoclave process uses the original stirred vessel reactor.[4] In this process ethylene and initiator are fed into the autoclave at one or more injection points. The polymerization takes place at temperatures between 150 and 300 °C and pressures between 1 200 and 1 800 atmospheres. Polymer properties are controlled by the initiator: temperature, pressure, residence time and reactor design. The reaction is highly exothermic and the design is limited by the lack of heat transfer mechanism to control the reaction. This and the vessel size limitations restrict plant capacity, which range between 10 000 to 100 000 tonnes/ year.

There are two basic types of autoclave reactors: the ICI and the Dupont types.[5] The ICI reactor is long and slender, and it has an internally mounted stirrer motor. This type of reactor is generally used to produce LDPE with a narrow molecular weight distribution (MWD), which is used in film and injection moulding. The DuPont type of reactor has an externally mounted stirrer motor and is shorter and wider than the ICI type. The polymers produced by this type of reactor have broad MWD, are high in long-chain branching and are used for extrusion coating, heavy films and copolymer applications.

In the tubular process, the limits of plant size of the autoclave process are avoided by the use of a long tube shape reactor.[6] The first companies to develop this technology were Basf in Germany and Union Carbide in the US. In the tubular process, ethylene and the initiator are fed into the reactor and they flow through in plug flow along a jacketed pipe of several hundred meters long. In this type of reactor, pressures up to 3 000 atmospheres are used. The process allows conversion rates between 30

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[3] Solvik and Kirch (1983).

[4] From Longley (1991) and CIS (1987).

[5] Solvik and Kirch (1983).

[6] Longley (1991).

and 35% and capacities up to 175 000 tonnes/year. It is primarily used to produce commodity film grades, which have some advantages over resins produced in autoclave reactors, such as better processability.

The technological regime of the LDPE industry can be identified with reference to the knowledge, skills, procedures and artifacts that have been developed to deal with problems associated with the high pressure polymerization of ethylene. It is a pool of knowledge which is shared by all LDPE manufacturers. This knowledge has it roots in the set of common problems with which both tubular and autoclave technologies have had to deal, namely, to operate at very high pressures and at temperatures in which ethylene is a supercritical fluid, to use free radical mechanisms of polymerization and to deal with the high exothermic nature of the reaction by finding methods of heat extraction. Although each design delivers products of somewhat different characteristics and controls them in different ways, there is a common body of knowledge focused on the relationship between polymerization conditions, molecular structure of the polymer and performance characteristics.

Despite their points in common, autoclave and tubular processes represent two different design configurations that have given quite different solutions to many of their common problems. As a consequence, there is also a knowledge associated with the specific problems of each process. The development of autoclave technology, for instance, has centred on the design of vessels. Two of the main areas of development have been the substitution of materials and the determination of safety factors linked to scaling up. Other important areas have been the design of safety valves or bursting discs to protect the reactor from overpressures and the introduction of bursting elements to control pressure and be able to produce different grades in the same reactor. The design of stirrer and zoning, which is of great importance for the quality of the product, has also been an important area of research in autoclave technology.

The tubular process has also followed its own line of development. Tubular reactors are constructed of lengths of high pressure tubing and their design presents its own specific problems, such as acoustic resonance of the presence of cyclic bending stresses. These problems have guided the development of this technology and extensive studies of fatigue on tubing have been made. The high pressure tubes are surrounded by heating or cooling jackets, as defense against over pressure-safety valves and rupture discs are needed. All these have been major areas along which this technology has developed.

Each process has its own advantages. Tubular reactors, for instance, produce polymers with broader weight distribution, while, in autoclave technology, large conversion rates can be achieved due to wide resident times. It is interesting to note that each technology has developed adaptations that seek to reproduce the conditions that are the basis of the advantage of the other design configuration: autoclave processes have introduce zoning while tubular technology has incorporated multiple initiation and injection of cold ethylene in multiple points. These kinds of convergencies are an expression of the common pool of knowledge shared by different designs which belong to the same technological regime.

There is also a degree of firm specificity in the particular designs on the basis of which different firms compete. Different companies have developed their own variants of the basic designs. Chem-Facts' 1987 world survey identified 19 different processes in use worldwide. ICI's technology was the more widely spread, being used by 22 licensees plus ICI's subsidiaries. The different LDPE processes available in 1987 are shown in table 6.1. The numbers in brackets beside each process refer to the number of companies that license the process.

Table 6.1 High pressure LDPE processes by type of reactor and initiator (number of licensees in brackets), 1987

TYPE OF INITIATOR	TYPE OF REACTOR		
	Autoclave	Tubular	No details available
Peroxide type	Gulf Oil (2) ICI (22)	Arco (1) Basf (6) Dow (2) Imhausen (3)	
Oxygen type	Sumitomo (2)	A.N.I.C (1) Sumitomo (0) Atochem (7)	
No details available	CdF (7) U.S.I. (7) Esso (0)	El Paso (3) D.S.M. (0) U. Carbide (4) Scientific Design (1)	DuPont (2) Koopers (1)

SOURCE: elaboration on CIS (1987).

A common feature of all high pressure polyethylene processes is that the vigourous nature of the high pressure reaction conditions leads to long chain branching and pendant C_2 and C_4. These and other irregularities are important determinants of LDPE properties: the molecules are unable to pack closely together giving a polymer of low density and low crystallinity. These common characteristic of the polyethylene obtained in high pressure reactors defines them as a product group.

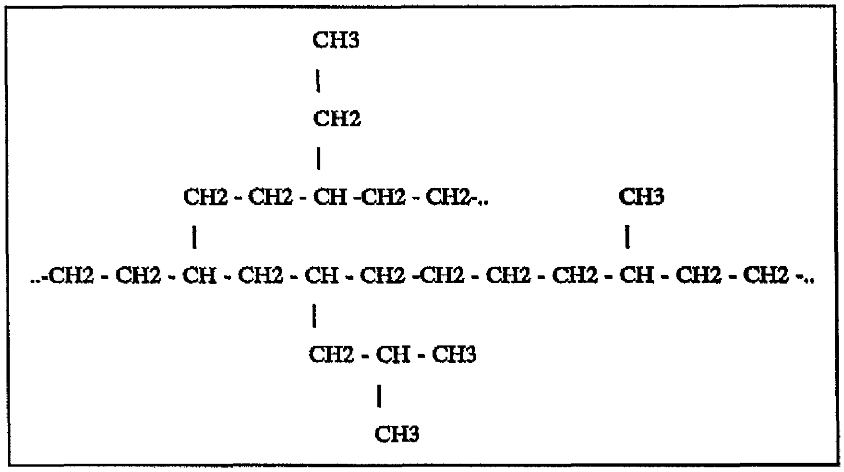

Figure 6.1 The structure of LDPE

The LDPE product group consists of materials that have a density in the range of .915 and .930 g/cm^3 and a melting point of 115 °C. LDPE is soft and flexible; is permeable to gases; has low tensile strength and an excellent impact performance. The largest proportion of this resin is used in the manufacture of film for the packaging industry. Tables 6.2 and 6.3 show the consumption of LDPE and the proportion that went to film in the United States and Western Europe for five different years.

Table 6.2 West European Consumption of LDPE (000 mt) and Share of Film and Sheeting (F&S) applications (a)

	1971	1976	1981	1986	1991
LDPE Consumption	2230	3220	3433	4403	5419
Share of F&S (%)	67	70	73	74	75

SOURCE: *Modern Plastics International*, January issues.
Notes: (a) from 1981 onwards, data include LLDPE.

Table 6.3 United States Consumption of LDPE (000 mt) and Share of Film and Sheeting (F&S) applications (a)

	1971	1976	1981	1986	1991
LDPE Consumption	1974	2620	3415	3576	4812
Share of F&S (%)	56	55	54	61	62

SOURCE: *Modern Plastics International*, January issues.
Notes: (a) from 1981 onwards, data include LLDPE.

The proportion of LDPE used in film is fairly constant over the years, but varies in the two regions, while it is of around 70% in Western Europe, it only amounts to approximately 60% in the United States. The reasons for these different proportions are complex and we will not attempt to pursue them here, all we want is to draw attention to the importance of film in LDPE consumption. Other miscellaneous uses, such as extrusion blow moulded bottles, injection moulded bowls and buckets, paper coating and rotationally moulded water tanks, make up the rest of the LDPE market.

6.2.2 High density polyethylene

In contrast with what happened in the case of LDPE, the discovery of the technology that led to the production of high density polyethylene did not occur in a single company. In the early 1950s, parallel research in different places resulted in the synthesis of polyethylene through a catalytic process. Three different types of catalysts were discovered in the mid fifties by Karl Ziegler, in Germany, and by Phillips Petroleum and Standard Oil of Indiana, in the US.

The discovery of the organo-metallic catalysts that lead to the synthesis of HDPE and polyethylene followed from lines of research different to those associated with high pressure technology. Ziegler's discovery stem from his long period interested in the chemistry of metal-alkyls which, it has been suggested, may be traced back to the revival of interest in inorganic chemistry after 1945 associated with the research in nuclear weapons.[7] The catalysts developed by the US firms were the result of research aimed at upgrading less valuable stream obtained from oil refining in the production of gasoline.

As in the case of LDPE high pressure technology, the research was not directly aimed at the production of a polymer, but the extensive work being done in this area provided a framework that served as immediate reference to the discoveries. The discovery of the catalytic-low pressure route for the polymerization of ethylene meant the emergence of a different technological regime and the creation of an industry.[8] It not only represented a different technology, which rested on a different knowledge base and skills, but also meant the introduction of a product group that could be used in a different set of applications that the ones in which LDPE was used.

In this technological regime, the central problems and the solutions

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[7] Allen (1967), pp.36, 47.

[8] In addition to the HDPE industry, also the polypropylene industry was born as a result of that discovery.

developed to deal with them are associated with the catalysts system. Instead of the reactor design problems of high pressure technology, in HDPE the design of process conditions (included reactor design) respond largely to the progress in catalysis. A good example of this is found in the particle form process and the loop reactor designed by Phillips in the mid sixties. Such a development and the replacement of Phillips' solution process were directly related to the development of more active catalysts, which left a minimum residue in the polymer and eliminated the need of removal of catalysts and purification of the diluent.[9]

Although in low pressure technology the most active role in technological development is found at the level of the catalysts, a design configuration should be defined in terms of both the kind of catalyst being used and the type of conditions in which it operates. Both aspects, combined, define the key characteristics of the manufacturing systems and its possibilities and limitations in terms of the product that they deliver.

In terms of the diversity of technologies, the situation of HDPE is analogous to that of LDPE. In this case, the different design configurations can be identified on the basis of the characteristics of the environment in which the polymerization occurs: slurry, solution or gas phase, and on the type of catalysts employed: Phillips and Ziegler types are the most common ones.[10] In contrast with the LDPE industry where two relatively stable basic types of process (reactor) have been present throughout the history of the industry, in the HDPE industry more variation is observed in process and reactor design. As new types and generations of catalysts are introduced, significant changes are made to equipment and process design to optimize the potential of the catalysts.

We will limit our description of the technology to some examples of widely used processes. The first plants made for HDPE were based on a solution process. In the Phillips solution process,[11] ethylene, powder catalysts and a solvent (cyclohexane) are fed continuously into stirred

[9] See Hogan and Myerholtz (1967) and Hogan (1981).

[10] The catalyst developed by Ziegler was a combination of aluminium triethyl and titanium derivative, while Phillips' catalysts on the other hand was chromic oxide supported on a stream activated silica-aluminia. Briston (1988), p.17.

[11] Hogan (1983).

reactors. Temperatures are kept between 125 and 160 °C and pressures at 30 to 35 atmospheres.

The next main development in HDPE process technology was the slurry process in which the catalyst is suspended in a solvent and the ethylene (and some times a comonomer) is fed as a gas. The polymerization delivers HDPE as a suspended solid, which is filtered and dried. As in the previous case, the process has several forms. The Phillips process uses a vertical loop pipe work as a reactor. There are other versions that use Ziegler catalysts in series reactors. In a typical Ziegler process, for instance, the catalyst is suspended in a liquid hydrocarbon through which ethylene gas is passed. The pressure is near atmospheric and the temperature around 50 to 75 °C. The polymer settles out as a granular powder and the resultant slurry is stirred until the viscosity interfere with efficient dispersion. The mixture is then passed through working up and solvent recovery stages.[12]

A third type of process was developed by Union Carbide in the mid 1960s, in which ethylene, a small quantity of hydrogen, catalysts and comonomer (if used) are fed continuously into a gas phase reactor, where polymerization takes place at pressures around 20 atmospheres and temperatures between 85 and 100 °C. Two advantages of this process are that it requires no solvents and catalyst efficiency is high. As a consequence, several steps present in other processes are eliminated, namely, separation of solvent, solvent recovery and the washing and drying of the polymerized product.[13]

As we mentioned earlier, various firms have developed their own proprietary HDPE processes. Chem-Facts 1987 world survey, identified fifteen different technologies operating worldwide, most of them slurry processes. Table 6.4 summarizes the characteristics of the different processes available and the number of licensees of each.

The structure of the molecules of HDPE is quite different to that of LDPE and this is the main cause of the different properties of the two resins. LDPE is characterized by long branches; in the HDPE case, the

[12] Briston (1988).

[13] Briston (1988).

Table 6.4 HDPE processes by type of polymerization environment and catalysts(number of licensees in brackets), 1987

TYPE OF CATALYSTS	TYPE OF POLYMERIZATION		
	Solution	Slurry	Gas Phase
Ziegler	Dow (0)	Ashai (2) Hoetsch (7) Mitsubishi (1) Montedison (1) Solvay (12) Nissan (2) Chisso (1) Huels (1)	
Chromium based		Phillips (9)	
Other or no details available	D.S.M. (0)	Mitsui (12)	Union Carbide (6) Amocco (1) B. P (see LLDPE tech.)

SOURCE: elaboration on CIS (1987).

hydrocarbon chains are linear and virtually unbranched.[14]

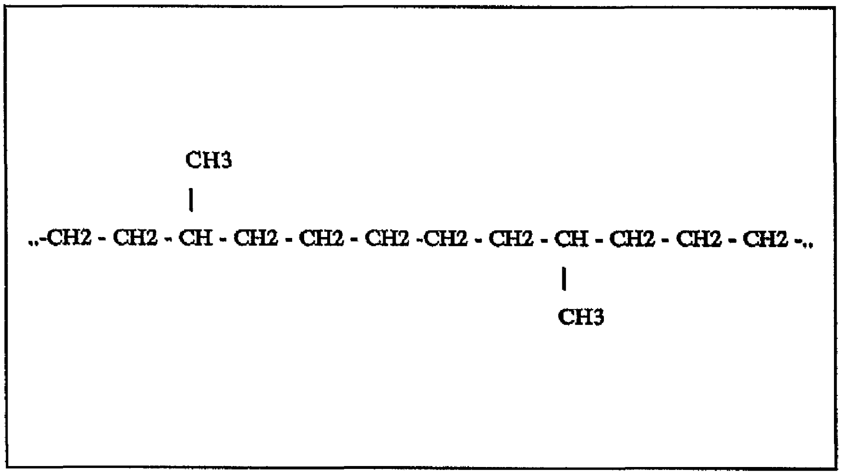

Figure 6.2 The structure of HDPE

The HDPE product group consists of materials with a density in the range of .945 and .960 g/cm^3, and a melting point of 135 °C, both higher than those of LDPE. The crystallinity of HDPE results in greater tensile strength, lower gas permeability and greater rigidity than LDPE.[15] As Tables 6.5 and 6.6 show, the main applications of HDPE are blow moulding and injection moulding, specially for making containers. In this applications, HDPE competes with other rigid materials, including other thermo-plastics like polypropylene.

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[14] HDPE has few side groups in the carbon chain. Polymer made by the Ziegler process, for instance, gives only between 5 and 7 per 1000 chain atoms.

[15] Birley and Heath (1988).

Table 6.5 West European consumption of HDPE (000 mt) and shares of blow moulding and injection moulding applications

	1971	1976	1981	1986	1991
HDPE Consumption	710	1180	1325	2019	3019
Blow Moulding (%)	40	36	43	42	41
Injection Moulding(%)	46	39	31	26	25

SOURCE: *Modern Plastics International*, January issues.

Table 6.6 United States consumption of HDPE (000 mt) and shares of blow moulding and injection moulding applications

	1971	1976	1981	1986	1991
HDPE Consumption	746	1255	1919	2778	3775
Blow Moulding (%)	47	42	40	39	36
Injection Moulding (%)	22	23	24	25	20

SOURCE: *Modern Plastics International*, January issues.

6.2.3 Linear low density polyethylene

Both LDPE and HDPE are produced in different grades according to the kind of application and to the way in which the resin will be processed. Although there is some competition between them in some applications, the bulk of the consumption of the two types of resin is found in different markets. An important point in common is that ethylene is their main raw material, but they are, in fact, different businesses with little competition between them.

In 1977, Union Carbide announced a low pressure process to produce LDPE. The process offered substantial reductions in plant costs, space and energy consumption with respect to the conventional high pressure processes.[16] In addition, the process delivered a LLDPE that was superior to conventional LDPE in several dimensions. It was estimated that LLDPE would impose a threat to 70% of the LDPE market.

LLDPE emerged as a third product group in the polyethylene markets. This product has, on the one hand, properties and applications which are close to those of LDPE. On the other hand, it is produced by a very similar process to that used by HDPE. As a result of the convergence of LLDPE with the LDPE markets and with HDPE technology, and due to other technological advances, such as the development of "swing" plants that can

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[16] Capital investment was estimated to be 50% of that required for an equivalent high pressure plant, and energy saving were estimated to be of 75%.

switch between the production of LLDPE and HDPE, the boundaries between what used to be two separate businesses are becoming increasingly blurred. Therefore, throughout the essay, we will talk of two polyethylene industries before the introduction of LLDPE and of a single industry after the innovation.

In spite of its great impact, the LLDPE innovation did not represent the emergence of a new technological regime in the production of polyethylene. There were three key aspects in the LLDPE technology introduced by Union Carbide. First, ionic polymerization of ethylene with modified chromium based catalysts. Second, the use of butene-1 comonomer to introduce branching in a linear polymer and reduce its density. Third, a gas phase polymerization process. Union Carbide's Unipol technology involved more than simply combining these elements; it also represented a progress in catalysis and plant design. However, the three elements listed above were already present in existing technologies applied to the polymerization of ethylene. Ethylene polymerization by means of organo metallic catalysts was the break through that gave origin to the synthesis of HDPE in the mid fifties. The use of butene-1 and other copolymers was widely known both in LDPE and in HDPE manufacturing as a way in which the density of the polymer could be controlled. Finally, the gas phase process had been introduced by Union Carbide itself in 1965 for the polymerization of HDPE. In fact, LLDPE can be seen as a HDPE in which a comonomer, such as butene-1, is introduced to produce a regular branching in the carbon chains, which reduces the density of the polymer. Furthermore, DuPont Canada had been producing LLDPE since the early 1960s with a technology based on a low pressure solution process for HDPE. However, the grades produced by DuPont were limited to relatively expensive speciality film applications and the process did not offer a cost advantage over LDPE. Therefore, this technology did not have a major effect on the industry.[17]

[17] Davies and Richards (1986).

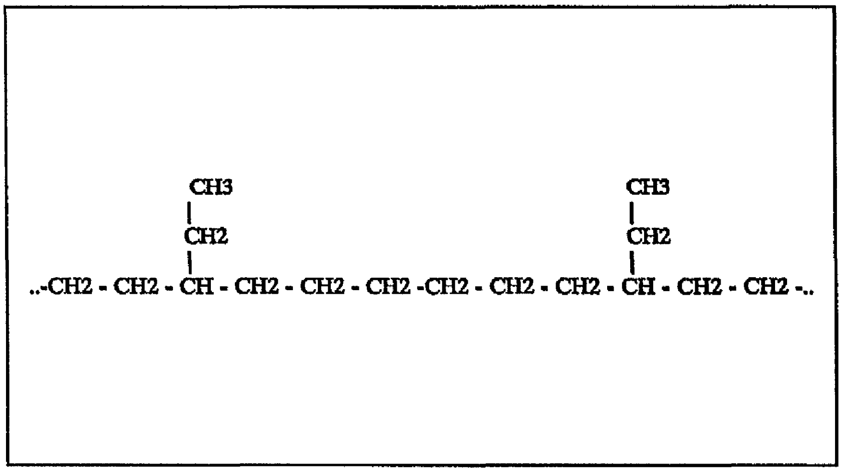

Figure 6.3 The structure of LLDPE

The reasons for the considerable impact of Union Carbide's LLDPE technology were related, both to the economies associated with the process and to the performance of the material. These two aspects combined made it a viable substitute for LDPE in many applications. Regarding the process, the most important advantages were the reduction in required capital investment (50% in the first version and two thirds in an improved technology) and the substantial energy savings (75%). According to 1982 estimates, a conventional polyethylene plant to produce 135 000 tonnes a year required an investment of 500 US dollars per annual tonne, while for a LLDPE plant of similar capacity, the cost was of only 240 US dollars per annual tonne.[18]

Regarding the characteristics of the resin, a first important consideration is that the new product was a general purpose film grade resin aimed to those applications that constituted the largest market of the LDPE industry. A second issue relates to the superior properties of LLDPE in most of the characteristics that are relevant for film applications. Particularly important was the fact that LLDPE combined toughness with a better draw down, which made it possible to produce film that, in spite of being thinner than the film made of LDPE, had the same or even superior performance. This property, referred to in the industry as "downgauging" was central for the appeal of using LLDPE in the large volume film markets. Downgauging is important in most film applications because it offers the opportunity of substantial economies in the consumption of material. Thus, the economies derived from lower production

[18] SRI (1982).

costs and from reductions in the use of the material needed to produce a given film area provided a strong incentive for the adoption of the new polyethylene.

The other important aspect of the LLDPE innovation is that it has opened a wider trajectory for the development of the technological regime that defined the HDPE industry. The range of service characteristics covered by the polyethylene grades that are produced by low pressure-catalytic polymerization has been considerably broadened. As a consequence, the technology that gave birth to HDPE in the 1950s has entered in more direct competition with that of the LDPE industry.

6.3 The development of LLDPE technology

In this section, we will look at the characteristics of the two technological regimes in competition and to the interrelatedness between polyethylene production and processing technologies. Our purpose is to identify the different factors relative to the technology that have been determinant of the development of LLDPE.

The low manufacturing costs and the good performance of LLDPE made the new technology a viable innovation to compete with the high pressure technology. However, the comparison between the two technologies at the time of the introduction of LLDPE was only a manifestation of the potential of the new technology. This has been changing with the competition between the two regimes and the development and diffusion of LLDPE technology.

There are two fundamental elements that have influenced the development of LLDPE technology. The first is the fact that it was mainly a market stealing innovation, which competed mainly in applications that used LDPE. The second is the state of development of the low pressure polymerization regime from which it emerged. The market stealing nature of the innovation has been important for two reasons. First, because this introduced important elements of inertia: the need to make changes in the equipment and to learn to process LLDPE discouraged its introduction. Second, because the diversity of LDPE grades that existed and the fact that there were applications in which those grades performed better than LLDPE grades has guided the development of the new technology. Regarding the state of development of low pressure technology, this has been a major determinant of the different configurations of LLDPE processes that have emerged, and of their cost performance relative to conventional LDPE technology.

In what follows, we will look, first, at the competition between LDPE and LLDPE in film markets. We focus on these markets because they make up the largest share of the consumption of the two resins. Afterwards, we will look at the various processes to produce LLDPE that have emerged. Throughout our discussion we will be concerned with the various elements involved in the comparison between LDPE and LLDPE technologies that were relevant for the decision to adopt the new resin.

6.3.1 The film market

A first important point is that LLDPE was not absolutely superior to LDPE. Table 6.7 shows how the basic general purpose grades of the two resins compared across several dimensions that are important for film applications. LLDPE superiority in break strength, rigidity, impact strength, elongation break and puncture resistance make it a tougher material than LDPE. These properties were important in most applications since they enabled processors to make thinner film of comparable or even superior performance. On the other hand, the fact that LLDPE was not better than LDPE in yield strength[19] was a limitation for downgauging in some applications, such as carrier bags, and required of changes in product design to make it possible. A crucial advantage of LDPE was its superior extrudability. LLDPE was more difficult to process in existing equipment and this has been a major factor that has helped the latter to keep its position in the market. Table 6.8 shows the structure of the LDPE markets in the US and Western Europe at the beginning of the 1980s, which are the early years of the diffusion of LLDPE. The diffusion of LLDPE depended not only on the general advantages and disadvantages with respect to LDPE, but on their relative performance in each application. The following review of three of these applications: bags, stretch film and shrink film, illustrates this point.

LLDPE had a general advantage in bag manufacturing and packaging not only because of its toughness, but because of its superior heat sealing

[19] Yield strength is the tensile stress at which the first signs of non-elastic deformation occurs. Briston (1988), p. 95.

Table 6.7 Key performance criteria for polyethylene film

LLDPE superior	LDPE superior	No significant difference.
Break Strength	Extrudability	Yield Strength
Rigidity	Opticals	
Impact Strength	TS Shrinkage	
Draw down	MD Tear Propagation Resistance	
Heat sealing		
Puncture resistance		
Gas permeability		
TD Tear propagation resistance		

SOURCE: Davies and Richards (1986).
Note: (a) MD = machine direction, TD = transversal direction, TS = transversal section.

Table 6.8 Shares of different applications in total LL and LDPE film consumption in Western Europe and the US, 1981 (%)

Western Europe		United States	
Garbage bags	12.2	Trash bags	27.5
Shopping bags	13.7	Bags: retail and carry out	6.7
Stretch wrap	3.1	Stretch wrap	1.8
Shrink wrap	14.7	Shrink wrap: including pallet	5.8
Heavy duty sacks	14.7	Industrial bags: various	10.9
Agricultural film	9.8	Agricultural film	3.1
Construction film	4.1	Industrial sheeting	4.7
Laminates	4.1	Food packaging	16.0
Food packaging	12.2	Packaging: miscellaneous	14.9
Other non-food pack.	15.3	Non packaging: miscellaneous.	8.6

SOURCE: Western Europe: elaboration on *European Plastic News* (December, 1982); US: elaboration on Modern *Plastics International*, January (1983).

properties. LLDPE not only offers a better sealing. Its hot tack strength (the strength of the seal while it is still molten) allows to perform the sealing operation faster. In addition, thanks to the broader sealing range of the resin, less time is wasted in setting up sealing conditions. The importance of other properties varies depending on the type of bag. In carrier and liner bags, LLDPE break strength and puncture resistance were its more important advantages. For produce bags, in addition to those two properties, the impact strength of LLDPE was also very relevant. In deep freeze pack, what was more relevant was its superior impact resistance at low temperatures.[20] Although LLDPE would tend to be preferred in most types of bags, there were niches were conventional LDPE was preferred. In some kind of shopping bags and in automation packaging, for instance, optical properties are particularly important and the superior clarity of LDPE gave this material an advantage over LLDPE.

Two other applications, which are worth commenting upon, are Stretch and shrink wrap films. Stretch film is an application in which the

[20] This superiority is related to the fact that LLDPE has a higher melting point than LDPE at the same density.

utilization of LLDPE has been particularly successful.[21] The stretchability of LLDPE is intimately related to its superior break strength: film made with this resin can endure considerable more elongation without breaking than LDPE one. The introduction of LLDPE has generated a considerable growth of this market through the introduction of very stretchable, tough and thin films. This is one of the few cases in which LLDPE was a market creating innovation. In the US for instance, while stretch wrap accounted for only 1.8 of the film market in 1981, ten years later the share of this application was of 9.5%.[22] Shrink film, on the other hand, is an example of a LDPE market not directly threatened by LLDPE. In contrast with LDPE film, LLDPE film has no shrinkage properties in transverse direction and, as a consequence, can not be used in heat shrink applications. However, to the extent that stretch film competes favourably with shrink film in some applications like pallet wrap, this market was also affected by inter-resin competition. The fact that in the US, for instance, between 1981 and 1991, the share of shrink wrap in low density polyethylene consumption diminished from 5.8% to 2.7%, while the share of stretch wrap increased from 1.8% to 9.5% was largely the result of the competition between these two types of film.

As the examples above make clear, the competition between the two types of polyethylene was on a niche by niche basis. By 1991, LLDPE had reached a share in the film markets of 18.3% in Western Europe and of 37.2% in the US.[23] Due to the differences in performance, described above, the penetration of LLDPE has been different in different markets. This can be seen in table 6.9 that shows the distribution of LLDPE consumption in different film markets for Western Europe in 1991.

6.3.2 Product variety and production technology

There are two fundamental aspects behind the diffusion of LLDPE that are missed in the discussion above, which ought to be consider to have a more clear picture of the competition between the two technologies. The first

[21] Initially LLDPE was used alone or in blends for this application and later mainly coextruded with other resins.

[22] Modern Plastics International, January issues (1983, 1992).

[23] This shares are measured as participation in the total tonnage of polyethylene consumed in film markets (elaboration on data in Modern Plastics International, January 1993).

Table 6.9 Share of different applications in total LLDPE film consumption in Western Europe, 1991 (%)

Refuse sacks	7
Carrier bags	9
Stretch, pallet	33
Shrink, pallet	9
Heavy duty sacks	10
Agricultural	6
Lamination	7
Others	19
LL film / Total LL	89
Total LL / Total LD+LL	18
Total LL film (000 mt/y)	810

SOURCE: *European Plastic News*, September (1992).

is that LDPE is not an homogenous product, but rather a product group. We saw earlier in the chapter that the different processes, associated with different design configurations, had advantages in the production of polymers with different characteristics. Hundreds of different grades of LDPE were in the market when Union Carbide introduced its LLDPE. As a spokesman of this company pointed out at that time, it was a matter of years before the firm could duplicate all the grades in the conventional LDPE repertoire.[24] The second aspect that needs to be considered is the dynamic nature of the competition between the two technologies. The diffusion of LLDPE has involved an innovative process in which grades are introduced to match applications and processes are modified to improve resin characteristics. The same has occurred with respect to LDPE and producers have fought back by improving their grades to compete with LDPE.

Polyethylene producers, in general, offer different grades that have enhanced performance on those characteristics, which are more relevant for some specific applications. This different grades are produced by varying the polymerization conditions. The characteristics of the process used by the manufacturers is very important, since it defines a set of basic polymerization conditions and the limits within which they can be varied. LLDPE can be tailored by varying four basic property parameters, namely, molecular weight (MW), molecular weight distribution (MWD), short chain frequency and short chain branching. In the case of LDPE, the property parameters are, in addition to MW and MWD, the extent of long chain branching and of short chain branching. The tailoring of a resin to obtain the desired properties is a complex activity. The way in which this is

[24] Modern Plastics, February (1978), p.40.

achieved, varies in the different design configurations of each technology, and is part of the inside knowledge of the different manufacturers. We will not enter here into the detail of how the tailoring of the resin is made in different processes.[25] What is important to stress is that the way in which it is done is significantly different in the high and in the low pressure processes. In the former, the basic conditions are temperature, monomer concentration and pressure, while in the latter they are catalysts and the type and amount of comonomer. This is an expression of the fact that they correspond to different technological regimes.

The diversity of LDPE grades that were available when LLDPE was introduced has defined to a great extent the route of product innovation in LLDPE technology. In 1982, for instance, Union Carbide introduced high clarity grades of LLDPE with comparable optical properties to those of LDPE. Frictional melt grades, which could be used in shrink applications, were also developed. These post-innovation improvements extended the use of LLDPE to some applications that, as we saw in the previous section, were initially perceived as niches reserved for the old resin.

The development of LLDPE technology has also proceeded through the exploration of the possibilities opened by the use of catalysts and comonomer. These make it possible to have a greater control over the molecular structure of the polymer, which is at the heart of the tailoring of its properties. LLDPE producers have introduced copolymers and terpolymers with higher α olefins as comonomers, such as 4-methyl pentene-1, hexene-1 and octene-1, instead of the butene-1 used initially in the Carbide process. Higher α olefin copolymers and terpolymers have superior properties to those of butene-1 LLDPE, and a different performance is obtained from the use of different comonomers.

Thus, product innovation in LLDPE technology has taken place both as an increase in the number of grades to suit better specific applications, and as an improvement in the properties of the resin for a given application. The representation of this process in terms of the characteristics vectors framework described in chapter four is shown in figure 6.4.

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[25] For a description of how it is done for LLDPE in Union Carbide's gas phase process, see Staubs (1983). The corresponding description for LDPE made in a tubular reactor can be found in Solvick and Kirch (1983).

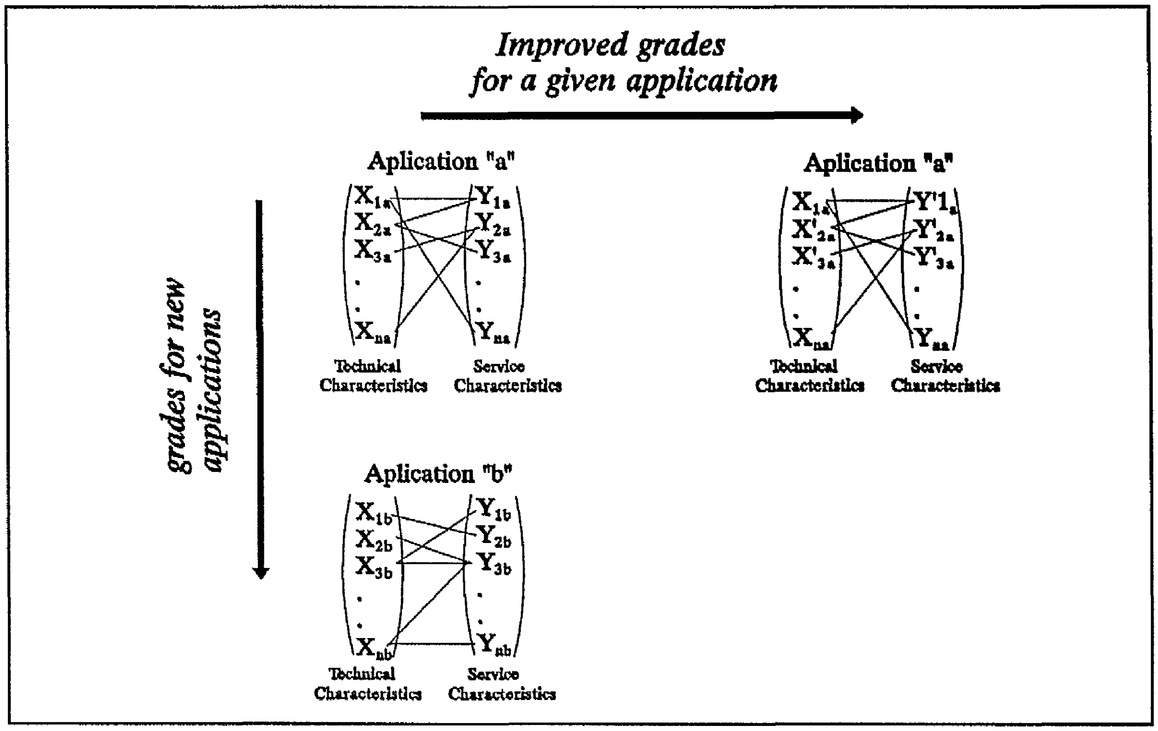

Figure 6.4 Product innovation in LLDPE

Finally, it is important to stress that conventional LDPE technology has not remained static. The challenge of LLDPE also set an agenda for further innovation in the old resin. This is exemplified by the introduction of "strong LDPE" technology by the engineering firm Imhausen. The company introduced a technology to produce LDPE terpolymers in tubular reactors. This polymers had improved properties that made it possible to produce film with increased impact resistance and tensile strength. In addition, it was claimed, the product allowed 20% downgauging with respect to conventional LDPE and without the processability problems of LLDPE.[26]

The question of the difference in extrudability of LL and LDPE resins brings into focus the next major theme in relation to the competition between the two technologies: the adoption decision of plastic processors.

6.3.3 Film technology and the introduction of LLDPE

The decisions related to the adoption of LLDPE by film producers were a more complex issue than a simple comparison of its performance in an application relative to that of LDPE. The numerous options available in terms of types of resin and grades are a first problem faced by a

[26] Imhausen, et. al. (1983).

polyethylene processor. In addition , there is the possibility of making the product from one resin only, or from a combination of various. The second problem is to decide on the way of processing the resin. This involves the choice of a particular technology and equipment. An important advantage of LDPE was that the equipment in place was designed to run with this material and that the processors were familiar with its properties. Switching to LLDPE involved considerable learning and required equipment modifications.

An extruder wanting to enter LLDPE processing faced various alternatives, which not only represented different costs, but had different implication on the characteristics of the product that they delivered. The extruder could choose among the following: to modify equipment to run LLDPE; to use additives and extrude LLDPE in unmodified equipment with a reduction in throughput; to blend LLDPE with other resins with only minor or no modifications in equipment; to coextrude LLDPE with other resins in equipment designed for that purpose; or to adopt some combinations of these alternatives. There were, for instance, various equipment modifications that allowed to use blends with different proportions of LLDPE. Different alternatives offered different advantages and disadvantages in terms of costs and of the characteristics of the film they deliver. Before entering to discuss this issues, it will be useful to give a short description of film manufacturing technology.

General aspects of film manufacturing technology[27]

There are two different types of techniques for the production of polyethylene film: blowing and chill-rolling (also known as flat die casting). In both, the polymer goes through an initial extrusion phase in which the raw material in the form of granules or pellets is plasticized. However, the characteristics of the die through which the molten resin is extruded and the remaining steps of the process are different in each technique. In blow moulding, the plastic melt is passed though an annular slot die and is expanded into a bubble by blowing air into the melt. The bubble is cooled, taken up to a reel, and the film is winded into reels. In chill-rolling, in contrast, the melt is passed through a flat die and

[27] The material in this section draws on Piner (1967). Rose (1983) and Briston (1988).

deposited on to a moving roll, which cools the extrudate creating the film.

There are a series of advantages of the blown process over chill rolling that have made it be preferred in most applications. Firstly, it is easier to manufacture bags from blown film since it is only necessary to seal one end of a cut length to make it. Secondly, the die in the equipment is easier and cheaper to manufacture than a slot die for chill rolling. This is particularly important when making wide films, which in general are cheaper to make with this process. Finally, blown film has better mechanical properties than chill rolled one. Chill rolling, however, has advantages that have gained it some applications: it has higher output rates and allows to produce film with less thickness variation. In addition , chill rolled film has better optical properties: transparency and gloss.

The blown process is normally used to produce film for bags, wide films, and films where toughness is relevant. Chill rolling is mostly used for thinner films, self adhesive films and films for laminating.

The interrelatedness between the characteristics of the material and the processing technology is not only central for the competition between LLDPE and LDPE, but is an important aspect of the technological change associated with the innovation. Although space precludes us from looking at this issues in detail, we will try to give an idea of this aspect of the development of LLDPE technology. First, we will look at the type of equipment modifications that were required to process LLDPE. Afterwards, we will illustrate the variety of blending possibilities opened to the manufacturer of a particular product by looking at the case of grocery sacks. Finally, we give an example of how the development of film technology has been affected by the LLDPE phenomenon.

Changes in processing equipment

A major difference of LLDPE with respect to LDPE is its melt rheology: it melts faster and has a higher viscosity under usual extrusion conditions and this has a major influence in required screw torque and melt temperature, which are specially important for blown film extrusion. As a consequence, LLDPE requires greater power to extrudate and a wider die gap to prevent melt fracture. Therefore, an extruder which wanted to run LLDPE at a similar throughput rate than LDPE had to replace or to modify its equipment. The possibilities of adaptation of old equipment to process LLDPE were different according to the characteristics of the equipment to be adapted. These adaptations could vary considerably in terms of cost, number of changes required and flexibility that they allowed to the producer.

The basic changes at the lower end of the spectrum involved adaptations of screw and dies and some adjustments to the air ring. The purpose of the screw modification was to limit shear and pressure. The precise nature of these modifications depended on barrel length and other features of the extruder design. Regarding the die, the basic adaptation involved modifying the mandrels to open die gaps in order to be able to run LL without increasing temperatures too much above those of conventional LDPE extrusion. Finally, the air ring adjustments were needed in order to cope with the instability of the lower-melt-strength LLDPE bubble and give a better support to it in its early melt stages.

More expensive adaptations involved incorporating low pressure dies to the front end and a low velocity air ring, which increased the throughput to the same level of LDPE processing.

After the first few years of the introduction of LLDPE, modification packages were followed by LLDPE purpose built extrusion lines. In general these gave the processor flexibility to process either LLDPE or LDPE or their blends. Table 6.10 lists the different design areas, which had to be taken care of, and the purpose of these changes when designing a LLDPE extruder for blown film.

Table 6.10 Areas of the design of a blown film extruder where changes are needed to process LLDPE

Area	Purpose of design changes
Extruder drive motor and gear box	sustaining higher torque requirements
screws with increased channel depth	control of torque requirements
screw and barrel design	control of melt temperatures
die and die gap	limit shear rate and control melt pressure
cooling system	control bubble stability and height of frost line
bubble guiding mechanism	control bubble stability and be able to influence its shape
film guiding and trimming equipment	avoid blocking effects, warpage and folds
blades	reduce wear out when cutting a tougher film
method of resin feeding	when using granules to handle the raw material

SOURCE: Based on *European Plastic News*, December (1982).

Blending

Resin usage and blending practices are a complex issue. The properties that are desired in a film respond to the particular use for which it is manufactured. These properties can be altered by the manufacturing method, by the type and specific grades of resins that are chosen and by the proportions in which the resins are combined in the blend. Therefore, a wide range of possibilities is open and choices depend on technical restrictions and economic considerations. The example of blending practices in grocery sacks provides a good illustration of the role of blending. In this applications LLDPE played an important role in allowing the displacement of Kraft paper bags, particularly in the United States. In these bags, some degree of toughness and avoidance of excessive stretching were required in terms of performance, while downgauging was of major importance as a source of cost reduction. In the early 1980s, the typical blending proportions were 70% LDPE and 30% LLDPE, but there were also bags produced with 100% of either LDPE or LLDPE, blends of LLDPE with other resins such as HMW-HDPE offered also a good alternative to producers with the equipment to process them. Table 6.11 shows various alternatives for grocery sacks in which in addition to the blending decision and the resin choice, two main variables that affect costs are considered: the impact of resin prices and the effect of the choice of gage.

Table 6.11 Cost of grocery sacks made of LDPE, LLDPE and a blend

Cost/price factor	LDPE 100%				LL/LDPE blend(a)				LLDPE			
					Butene Comonomer		Octene Comonomer		Butene Comonomer		Octene Comonomer	
Gage Range	1.75-2.0				1.1-1.5		1.1-1.15		1.0-1.3		1.0-1.3	
Gage,mils.	1.75		2.00		1.20		1.20		1.01		1.01	
Weight bag,lb(b)	0.052		0.060		0.036		0.036		0.030		0.030	
Resin cost,c/lb(c)	32.0	41.0	32.0	41.0	32.0	41.0	32.6	41.9	32.0	41.0	34.0	44.0
Resin cost,c/bag	1.67	2.14	1.91	2.45	1.15	1.47	1.17	1.50	0.97	1.24	1.03	1.33

SOURCE: From Modern Plastics International, December (1981).

Notes: (a) The typical blend in grocery sacks is 30% LLDPE and 70% LDPE

(b) Calculations take into account differences in polymer specific gravity and film gage. Bag size is equivalent, in terms of load volume to that of a 1/6 barrel kraft grocery sack.

(c) The two prices cited for each material are, first, market price reported by industry sources for 3rd-quarter 1981 (when prices were far below list);second, hypothetical price used to demonstrate effect of sack economics if resin were selling close to current lists.

(d) Additional technical notes accompany the table in the original source. Here the table is only used as an illustration of blending possibilities and of the effect of changes in resin prices.

Needless to say, the above is only one among a great number of blending possibilities in different applications. LLDPE is not only blended with LDPE to give toughness to the film and allow downgauging. It is also used at relatively low levels with other polymers to gain other performance advantages.[28] In shrink film, for instance, where LLDPE was

[28] Davies (1984).

not thought to be a threat to LDPE, it is blended with LDPE to improve burnthrough resistance. LLDPE is also blended with substandard and regrind to upgrade performance and reduce bubble break during blown extrusion.

Although the blending of different grades of polyethylene between them and with other polymers was not a new practice, it acquired considerable importance in relation to LLDPE. This alternative made it possible to enhance the properties of the film and to achieve some degree of downgauging with only minor modifications in the equipment, or even without having to change the equipment at all. Extruders, which were reluctant to commit their facilities to LLDPE only, chose to use it in blends. As a consequence, during the first years, the most spread practice was to use blends of the two resins and the development of blending technology received considerable impulse. However, blending has some shortcomings and many high performance applications have gradually shifted to coextrusion.[29] In the latter also two or more resins are used, but special purpose built equipment is required. Needless to say, these practices have had major consequences for the actual impact of LLDPE on the LDPE market and for its overall diffusion. They opened the possibility not only for a gradual transition from one type of resin to the other, but for the coexistence between the two.

Changes in processing technology

The final topic on film technology, which we will comment upon, is the development in equipment technology and usage associated with the introduction of LLDPE. Some of these have already been mentioned, such as the equipment adaptations and new equipment designed to process LLDPE. Here we will look at an example of how the developments in technology affected the relative use of the two main types of processing technique.

Stretch film was one of the applications that received more impulse by the appearance of LLDPE. For this film the best manufacturing technique is die cast chill-roll because of the great control that it has on film thickness and the good optical properties that it delivers. Thus LLDPE gave an important impulse to this processing technique, which previously

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[29] It has been found that miscibility is the exception rather than the rule, and blends of LDPE and LLDPE tend to become "unmixed" into separate crystalline phases and, thus, fail in critical applications. See Birley and Heath (1988).

accounted for a marginal part of overall film processing.[30]

On the other hand, the introduction of LLDPE has also promoted the development of blown film technology: the emphasis on downgauging has been an incentive to innovation in this technology. Innovation in blown film has translated into higher line speeds that allow to run LLDPE (and HMW-HDPE) at profitable rates. Another important development in blown film technology is the introduction of equipment to coextrude LLDPE with other resins. The use of this type of equipment can deliver advantages not only derived from enhanced film properties but also from economies in resin usage (although this is achieved at the cost of higher equipment costs in comparison with those associated with monoextrusion).

An interesting phenomena is that the improvements in productivity in blown film technology, coupled with the developments in coextrusion, have allowed this technology to close the gap with the chill roll process in output rates and control of film thickness, which are two of the major advantages of the latter. As a result coextruded blown film technology has entered to areas traditionally reserved for chill-rolling, like the manufacture of stretch wrap film. This has tended to offset the impulse that LLDPE has given to the chill roll process. This example illustrates the mixed effects that have arisen from the developments in film manufacturing technology.

6.3.4 Production technology and inter-resin competition

Another fundamental element driving the development of LLDPE technology is the state of development of the regime from which it emerged. On the one hand, it is from that basis that the different design configurations of LLDPE processes have emerged. On the other hand, it has defined, to a great extent, the scope for subsequent process improvements, such as the extent to which efficiency can be increased to reduce the costs of the polymer.

Although Union Carbide's gas phase process was the one that gave origin to the LLDPE phenomenon, DuPont and, arguably, Phillips had produced the resin earlier. In addition to these firms, other producers have also developed proprietary technologies. As the following description will make

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[30] Rose (1983).

evident, the main LLDPE processes are based on HDPE technology.

The main types of technology to produce LLDPE are the gas-phase and the liquid phase ones. In the Union Carbide gas-phase process, ethylene and a comonomer are copolymerized in the presence of a chain transfer agent. The monomers are fed continuously into a fluid bed reactor made of granular polyethylene polymer, and the catalyst is added separately. Reaction pressure is between 7 and 20 atmospheres and temperature in the range of 75 to 100 °C. Overall average conversion rate of ethylene and comonomer is between 97 and 99%, and average polymer residence time is of 3 to 7 hours.[31]

The liquid phase processes to produce LLDPE are modified versions of the slurry and solution technologies used to produce HDPE. In the Phillips particle-form process, for instance, ethylene, a comonomer (such as butene-1), a light hydrocarbon diluent and chromium supported catalysts are fed continuously into the reactor. The process operates at temperatures around 100 °C and pressures between 7 and 50 atmospheres. One of the firms that uses a solution process is Dupont. According to an author, the process is believed to be based on continuous polymerization of ethylene with octene-1 in cyclohexane. Temperatures and pressures are of the order of 250°C around 80 atmospheres respectively, and the process uses a Ziegler type catalysts.[32]

There are also LLDPE processes that have been developed from high pressure technology. CdF Chimie, for instance, introduced a high pressure ionic polymerization, which uses binary catalysts (like those developed in the mid 1950s by Standard Oil Ind.). In this process, polymerization occurs in an autoclave reactor vessel at pressures, which can be as low as 300 bars and temperatures up to 300 °C.[33]

As the result of the technological effort by polyethylene producers to develop alternative routes for the production of LLDPE, by 1981, just 3 years after Union Carbide's announcement, 18 processes were being developed. A year later, the number had raised to 21.[34] Although many of them were not commercial, these have generated a diversity in LLDPE

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[31] See Staubs (1983) and Karol (1986).

[32] See Short (1981).

[33] A description of the process can be found in Machon (1983).

[34] Chemical Engineering, August (1981), Modern Plastics, April (1982).

processes that resembles that of the other two polyethylene resins. The processes that have been developed and are used commercially are shown in tables 6.12 and 6.13.

Table 6.12 LLDPE low pressure processes according to process characteristics and characteristic comonomer (number of licensees in brackets)

TYPICAL COMONOMER	TYPE OF POLYMERIZATION		
	Gas phase	**Solution**	**Slurry**
hexene	U. Carbide (18)		**Phillips (1)**
octane		DuPont (4) Dow (0) D.S.M. (3)	
4-methyl-pentene-1	B. P. (7)	Mitsui (0)	
not specified	Neste (0) Atochem (0) Basf (0)		U.S.I/ Arco (0)

SOURCE: elaboration on CIS (1987); *Modern Plastics International*, various issues, and *European Plastic News*, various issues.

Table 6.13 LLDPE processes derived from LDPE High-pressure technology (number of licensees in brackets)

	TYPE OF REACTOR	
Autoclave	**Tubular**	**No details available**
CdF (3)	Atochem (0) Ube (0)	Montedison/ El Paso (0) Alcudia (0) Showa Denko (0)

SOURCE: elaboration on CIS (1987) and *Modern Plastics International*, various issues.

We have classified the low pressure processes according to the type of polymerization environment and the higher α olefin comonomer used to produce superior grades.[35] Another important characteristic, not included in the tables, is the type of catalysts used. Catalysts tend to be firm specific and can be broadly classified in the same groups as those of HDPE processes. These are the three most distinctive aspects that define the different design configurations. Similar processes not only produce resin of similar characteristics, but are also close in terms of the knowledge and skills required and in the type of problems faced in the development of the technology.

Since the relevance of the Union Carbide innovation shifted its emphasis from costs of production to resin properties, some firms developed LLDPE processes based on high pressure technology. The main advantage of

[35] Comonomers can not be used indistinctively in all processes. Therefore, this is a distinctive characteristic.

these processes was that they made it possible to convert existing plants for the production of LLDPE at a low cost. However, they were not competitive on a new plant basis.

At the time when they were introduced these conversion technologies had their rationale as a way to enter the production of the new resin, which avoided heavy investment in new plants. But, as new purpose built capacity has entered the market, their participation has diminished to become negligible. Table 6.14 shows the relative importance reached by the different type of processes in 1988. It also shows an important feature of the new technology: it is possible to build plants that can switch from the production of LLDPE to HDPE. However, switching is costly. Therefore, producers tend to dedicate their lines to one type of resin and to operate at most one of their plants in a given location in "swing" mode (i.e. as a plant that actually switches between producing LLDPE and HDPE).[36]

Table 6.14 Composition of World capacity by process, 1988 (%)

Process	LLDPE	LL/HDPE	% OF TOTAL
Gas-phase	18	52	70
Solution	7	17	24
Modified H-P	4	-	4
Slurry	-	2	2
Total	29	71	100

SOURCE: SRI (1990).

The focus on the diversity of designs within LLDPE technology unveils another dimension of the development of technology: namely, that it is the outcome of the competition between firms that champion different configurations. Each configuration differs in terms of the range of products that it delivers. Firms championing different designs follow different routes to improve their products and to match the improvements of their competitors. A good example of this is the use of comonomers. Octane based LLDPE has been produced since the early years of the introduction of LLDPE as a premium material. It has particularly good mechanical properties, improved puncture resistance and better saleability than other types of LLDPE. However, octane can not be used in the gas phase plants because the conditions of the process limit comonomer use to hexene. It has not been but until 1992 that Mobil, a licensee of Union

[36] In 1985, for instance, 30% of the world linear polyethylene capacity had swing capabilities, and 36% of that 30% did actually operate in swing mode. Sinclair (1986).

Carbide's gas phase technology, was able to achieve the improvements in catalysts that allow to produce an hexene-LLDPE equivalent to the octane grades. The improved catalysts gives more control of the MWD and yields a polymer that can compete in the high strength LLDPE segment of the market. However, in that same year, Dow (an octene LLDPE producer) announced a new generation of polymerization catalysts that, it was claimed, allows to produce narrow MWD polymers with better improved toughness and with no fall in processability relative to other LLDPE resins.[37]

Needles to say, technological progress has also taken place in plant efficiency. A good example is that of Union Carbide. A few years after the LLDPE innovation, the firm reported improvements in catalysts and operating conditions that, together with modifications in pre and post-reactor equipment, increased the capacity of a reactor by 65%.[38] It ought to be mentioned, however, that the impact on the unit cost of the resin of such increases in productivity is limited. As a result of both the progress already achieved in low and high pressure polyethylene technologies and the relatively high price of hydrocarbons, fixed costs account only for a small proportion of total costs. With the share of ethylene in unit costs being of around 70%, the effect of reductions in fixed costs is bound to be relatively small even for dramatic increases in plant efficiency like the one just mentioned. This brings us to the question of the comparison between high pressure and low pressure technologies in terms of the costs of production, which is the last theme that we will discuss in relation to the competition between LLDPE and LDPE.

It is widely recognized that on a new plant basis a state of the art gas phase plant is a better option than either and autoclave or a tubular plant. In 1982, for instance, it was estimated that a new gas phase plant required 48% of the investment per tonne associated with a conventional LDPE plant.[39] Table 6.15 compares the cost structure of a tubular and a gas phase plants. On that basis, the only reason to build a new LDPE plant would be that the markets niches where the producer competes required

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[37] The new system is called constrained geometry catalysts technology (CGCT).

[38] Modern Plastics International, april (1982).

[39] SRI (1982).

precisely that type of resin.

Table 6.15 Typical costs for a LDPE tubular plant and a LLDPE gas-phase plant (US dollars/mt)

	LDPE	LLDPE
Capacity (mt/y)	150,000	200,000
Raw materials	501	527
Utilities	55	20
Operating costs	22	22
Overhead costs	99	88
Costs of production	677	657
Transfer price	840	787

Source: List (1986), pp. 86-87.

A major factor operating in favour of LDPE is that the plants for this resin are already on site, and many of them have already been fully depreciated. Scraping and replacing them only makes sense in those cases in which the operating costs are so high that the savings that would accrue from switching to a new plant are sufficient to cover the repay of capital investment and earn a normal return.[40] Due to the different cost structure of the plants, the cost comparison between conventional LDPE and LLDPE varies with the price of oil. The latter affects the price of ethylene and the relevance of the energy savings associated with gas phase processes. The rise in the price of oil during 1979 and 1982, made the comparison favourable to LLDPE due to the greater weight of ethylene and energy in the cost structure of conventional processes. Lower oil prices from 1983 onwards weakened the case for scrap and replacing. The following figure shows the effect of the price of oil in relative costs comparisons.

Figure 6.5 provides only a rough idea of how the plants cost of the two technologies compare with each other. In practice not all plants are equally efficient. Comparisons have to be made in a plant by plant basis: vintage, scale, location and many other considerations are important. Longley, for instance, provides some estimates for Western Europe in the third quarter of 1989, when oil prices were around 18 US dollars per barrel. According to those estimates, at that time, a scrap and rebuild decision only made sense for what he calls a 'laggard' plant provided that investment was in a very large scale LLDPE gas phase plant.[41]

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[40] See Salter (1966), pp. 57-58, 90.

[41] See Longley (1991), pp. 90, 93, 97.

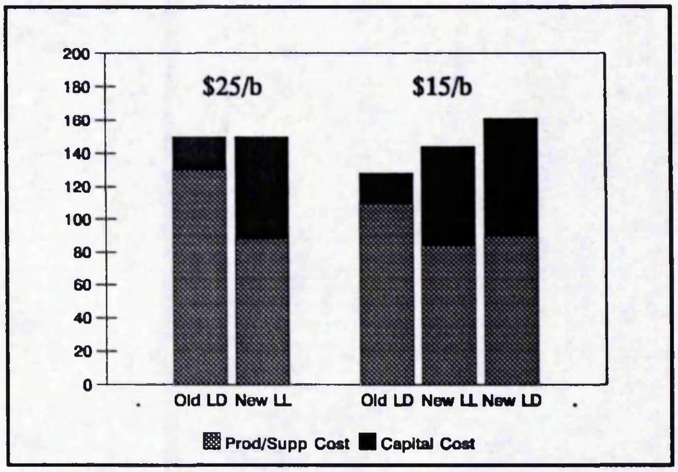

Figure 6.5 Cost comparison between a tubular LDPE plant and a gas phase LLDPE plant
SOURCE: List (1986).

As Longley notes, producers would hesitate about building such a large scale plant due to the problems of sourcing the ethylene and distributing the product of a large line making few grades.[42] On the other hand, there are other reasons, like the flexibility of a swing plant that can switch between the production of LLDPE and HDPE, which could be a good incentive to invest in the new technology.

The purpose of this section has been to give an overview of the numerous factors relative to the technology that were involved in the diffusion of LLDPE. We have also tried to illustrate the different dimensions of the development of LLDPE technology, such as: the emergence of different design configurations, the increase in product variety, the improvements in process and plant efficiency and the enhancement of resin properties. Our focus has been on the factors relative to the two technologies that have affected the adoption and the course of post-innovation improvement, which is so important for the diffusion of a technology. In the following section, we will shift our attention to another group of fundamental aspects of this process: the factors relative to the firms in the industry and to the competition between them.

[42] This is so, because the favourable cost comparison also depends on producing a limited number of grades in large quantities. The more grades are produced by the same plant the grater are the costs of the polyethylene produced.

6.4 The development of LLDPE technology and competition in North America and Western Europe

In this section, we look at the competitive process among polyethylene producers. We will centre our attention on the behaviour of North American and West European firms in relation to entering the production of LLDPE, developing proprietary technology and increasing their stakes in the new technology. For expositional reasons, we have opted to discuss the events in the two regions separately. However, issues related to the differences between the two regions will only receive here a marginal treatment, since that is the topic of section 6.5.

The production of polyethylene is part of a wider technology system of activities that are technological and economically interrelated.[43] LLDPE represents a single node within that wider net of activities. Thus, it is worthwhile presenting a brief overview of the polyethylene industry in order to understand better the context of the diffusion of this technology.

6.4.1 Overview of the polyethylene industry

Polyethylene production is a part of the petrochemical industry that is intimately related to the business of cracking feedstock to produce ethylene. Polyethylene absorbs more than half of the ethylene produced and, since ethylene has no final use in itself and it is difficult to transport, the construction of a polyethylene plant is almost always part of the project of building an ethylene cracker. Furthermore, the vast majority of polyethylene producers operate also ethylene crackers. The link between polyethylene production and ethylene cracking is very important when assessing the competitiveness of a polyethylene plant. Integration provides a producer with an advantage over a non integrated one, and a relatively inefficient plant can see its competitiveness improved if it is integrated with an ethylene cracker of above average efficiency. There are also locational factors associated with transport costs, which can alter the competitiveness of a polyethylene plant.

The production of ethylene involves, in most cases, the production of other coproducts, which are an important part of the business (the

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[43] See Freeman and Perez (1988).

Table 6.16 Share of polyethylene in ethylene consumption, 1988 (%)

Country / Region	LDPE	LLDPE	HDPE	PE
United States	18.3	9.0	23.4	50.7
Western Europe	32.9	3.6	18.8	55.3
Japan	23.7	6.1	21.5	51.3

SOURCE: Longley (1991).

coproducts and quantities produced of them vary depending on the feedstock and cracking process used). These coproducts have a large number of alternative uses in the production not only of plastic materials, but of many other products. As a consequence, firms that produce polyethylene and also operate ethylene crackers are usually diversified in a number of other petrochemical activities. In general, the firms in the polyethylene industry are part of very large corporations. Most of them participate either in the oil business, or in other chemical industries, or in both. The scope of activities and product mix of each corporation is, in general, different to that of others. Thus, the significance of the polyethylene business varies for each. This affects their decisions related to, and shapes the nature of, their respective polyethylene activities.

Shortly after LLDPE was introduced, the petrochemical industry went through a period of recession and a crisis of overcapacity. These were important determinants of the actions taken by the firms. During the period that we are studying, the industry underwent an important restructuring, both in North America and (more markedly) in Western Europe. There were mergers, takeovers, joint ventures and firms abandoning the business.

In what follows, we will look at the competitive moves of some of the major participants in the polyethylene industries of the two regions. Although the broader context in which polyethylene producers operate will be kept in mind, our analysis will concentrate on the activities of the firms in relation to polyethylene only and, in particular, with respect to the LLDPE business. The competitive moves of the companies in relation to LLDPE responded both to the critical conditions that prevailed in the industry and to the competition arising from the new technology. The influence of the different factors behind those moves can be identified in some cases, but it is difficult to say anything about their relative weight.

6.4.2 The development of LLDPE technology and the competencies of the firms

In this section, we will look at the diversity of the firm's imitative and innovative responses to the introduction of Union Carbide's LLDPE technology. The final part of the section is an attempt to assess the nature of the LLDPE innovation in relation to the technological competence of various polyethylene producers.

It has been mentioned that, although it was Union Carbide's technology the one that provoked the LLDPE phenomenon, this company was not the first one to produce this type of resin. DuPont Canada had been producing LLDPE commercially since 1960 using its own catalysts (of Ziegler type) in a highly flexible solution process, which was a modification of DuPont's HDPE low-pressure technology. However, the production was limited to the Canadian market and to special applications and, thus, had no significant impact on the world's polyethylene market.

In 1969, Phillips Petroleum also used its HDPE slurry technology to produce a linear polyethylene resin, which was in the upper limit of the density range in which LDPE is classified. However, the company opted to limit itself to the production of medium and HDPE resin.

Union Carbide's gas phase technology was first used to produce HDPE in 1965. The commercial production of LLDPE using this process began ten years later, after a research programme that culminated with Union Carbide's announcement, in 1977, of a new process to produce LDPE at low pressures. Following that announcement, the company undertook aggressive actions in the market both in terms of investment in LLDPE capacity and in the commercialization of its technology.

Union Carbide was very soon joined by other firms in the LLDPE race. In 1977, Dow started to produce small quantities of LLDPE and, in 1979, announced its own solution process to produce this resin and made public its intention to engage in considerable capacity expansions. Regarding licensing, Dow followed its traditional policy of keeping the technology for itself and, in contrast with Union Carbide, decided not to license it. Although the technological merit of the different processes has been central for their diffusion, these different attitudes towards licensing have also been an important factor shaping the diffusion of the different types of LLDPE technology (see table 6.14 in section 6.3.4).

In Europe, LLDPE processes were first developed three years after Union Carbide's announcement. The first successful European effort was the process developed by CdF Chimie to produce LLDPE using existing high-pressure autoclave reactors. Since the mid 1960s, this company had been experimenting with high pressure polymerization using Ziegler catalysts, and, in 1979, it had already reconverted a 30 thousand tonnes high-pressure plant for the production of HDPE. The LLDPE phenomenon led to a reorientation of the research effort. By 1981, the company had developed its own high-pressure LLDPE process and was producing this resin in a converted plant. In a recessive period, like the one experienced by the industry in the early 1980s, CdF's technology seemed particularly attractive. This technology offered the possibility of entering the LLDPE market by reconverting existing high pressure autoclave reactors, without having to incur in heavy investment. This feature very soon gained some licensees for the company.

The development of technologies to convert existing high pressure capacity to produce LLDPE was carried out by several firms. Union Carbide developed a technology that made it possible to convert old plants to its Unipol gas-phase process. Dow, which usually does not license its technology, developed an autoclave and, later, a tubular conversion that were offered for licensing. Also CdF, whose original process was for autoclave reactors, and the German company Ruhrchemie introduced their respective tubular conversions.

Regarding low pressure LLDPE technology, another gas-phase process, similar to that of Union Carbide, was developed by British Petroleum on the basis of a technology generated, in 1981, by Naphtha Chimie (a French joint venture with Rhone Poulenc). In 1982, a converted HDPE facility using this technology was producing LLDPE. However, it was not but until 1986 that the first new plant using British Petroleum's gas-phase technology started to operate. DSM is another company that made an early conversion, in 1982, of a HDPE plant for the production of LLDPE. The process used was an adaptation of DSM's compact solution technology.

There were other firms which joined the race to develop LLDPE processes, both in the United States and in Western Europe, but later opted to abandon the business. In the US, Rexene (El Paso) developed a conversion LLDPE technology but only produced the resin in small quantities in a ten thousand tonnes converted polypropylene unit. Also in the US, just one year after having announced its own process to produce LLDPE, Arco abandoned polyethylene production. A case that received much publicity was the exit of ICI from the European polyethylene business. In 1980, ICI and the North American firm City Services signed a cross licensing agreement to cooperate in their efforts to develop a LLDPE process. However, in 1982, both companies announced their decision to abandon the production of polyethylene in their respective markets. The event attracted the attention since ICI was the company which discovered the original process to produce LDPE, while its partner was building a grass roots polyethylene plant at the time of its withdrawal.

It is worth stressing that although the advent of LLDPE had an influence in the decisions of some companies to leave the polyethylene business,[44] there were other factors that also contributed, such as the overcapacity problems in the industry and the upward tendency in the price of oil (that strengthened the position of producers which were backward integrated). It was the general assessment of the situation in the polyethylene industry and the perspectives offered by alternative business opportunities that ultimately produced these decisions.

Needless to say, pursuing alternative routes in order to develop a proprietary technology was not the only way to enter the LLDPE business. Some firms opted to license and, to date, they continue producing with licensed technology. That is the case of companies like Exxon, Mobil, and Novacor, in North America, and many other companies in Japan and other parts of the world. However, some of the firms that started using the technology of other companies (either by initial licensing or by takeover of the production facilities of other manufacturers) have managed to develop a process of their own. Neste, in Western Europe, and Quantum, in the US, are two examples of this case. There is no doubt that, as time passes, other licensees will gain experience and be able to develop their own variants of LLDPE technology.

[44] ICI's chairman H. Jones, for instance, commented shortly before the exit of the company from the polyethylene business: "I think we made a misjudgment by not exploring the technology... Now the field is going to be very crowded" (quoted in European Plastic News, April (1982), p. 45).

Innovation and the competencies of the firms

As Tushman and Anderson have pointed out,[45] innovations can be competence enhancing or competence destroying. In numerous cases, they have a destructive effect on some competencies, while others are enhanced or left untouched. Regarding LLDPE, it is clear that, for producers wanting to shift completely from high pressure to low pressure technology, this meant turning obsolete a substantial part of the knowledge and skills associated with the old technology. That is the case, for instance, of the engineering expertise for the design of high pressure reactors and of the accumulated knowledge associated with combining temperature, pressure, initiator and other process conditions to taylor the product. There are, of course, many aspects shared by the two technologies and not all of this knowledge was useless for the new process.

On the other hand, being LLDPE the product of a research agenda rooted on the HDPE technological regime, it had an enhancing effect on some of the competencies associated with this regime. The impact on specific firms, which had HDPE processes, depended on the particular design configuration to which the process belonged. DuPont Canada, for example, was operating a solution process and producing some LLDPE grades. The relevance of these technological capabilities was boosted by the LLDPE phenomenon and the company soon gained various licensees. Other companies operating under similar design configurations, such as Dow and DSM, also found themselves in a favourable position to enter the LLDPE market. In the case of British Petroleum, the fact that its French subsidiary Naphthachimie had been doing research on gas-phase technology to produce HDPE put the company in a good position to develop a viable LLDPE technology.

The situation was different for producers with slurry HDPE processes. These type of processes are not so flexible to be adapted to produce low density resin and firms based on this technology have found it more difficult to enter LLDPE production. Phillips Petroleum, for instance, produced in the late 1960s, some linear polyethylene in the upper bound of the low density range, but opted to concentrate on the medium and high density range. For that reason, few slurry processes are dedicated to

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[45] Tushman and Anderson (1986).

produce LLDPE.

In addition to the differences in the type of plant design, there are many other aspect in which firms differ from each other. One consequence of this diversity is that different firms follow different research strategies. Thus, the impact of an innovation may be quite uneven for firms operating similar technologies. An interesting example is that of CdF Chimie, which operated autoclave LDPE facilities. As we noted above, during the same period that Union Carbide was developing its Unipol process to produce LLDPE, CdF was working on ionic polymerization to produce HDPE in high pressure reactors. When LLDPE was introduced, CdF found itself in a good situation to reorient its research towards the adaptation of high pressure reactor to produce LLDPE. Although this conversion was competitive only on a short time basis, the technology had some success, during the early 1980s, among firms which wanted to produce LLDPE without investing in a new plant.

The situation of other producers committed to high pressure LDPE technology was different. ICI and Basf, for instance, were the main high pressure technologists in autoclave and tubular processes respectively. ICI made an unsuccessful joint effort with the US firm City Services to develop a proprietary LLDPE technology. In the end, with ageing plants and lack of a strong backward integration in the supply of raw materials, the company opted to abandon the polyethylene business. Basf, on the other hand, had a gas phase process for polypropylene and it developed a LLDPE technology on that basis. However, the company was not well positioned in all other aspects. The joint LDPE capacity of Basf and ROW (Basf's joint venture with Shell) was the largest in Europe. Some of the plants had an ageing problem similar to that of ICI. In addition, these plants are based on a tubular technology and it was precisely tubular film grades that competed more directly with LLDPE . These factors, added to the crisis of overcapacity of the early 1980s, made capacity reduction, rather than new investment, the most sensible strategy for the firm. As table 6.17 shows, the greatest LDPE capacity cuts between 1980 and 1982 were in Basf and ROW's joint capacity.

The last two cases illustrate the fact that there are other competencies related to the market position of firms that, in addition to the technological ones, were also important for the behaviour of firms with respect to LLDPE. As we will see in section 6.5, all the firms that have

Table 6.17 LDPE capacity closures in Western Europe by firm during 1981 and 1982

	(000 mt/y)	Share (%)
Basf & ROW	220	27.7
ICI	155	19.5
CdF Chimie	150	18.9
Ato Chimie	75	9.4
Danubia	65	8.2
DSM	60	7.5
Monsanto	50	6.3
BP Chemicals	20	2.5
Total	795	

SOURCE: *European Plastics News*, January (1983)

entered LLDPE production were producers of LDPE; some, but not all of them, produced HDPE. On the other hand, those companies that only produced HDPE have not entered yet to produce LLDPE. Although as we mentioned above this is partly due to technological reasons, it also suggests that market related competencies derived from having a position in the markets where the new resin is bound to compete have played a central role in the decision to enter the industry.

Another idea that has direct bearing on the case that we are studying is Henderson and Clark's concept of architectural innovation. This concept highlights the effects of an innovation in the organization that arise from the systemic nature of the process of production. Architectural innovations are those in which the components of the system are left relatively untouched, but the way in which they are integrated does change. These type of innovations affect the technical knowledge, communication channels and other competencies related to the integrating role of the firm and can be very disrupting.[46] This concept can be applied to the LLDPE case. As we noted earlier, nothing was new in the key components of this technology. However, if we consider a producer which wanted to develop a LLDPE process from a HDPE low pressure process, the shift implied a rearrangement of major component of the system. What the concept of architectural innovation highlights is that the mastering of the new technology involved, not only having the competencies associated with the component of the process, but a readjustment of the knowledge, routines and communication channels at a more general level. This readjustment was needed in order to integrate the different elements in a working system.

Before concluding this section, some important qualifications to our

[46] Henderson and Clark (1990).

argument on the effect of the LLDPE innovation on conventional LDPE producers are in order. If LDPE and HDPE were completely separate industries, our analysis suggests that the disruptive effect of LLDPE on LDPE producers would be bound to be very strong. However, the diversification of firms' activities is an important factor that has weakened this effect.[47] Most LDPE producers in North America and Europe were also HDPE producers. This diversification affects considerably the range of competencies of a LDPE business unit belonging to a larger firm, and was an important factor that significantly modified the impact of the innovation. Such a diversification of activities has also helped to attenuate the competition between the two technologies. To the extent that most LLDPE producers are also major LDPE producers, they are not interested in a fierce competition between their own products. This has contributed to a more gradual displacement of LDPE by LLDPE.

6.4.3 The diffusion of LLDPE among North American and West European firms

The other important aspect of the diversity of firms' behaviour in relation to LLDPE was its role in the diffusion of the innovation. The acquisition of the technology, either through licensing or by the development of a proprietary process, acquires economic importance to the extent that the firms commit themselves to invest in productive capacity. In what follows we will present a picture of the diffusion of LLDPE in the North American and West European industries.

LLDPE in North America

Union Carbide was the firm that gave origin to the LLDPE innovation and provides the best starting point for the analysis of the diffusion of LLDPE in North America. The firm started to produce LDPE during the second world war using a tubular technology, and, by the end of the war, it dominated the US LDPE market. Although LDPE technology started to be widely licensed in the 1950s, Union Carbide managed to stay as US leader and it still held approximately one third of that market in 1965. However, during the late 1960s and throughout the 1970s, as a result of increased competition, its

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[47] See Coombs (1988).

participation declined to reach a 10.7% in 1980.[48] The firm was an important competitor not only in polyethylene, but in other thermoplastics, and had extended its activities to other countries including some in Western Europe. However, its competitive position and the attractiveness of some of its businesses had eroded. During the 1970s, the company made a reassessment of its petrochemical activities and exited from some commodity plastics in the US and Western Europe, such as PVC and polystyrene. At the same time, it concentrated its efforts in major opportunities were the company's position was stronger. Union Carbide was a pioneer in ethylene derivatives and, given this expertise, this was one of the areas that received support. The strong funding of the research programme that led to the development of its Unipol LLDPE technology was one of the outcomes of these strategic moves.

After the LLDPE breakthrough, Union Carbide undertook a series of aggressive movements in the marketplace. The first was to make considerable investments, both in new plants and in plant conversions for the production of LLDPE. Parallel to the announcement of its new technology, Union Carbide announced the build up of a 135 000 tonnes LLDPE plant to start up in 1980 and additional build up and plant expansions, which would bring 300 000 tonnes more of LLDPE capacity in 1982. This new facilities represented a 66% increase over the 660 000 tonnes of LDPE capacity held by the company by the end of 1977.[49] The shift of Union Carbide towards the new LLDPE technology has been radical and 83% of the company's polyethylene capacity operated with its Unipol gas-phase technology in 1991.

A second aspect of Union Carbide's strategy was the active promotion and extensive licensing of the Unipol process. Right from the beginning, Union Carbide sought to commercialize the technology both in North America and abroad. In 1978, the company got the first licensee of this technology and, in a period of ten years, it became the polyethylene technologist with the largest number of licensees.

Various conditions seem to have contributed to Union Carbide's

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[48] Bower (1986).

[49] In fact Union Carbide's capacity in the US expanded between 1977 and 1982 by only 44%, since shut downs reduced conventional LDPE capacity to 365 000 tonnes. However, by 1982, the company had already added to its North American capacity a 115 000 tonnes LLDPE plant in Canada.

licensing policy, in addition to the fact that this was an attractive way to profit from its innovation. A first element is that, given the size of the market and the strength of its competitors, it was clear that it would not be possible to maintain a monopolistic position in the new resin. The rapid reaction of other companies to develop their own proprietary technology shortly after Union Carbides announcement in 1977 indicates that this was the case. In second place, the market success of the new product, in a massive market like the polyethylene one, required a movement of enough scale to create favourable expectations regarding the possibilities of the new resin in the market. Thus, it was better for Union Carbide to share its technology and to have other companies moving in the same direction, helping it to promote the new resin in the market; even more so when the adoption of the new resin by plastic processors required them to undertake equipment modifications and the acquisition of some new equipment. A third factor was the interest of Union Carbide in imposing a standard in the form in which LLDPE was delivered, which would confer an important cost advantage to the firm.

Before the introduction of Union Carbide's technology, the production of polyethylene required, to make it usable by plastic processors, a final stage in which the resin was transformed into pellets. Gas phase technology delivers the product from polymerization in a granular form which can be directly processed. Therefore, the pelletization stage can be eliminated. This aspect of the technology was seen as an important advantage, since the elimination of this final step was responsible of a significant part of the energy saving and associated cost reductions offered by the new technology. Table 6.18 gives us an idea of the magnitude of the savings that could be achieved by producing granules (powder).

Table 6.18 Production costs comparison between granules (powder) and pellets in a LLDPE gas phase plant. (pellets = 100)(a)

	Powder	Pellets
Total capital costs	90	100
Raw materials	99	100
Utilities	50	100
Fixed costs	90	100
Total cash costs	96	100
Total cost including depreciation	95	100

SOURCE: Davies and Richards (1986).
Notes: (a) Calculations assume a 130 000 metric tons plant.

The imposition of the granules standard represented a change in the competitive environment of the polyethylene market that would favour Union Carbide by giving the company, and its licensees, a substantial cost advantage. However, the change from granules to pellets required from processors additional investment in equipment to handle the material in this form. Thus, also here, it was important for Union Carbide to have allies which helped to create the necessary pressure to make processors move toward LLDPE granules. In the end, the "granular only" approach for LLDPE, promoted in North America by Union Carbide, Exxon and Esso Canada, lost ground. Although in 1986 still more than 50% of the North American LLDPE was sold as granules, the tendency has moved towards the utilization of pellets.[50] The main reasons of this have been, first, the resistance of extruders to take the burden of the switching costs and, second, that other suppliers, including some Unipol licensees, offer the resin in pelletized form. In addition, LLDPE is often used with other polyethylene resins, which are delivered in pellets and the utilization of both granules and pellets introduces complications to processing.

There are three firms, in addition to Union Carbide, that contributed to strengthen the LLDPE phenomenon in its early stages: Dow, Exxon and DuPont Canada.[51]

Dow was the second largest supplier in terms of installed capacity and one of the first firms to join the competition in LLDPE. The company reacted immediately after Union Carbide announced its own solution process to produce LLDPE. It also disclosed, in 1979, its commitment to build up considerable LLDPE capacity. The company's investment programme in North

[50] Modern Plastics International, October (1986).

[51] DuPont had been producing LLDPE since 1960.

America was similar in magnitude to that of Union Carbide. Since Dow is a more transnational corporation than the latter, its competitive moves regarding LLDPE in North America were followed by similar actions in other regions including Western Europe.[52] Here, we will limit to comment the events in North America. The role of Dow in the Western European context will be discussed later on. By 1982, Dow had already installed 315 000 tonnes of LLDPE capacity in the United States and was still undertaking plant conversions to LLDPE. Dow's Canadian LLDPE capacity, however, did not came on stream but until 1987, much later than that of Union Carbide.

Regarding technology, Dow followed its usual policy of not granting licenses; instead, it sought to exploit the possibilities of product differentiation offered by its process: Dow's resin is a higher alpha-olefin LLDPE that has some superior characteristics in comparison with the butene based resin initially offered by Union Carbide. This superiority has provided Dow with an advantageous position in some market niches, where users are willing to pay a premium for better performance. Dow has a strong market position in the three types of polyethylene; in the low density segment, as Union Carbide, the company has been moving towards LLDPE and, in 1991, 62% of the company's low density capacity was of linear type.

Exxon is another of the North American suppliers which made an early entry into LLDPE. It was the first licensee of Union Carbide in the United States and played an important role in the diffusion of the new resin. The company's major strength comes from its oil activities. Exxon has been in the commodity plastics business since the 1960s, when it entered as part of its forward integration strategy, but ethylene and its derivatives are seen mainly as part of the oil and gas business. LLDPE represented a good opportunity for Exxon: it is an ethylene derivative that was bound to capture a large market, and the opportunity of licensing state of the art technology to produce it was readily available. The company entered the North American market with facilities in the US and Canada, and it participated in LLDPE joint ventures in Saudi Arabia and Western Europe.

DuPont's strategy is different to that of the firms discussed above in that it tends to place itself in market niches, in order to hold

[52] Dow also had projects of joint ventures in Saudi Arabia and Eastern Europe which had to be abandoned due to financial difficulties.

monopolistic market positions on the basis of its technological superiority. Its role in the LLDPE movement is illustrative of this tendency. In spite of having its own technology, the company has limited itself to produce it at its Canadian subsidiary and does not produce it in the US. Nevertheless, the LLDPE phenomenon gave DuPont the opportunity to license its process. According to a Chem-Facts survey, it had already four licensees in 1987.

In addition to the four companies on which we have commented, other firms have gradually entered LLDPE production. Tables 6.19 and 6.20 describe the pattern of entry into LLDPE production in North America.

Table 6.19 US linear low density polyethylene capacity various years (000 mt/y) (a)

	1981	1983	1985	1987	1988	1989	1991
Union Carbide	275	570	735	735	741	819	1138
Dow Chemical	135	320	320	456	455	428	755
Mobil	-	-	170	204	225	205	546
Exxon	-	135	295	295	282	364	544
Quantum (b)	-	-	-	114	250	250	425
Chevron	-	-	-	-	-	-	200
Soltex	-	-	-	-	-	46	46
Norchem (b)	-	-	115	-	-	-	-

SOURCES: *Modern Plastics International*, January issues; Longley (1991); CIS (1993).
Notes: (a) In 1991 the capacity is low pressure technology used to produce both LLDPE only and LL-HDPE in switch plants. In 1983 we omit 10 000 tonnes that where operated by El Paso who later abandoned LLDPE production.
(b) The capacity belonged to Norchem was sold to Quantum.

Table 6.20 Canadian linear low density polyethylene capacity various years (000 mt/y) (a)

	1980	1983	1985	1987	1988	1989	1991
Novacor (b)	-	-	270	455	485	446	521
Dupont	97	235	235	236	235	237	237
Esso Canada	-	-	135	135	135	175	187
Shell	-	-	-	-	-	-	171
Dow	-	-	-	125	160	160	164
Union Carbide (b)		115	115	-	-	-	-

Source: *Modern Plastics International*, January issues; Longley (1991), CIS (1993).
Notes: (a) In 1991 the capacity is low pressure technology used to produce both LLDPE only or LL-HDPE in switch plants.
(b) In 1987 Union Carbides Canadian capacity was sold to Novacor.

The restructuring of the polyethylene industry in North America

During the 1980s, the United States petrochemical industry underwent an important restructuring, which ran in parallel with the LLDPE phenomenon. There were capacity reductions and a number of exits and takeovers, the outcome of which has been a fall in the number of participants in the polyethylene industry and important changes in the relative position of some competitors. Figure 6.6 provides a graphic picture of this restructuring. Firms have been divided in two groups: the firms at the top are those that produce some LDPE, and those at the bottom produce HDPE only. Within each group the firms have been ordered according to their share in total US polyethylene capacity. An arrow to the left of a firm indicates that it abandoned the industry. An arrow joining two firms denotes a change of name or a new firm which is basically the same to that in the left. Lines joining firms indicate that the polyethylene capacity of the firm to the left passed to the one in the right (a doted line indicates that only part of the capacity was sold). PE and H, at the top, are the total polyethylene capacity and the Herfindhal index respectively. The increase in the Herfindhal index that we observe in the table reflects the increase in concentration that was already suggested by the fall in the number of firms.

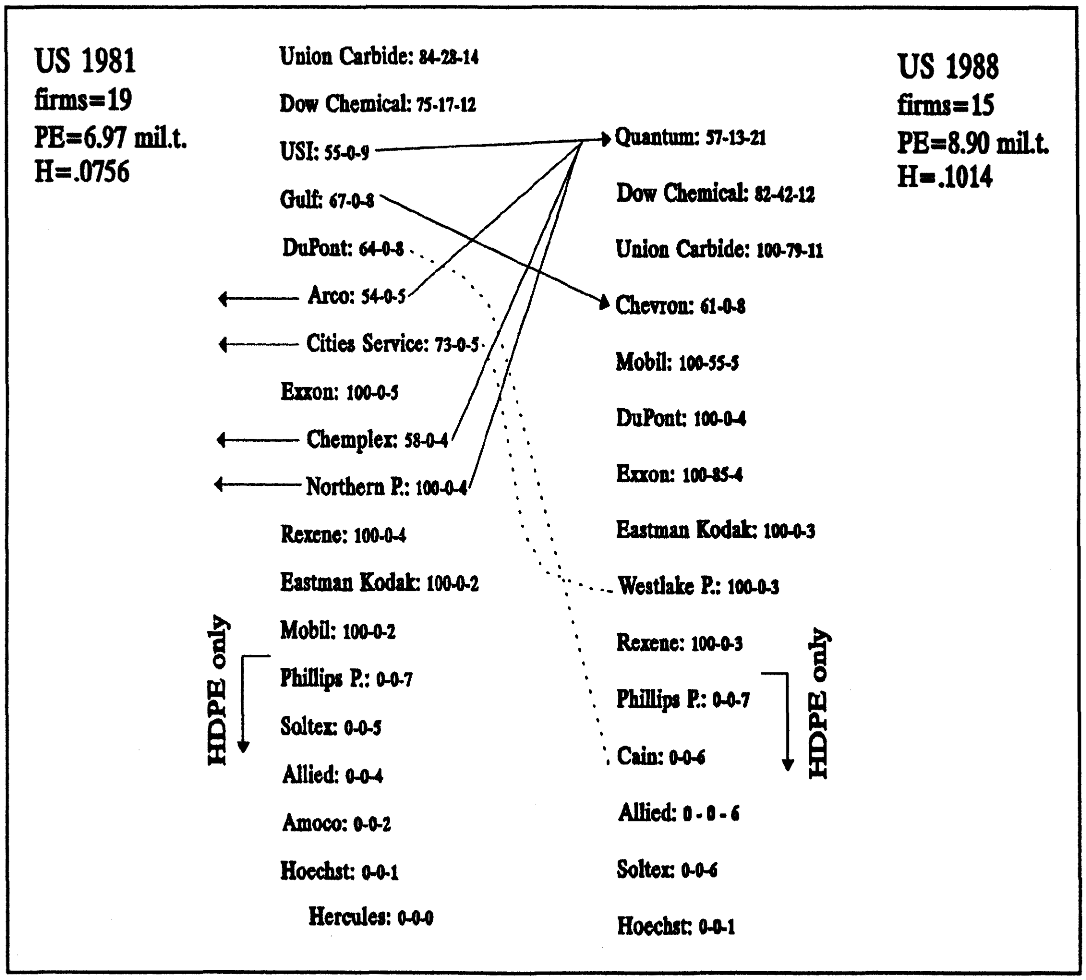

Figure 6.6 The restructuring of the polyethylene industries in the US
SOURCES: elaboration on various sources. Capacity data: 1981, Modern Plastics, January (1982); 1988, Longley (1991).
Note: (a) the numbers to the right of each firm are: the share of the aggregate of LL and LDPE in the firm's total capacity - the share of LLDPE in the firm's total polyethylene capacity - the share of the firm in the total US polyethelene capacity (%).

Among the many changes that have occurred in the industry, stands out the fall of Union Carbide from the first to the third place. After a decade of expansion, Quantum (formerly USI, the petrochemical division of National Distillers) has taken Union Carbide's lead in terms of polyethylene installed capacity. The outstanding growth of Quantum has been the combined result of a series of takeovers and new capacity build up. On the one hand, the LDPE and HDPE capacities of Norchem (which had in turn previously acquired those of Chemplex) and the HDPE capacity of Arco and Amoco have added to USI original facilities. Taken together, all that polyethylene capacity amounted to approximately one million tonnes per year. In addition, the company has entered LLDPE by building two gas-phase plants with a joint capacity of 310 000 tonnes: one using Union Carbide's technology and the other using British Petroleum's. As a result of the way in which Quantum has achieved its actual size, its plants are spread in different locations and the firm operates with several technologies and under various licenses.

The case of Quantum and Union Carbide calls the attention to the fact that market shares respond to many other factors and not only to successful innovative activity, which they only reflect partially. The shares in capacity, which we use here as a proxy for market share, are an even more rough indicator. What one would really like to know is, first, the net income that the firms derive from the ownership of their technology, from both profits and royalty payments; and second, their position to continue obtaining that income in the future. The diffusion of the technology owned by different firms is indicator of these aspects. In that area, Union Carbide is the world leader in both the number of operating and planned plants using its technology, which are thirty three and sixteen respectively. The high number of planned plants is important because it gives us an idea of the considerable diffusion that the technology of the firm is experiencing. It is significant that the two firms that follow Union Carbide in number of planned plants that will use their technologies are also two major LLDPE technologist: BP and DuPont, with seven and four planned licensees respectively.[53]

Going back to the question of the restructuring of the US industry,

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[53] See table 6.38 for list of the major polyethylene technologists and of the number of planned and operating plants using their processes. For the location of operating plants see table B.2 in appendix B.

the counterpart of Quantum's expansion has been the partial or complete withdrawal of some companies from the polyethylene business. As we already mentioned, the capacities of Amoco, Arco and Norchem, which opted to leave the industry, were in the end absorbed by Quantum. Another company that also decided to quit was City Services and part of its capacity has recently been purchased by Westlake polymers, a new entrant. Finally, DuPont also sold its US HDPE business. The first company to take it over was Cain, also a new entrant. However, the latter has recently sold its facilities to Oxychem (the petrochemical subsidiary of Occidental, an oil company). The responses to the appearance of LLDPE by the firms that later decided to exit the industry was varied. Arco and City Services, for instance, worked in the development of LLDPE technology; Chemplex, in contrast, had opted to enhance the properties of its conventional LDPE resins. A final point that is worth noting is that producers of HDPE only have not shown a tendency to enter LLDPE production. This, as we noted in section 6.4.2, seems to be largely due to the slurry design configurations championed by most HDPE producers.

LLDPE in Western Europe

In Western Europe, the crisis and the overcapacity problems were more acute than in North America. A consequence of these was that the restructuring of the petrochemical industry dominated the West European scene. As in the US, Union Carbide was the first to introduce LLDPE in Western Europe. It adapted some HDPE capacity of Unifos Kemi, its Swedish joint venture with Pekema Oy. The first company to follow its lead was the French state-owned company CdF Chimie, with a converted high pressure plant that started to produce LLDPE in 1981. Given the difficult circumstances through which the West European industry was going, the strategy followed by most of the producers was to try to convert some of their capacity to produce LLDPE and, in this way, secure a position and gain experience in LLDPE without having to undergo heavy investments. Table 6.21 shows a comparison of production costs between the gas-phase and the high pressure plant options to produce LLDPE.

Clearly, the main advantage of a high-pressure retrofitted plant was the low cost of making the conversion, compared with the investment required for a new facility. But, if we compare both processes on a new

Table 6.21 Production costs comparison between gas-phase and high pressure LLDPE processes (gas-phase=100)(a)

	Gas phase (pellets)	High pressure new	High pressure retrofit
Total capital cost	100	142	30
Raw materials	100	98	98
Utilities	100	200	200
Fixed costs	100	143	130
Total cash costs	100	105	105
Total cost including depreciation	100	110	98

SOURCE: Davies and Richards (1986).
Note: (a) Calculations assume a 130 000 mt/y plant.

plant basis, the gas phase technology offered a lower cost alternative. For this reason, the production of LLDPE in high pressure plants was bounded to be only a temporary phenomenon which, with the passage of time, has lost importance in terms of its weight in overall LLDPE capacity (see table 6.14 in section 6.3.4)

British Petroleum was another West European firm that made a relatively early entrance and also started to produce LLDPE with its own, gas phase, technology. Its initial capacity was 10 000 tonnes in a plant at Lavera, France, that started in 1982. DSM also developed its own LLDPE process. It converted some HDPE facilities and, in 1982, it had a 30 000 tonnes plant at South Limburg in the Netherlands. In 1983, Enichem also retrofitted some capacity and started a 20 000 tonnes facility at Cagliary in Italy, using El Paso/Enichem technology. Atochem, the other large French polyethylene producer, also used proprietary technology to convert a high pressure reactor to the production of LLDPE and, in 1984, started a 30 000 tonnes plant at Balan, France. Finally, in Spain, Alcudia, Repsol's subsidiary, started a 15 000 tonnes LLDPE plant using its own proprietary technology in 1985.

In contrast with the strategy of the firms above, Neste opted for Union Carbide's technology. The company first adopted these technology as a consequence of its purchase of Unifos Kemi (Union Carbide's joint venture in Sweden). Later, it continued building up capacity using that technology. However, it has recently developed its own process, which is used in two new plants in Finland and Belgium.

Other private firms operating in Europe, such as Exxon, the German firm Basf and Shell, did not start to produce LLDPE but until the late 1980s, once the economy had recovered and most of the restructuring of the industry had occurred. Basf had developed its own technology and it started to produce some LLDPE. Recently, Basf involvement in LLDPE expanded through its subsidiary ROW in join venture with Shell. Another recent entry is that of Exxon and Shell in a joint venture that will use Union Carbide's Unipol technology.

Table 6.22 summarizes the pattern of investment in LLDPE capacity by West European Producers. Although the timing of entry of the various polyethylene producers has been different, a significant LLDPE capacity has gradually been built in Western Europe. Dow, British Petroleum and Neste are the firms with the largest LLDPE capacity within Western Europe, and the three firms have developed their own LLDPE technologies. They also characterize for being the most transnational polyethylene producers in Western Europe, that is, the ones with production facilities in more West European countries: British Petroleum and Neste have, both, polyethylene plants in four countries, and Dow in three. A final characteristic that the three firms have in common is that, after the restructuring of the 1980s, they have managed to grow and increase their relative importance in the West European polyethylene industry. Dow has grown mainly through new investment, while British Petroleum and Neste through a combination of acquisitions and new investment (see figure 6.7).

In table 6.22, we also find a confirmation of the observation made earlier in the sense that most of the West European producers that entered LLDPE production operated low capacity plants for several years. It was until the end of the decade that the firms started to engage in large investments in LLDPE.

Table 6.22 Western Europe linear low density polyethylene capacity various years (000 mt/y) (a)

	1981	1983	1985	1987	1988	1992
Dow	-	75	130	140	300	370
Neste(b)	-	-	-	300	300	540
British Petroleum	-	12	60	140	140	345
British Petroleum	-	20	20	160	160	240
Shell/Exxon	-	-	-	-	-	220
Basf/BP	-	-	-	-	-	120
D. S. M.	-	30	60	110	110	110
Copenor (CdF)(b)	30	55	100	100	100	-
Atochem	-	-	30	30	30	70
ROW (Basf/Shell)	-	-	-	-	30	30
Alcudia	-	-	15	20	15	30
Unifos Kemi(c)	25	75	150	-	-	15

SOURCE: *European Plastic News*, *Modern Plastics International*, various issues; SRI (1990); CIS (1993).

Notes: (a) High pressure and low pressure capacity used to produce LLDPE and low pressure capacity which can produce both LLDPE only and LL-HDPE in switch plants.

(b) The capacity of CdF was sold in 1989 to Copolynor, owned by Enichem.

(c) The capacity of Unifos Kemi was sold to Neste in 1985.

Apparently, the concern of not being left behind was an important motivation for the early entry into LLDPE. The early West European effort was mainly to develop their own LLDPE technology. The majority of the LLDPE plants running in Western Europe were pilot plants, most of them of firms with state participation. More recently, some companies (like the three mentioned above) are increasingly putting their stakes on LLDPE. However, the interests that arise from having huge conventional LDPE capacity still have a considerable weight in Western Europe. While in the United States some companies took the decision to switch to LLDPE by shutting LDPE capacity and replacing it with LLDPE, this did not happen in Western Europe. There were important capacity cut backs and plant closures in Western Europe; but they were mainly result of the bad situation through which the industry was going and were required to eliminate overcapacity. The difference in the commitment to LLDPE in the two regions is illustrated by the fact that, for example, in 1988, the capacity of this resin exceeded that of LDPE in six out of nine LLDPE producers in North America. In Western Europe, in contrast, all producers held a larger proportion of LDPE capacity than that of LLDPE in that same year.

The restructuring in Western Europe

The West European polyethylene industry, and petrochemicals in general, experienced a significant restructuring during the 1980s. Figure 6.7 gives a picture of the changes that took place in the West European polyethylene industry between 1980 and 1988. As in the case of the US industry there has been an increase in the concentration of the industry and significant changes in the position of the firms. The symbols used are the same as in figure 6.7. In this case, however, most of the joining of firms by continuous lines responds to mergers. In the case in which the change of name is minor, the association between the firms in the left and in the right is evident and we have omitted the arrows. This has been done to avoid having too many lines in the figure.

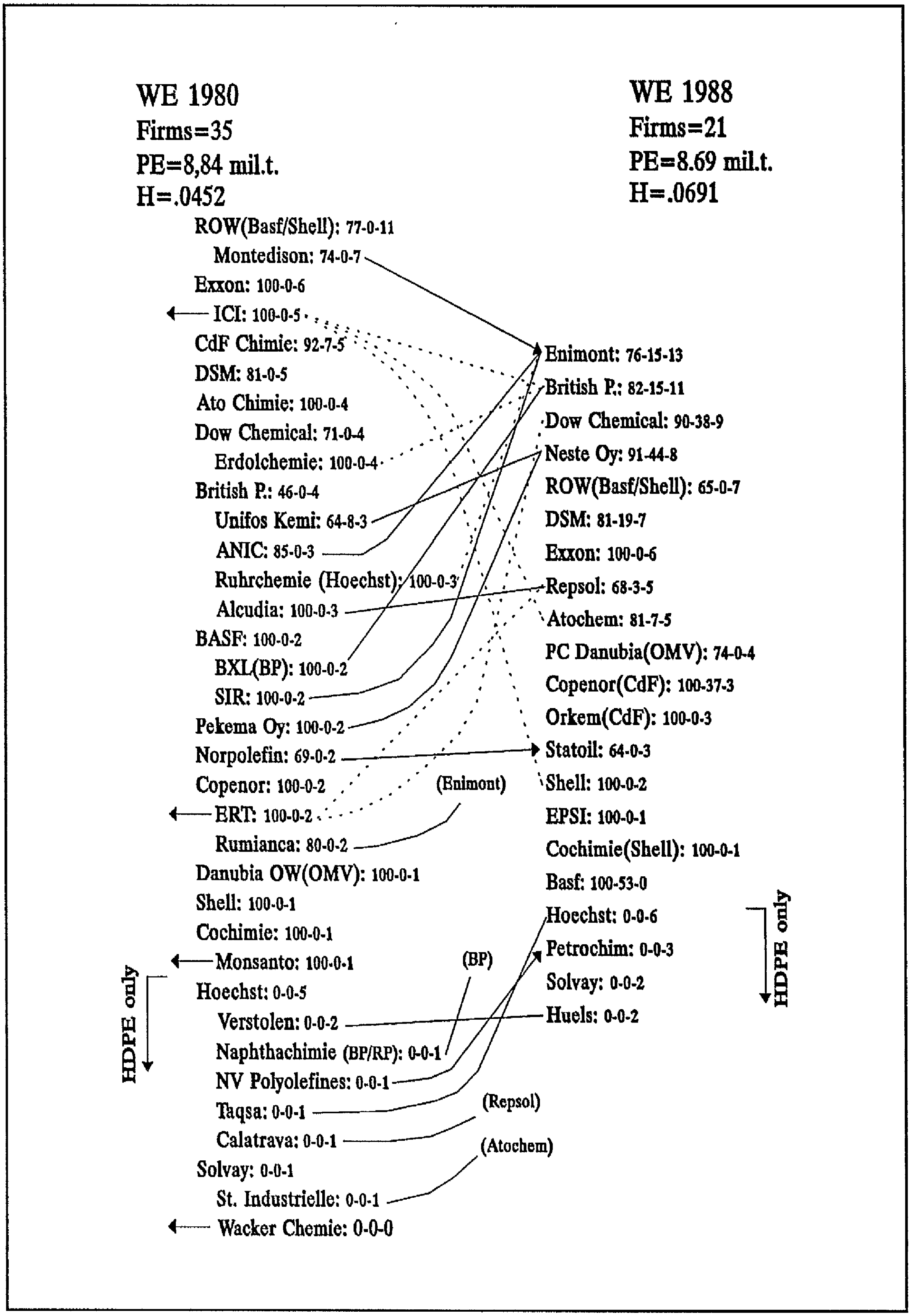

Figure 6.7 The restructuring of the polyethylene industries in Western Europe
Sources: elaboration of various sources. Capacity data: 1980, European Plactic News, August (1980); 1988, Longley (1991).
Note: (a) the numbers to the right of each firm are: the share of the aggregate of LL and LDPE in firm's total polyethylene capacity - the share of LLDPE in the firm's total polyethylene capacity - the share of the firm in the total West European polyethelene capacity (%)

One of the most widely publicized events was the exit of ICI from the polyethylene business, in a capacity swap with British Petroleum. However, the most considerable changes in terms of mergers took place in the French and in the Italian industries. Their present situation has been, to a great extent, the result of considerable state intervention.[54]

In Italy, the state owned Enichem, which holds the largest polyethylene capacity in Western Europe. This has been achieved, firstly, through a series of takeovers by which the state integrated the capacity of various smaller Italian producers into one single company. ANIC, Rumianca and SIR are some of the major companies that were merged to create Eni (later Enichem). The other factor that has contributed to make this company the largest West European producer was a series of negotiations between the government and Montedison, the largest privately owned chemical company in Italy. These negotiations led to an exchange of production capacity that left Enichem as the only Italian producer of polyethylene.[55] The company has expanded to Germany and France through the acquisition of polyethylene facilities in these countries.

In France, the State has also played a major role in the restructuring of the petrochemical industry. In 1983, the French owned petrochemical industry passed to state ownership and was consolidated in three major companies: Rhone-Poulenc, Atochem (the petrochemicals division of Elf), and CdF Chimie. Atochem and CdF became the only French owned polyethylene producers until the late 1980s, in which the latter abandoned. Atochem enjoys the advantage of being backward integrated, which has given it a better raw materials position to compete in the polyethylene business. In LLDPE in particular, Atochem has moved forward by developing its own gas phase process. CdF, on the other hand, despite its early start in LLDPE, has abandoned the polyethylene business and sold its 100 000 tonnes LLDPE plant to EniChem. The lack of backward integration was, apparently, the main weakness of the company to compete in this market.

The dominant characteristic of the restructuring of the polyethylene industry in Germany was the reduction of productive capacity. The German petrochemical industry is dominated by three large companies: Basf, Hoechst

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[54] See Martinelli (1991) and Bower (1986).

[55] The firm that appears in figure 6.7 is Enimont, which resulted from the short-lived merger of Eni and Montedison.

and Bayer. The first two are the ones more involved in polyethylene production. At the beginning of the 1980s, ROW, a Basf/Shell joint venture, was the largest producer of polyethylene and, in particular, of LDPE in Europe. The same was true about Hoechst with respect to HDPE, which also had shares in Walker Chemie and Ruhrchemie. Regarding Bayer, its subsidiary Erdolchemie, was also an important LDPE producer.

As a response to the overcapacity problem of the early 1980s, ROW cut back its capacity by one third. Hoechst has concentrated on the production of HDPE, and the LDPE facilities at Ruhrchemie have partly closed and what remains of that capacity is operated by Enichem. Finally, Bayer has left the commercialization of the LDPE production of its subsidiary Erdolchemie to British Petroleum. As a consequence, there has been a contraction in the relative participation of German firms in the LDPE market, although Hoechst still keeps its European leadership in HDPE.

A comparison between the US and Western Europe reveals two differences. First, we observe a more severe restructuring in the latter in terms of mergers, takeovers and capacity closures. Second, there has been a greater penetration of LLDPE in the US than in Western Europe, at the level of both the regions as a whole and the individual firms. It is interesting to note that such a difference in intra-firm diffusion applies also in the case of Dow, which operates in the two regions. In the next section we will try to identify the different factors that have contributed to these differences and the factors that have influenced the spatial dimension of the diffusion of a technology.

Before passing to analyse the factors that have contributed to a different pattern of diffusion in the US and Western Europe, it is worth commenting on the response of HDPE producers in relation to LLDPE. Both in the US and Western Europe, we observe that all LLDPE entrants were LDPE producers while HDPE only producers have not shown a tendency to move towards LLDPE.[56] The entry by LDPE producers is apparently due to the market overlap between these two materials. The threat to the market position of the firm has been a major incentive to license or develop a LLDPE process. The absence of entry by HDPE producers, on the other hand,

[56] This shall not be taken to mean that HDPE producers remained passive. Most HDPE producers repone to the introduction of LLDPE was to compete producing high molecular weight (HMW)-HDPE: a variety of HDPE that has film applications.

can be explained, in part, by the fact that most HDPE producers operate with slurry low pressure design configurations, which are not well suited for LLDPE production.

6.5 The diffusion of LLDPE in North America and Western Europe

This section focuses on the different factors that have contributed to a different penetration of LLDPE in North America and Western Europe. Although this question is of interest in itself, our main purpose is to illustrate the fact that contingencies and environmental factors that affect the competitive process are important determinants of the diffusion of innovation in its spatial dimension.

As table 6.23 shows, the penetration of LLDPE in consumption and installed capacity has been greater in the US than in Western Europe.[57]

Table 6.23 Penetration of LLDPE in the US and Western Europe: LLDPE share in polyethylene consumption and share of LL-HDPE in polyethylene capacity, 1992 (%)

	Western Europe	United States
Film and Sheet	18.3	37.2
Overall PE market	12.2	24.1
LL-HDPE capacity 1992	16.5	37.0

SOURCE: own elaboratio. Consumption data: *Modern Plastics International*, January (1993); Capacity data, CIS (1993).

There are three major circumstances that have combined to give rise to differences in the diffusion of LLDPE in North America and Western Europe: first, the country origin of the innovation and the lag in its introduction to Western Europe; second, the fluctuations of the price of oil and their timing with respect to the introduction of LLDPE in the two regions, and third, structural differences between the industries of the two regions, which are associated with differences in their histories and their environments. In the following section, we will look at questions related to the timing in the introduction of LLDPE and to the fluctuations in the price of oil, which affected the behaviour of the polyethylene producers in the two regions. The second section will focus the attention on various aspects of their respective environments.

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[57] As we pointed out in section 6.2.3, some of the new LLDPE plants are "swing" plants that can switch between LLDPE and HDPE production. Capacity data is usually reported as the aggregate of both types of plants. Throughout the text, abbreviation LL-HDPE is used to denote the aggregate of LLDPE only and "swing" capacity. In some cases the abbreviation is also used to denote "swing" plants in which case it will be clarified.

6.5.1 Imitation gaps and path dependencies

Ethylene is not only the basic raw material of the polyethylene industry, but also the largest component of the production costs. At the beginning of the 1970s, before the oil shock of 1973, polyethylene production was dominated by fixed costs: they accounted for around 70% of the manufacturing costs, the rest being variable costs. A decade later, the rise in the price of oil changed the situation radically. In 1982, feedstock and energy costs accounted for 75 to 80% of the total cost of production.[58]

The oil shock of 1979 occurred shortly after the introduction of LLDPE, and the technological opportunity offered by the innovation was reinforced by the oil price situation. 1979-1982 was a period of oil price increases that favoured the diffusion of the new technology in two ways. Firstly, the savings in production costs and in resin use associated with LLDPE acquired more relevance. They helped to offset the effects on demand from higher resin prices that would have resulted from the upward tendency in the price of raw materials. Secondly, the high oil prices made the gas-phase technology compare more favourably with conventional LDPE processes. By the end of 1982, Saudi Arabian crude was being sold at 34 US dollars/barrel. As we noted in section 6.3.4, a gas-phase plant becomes a much more attractive option at such levels.

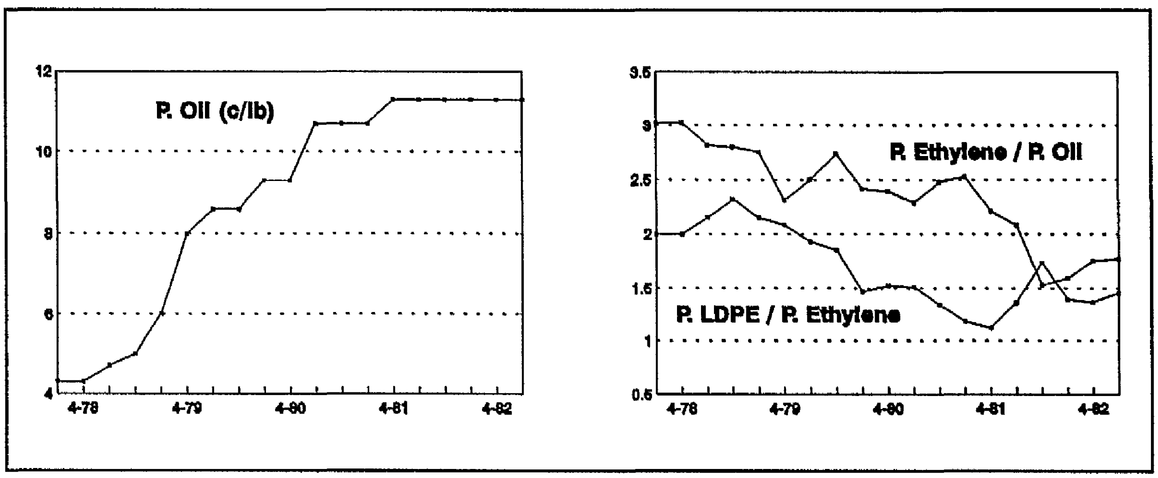

Figure 6.8 Evolution of the price of oil and of the price ratios of ethylene to oil prices and of LLDPE to ethylene (%), quarters 3rd. 1978 to 1st. 1983
SOURCE: Modern Plastics International December (1981), april (1983).

The early 1980s were also a period of major capacity expansion in

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[58] SRI (1982).

North America. In 1979, Union Carbide, Exxon and Dow announced that they would bring extensive LLDPE capacity on stream in the US. This capacity build up in the US was followed by similar investment in LLDPE and LL-HDPE "swing" capacity in Canada. The plant capacity built in Canada represented a level of polyethylene production that would exceed, by far, Canadian consumption, and most of the production was clearly aimed at the US market. Investment in Canada by US firms was particularly attractive at that time and was mainly driven by the availability of cheap ethane in the region.

The Canadian case illustrates the important role played by the high oil prices. Ethylene can be obtained from different feedstock. The most important ones are: naphtha, liquified natural gas, liquified petroleum gas, gas oil, ethane and propane. In a situation like the one just described, in which the price of oil was high, having access to a source of cheap non-oil based feedstock like ethane offered a major cost advantage over competitors producing polyethylene with an oil derivative like naphtha. The availability of ethane with low alternative value in the West coast of Canada offered a good opportunity for building ethane crackers and LLDPE plants using the new technology.

West European producers, in contrast, started to engage in LLDPE production in 1981. This delay was due partly to the fact that imitators took time to develop their own processes. In addition, a more severe crisis of overcapacity in the petrochemical industry of this region contributed to greater resistance to invest. Between 1981 and 1983, some firms converted small capacity LLDPE plants, but these were not followed by expansions of further investment of a similar magnitude to the one that took place in North America. The firms that operated these plants were interested in acquiring the technological knowledge associated with LLDPE, but were less willing to commit to larger investment in a period in which polyethylene capacity was being closed rather than expanded. It is also for this reason that, in Western Europe, conversions of existing plants to LLDPE, which have a lower cost than building a new plant, were more widespread than in the US.

In 1983, the restructuring of the industry and the fall in oil prices brought a period of recovery in the West European industry. Market growth also made investment more attractive and some investment in new capacity, LL included was made. However, the lower price of oil also means a weakening of the advantages of gas phase LLDPE technology. In this new situation, there was less pressure on the industry two switch to this technology. Thus, during the first years of the diffusion of LLDPE in the US, high oil prices favoured the adoption of LLDPE technology. In Western Europe, the early period of the diffusion of LLDPE coincided with the subsequent fall in oil prices, which reduced the attractiveness of this technology.

The different behaviour of polyethylene producers in the two regions also had implications for the development of the LLDPE market. In North America, the aggressive movement by various resin suppliers towards LLDPE, created to a certain extent a bandwagon effect in plastic processors. With the perspective of an abundant supply of LLDPE, they were prepared to undertake the investment and pay the learning costs of adopting the new resin. The environment became, thus, more favourable for further diffusion of LLDPE. In Western Europe, in contrast, where a flood of LLDPE did not seem as imminent, there was not so much concern on the part of plastic processors about being left behind. Furthermore, the switch to the new material was not costless and uncertainties about material availability implied a major risk, so there was not an strong incentive to make the necessary conversions to use the new resin.

The difference for plastic processors in the US and Western Europe during the first years of the introduction of LLDPE was not only a question of expectations. In the US, low introductory prices were set in order to attract customers. Union Carbide, for instance, reduced the price of LLDPE one cent below that of LDPE to persuade processors to switch to granules,[59] and, in general, price competition in the polyethylene market was particularly strong after the introduction of LLDPE.[60] In Western Europe, in contrast, LLDPE was sold at a premium because of its limited availability. It was not until 1984 that LLDPE prices came in line with those of LDPE.[61]

The different conditions that prevailed in the two regions in the early period of diffusion, not only gave origin to quantitative differences

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[59] See Gray (1984), p. 97.

[60] In 1981 a trade journal commenting on the situation of the US polyethylene market reported the following: "US suppliers of low density resins have been engaged in a price war so fierce that per pound rates have hovered only three or four cents above the cost of ethylene feedstock." Modern Plastics, December (1981), p. 27.

[61] European Plastics News, April (1984).

in the development of the LLDPE market, but also contributed to create different patterns of resin usage by plastic processors. The practice of blending LLDPE with LDPE allowed to downgauge film in approximately 20% and to take advantage of the superior properties of the new resin. This practice, although used in both sides of the Atlantic, became much more widespread in Western Europe, and has got hold in the region.[62] The effect of this on the diffusion of LLDPE is summarized in the following statement made at a LLDPE congress in 1986: "The success of the European fabricators in exploiting LDPE/LLDPE blends to produce films of excellent technical performance in a wide range of applications will make the blending phenomenon more enduring than we would have predicted four years ago, and this must be one of the factors retarding the penetration of LLDPE into the European market."[63]

There is much that was unpredictable in the events that we have been describing. The point that ought to be stressed is that these events contributed to create patterns of behaviour, with respect to LLDPE, that have had long lasting effects on the diffusion of this technology.

6.5.2 Differences in regional environments and industrial structure

The various elements mentioned above, however, did not operate in isolation. The different characteristics of the environments and the specificities of the polyethylene industries of the two regions were also important. In these, we find additional elements that have contributed to shape the competitive behaviour of firms that led to the patterns of diffusion of LLDPE that we observe. In what follows, we will discuss very succinctly a series of additional elements characteristic of the industries and the market environment of the two regions. These were an important part of the context in which the decisions of firms regarding LLDPE were made.

A first important element that impinged on the different behaviour of the North American and West European firms was, as we noted earlier, the greater severity of the crisis of the West European petrochemical industry,

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[62] It should be mentioned, though, that blending has traditionally been a more extended practice in the West European plastics processing industry than in the North American one.

[63] Davies and Richards (1986), p 38.

relative to that of their North American counterpart. Differences in the structure of these industries and in their feedstock position had and important bearing on this.

In contrast with North America, Western Europe is a region divided in many different countries and, despite the high volume of trade between them, this is something that still causes segmentation of the markets from the demand point of view. In the supply side, the effect of having several countries creates even sharper differences between the West European industry and its North American counterpart. In North America, the petrochemical industry consists of private firms, while in Western Europe there is, in many cases, a close association between governments and firms. Companies owned by the state or with state participation play an important role in the West European petrochemical industry. These companies are some of the major West European polyethylene producers. This characteristic of the industry affects the performance and strategic decisions of the companies, and one finds different patterns of company behaviour depending on whether the firms are private or state owned.

In the mid 70s, large investments had been made both by firms already in the industry and by new entrants. Too optimistic expectations for the early 1980s generated excessive investment. As a result, the petrochemical industry found itself with considerable excess capacity at the end of the 1970s. In order to keep acceptable rates of operation and sell their product, many firms were offering their products at very low prices and almost all participants in the industry experienced heavy losses during the early 1980s. An essential requirement for a way out of the crisis of the industry was the exit of firms and capacity closures, but this was something difficult to achieve. There were huge barriers to exit, many firms with resources to stay in the industry, and no mechanisms existed to agree and coordinate shutting down capacity.[64]

The situation in the West European petrochemical industry was worse than that of its North American counterpart. In Western Europe there were more producers; resistance to exit and to close capacity was stronger. The fact that different countries were involved, and that several state owned companies participated in the industry, introduced many political elements

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[64] The structural problems faced by the petrochemical industry and the way in which it restructured are documented in Bower (1986) and Martinelli (ed.) (1991).

into the process of finding a way out from the crisis. In addition, the overcapacity problem was more acute in Western Europe. This can be seen in table 6.24, by comparing the capacity that existed before the recession and several years after. In 1988, total polyethylene capacity in Western Europe had not recovered yet the level of 1980. In the United States, in contrast, the main closures took place in 1982, leading to a drop of capacity the following year; but the trend has been one of capacity growth.[65]

Table 6.24 Polyethylene capacities, shares of different processes (%)

	1978	1980	1982	1983	1984	1985	1988
United States							
TOTAL (000 mt/y)	5,760	na	7,297	6,845	7,465	7,770	8,285
HDPE	38		38	40	40	39	38
LDPEa	62		52	44	41	40	39
LL&HDPE	na		11	15	19	21	23
Canada							
TOTAL (000 mt/y)	na	699	na	765	900	1,103	1,368
HDPE		37		5	4	4	4
LDPE		47		49	42	27	26
LL&HDPE		16		46	54	68	71
Western Europe							
TOTAL (000 mt/y)	na	8,837	7,895	7,240	7,350	8,305	8,693
HDPE		25	32	30	30	30	27
LDPE		75	67	66	66	62	59
LL&HDPE		0	1	4	4	8	14

SOURCES: *Modern Plastics International*, various issues; *European Plastic News*, various issues, and Longley (1991).
Notes: a) The data for 1978 includes LLDPE.

Another important factor that contributed to the worse situation of the West European petrochemical industry was the different feedstock position of the two regions. In Western Europe, the industry relies mainly on naphtha, which is obtained from the refining of oil, most of which is imported. In North America, due to natural resources availability, gas feedstocks are the main raw material and the feedstocks for petrochemicals come mainly from domestic supplies. Before the first oil shock, US regulation of energy prices had created a situation in which the prices of hydrocarbons were above those in other parts of the world and, in particular, those in Western Europe. The changes in the price of oil changed this situation dramatically. After 1973, the price of hydrocarbons in the US was significantly below that in Western Europe, and, although deregulation in the US created a tendency of US prices to converge with international ones after 1979, they remained being lower throughout the

[65] The closures have been mainly in LDPE capacity which has been replaced with new LLDPE capacity.

1980s.[66] Thus, the impact on raw material costs of the 1979 oil shock was more severe in Western Europe than in the US.

In summary, a stronger impact of oil prices, an industry structure with more firms and the presence of more political elements affecting investment and divestment decisions were important factors behind the greater severity of the crisis of the early 1980s in Western Europe relative to the US. This crisis was an important factor affecting the investment on LLDPE and its diffusion.

There are, in addition, other differences between the two regions that, added to the factors mentioned above, are likely to have contributed to the differences in the diffusion of LLDPE technology in the two regions. On the resin production side, for instance, there is some evidence of a higher price of butene-1 comonomer relative to that of ethylene in Western Europe, while the opposite relation is found in the US.[67] This makes the conditions in the US more favourable for the production of LLDPE, since it requires less ethylene than LDPE for its production, but uses a comonomer such as butene-1 (which is not used in the production of LDPE).

Regarding plastics processors, it has been suggested that differences in the type of equipment used in the two regions have also affected the diffusion of LLDPE. The extruders used by most of the North American plastic processors could be more easily adapted for processing the new resin than that used by their West European counterparts.[68]

A basic aspect of retrofitting an extruder to process LLDPE consists of changing the extruder screw by a design able to deal with LLDPE's faster melting and higher viscosity. However, because of the kind of equipment used by the majority of the European film manufacturers, the extrusion screw technology picture in this region was more complex than in North America. In 1982, around 80% of the film extruders in Europe employed grooved feed bushings. For these extruders screw, the design is a function of the design of the grooved feed bushings, which often varies substantially. In addition, the behaviour of these type of extruders

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[66] See Chapman (1991), pp. 186,194.

[67] According to SRI (1990) plant cost estimates, in the US the ratio of the prices of butene-1 and ethylene was 0.897 in 1988. Plant cost estimates for Western Europe by Longley (1991), on the other hand report that in this region that price ratio was of 1.306 in 1989.

[68] What follows draws on Kurzbuch (1982).

changes depending on whether the feed is in granular or pelletized form. In North America, in contrast, extrusion equipment is more standard and the majority of the manufacturers use smooth bore extruders, which do not display sensitivity to the particle size of the feed. As a consequence, in North America, there were in the market several screw designs that were operating successfully in the extrusion of LLDPE and LLDPE/LDPE blends since early 1981. In Western Europe, in contrast, the varied mix of extruder technology made screw design requirements more complex and demanded a greater involvement of extruder manufacturers in screw design.

The case of the extruder screw provides an example of technological interrelatedness that, given the diversity of technologies, can create differences in the adoption and diffusion of a technology. Therefore, regional differences in equipment may have also played a role in easing or making more difficult for the film processors to enter LLDPE production. It is important to stress, however, that there were many other changes in the extrusion line that were needed to make it adequate for LL processing. A more detailed analysis of the various areas of design modification and the costs involved would be needed to make a more precise assessment of the relative importance of differences in equipment as a determinant of the diffusion patterns of the two regions.

Finally, it has also been suggested that various differences in the characteristics of the North American and West European market may have favoured the higher relative consumption of LLDPE in the former region. In Western Europe, there is a larger proportion of the film market that corresponds to applications in which conventional LDPE has an advantage. One important difference is that, in Western Europe, heavy gauge films such as sacks, pallet shrink and green house films, represent a much larger share of the LDPE market than in the US. Another important difference is found in the refuse bag market. In the US, bags are mainly sold in supermarkets and the market is controlled by major LLDPE producers, some of which, like Mobil, are integrated forward and produce the film themselves. In Western Europe, in contrast, refuse bags are sold to local authorities at very low prices and producers tend to dispose of substandard polymers precisely in this application.[69]

Therefore, there were also a series of differences in the structure

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[69] For a detailed discussion of this issue see Gray (1984).

and in the practices in the polyethylene industries and markets of the US and Western Europe that contributed to the greater penetration of LLDPE in the former. These differences have added to other factors, such as the country origin of the innovation and the situation created by the changes in the price of oil, to generate different patterns of diffusion in the two regions.

6.6 The international diffusion of polyethylene and the patterns of trade

An important aspect of the process of diffusion, intimately related to its spatial dimension, is the emergence of trade flows. The purpose of this section is to look at the relationship between the patterns of trade and the diffusion of technology.

Statistics on LLDPE trade have started to appear very recently, and only for a few countries. However, according to the following estimates of trade in polyethylene, important trade flows in this resin have emerged only ten years after the introduction of LLDPE. This flows are of an order of magnitude similar to those of the two other polyethylene resins.

Table 6.25 Trade in polyethylene, 1988 (000 mt)

Country / Region	LLDPE	LDPE	HDPE
United States	-384	346	250
Canada	480	110	0
Latin America	-5	-105	-203
Western Europe	-150	250	50
Middle East	460	84	260
Africa	-7	-185	-30
Japan	-15	35	124
Other Far East	-400	-659	-450
Net exports	825	686	940

SOURCE: Longley (1991).

The recent trade flows in polyethylene can only be understood in the context of the history of the development of the polyethylene industries in different parts of the world. In this section, we will adopt a wider perspective and look at the early years of the diffusion of polyethylene technologies and at the trade in these resins that emerged in parallel. The patterns of trade in LLDPE that have emerged in the last ten years will be discussed in the final part of this section.

The scope of our discussion leads us most of the time to focus the attention on aggregate data and on the artifact dimension of the technology. It is important to stress that the diversity and the multiple dimensions of technology, which were highlighted in previous sections, are important elements operating in the background of the general trends that will be discussed here. The international diffusion of polyethylene has been the outcome of a competitive process driven by the diversity of firms behaviour and by the changing conditions of the national environments in which the firms operate.

6.6.1 Technological leadership and the early years of the diffusion of polyethylene technologies

The early years of the development of the polyethylene technologies were characterized by the domination of the industry by firms from a reduced number of countries. These countries have concentrated the major share of the productive capacity. It is also a reduced group of large firms based in those countries which, since then, have been the dominant force in the development of the technologies.

LDPE was first produced commercially in Britain in 1939. During the second world war, it was also produced by DuPont and Union Carbide in the US, which operated under ICI's license but developed their own high pressure processes. The other early producer was Basf in Germany which, in the course of the war, was able to develop its own high pressure tubular process and started to produce LDPE at Ludwigshafen in 1944. After the war and until the early 1950s, ICI and the two North American companies enjoyed a virtual monopoly of polyethylene production.[70] However, as a result of antitrust action against DuPont and ICI in the US, the latter was compelled to license the technology to other companies.[71]

The fifties witnessed an enormous expansion of polyethylene capacity, particularly in the US. This expansion resulted not only from the licensing of high pressure technology, but from the almost simultaneous discovery in the US and in Germany of low pressure organo-metallic processes for the synthesis of high density polyethylene.

In addition to the leadership of the United States, the second characteristic of the early years of the diffusion of polyethylene

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[70] German production of chemicals was severely constrained in the years that followed the war, it was not but until 1953 that IG Farben's assets were divided between the four firms that succeed it. (Chapman, 1991, p.81.)

[71] Hufbauer (1966), p. 59.

technologies was that production concentrated in a reduced number of West European countries and Japan. Table 6.26 shows the state of polyethylene capacities in 1964 and allows us to see the relative importance of the different countries that formed the group of leading producers.

Table 6.26 Polyethylene capacities, 1964 (000 mt) and share in World total capacity (%)

	LDPE	HDPE	TOTAL	% World
North America	952	352.7	1304.7	55.6
US	900.7	325.9	1226.6	52.3
Canada	51.3	26.8	78.1	3.3
Western Europe	630	119	749	31.9
UK	187	29	216	9.2
W. Germany	153	54	207	8.8
Italy	129	14	143	6.1
France	66	10	76	3.2
Netherlands	50	12	62	2.6
Other W.Europe	45	0	45	1.9
Japan	161.5	64.7	226.2	9.6
Other World (a)	60.6	4	64.6	2.8
WORLD TOTAL (a)	1804.1	540.4	2344.5	100

SOURCE: *European Chemical News*, 19 June (1964).
Notes: (a) The figure excludes the eastern block countries and is slightly underestimated, since ICI LDPE capacity in Australia is missing from the total.

The concentration of polyethylene production in these countries is part of a more general phenomena: the leadership of these nations in the production of plastic materials during that same period. As table 6.27 shows, the leaders in polyethylene production were also leaders in plastics production.

Table 6.27 World plastics production and shares of major, producers 1950-1963

	1950	1955	1960	1963
World (000 mt/y)	1,395	2,989	6,183	9,778
Share major producers (%)	95.9	92.8	89.2	86.5
US	70.5	57.3	45.1	38.7
Japan	2.9	4.6	8.9	14.4
France	2.4	3.4	5.6	5.1
W. Germany	7	13.7	15.6	14.6
Italy	1.6	4.2	4.8	6
UK	11.5	9.7	9.2	7.7

SOURCE: UN (1967).

The position of these countries in plastics production is, to a great extent, an expression of the more general economic leadership of these countries. It is, however, those aspects that are specific to plastics, and in particular to polyethylene, that are of interest to us. In this respect, the six countries listed above were among the more advanced in the development of their chemical industries. Regarding synthetic materials, in particular, the majority of the most important innovations were first introduced in the US, Germany, the UK, France and Italy.[72] In addition, these countries, and Japan as well, were relatively fast in following any innovation introduced by a member of the group. The leadership of these group of countries, not only in production but also in the development of technology, is clear in the polyethylene case (which is only a representative example of the more general situation that has prevailed in petrochemicals). This is illustrated by table 6.28, which shows that practically all the polyethylene technologies available by 1987 have been originated in these countries.[73]

Table 6.28 Number of polyethylene technologies available by country of origin in 1987

	LDPE	HDPE	LL-HDPE
Total	19	14	15
U.S.	10	4	4
Japan	2	5	3
Germany	2	2	1
France	2	0	2
Italy	1	1	1
U.K.	1	1	1
Netherlands	1	1	1
Belgium	0	1	0
Canada	0	0	1
Spain	0	0	1

SOURCE: CIS (1987).

Germany had been the world leader in the chemical industry since the second half of the nineteen century, and until the second world war.[74] After the war, the US became world leader in petrochemicals. This was in part due to the economic power with which the US raised after the war, but also to the fact that it was there where the petrochemical industry was born. The various accounts of the rise of the petrochemical industry in the US converge in pointing out a series of conditions that contributed to

[72] According to Hufbauer's study of 56 mayor innovations in synthetic materials all 56 innovations were first introduced in one or more of these five countries. Germany appeared in 22, the U.S. in 29, the U.K. in 4, Italy in 5 and France in 3.(In Hufbauer's study, countries that enter the production of a material in the first year of its commercial production are considered as innovators. In some cases there more than one country started the production of a material in the first year of commercial production. For this reason, the sum of innovators may exceed the number of innovations). Hufbauer (1966).

[73] As Dosi, Pavitt and Soete (1990) have convincingly argued, this technological leadership, which is also found in most manufacturing industries, is closely related to the dominant position of these countries in terms of shares in world exports and to their high levels of income.

[74] See Haber (1971) and Freeman (1963).

the North American lead[75]: the size of its market, the availability of oil and gas and the considerable development of its oil refining industry. In addition, the US had the chemical and oil companies with the technological capabilities to exploit the potential of oil derivatives as raw materials that could replace the traditional ones. The analysis of the development of the US petrochemical study is beyond the scope of this study. We only want to stress that the various factors that explain its leadership in petrochemicals also explain the leadership of the US polyethylene in production, and that the presence of firms with strong technological capabilities was an important factor.

Let us concentrate for the moment on the lags and leads in production within the group of six countries mentioned above, and see whether they were associated with changing patterns of trade. As it has already been mentioned, LDPE was first produced in the UK and the US. During the 1950s and early 1960s, the US and the UK were major exporters of polyethylene. The export performance of these two countries in those years is shown in tables 6.29 and 6.30. We observe a rising trend in the volume of exports in the two countries throughout the period. However, in both cases, the export-production ratio peaks in the late 1950s and starts to decline in the 1960s. This was related to increased production in other West European countries and Japan.

Table 6.29 US domestic production and exports of polyethylene 1954-1964. (000 mt)

	1954	1956	1958	1962	1964
Production	95	257	392	919	1185
Exports	5	57	110	177	210
Exp./Prod. (%)	5.3	22.2	28.1	19.4	17.7

SOURCES: exports: US Department of Commerce; Production: Sitting (1961), and Goldstein and Waddams (1967).

Table 6.30 UK domestic production and exports of low density polyethylene, 1954-1964 (000 mt)

	1948	1954	1958	1962	1964
Consumption	1	17	68	155	202
Exports	na	7	37	67	69
Exp./Prod. (%)	na	41.2	52.9	43.2	34.2

SOURCE: Rusell T. J., in Reuben and Burstall (1973).

Data about the destination of these exports is only available for the

[75] See for instance, Spitz (1988), Landau and Rosenberg (1992), and Chapman (1991).

US from 1960, and for the UK from 1965.[76] The export data from the US show that Japan and the largest West European countries were the major recipients of those exports in 1960, but had diminished in importance by 1965.[77]

Table 6.31 US polyethylene exports and shares of its ten major destinations, 1960, 1965 (000 mt)

	1960		1965
Total	149.8	Total	195
Share major destinations (%)	73.9	Share major destinations (%)	61.2
Japan	14	Mexico	12.6
Netherlands	14	Spain	10.1
Bel-Lux.	11.7	South Africa	6.8
Canada	9	Hong Kong	6.5
Hong Kong	6.1	Netherlands	5.4
UK	4.9	Canada	5
Italy	4.2	UK	5
Mexico	4.1	Sweden	3.4
W. Germany	3.1	Denmark	3.3
France	2.8	Bel-Lux.	3.1

SOURCE: US Deptartment of Commerce
Notes: (a) quantities have been converted to metric tons.

Trade data for Japan and some major West European countries for 1960 and 1965 are presented in table 6.32. For each country, we give the main countries of origin of their imports in 1960 and the main destinations of their exports in 1965. In 1960, these countries had a deficit and the US and the UK were the origin of their imports. As the process of diffusion advanced, the relative importance of the imports from those countries diminished. Furthermore, most of these countries were net exporters by 1965 (France did not become a surplus country in polyethylene but until 1970). In general, the weight of the trade between these countries and the US diminished and started to be replaced by regional trade.

Regarding the weight of Western Europe as a destination of US polyethylene exports, its participation diminished from 49.6% in 1960 to 41.1% in 1965 and continued declining in subsequent years.[78] The decline

[76] The UK export data correspond to the aggregate of polyethylene and polypropylene and refer to the time in which patterns of trade that we want to illustrate had already changed. Thus, they are of limited use for our purposes and have not been reproduced here.

[77] The aggregate share in US exports of Japan, UK, Italy, West Germany and France was 29% in 1960 and only 10% in 1965. Note that, in 1965, the UK figures as an important destination of US exports. The bulk of those exports were of HDPE. Regarding LDPE the UK was a net exporter throughout the period in question.

[78] The share of Western Europe in US polyethylene exports dropped to 22.9% in 1970, 13% in 1980 and by 1988 it was less than 6%.

Table 6.32 trade statistics of major polyethylene producers (000 mt). Main countries of origin of their imports in 1960, and main destination of their exports in 1965

FRANCE			ITALY			JAPAN		
	1960	1965		1960	1966		1960	1965
Balance	-12.2	-18.4		-5.6	95.4		-22.2	70.1
Imports	13.3	50.6		9.2	8.3		23.4	1.5
Exports	1.1	32.2		3.6	103.6		1.2	71.5
	Imports (%)			Imports (%)			Imports (%)	
US	54	8	US	57	4	US	92	94
UK	29	6	UK	34	4	Canada	5	0
W Germany	12	21	France	1	46	UK	1	2
Bel-Lux	3	5	W Germany	3	24	Australia	1	0
Italy	0	20	Netherlands	2	16	W Germany	0	3
	Exports (%)			Exports (%)			Exports (%)	
W Germany	6	25	France	0	15	Hong Kong	8	27
Portugal	7	12	Spain	12	13	Thailand	0	12
Spain	3	7	W Germany	0	11	China	0	11
Netherlands	2	7	Bel-Lux	22	10	Taiwan	0	6
Belgium	1	5	Netherlands	0	4	Philipines	0	5

BELGIUM			NETHERLANDS			GERMANY	
	1960	1965		1960	1965		1965
Balance	-8.7	-20.1		-2.5	11.5		57.8
Imports	10.2	26.8		9.1	22.9		44.2
Exports	1.5	6.7		6.6	34.4		102.0
	Imports (%)			Imports (%)			Imports (%)
US	60	0	US	60	2	Italy	24
Netherlands	21	32	Bel-Lux	13	28	France	17
Italy	0	21	W Germany	12	42	UK	16
W Germany	0	17	UK	9	14	Netherlands	15
UK	0	12	Italy	5	7	Bel-Lux	7
	Exports (%)						Exports (%)
France	14	40				France	24
W Germany	0	39				Netherlands	9
Spain	0	2				Australia	8
						Switzerland	6
						UK	6

SOURCES: Countries' national trade statistics (see bibliography).

of US exports to Japan and Western European nations in the 1960s was to a great extent the result of the increased production in these regions. This was brought about by the build up of polyethylene capacity both by native producers and by US companies as the latter started to switch from exports to direct foreign investment to compete in those markets.[79]

[79] By 1964, Union Carbide, Dow Chemical, Phillips Petroleum and Monsanto were already engaged in polyethylene production within Western Europe, either through subsidiaries or participating in joint ventures. European Chemical News, 19 June (1964).

Table 6.33 Polyethylene production major countries 1961-1964 (000 mt)

	1961	1962	1963	1964
US	716	876	1075	1229
UK	126	155	186	202
West Germany	98	148	165	226
Japan	58	142	223	NA
Italy	54	80	91	NA
France	30	63	65	79

SOURCES: UN (1967); *Modern Plastics*, various issues, and Rusell, in Reuben and Burstall (1973).

In his study on synthetic materials, Hufbauer (1966) suggested that polyethylene offered an example of technology gap trade. The trade and production data that we have presented indicate that in the initial period of US and UK lead in polyethylene manufacturing there were, in fact, trade flows between the group of countries being studied that fit into the definition of technology gap trade proposed by Posner (1961). Not all trade, however, was of a technology gap type. The diffusion of polyethylene technologies within this group and the associated build up of productive capacity modified the patterns of trade.[80] One of the most evident changes was the reduction of the share of UK and US exports that went to the other West European nations. There are, however, other changes. Table 6.33 also suggests an increasing flow of international trade in polyethylene taking place among neighbouring countries that is particularly clear in the case of Japan and Western Europe. A full list of export destinations for the countries above (not shown) reveals the increasing importance of other countries (such as Canada, Denmark, Hong Kong, Mexico, Portugal, Spain, South Africa and Sweden) as destination of the exports of the major producers.

On the basis of these findings, it is reasonable to ask whether a similar pattern to that observed in the group countries analysed above repeats subsequently in other countries as technology diffused. We will start by looking at the process within Western Europe. This is a highly integrated economic space and most of the trade in the region is intra-European. Thus, any trade implications of the diffusion of the technology in the region is most likely to be observable in intra-regional trade

[80] On the notion of diffusion based trade see Metcalfe and Soete (1984).

flows.[81]

6.6.2 Changing patterns of polyethylene trade in Western Europe

Polyethylene capacity has gradually been built up in other West European countries that figured in the list of major importers in the mid 1960s. Table 6.34 shows the recomposition of supply in the region

Table 6.34 West European polyethylene capacity (000 mt/y) and shares by country, 1964-1988

	1964	1973	1980	1987	1992
Western Europe total	749	5150	8837	8538	10467
Shares (%)					
UK	28.8	9.6	8.4	4.8	5.4
W. Germany	27.6	30.2	27.5	22.5	19.5
Italy	19.1	17.3	14.7	10.7	11.5
France	10.1	17.6	15	16.4	17.5
Netherlands	8.3	8.8	8.1	10.3	9.7
Belgium	2	7	10.1	10.7	13.2
Denmark	2	0.7	0	0	0
Sweden	0	3.6	3.3	5.1	4.2
Spain	0	3	7.6	9.2	8.8
Finland	0	1.7	1.9	2.1	2
Austria	0	1.3	1.5	3.5	3.2
Norway	0	0	1.8	2.5	2.6
Portugal	0	0	0	2.1	2.3

SOURCES: data for 1964 and 1973: *European Chemical News* (1964, 1973); data for 1980: *European Plastics News*, April (1982); data for 1987 and 1992: CIS (1993).

Another early entrant not mentioned in the previous section was Denmark, but, as table 6.34 illustrates, an early entry is not all that matters. Although Belgium and Denmark had the same capacity in 1964, the former has grown to become Europe's third largest producer, while polyethylene production has been abandoned in the latter. In 1973, in addition to the six leading countries, there were five suppliers which accounted for 10.3% of West European capacity. By 1992, the group consisted of six and their capacity represented 23.1 of the total. As it would be expected, the geographical spread of polyethylene production has been accompanied by significant changes in trade patterns. Table 6.35 shows the changes in the trade balance in polyethylene for some West European countries.

A change from deficit to surplus, like the one observed in the major polyethylene producers in the 1960s, is also found in some of the countries that entered production later. Needless to say, nations that have not

[81] The importance of inter-regional trade in Western Europe is illustrated by the fact that, according to Eurostat trade statistics, in 1988, 81.1% of EEC polyethylene exports and 88.6% of its polyethylene imports were intra European trade.

Table 6.35 Polyethylene trade balances and trade volume West European countries (000 mt)

	Trade balance			Trade volume (a)		
PE	1972	1979	1988	1972	1979	1988
Netherlands	297	424	679	432	713	1,167
Belgium	215	484	430	435	906	1,481
France	115	351	220	532	1,008	1,343
Spain (b)	(135)	57	126	143	128	389
Norway	(71)	1	125	72	160	248
Sweeden	(74)	19	95	90	300	491
Portugal	na	(77)	77	na	77	129
Ireland	na	(38)	(42)	na	39	43
Switzerland	na	na	(116)	na	na	130
Greece	na	(79)	(116)	na	79	117
Denmark	na	(121)	(192)	na	131	211
W.Germany	167	149	(261)	861	1,464	1,813
Italy	100	(101)	(269)	325	561	983
U.K.	(5)	(213)	na	175	412	na

SOURCE: Countries' national trade statistics (see bibliography), CIS (1987,1993)
Notes: (a) volume of trade = exports + imports.
(b) the data for Spain in the 1972 columns are 1973 data.

developed a domestic industry like Greece, Ireland and Denmark have a deficit. Of more interest to us is the fact that the UK, Germany and Italy have turned from being surplus countries in polyethylene to having a significant deficit. Figure 6.9 shows in more detail the evolution of the trade balance of these countries around the year in which their surplus turned into a deficit.[82]

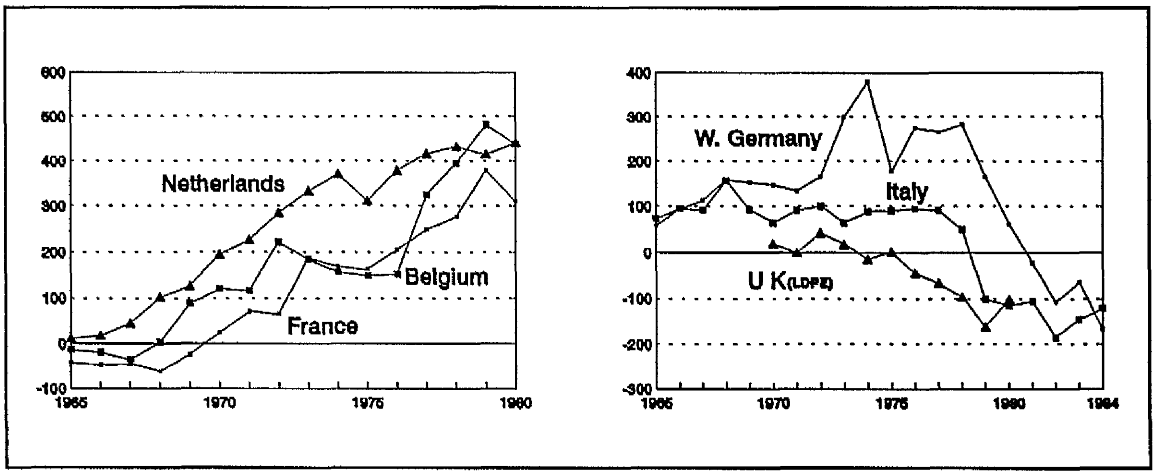

Figure 6.9 Evolution of the trade balances of the major polyethyelen producers in Western Europe (000 mt)
SOURCES: Official trade statistics of the countries and Predicasts, Eurosat Trade Statistics and Chemical Market Abstracts (various years).

A comparison of this figure and table 6.34 indicates that there is a correspondence between the falls in capacity shares and the deterioration of the trade balance position of the three countries. In contrast, Belgium, the Netherlands and France have retained both their capacity

[82] For the UK the complete series was only available for LDPE and it is that series which is presented in the figure.

shares and a considerable trade surplus. Although complete country by country series of polyethylene consumption are not available, this suggests that the changes in the patterns of trade are largely driven by the changes in the location of production.

Let us look briefly at the different factors that have contributed to the patterns of location of production and trade described above. On the one hand, there has been an increasing participation in production by new entrants. In some countries, like Spain and Sweden, the existence of relatively large domestic markets has made them attractive location for private petrochemical companies to invest in production facilities. In addition in these countries, as in Norway and Portugal, the build up of capacity has been promoted, to a different degree in each case, by the public sector, either with incentives, or directly through firms with state participation. The industries in this countries have tended to grow to the size of their domestic markets, and some of them have even generated a positive trade balance. Consequently, markets traditionally served by the major exporters have been preempted by the new entrants.

The cases of Belgium and the Netherlands are quite special. Each has very important oil related complexes, in Antwerp and Rotterdam respectively, which made them good locations for the production of petrochemicals in general. Since the early years of the development of the Western European petrochemical industry, they have been poles of attraction for the investment of large petrochemical corporations. Some polyethylene producers, in particular, have established facilities there to compete in the West European market. In 1980, for instance, in addition to the indigenous polyethylene producers, Dow and ICI had facilities in the Netherlands, while Basf, BP, Dow and Exxon had facilities in Belgium. The concentration of production in these countries and in France has been an important factor behind the deficits of Germany, Italy and the UK. Looking at intra-EEC trade flows, one observes that the three countries that experienced a reversal in their trade balance have a considerable deficit in polyethylene trade with Belgium, Netherlands and France.

The other aspect of the change in the trade position of the three former surplus countries has been the relative decline in their share of

Table 6.36 Polyethylene trade balances between some major West European countries in 1988 (000 mt) (a)

Countries with surplus	Countries with trade deficit		
	W. Germany	Italy	UK
Bel-Lux.	185.3	102.7	150.2
Netherlands	176.6	76.2	135.5(b)
France	133.4	100.0	98.9
Total	495.3	278.9	249.1

SOURCE: elaboration on Eurostat, External Trade.
Notes: (a) The table is built using import data for the countries except in the case of the UK where data on imports of LDPE and HDPE were not available. We have used data on exports from the surplus country to the UK.
(b) The figure is only for LDPE and LLDPE trade.

West European production.[83] Regarding the UK, the fact that ICI was, in the mid 1970s, the company with more plants in other European countries indicates that its strategy to compete in these markets has tended to emphasize direct investment. The position of the UK in the geography of Europe and the advantages of direct investment to have access to the EEC markets, before the UK joined in 1976, have contributed to this tendency. In addition, ICI was experiencing difficulties in its facilities at Wilton in the late 1970s , which led to capacity cuts and increased imports of LDPE in the UK.[84] Further cuts followed from the withdrawal of Monsanto from LDPE production in the UK, and of ICI from the polyethylene business, in 1982. All these contributed to the deterioration of the trade balance of the UK. The UK was not alone in this respect. In Germany, Basf was the European producer that made the most significant cuts in the early 1980s. Between 1980 and 1983, Germany, the UK and Italy were, in that order, the countries that closed more polyethylene capacity in West Europe.[85] The more difficult conditions experienced during the slumps that followed the two oil shocks sharply reduced the profitability of most petrochemical activities, including polyethylene, and made many plants uneconomical. The closures were the result of the combined effect of more severe competition,

[83] In what follows we will focus the attention on the UK and Germany. In Italy the control of polyethylene production by state owned firm introduces many political elements, which make it difficult to analyse the developments in that industry in economic terms.

[84] European Plastic News, January issues (1979, 1980).

[85] The capacity closed in thousands of metric tons was the following: Germany 550, the U.K. 310, Italy 300 and France 210; which as a proportion of their 1980 capacity represent 22.6%, 41.8%, 23.1% and 15.8% respectively. See European Plastic News, August (1980) pp. 8-14 and January (1984), p. 3. The different attitude of public and private firms with respect to capacity closures may have also played a role in the differences observed in the distribution of plant closures in Western Europe. On these, see Bower (1986), Grant (1991) and Adams (1991).

which has contributed to a profit squeeze, and the fact that these countries had some of the older facilities, which were built in the early days when they were the only large producers. The developments in the UK and Germany were related to the behaviour of their LDPE national champions in relation to the polyethylene business. The firms in the leading countries did not reinvest in sufficient magnitude as to return to their position before the crisis. In the new conditions of the industry, profitability levels in Western Europe do not make it as attractive to invest as it was in the past. Associated with this, there has been a tendency for producers coming from a chemical industry background to move away from the production of bulk thermoplastics and leave the field to oil companies which, thanks to their backward integration, are in a more favourable position to compete.[86] The main producers from UK and Germany came precisely from a chemical tradition and have been less enthusiastic about investing in this business. Technologically strong chemical companies have tended to move to more profitable areas, like bio-technology and pharmaceuticals. Finally, government incentives and environmental issues have also played a role. In the case of Germany, for instance, environmental controls on petrochemicals are particularly strict. The Belgian government, in contrast, gives incentives to the establishment of petrochemical facilities.[87] After the closure of plants, this kind of considerations may have made it more convenient to build plants in other locations.

A final point that ought to be stressed is the key role played by the major companies that dominate the industry in the diffusion of the technology. US transnational corporations (TNCs) had a very active role in the development of the West European polyethylene industry and, in general, of its petrochemical industry. Between the second half of the 1950s and the early 1970s, several US companies undertook considerable investments in polyethylene production in Western Europe, and also participated as licensors of process technology. However, in the late 1970s and early 1980s most of the US based corporations withdrew from the West European market. The large West European corporations have also played an important role in the diffusion of polyethylene, not only within

[86] See Bower (1986).

[87] Interview with an industry analyst.

their own countries of origin, but through joint ventures and subsidiaries in other European countries. Tables 6.37a and 6.37b present a list of the major TNCs in Western Europe that were operating beyond their national borders in 1973. Needless to say, the tables only provide a snapshot at a particular point in time. Withdrawals, mergers, joint-ventures, acquisitions and, in some countries, government intervention have changed considerably the shape of the West European Industry.[88]

Table 6.37a US companies participating in the West European polyethylene industry with direct investment or as licensors of technology in 1973

Company	Direct investment (product, place)	Technology Licensees
U.Carbide	LDPE, Belgium LD & HDPE, Sweden	Montedison, Italy BXL, UK
Phillips	HDPE, France HDPE, Spain HDPE, Belgium	ROW, Germany BP, UK
Dow	LDPE, Netherlands LD & HDPE, Spain	
USI	LDPE, Belgium	Pekema Oy, Finland
Monsanto	LDPE, UK	
DuPont		Erdolchemie, Germany

Table 6.37b WE companies participating in WE polyethylene industry in more than one country with direct investment or as licensors of technology in 1973

Company	Direct investment (product, place)	Technology licensees
ICI	LDPE, UK LDPE, France LDPE, Netherlands LDPE, Spain	Maersk Kemi, Denmark ANIC, Italy Montedison, Italy DSM, Netherlands
BASF	LD & HDPE, Germany LDPE, France LD & HDPE, Germany LDPE, Belgium	Petrochemie, Austria ABCD, Italy
Shell	LD & HDPE, Germany LD & HDPE, France	
Solvay	HDPE, France HDPE, Italy	
BP	HDPE, France HDPE, UK	

SOURCE: elaboration on *European Chemical News* (1973).
Note: (a) We consider participation in production both through subsidiaries and in joint ventures.

The important point is that not only in Europe, but in the rest of the world, there is a reduced number of major TNCs from the US, Western Europe and Japan that have played a central role in the development of the polyethylene industry. These firms characterize by having considerable market shares and by enjoying a high degree of technological competence, which allows them to participate either as innovators or as fast imitators of the developments of their competitors. These firms, listed in table 6.38 constitute a "hard core" within the industry and have developed the main polyethylene technologies available. Most of them were present in the industry since the early years of its development. Practically in every new plant, a firm from this group is found participating either with direct

[88] Of the US companies listed in table 6.37, for instance, only Dow has stayed in Western Europe as a polyethylene producer. Exxon entered the market later and acquired the facilities of USI. The others firms, either sold their plants to West European firms, or closed them down.

investment, or as the licensor of the technology.

Table 6.38 Major polyethylene technologists, number of plants world-wide using their technologies, 1992

	Total Operating	Total Planned
North American	83	23
Dow	13	-
DuPont	6	4
Phillips	19	3
Quantum	12	-
U.C.	33	16
West European	105	18
Solvay	6	1
Atochem	11	-
Enichem	17	3
Basf	11	2
Hoechst	13	1
Stamicarbon	3	2
BP	13	7
ICI	31	2
Japanese	20	2
Mitsui	15	2
Sumitomo	5	-
Total	208	43

SOURCE: elaboration on CIS (1993).

6.6.3 International diffusion of polyethylene technologies and the LLDPE innovation

A general picture of the pattern of diffusion of the high pressure (LDPE) and low pressure (HDPE) polyethylene regimes, and of the evolution of trade patterns until 1965 is presented in tables 6.39 and 6.40. The data reflect the early domination of the US, particularly in LDPE, and the subsequent emergence of Japan and Western Europe (mainly EEC countries) as polyethylene producers. The large excess of demand over supply among this group reveals another early pattern, which has persisted throughout the process of diffusion of polyethylene technologies, namely, the role of the US, Japan and Western Europe as suppliers of the excess of consumption over production of the rest of the world.

Table 6.39 Production-consumption balances of polyethylene major producers, 1955-1965 (000 mt)

	LDPE			HDPE	
	1955	1960	1965	1960	1965
US	54	182	122	30	56
EEC	-10	-18	33	7	46
EFTA	2	6	-30	-4	-31
Japan	-5	-33	72	13	11
Rest of World	-16	-70	-233	-4	-51

SOURCES: As in table 6.40.

The development of the polyethylene industry, and in general of

Table 6.40 World polyethylene production (000 mt) and shares by region, 1955-1965

	Low Density Polyethylene			High Density Polyethylene		
	1955	1960	1965	1956	1960	1965
World	228	809	2,296	3	175	696
Shares (%)						
US	80.3	63.2	44.0	0.0	54.9	51.1
EEC	5.7	14.1	20.0	100.0	24.6	24.9
EFTA	11.8	13.0	10.8	0.0	2.3	4.3
Japan	0.0	2.7	13.3	0.0	15.4	13.2
Rest of World	2.2	7.0	11.8	0.0	2.9	6.5

SOURCES: Pearce and Smith, as quoted in Clegg (1967). Predicasts *Chemical Market Abstracts* (1966), pp. 1121-1123. (the figures have been converted to metric tons)
Notes: (a) EEC comprises Belgium, France, W. Germany, Italy, Luxemburg and Netherlands. EFTA comprises Austria Denmark, Norway, Portugal, Sweden, Switzerland, UK and Finland (associated).
(b) In EFTA the only HDPE producer in these period was the UK.

petrochemicals, in the rest of the world has been, as in some of the countries reviewed above, a combination of the international expansion of the major TNCs and a direct participation of the governments of those countries. However, government intervention has played a more important role in less developed regions.[89] A major difference between the less developed countries and the developed ones has been the absence in the former of large private firms of comparable technical and financial strength. In addition, the limited size of the domestic market and the lack of sufficient infrastructure tend to make them less attractive to invest. Since petrochemicals has been seen traditionally as an industry of strategic importance, in many countries it has been promoted by national governments, directly with investment and by giving incentives to foreign investors

Although the major TNCs have not been the only agents in the diffusion of polyethylene technology to the rest of the world, they have played a central role. A key element behind the pervasiveness of their participation in the worldwide diffusion is that they own the technological know how. This is illustrated by the history of the beginning of three of the earliest producers in the rest of the world: Australia, Canada and India. In Australia, LDPE was first produced in 1957 by ICIANZ, a subsidiary of ICI. By 1964, there was already a second LDPE producer, a Union Carbide subsidiary, and HDPE was introduced a few years later by Hoechst. Canada also had a very early start in polyethylene production: LDPE was introduced in 1954 and HDPE three years latter. As in Australia, the first LDPE producers were subsidiaries of ICI and Union Carbide, while

[89] See Chapman (1991).

it was DuPont that pioneered Canadian HDPE production. Finally, in India, where the government has played an important role in the petrochemical industry, it was also ICI which introduced LDPE production in 1959, through its subsidiary Alkali and Chemical Corporation. The first HDPE facilities in India were established as part of a wider petrochemical project of a government controlled firm, in collaboration with Shell and Hoechst.

The beginnings of the three major Latin American producers of polyethylene closely resembles that of the three countries mentioned above. In Brazil, the two types of polyethylene were also introduced by major transnational corporations: LDPE by Union Carbide in 1958 and HDPE by the Belgian company Solvay in 1965. In Argentina, the first polyethylene producer was IPAKO a company 50% owned by Koopers International, which started LDPE production in 1963 in a plant operating with Koopers' technology. The following year it was joined by Dupeiral, an ICI subsidiary. Finally, in Mexico, where legislation limited the production of basic petrochemicals to the state and required majority of domestic capital in other petrochemical activities, LDPE was first produced in 1966 by Polirey, a mixed enterprise. The state owned PEMEX, national private investors and ICI participated each with one third of the capital, and ICI technology was used. HDPE was introduced in 1978 in a plant owned by PEMEX using Ashai's technology.

Regarding the trade performance of countries outside the three leading regions (US, Western Europe and Japan), an important difference is that, at least until the late 1970s, practically all of them remained as net importers of polyethylene. At most, they have managed to roughly balance production and domestic consumption. As the case of Denmark illustrated, and early entry is not all that matters. Countries like the ones described above, which had a relatively early entry into polyethylene production, did not follow a similar pattern to that of the leading countries. As table 6.41 shows, rather than turning their deficit into a surplus in a relatively short period, they remained with a deficit until the late 1970s.

However, there have been significant changes in the trade balance situation of various countries during the last fifteen years. Three of the countries in table 6.41 have developed a surplus and the same has occurred with other traditional importers in the Far East, like South Korea and Singapore. In addition, there are other countries, like Saudi Arabia and

Table 6.41 Polyethylene trade balances, various countries, 1971-1988 (000 mt)

	1971	1974	1977	1980	1984	1988	Last year Available	
Canada	(42)	(144)	(84)	104	95	575	821	-1991
Australia(a)	na	na	15	37	17	(40)	(30)	-1990
India(b)	(3)	na	(58)	(37)	(150)	(183)	-	
Argentina(c)	(12)	(35)	(11)	(4)	(1)	(1)	91	-1989
Brazil	(72)	na	(52)	(4)	249	233	190	-1989
Mexico	(39)	(44)	(87)	(185)	(122)	(97)	(52)	-1991

SOURCES: for Brazil 1971: Ribeiro and Silva Filho (1974); for Mexico 1971-1977: ANIQ (1971-1977); for Canada 1971-1977: Dominion Bureau of Statistics; other data 1971-1974: Predicasts *Chemical Market Abstracts* and *Overview of Markets and Technologies*, various issues; other data 1977-1991: CIS (1987, 1993)

Notes: (a) the data for Australia in 1988 column are for the year 1987.
(b) the data for India in 1984 column are for the year 1985.
(c) the data for Argentina in 1971 column are for the year 1972.

Qatar, that have recently developed export oriented petrochemical industries and have a significant surplus in polyethylene trade. The recent changes in trade patterns have been associated with a considerable build up of capacity outside the leading regions, during the last fifteen years.

Table 6.42 Polyethylene capacities in developing countries from plants that have started to operate in 1979 or later (000 mt/y)

	"New" Capacity			"New"	Total	New in
	LDPE	HDPE	LL-HDPE	(79-92)	1992	Total (%)
Algeria	48	-	-	48	48	100
Argentina	-	62	120	182	309	59
Brazil	295	320	260	875	1308	67
China	60	280	245	585	1196	49
India	80	-	425	505	535	94
Israel	96	-	-	96	125	77
Mexico	240	-	-	240	550	44
Qatar	180	-	-	180	180	100
S. Korea	192	680	456	1328	1654	80
Saudi Arabia	-	-	910	910	910	100
Singapore	160	-	-	160	335	48
Taiwan	100	144	-	244	504	48
Turkey	165	40	-	205	233	88
Venezuela	-	60	-	60	165	36
Total	1616	1586	2416	5618	8052	70

SOURCES: CIS (1993): CDS (1978-1983); Longley (1991); *Modern Plastics International*, various issues.

The counterpart of these changes has been a weakening of the trade position of some of the traditionally surplus regions. As figure 6.10 shows, there has been a decline in the export propensity of the traditional exporters, mainly in Western Europe and Japan.

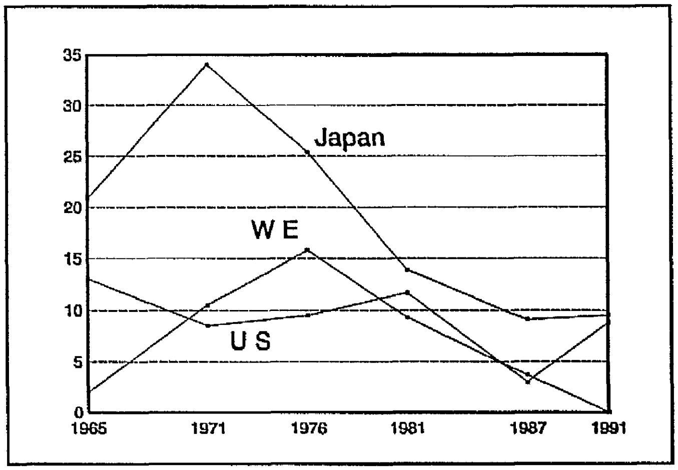

Figure 6.10 Polyethylene trade balance-production ratios (%)
SOURCE: elaboration on various sources. See table B.1 in Appendix B.

The diffusion of polyethylene technologies has led to a higher rate of growth in the rest of the world as an aggregate with respect to the leading regions. These developments are not only a natural result of the geographical spread of polyethylene production in the world, but an expression of more fundamental changes in the polyethylene industries. As it can be seen in table 6.43, the pattern of growth of polyethylene industries in the different regions has been decreasing throughout the period considered. This phenomenon, often referred to as "retardation", was observed long time ago by Burns and Kuznets in their studies of industrial growth in the US.[90] Figure 6.11 shows that this slow-down has been greater in the regions where the industry developed first.

Table 6.43 Average logarithmic rates of growth of production for the world and major producers, 1965-1989 (%)

	1965-69	1970-74	1975-79	1980-85	1985-89
US	11.7	9.4	6.8	3.3	2.0
Western Europe	22.1	15.1	4.6	3.4	3.2
Japan	22.6	11.1	0.7	0.8	3.7
Rest of World	25.3	22.0	18.0	14.1	7.9
World	18.1	12.7	6.5	4.8	4.0

SOURCES: own elaboration. Data for 1965-1979: Predicasts (1982); data for 1980-1989: UN, *Yearbook of International Trade Statistics*.

[90] See Burns (1934) and Kuznets (1954).

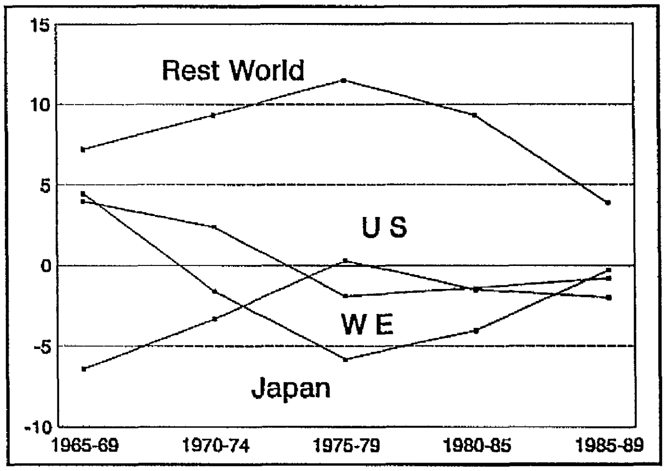

Figure 6.11 Deviation from the average rate of growth of world polyethylene production (%)
SOURCE: As in table 6.43

The polyethylene industries show clear symptoms of maturity. As it was suggested in section 6.3, the two technological regimes associated with the polymerization of ethylene seem to have virtually exhausted their potential for further innovation led growth. Even a major innovation, like LLDPE, did not translate in cost reductions or in new applications of enough magnitude to change the tendency to a growth slow-down in the industries. The maturity of the polyethylene technologies is reflected in the slow-down in the growth of polyethylene consumption in the US, Western Europe and Japan.[91]

Table 6.44 Average logarithmic rates of growth of polyethyene consumption, 1961-1990 (%)

	1961-65	1966-70	1971-75	1976-80	1981-85	1986-90
US	24.4	13.3	4.9	9.0	5.5	6.9
Western Europe	na	na	4.4	7.5	2.4	7.1
Japan	42.0	21.2	-1.1	na	3.7	7.0

SOURCE: elaboration on *Modern Plastics*, various issues; *Modern Plastics International*, various issues.
Note: (a) for Western Europe the average in the column 1971-1975 is the average for the rates of growth 1972-1975.

Between the 1950s and early 1970s, the polyethylene market in those regions was experiencing considerable growth and they were the pole of attraction for investment. Process improvements and scaling up of plants reduced the prices of the polymer and new applications were continuously developed. Until the mid 1970s, the polyethylene industry in the leading

[91] It ought to be pointed out that the situation in polyethylene is part of a more wider phenomenon associated to the maturity of most petrochemicals. The crisis of petrochemicals in Japan, Western Europe and the US during the 1980s was to a great extent a manifestation of this phenomenon. Walsh (1984), for instance, has identified a slow down in patenting and in the publication of scientific papers in chemicals, that can be seen as an expression of this maturity.

countries, as the rest of the petrochemical industry, experienced very fast growth in the core countries. It is true that during this period the technology also diffused to some countries in the rest of the world, but in most of them the industry remained stagnated: it grew in a piecemeal fashion, in most cases under the sponsorship of governments. In many cases, supply lagged behind demand, partly because the polyethylene markets were small and excess demand was also small relative to the scale of a new efficient plant; but also because the inability to compete in export markets made it unattractive to build ahead of demand. The major transnational corporations supplied these markets with the excess capacity from the fast growing capacity in core countries. However, in the 1970s, the rationale of shifting investment to other parts of the world has increased. The growth slow-down in the major markets, the increased weight in cost of raw materials and the narrowing of profit margins have contributed to this change. Investing in traditional sites mainly to export is not a sound option. For the major TNCs, licensing and direct investment in joint ventures have gained importance over exports as a way to profit in foreign markets from the ownership of their technologies. The other important element behind the new investment has been the strong political will to develop a petrochemical industry in countries with oil and in regions with fast growing markets.

It is in the context described above that the LLDPE innovation emerged. The diffusion of this technology has been largely driven by the opportunities and environmental conditions created by the state of development of the polyethylene technologies and their uneven spatial diffusion. The considerable capital cost savings of a technology like that of Union Carbide were particularly relevant for LDCs since they lowered the barriers to entry associated with investment requirements. It is significative that the first licensee of Union Carbide was the Argentinean firm IPAKO. Although the earliest low pressure LLDPE plants were built in North America and Western Europe, the technology has recently had considerable diffusion in LDCs.

A central element in this process has been the interest of leading polyethylene technologists to license their technologies. Union Carbide is perhaps the best example of this. In a first stage, the company was very active both through investment abroad and through licensing. However, more recently, the company has been selling to other producers its

Table 6.45 Type of polyethylene produced in new plants of developing countries that started to operate from 1979 onwards (capacity in 1992) (a)

	Share (%)
LL-HDPE (b)	43.0
LDPE	28.8
HDPE	28.2
Total capacity (000 mt/year)	5,618

SOURCE: as in table 6.42.
Notes: (a) aggregate data for countries in table 6.42.
(b) some LL-HDPE may be dedicated to produce HDPE, and a small proportion of plants are LD-LLDPE plants.

facilities outside the US and has moved towards a grater emphasis on the commercialization of the technology. Apparently, the company has found in the royalties derived from licensing and in the service business a less risky and more profitable way of getting a share of the revenues generated by the polyethylene business outside the US.

As with most innovations, statistics are hard to come. Official trade statistics disaggregating for LLDPE are not available for the countries in table 6.42. However, the high penetration of the technology in some of this countries and that some of them have export oriented plants, which clearly generate a trade surplus, indicate that the patterns of trade in the new resin is bound to be different to that of the two types of polyethylene that preceded it.

The diffusion of LLDPE technology has responded to the more general tendencies of the polyethylene industries. However, at the same time, it has had significant effects on international trade flows. Massive imports of LLDPE have contributed to a fall in the US surplus in polyethylene trade. This change in the pattern of trade has resulted mainly from exports of LLDPE to the US from subsidiaries of US companies in Canada. In the case of Western Europe, the deterioration of its polyethylene trade balance is largely due to a flow of LLDPE and HDPE imports from Saudi Arabia. These have been introduced in the European market by Exxon and Mobil, SABIC's partners in the Saudi Arabian joint venture. As part of the joint venture deal, these firms are in charge of marketing 50% of the output of the plants. The magnitude of the exports of Canada and Saudi Arabia to the US and Western Europe in 1990 is shown in table 6.46.[92]

[92] In the case of Western Europe, the gradual build up of capacity of East European countries and their exports to Western Europe has also had some bearing in the deterioration of this region's trade surplus.

Table 6.46 US and EEC imports from Canada and Saudi Arabia, 1990 (000 mt/y)

	US imports			EEC imports		
	LLDPE	LDPE	HDPE	LLDPE	LDPE	HDPE
Canada	356.6	92.2	88.8	23.7	8.9	6.6
Saudi Arabia	0	0	5.5	156.6	1	127.4

SOURCES: US Department of Commerce; Eurostat.

The construction of polyethylene plants in Canada and Saudi Arabia were the combined result of technological opportunity, resource availability, government intervention and of the particular situation through which the industry was going at the time when the projects were decided. In the conditions of high oil prices that characterized the first half of the 1980s, the region of Alberta, in Canada, and Saudi Arabia appeared as particularly attractive locations from a raw material point of view. Both countries offered ethane from natural gas with no alternative use, which made it very cheap. Ethylene could be produced from this feedstock at a much lower cost than through the production of naphtha.[93] Thus, the investments in polyethylene were part of wider petrochemical projects, which involved the construction of ethylene crackers.

The incentives from the costs side were complemented by further incentives and pressures from the governments of the countries involved, which were moved by the interest of developing their petrochemical industries. Chapman has convincingly argued that, in the case of Saudi Arabia, its dominant place in world oil production may have given it negotiation power to persuade the oil companies that participated in the join ventures with SABIC.[94] In the Canadian case, the regulation on the price of oil and gas imposed by the Canadian government after the first oil shock played an important role.[95] The price adjustment program discriminated in favour of gas, in order to promote the shift towards a more intensive use of this resource. In relation to petrochemicals, this policy favoured investing in Alberta versus the already existent, oil based petrochemical centre in Sarnia. It ought to be stressed, however, that the trade between Canada and the US refers to flows within a highly economically integrated region and responds above all to investment driven

[93] On these issues see Longley (1991), pp. 59-60, and Chapman, (1991), p. 81.

[94] Chapman (1991), pp.185-6. See also Auty (1988).

[95] Chapman (1991), p. 196.

by the availability of resources.

Official data on LLDPE trade are available only for EEC countries and for the US and they are relatively recent (they start from 1985). As the data in table 6.47 show, both regions have a trade deficit in LLDPE. In the two regions it is the trade in this polymer that makes the main negative contribution to the trade balance. However, an important difference is the fact that the US deficit with Canada is mainly the result of foreign investment by US firms. Furthermore, the US, despite its deficit with Canada, has been increasing its exports of LLDPE. In 1991, it managed to obtain a slight surplus in this polymer. Although these changes are very recent and insufficient to identify a trend, it would not be unlikely that the US became a major net exporter given the high proportion of new LL-HDPE capacity in that country. These differences illustrate the importance of the differences in diffusion of the country origin of the innovation.

Table 6.47 Trade balances in LLDPE US and EEC polyethylene producers, 1990 (000 mt)

LLDPE	US	EEC(a)	Bel-Lux	Germany	Spain	France	Italy(a)	Nether.	Portugal	UK(a)
Imports	363	339	228	176	17	107	127	72	11	199
Exports	138	87	42	23	10	149	43	355	0	8
Balance	(225)	(252)	(186)	(153)	(7)	42	(84)	283	(11)	(191)
LDPE										
Imports	106	389	234	604	94	349	363	181	30	350
Exports	388	576	571	423	183	370	170	598	76	0
Balance	282	187	337	(181)	89	21	(193)	416	47	0
HDPE										
Imports	221	358	245	417	124	266	193	114	14	248
Exports	418	257	424	312	75	163	165	170	56	104
Balance	197	(101)	179	(105)	(49)	(102)	(28)	55	42	(144)
PE balance	254	(166)	330	(439)	32	(39)	(305)	755	78	0
LL bal/ PE bal(%)	-88.6	151.8	-56.5	34.8	-22.8	-109.6	27.5	37.5	-13.6	0.0

SOURCES: US Department of Commerce; Eurostat External Trade.
Notes: (a) The figures for the EEC are extra-EEC trade for 1989. In 1990 the export data for Italy and the UK are confidencial and 1990 EEC data underestimate exports considerably. The 1989 export figures are also underestimated because UK LDPE exports are not included.
(b) The figures for Italy and the UK correspond to 1989.

The data for Europe shed some light on the relevance of the links between firms and countries. Firms that champion specific technologies tend to build their plants in the countries in which they have established throughout the history of their transnationalization. This can be observed in the location of LLDPE plants in Western Europe and in the trade flows of this resin. France and Netherlands are the only EEC countries with a surplus in LLDPE. The firms that entered relatively early and have committed more to the LLDPE business had major investments in those countries: CdF and BP in France and Dow and DSM in the Netherlands. Sweden is another major exporter of LLDPE in Western Europe; the first production of the resin there was a joint venture of Union Carbide and Pekema Oy.

6.7 Concluding remarks: technology and trade

The analysis of the relationship between technology and trade of this chapter has extended beyond the LLDPE innovation. LLDPE is a case of an innovation that brought into direct competition two relatively mature technologies. This, we have argued, has been an important element for the subsequent development of LLDPE technology and has driven us to look at the two technological regimes that are relevant for the innovation.

The evolution of the patterns of trade in polyethylene illustrates clearly how those patterns change with the diffusion of technology, and sheds light on different aspects of this relationship. In the first place, we have identified the role played by the differences in the timing of entry and the uneven geographical spread of the innovation. We found evidence of technology gap trade appearing and disappearing in a pecking order as the technology spread and production began in different countries.

A second aspect that emerged, in particular in the analysis of intra-European trade, was the complex changes in trade flows that take place during the diffusion of the technology. As in the previous case study, we have established that the changes in the patterns of trade are based on the pattern of diffusion.[96] We identified a number of facto that affect the behaviour and performance of the firms in the industry, which are behind the changes in trade. Firstly, the factors that affect the decisions of TNCs about the location of plants, such as proximity to markets, the logistics of the petrochemical industry and government intervention. Second, the factors that lead to change in the market position of firms with facilities in particular countries. These include a wide variety of elements that go from the impact of an innovation like LLDPE, to the lack of backward integration or two the greater attractiveness of other business opportunities.

A third important aspect of the relationship between trade and

[96] On this see Metcalfe and Soete (1984).

technology is that the relevance of factors like the ones mentioned above changes depending on the state of development of the technology. In our analysis of polyethylene this appears more clearly in relation to the broad patterns of diffusion and trade at a worldwide level, confirming the basic insight of the product life cycle idea.

The maturity of the two technological regimes associated with the polymerization of ethylene and the fact that they had experienced a considerable diffusion in the US, Western Europe and Japan, are intimately related to the changes in the patterns of international investment and trade. In the past, with relatively fast growth in these regions, and capacity being built usually ahead of demand, export markets were a natural way out for excess production. With the maturity of polyethylene technologies and the phenomena of retardation in those regions, the conditions have changed. A consequence of these is that capacity has been increasingly being built in countries with oil and gas resources and near the fastest growing markets in the rest of the world. New capacity (mainly in the Far East, the Middle East and South America) is serving regional markets to which the surplus regions exported in the past and are the main force behind the loss of grip of the traditional exporters in world markets. Another important factor behind these developments has been the existence of a strong political will to establish or expand petrochemical production in those countries. The disposition of the companies with the technology to license and/or invest in less developed countries has also been an important factor that has made possible these investments.

Thus, the insights of the product life cycle model have been useful to understand the broad trends in the international location of polyethylene capacity described above. However, as various authors that have applied this framework to the analysis of petrochemicals have noted, this requires us to introduce additional elements to Vernon's basic scheme.[97] In particular, it is necessary to consider important elements like the influence of the dynamics of the different regional markets, the role of government intervention and contingencies, such as the fluctuations in oil prices, that affect the patterns on the location of capacity.

In the mature stage of the industry, the life cycle model would also predict a reversal of trade flows. Although such a reversal has appeared

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[97] See Stobaugh (1970), Auty (1988) and Chapman (1991).

in some instances, it is of a limited nature. They have been associated with the exports to the US, Europe and Japan from Canada and Saudi Arabia that will be discussed below. It is true that there is a tendency towards the contraction of the polyethylene trade surplus of the traditional exporters. However, a major reversal of trade flows has not occurred even in the case of Western Europe and Japan, which depend considerably on oil imports. There are factors that impose limits to the extent that this may occur. The existence of an industry in these countries, in which the major players are also the main investors and suppliers of technology of the new exporting countries, is an important element that limits the penetration of polyethylene imports into core countries. Oil continues being imported in large quantities for energy use, which represents the largest share of its consumption. Given the considerable development of the oil tanker industry, transport costs are relatively low and the availability of oil in other countries does not represent a major advantage. The economies derived from the existing infrastructure, such as ethylene pipelines, the proximity to markets and suppliers, and the fact that firms based on these regions own the technology and continue developing it are created advantages that make firms in the advanced regions very resistant to competition by producers from abroad.

Finally, let us look at the diffusion and trade of LLDPE. It is true that LLDPE has had significant effects on international trade flows. However the diffusion of LLDPE has been itself shaped, to a great extent, by the general tendency marked by the maturity of the industry. The major trade flows in LLDPE are associated with the creation of the large petrochemical centres in Canada and Saudi Arabia. There are various factors behind the creation of those centres as export oriented projects. A first factor was the high prices of oil, and the fact that the state of development of the technologies made these particularly important. The availability in Canada and Saudi Arabia of cheap ethane feedstocks for the production of ethylene, coupled with the technological opportunity opened by LLDPE, made them attractive locations to build capacity. Another important factor that contributed to their realization was that, as in other countries, investment in petrochemicals was actively promoted by local governments. The relevance of the origin of the LLDPE innovation in relation to these projects is reflected by the fact that US firms with proprietary or licensed technology were the major participants in both projects. The importance of the country origin of the innovation has also found expression in the high share of LLDPE in the US polyethylene capacity and on the high volume of exports of this resin that originate in this country.

A final question that has emerged throughout the case study is the key role played by the reduced number of TNC from a small group of leading nations that have developed and own the technology. The competition between these firms and their decisions about how to profit from their technology are key elements driving the diffusion of polyethylene technologies and the patterns of trade associated with it.

7 Concluding remarks: the relationship between technology and trade

7.1 Introduction

In this the last chapter we bring together the main insights that can be gained from the two case studies and from the review of the literature on technological change and international trade.

In section 7.2, we present briefly the main ideas of the five essays in chapters 2 to 6. Section 7.3 focuses on three important characteristics of technological change, which were repeatedly highlighted throughout the thesis, and comments on their relevance in shaping the patterns of international trade. Section 7.4 outlines an argument on trade and technology along evolutionary lines at an industry level which seeks to complement the ideas advanced in chapter 3. This argument puts at its centre the various dimensions of technology and technological change discussed in section 7.3. Finally, section 7.5 comments briefly on the contribution of the evolutionary approach to the analysis of international trade and looks at aspects in need for further exploration.

7.2 The essays on the technology and trade relationship: a summary

The review of the models of trade in the neoclassical tradition of chapter 2 centred the attention on two issues. First, it assessed the adequacy of the equilibrium approach for the analysis of the relationship between technological change and trade. Second, it discussed the treatment given in the models to questions related to product innovation. Regarding the first issue, it was noted that the major strength of the equilibrium approach is its ability to deal with economic interdependence. However, the framework is essentialy static, even in the models which attempt to be dynamic and look at technological change and growth. This is a major shortcoming of equilibrium models which address the problem of economic change. They are unable to incorporate the qualitative changes that occur in historical time, neither are they able to deal with the open nature and path dependency that characterizes developmental processes like technological change. A second limitation of the equilibrium approach arises from its focus on representative agents and from the associated notion of competition that permeates the analysis. A consequence of this is that it overlooks aspects of the competitive process which play a major role in economic change.

Taken together, the models reviewed in chapter 2 are an important contribution to the analysis of product innovation and trade. First, they call our attention to the role of diversity as a source of intra-industry trade. Second, they analyze the differences and similarities between innovation as increased variety and as increased quality. Third, they formalize some of the most basic propositions of the technology gap and product life cycle theories of trade and show how asymmetries in innovative and imitative performance can be the source of trade. Finally, they highlight the fact that innovation is a profit seeking activity which requires resources. It was argued, however, that their treatment of technological change is unsatisfactory. One of the main criticisms raised in this respect is that, in order to be able to introduce differentiation and product innovation in such a way they can be incorporated into the equilibrium framework, they have to resort to a very stylized treatment of both technology and technological change. The problem with such a treatment is that the explanation of the processes being analyzed does not reflect the operation of the mechanisms that one observes in practice. This is largely due to the fact that important aspects of the process of technological change are missed, such as the diversity in technology that stems from the supply side and the fact that the technology continues being developed and its markets being created after the innovation is introduced.

Chapter 3 proposed an alternative perspective for the analysis of the relationship of trade and technology. It was argued there that, since the evolutionary approach is centred on the analysis of economic change, it is better suited for the analysis of that problem. This approach has two main advantages. First, it conceives of economic change as a process whose outcomes are open and which is driven by mechanisms that create variety and by mechanisms of selection. Second, it looks at competition in the market as a struggle between firms which are different from each other. As a consequence, it adopts a population perspective for the analysis of the competitive process which allows it to incorporate this diversity. As a result, fundamental aspects of technological change, which are not properly considered in equilibrium models, are found at the centre of the evolutionary approach. These are: the diversity that exists within the industry, the competitive process that drives the development of the technology, and the qualitative changes that occur in the process of development of the technology and the industry.

On the basis of a review of the literature on trade and technological change, an evolutionary argument on the relationship of trade and technology was outlined in chapter 3. Three main points stressed in that argument were: first, the importance of technology in explaining differences in wealth and income between countries; second, the relationship between differences in technological development and patterns of specialization and trade between countries; and, third, the relevance of the technological competencies of firms, which are man created, as a determinant of trade flows. An important conclusion that emerged in chapter 3 was that, in order to advance the argument on the technology-trade relationship, further research on the way in which specific technologies develop and diffuse internationally and on how this relates to the changes in trade patterns is required. With this in mind, chapter 4 reviewed a series of ideas from the literature on technological change and articulated them in a framework which could be used in the empirical analysis of specific technologies.

The framework proposed in chapter 4 adopted an evolutionary perspective and focuses on three key elements of the evolutionary process: the technology, the firms in the industry and the environment. This way of proceeding directs our attention to the way in which the mechanisms that generate variety and the mechanisms of selection operate. From this perspective, the analysis of the technology trade relationship at the level of an industry can be made by looking at trade flows as an aspect of the spatial dimension of the international diffusion of an innovation.

The ideas developed in chapters 3 and 4 were applied to the analysis of two innovations. The innovations considered belonged to two very different types of industries: IEP, an assembly industry, and LLDPE, a chemical processing industry. The IEP case, presented in chapter 5, is an innovation which led to the emergence of a new technological regime and to the birth of a new industry. In the years that followed the end of the Xerox monopoly in the industry, major changes occurred in the location of production, which altered considerably the patterns of international trade. These changes occurred during the fluid period in the development of the technology: new design configurations were being introduced, and the markets for the product were being created. The course followed by the diffusion of IEP, and in particular the pattern of location of productive capacity, were shaped in a competitive struggle. The outcome of this struggle depended, on the one hand, on the innovative performance of firms in product, process and market practices and, on the other hand, on the differences in the national environments where the firms were located. The LLDPE innovation analysed in chapter 6, in contrast, did not result in the formation of a new industry. It was rather the case of a major innovation that emerged within a mature technological regime. This circumstance contributed to an evolution of the patterns of diffusion and trade in LLDPE which has been significantly different from that followed by other types of polyethylene resins introduced earlier. The maturity of the technologies associated with the polymerization of ethylene and their different diffusion in different parts of the world have been fundamental elements driving the spatial dimension of the diffusion of LLDPE. Other factors in the national and international environments such as government intervention and contingencies like the fluctuations of the price of oil were also important in shaping the patterns of diffusion and trade.

The case studies have served two purposes: first, they showed that specific innovations can be fruitfully analyzed by applying the evolutionary framework proposed in chapter 4. Second, they allowed us to establish, in two specific cases, how the introduction of innovations and their subsequent development related to the emergence and change in trade flows. The theoretical exercise of the first three essays and the case studies provided a number of insights into the relationship between trade and technological change which are summarized in the following two sections.

7.3 The process of technological development and the patterns of international trade

This section concentrates on three aspects that were identified as fundamental for an understanding of the process of technological change and its relationship with the changes of trade flows within an industry. The first aspect is the notion of technological change and industrial development as a process of co-evolution, which takes place in historical time, involves qualitative changes and is path dependent. The second is what we have referred to as the three dimensions of technology: namely its knowledge, routine and artifact dimension. The recognition of these dimensions is important because the acquisition and development of a technology requires the articulation of these three dimensions within a firm. The third aspect is the technological diversity that exists within the technological regime that defines an industry.

The three aspects mentioned above have already been discussed at length and exemplified in other chapters so there is no need to go over them again. We will rather look at what they imply for innovation, diffusion and its associated patterns of trade.

Posner's technology gap and Vernon's product life cycle theories of trade are the best known propositions on the relationship between technological change and international trade. The influence of these theories was identified in both the equilibrium model of chapter 2 and the evolutionary argument in other chapters of the thesis. Although apparently similar, the interpretation of Posner's and Vernon's theories adopted by the equilibrium and the evolutionary approach has some fundamental differences.

In the North-South models of chapter 2, for instance, the propositions have been reduced to the following two basic ideas. First, innovations provide a basis for export from the innovating country to the extent that the technology and the production stays in the innovating country, but there is demand for the innovation overseas. Second, when the technology to produce what used to be a new product becomes common knowledge, the location of production will be determined according to comparative advantages in production (in general seen as determined by relative factor abundance). Thus, the end of the monopoly position may lead to changes in the patterns of trade. However, there is a deeper message underlying Posner's and Vernon's trade theories. Namely, that the flows of international trade are not only created by innovations but are also shaped by the process of development of the technologies associated with these innovations and by their international diffusion.

As we noted above, although apparently similar, there are fundamental differences in these two interpretations. In the former, the innovation is seen as an artifact, and the technology associated with it as a set of blue prints. Thus, either the technology is seen as not changing after its introduction, or that any changes are considered irrelevant. The effect of technological change on trade is reduced to the question of whether an innovation is monopolized or made freely available. In the second interpretation the recognition of the knowledge, routine and artifact dimensions of technology is crucial. The question of the relationship between technological change and trade is addressed by focusing on the process of development and diffusion of a technology at an international level. According to this perspective, there is much more involved in this international diffusion of a technology than its simple geographical spread.

Entry to an industry and the mastery of the technology by a firm requires of a series of competencies which enable the acquisition of knowledge and skills and their articulation within the organization. Whether an industry will be established in a country and remain operating successfully will depend on the existence of the relevant competencies in that country. This, in turn, depends largely on the activities of the firms established in a country and on the capabilities available from other institutions in the technology support system. TNCs are a possible source of technology and organizational competence for countries which do not have the technology or the firms able to enter with the required level of competitiveness. This involves, however, direct foreign investment, which is not indifferent to the conditions offered by the national environment in terms of institutions, firms in supply industries and availability of people with the required knowledge and skills. In summary, the technological conditions in a country, which result from the trajectory of its development, are an important determinant of the location of production facilities and, consequently, of the patterns of trade in an industry.

A second question is the nature of the process of development of the technology and of its associated industry that follows from the introduction of an innovation. The creation and expansion of the markets for a product, the changes in the technology, the entry of new competitors and the establishment of production facilities in other countries are all outcomes of a competitive process. Throughout this process there is learning by both consumers and producers. As the technology is developed to fulfil needs in a cheaper and better way, product and process development in the supply side contribute to extending the reach of the product to a larger set of buyers.

Due to the different conditions that prevail in different countries, the market sizes and rates of market expansion will, in general, differ at different points in time. The evolution of the demand side is one aspect driving the changes in patterns of trade. As we saw above, the other important aspect are the outcomes of the competition between the firms in the industry, which are located in different countries and compete not only in their own national markets but overseas. The technological competence of the firms is a key factor in determing their competitive performance. This competence is built by the presence in the industry and, although there are aspects of the technology that are codified and released to the public domain, there is a great deal of individual and collective knowledge and skills in the organizations which remain within the firms.

Needles to say, the differences in the competencies of individual firms and in the technological capabilities available in different countries, although important, are not the only element that determines the location of production in an industry. There are other differences in the national environments which, at different points in time, will contribute to shape the international distribution of production facilities in an industry. Factors such as general economic conditions, exchange rates, prices of primary factors of production, government policies, relationships and access to regional markets and so on. Sudden changes in the conditions of particular countries or of the international environment can have major, long lasting, effects in shifting the competitive balance between companies and in their decisions regarding location. Firms favoured by domestic factors at a critical stage in the competition within the industry may be able to build a strong technological and market position in the industry. That was the case with the Japanese firms in the IEP industry during the fluid period of innovation and market creation. The advantages built during that time can be resilient to subsequent changes in the environment, as we saw in that case study. On the other hand, when a firm abandons an industry, because of unfavourable domestic conditions, much of the collective routines and knowledge of the organization associated with the technology disintegrate and they may prove extremely difficult to put back together. Furthermore, to the extent that the technology does not remain static, the learning foregone from the absence in the market can be a considerable barrier for a successful re-entry, even with changed, more favourable conditions.

Some of the points made above are somewhat obvious, however, given the tendency in economic analysis to replace historical by logical time and to neglect the path dependency and the irreversibility of many aspects of developmental processes, a stress on these points is more than justified. The corollary to the foregoing argument is that comparative advantages are largely man made. The knowledge and skills and the material base that allows countries to compete successfully in different industries appear and disappear as industries and technology develops and diffuses to different countries and the competitive balance shifts in favour of some producers and away from others.

A third issue, with respect to the technology trade relationship, is the role of variety. The diversity in the technologies deployed by the firms is an important aspect of this variety. This aspect is at the heart of an evolutionary approach and is overlooked in models that focus on representative firms and assume a single identical technology. It is true that the equilibrium models of monopolistic competition and intra-industry trade reviewed in chapter 2 attempt to incorporate the role of variety. However, their focus on product differentiation and on the demand side leads them to overlook the technological diversity, which has it roots in the differences between firms and in the multiple trajectories that the development of a technology can follow.

As the case studies showed, in practice, different design configurations of the same technology coexist. Variety within the technology, the multiplicity of applications that can be given to a same product and the diversity in the subjective preferences of buyers contribute to the segmentation of markets into different niches. It is useful, thus, to distinguish between the different sources from which the diversity of the products in an industry emerge, rather than to lump them under the label of differentiation.

The difference in design configurations is a source of basic differences in key performance characteristics. There are also differences which emerge from the specificity of competing firms. Imitation and market selection tend to eliminate diversity, while innovation creates it. In the process of the development of the technology some standards in design emerge which are shared by different configurations. There are also designs which are eliminated by competitive selection while one or a few are becoming dominant in the industry. However, our two case studies have suggested that, although in its development the technology tends to move along a smaller number of trajectories (designs), and although these trajectories may be narrowed by standardization; technological variety tends to persist as a result of firms diversity and their creativity. Markets heterogeneity and the incomplete information sets of buyers allow firms with very different performance to share the market. Thus, product differentiation, as portrayed in some of the models reviewed, is only one of the levels of diversity.

It should be noted that the models of monopolistic competition reviewed look at elements that can be incorporated by any producer, regardless of the design in which it operates. In practice, these elements, if successful, are very soon imitated by other firms. That was the case with the introduction of features and minor design improvements in IEP equipment and of grades for specific applications in LLDPE. Furthermore, as we saw there, firms tend to produce several specifications of their product to compete with others in the different niches of the market. Therefore, the contribution to trade of this component of diversity is likely to be less important than is suggested by the monopolistic competition models in which each firm stuck to a single specification. In any case, whatever its source, the presence of diversity, as suggested by those models, is a possible source of intra-industry trade.

It ought to be pointed out that, in relation to the two case studies presented in this thesis, we can only conjecture about the role of diversity as a source of intra-industry trade. It proved to be very difficult to find data on the relationship between the diversity in design configurations and the patterns of international trade. The main problem is, on the one hand, the confidentiality with which the sales and export data of individual firms are treated. Firms do not make that information public and, in general, national statistics withhold sectoral data which could disclose information on individual firms. In addition, published trade and production statistics usually do not have the level of disagregation required to identify directly trade flows associated with different design configurations. Case studies on individual firms would be required to shed more light on this issue.

7.4 An evolutionary argument on international competition within an industry

The various remarks on technology and trade made in the previous sections can be integrated in an evolutionary account of international competition. The development of a technology and of its associated industry, in different countries, is a process driven by the generation of variety and by the selective forces of the market environment. In this context, the changes in the flows of international trade appear as one aspect of the spatial dimension of the development of a technology and its associated industry. In this section, we outline the basic elements of this argument. What follows draws on the insights provided by the two case studies and on the theoretical propositions of previous chapters. However, at various points, the argument is speculative. Our objective is to advance some plausible theoretical generalizations suggested by the present research and to propose a few conjectures that can serve as hypotheses for further research.

Industries are born as a result of what are usually called radical innovations. As the examples of IEP and polyethylene suggest, these innovations can vary considerably in the degree to which their nature and market potential can be anticipated. It is through repeated trials in the market and experimentation in different applications that these are gradually discovered. The two case studies suggest that there are some differences in this respect between types of industry. In the case of assembled artifacts, which are designed with a function in mind, there tends to be a clearer understanding at least of the properties of the product. Radical innovations in chemical processes, on the other hand, are often surrounded by greater uncertainty as the largely unexpected discovery of polyethylene illustrates.

Although to a different degree in each particular case, it can be said that, in general, the market potential of an innovation only becomes apparent as the technology is developed. The innovation opens new business opportunities which, to a varying degree, steal existing markets and create new ones. Innovations also open avenues for further technological innovation.

A first implication of innovation for trade, on which equilibrium models of product innovation and trade have concentrated, is that while the technology is monopolized, and to the extent that the monopolist sells beyond its national borders, innovation is a source of trade flows. The key issue, however, is that the radical innovation only represents the first step of a process of technological development, whose trade implications are more complex. The innovating firm pursues one route of development but a wider trajectory is open. This trajectory is subsequently explored by other firms that enter the industry seeking to capture a share of the expanding market and to profit from the business opportunity opened by the innovation. The proliferation of designs that often accompanies the entry of firms to an industry is the most clear manifestation of this process. This appeared very clearly in the case of IEP. The LLDPE case, which was a major innovation within an long established technological regime, showed that the diversity of designs which had prevailed in the industry was important for the competitive situation of firms in the face of subsequent innovations within the industry.

As the technology develops, the relative position of the different designs, and that of the companies that champion them, changes. An example of this, in the IEP case, is found in the success during the 1970s enjoyed by copiers based on liquid systems in the low end of the market, and in their subsequent displacement by dry toner systems. In the LLDPE case, the lack of flexibility of HDPE slurry processes to be adapted for the production of LLDPE grades has made them lose ground in what is increasingly becoming a single polyethylene industry. In both cases we find firms in a different competitive position according to the design configurations on the basis of which they compete. The persistence of diversity at the level of design configurations and its role in competition identified in our two cases suggest that this is an element that is worth studying when analysing other industries.

In the same way that a radical innovation inaugurates a new industry and creates markets, the introduction of new designs and subsequent innovations are also sources of market expansion. This diversity, as we noted above, is different to the traditional idea of product differentiation and is a source of international trade. In the IEP case, the expansion of the low end of the markets by the introduction of low cost low volume copiers, was an important element in the export performance of

Japanese firms. At the level of an individual firm the idea was also illustrated by the case of Canon's personal copier.

Needless to say, a fundamental aspect which will shape the evolution of trade patterns relates to whether or not the countries have the conditions for the emergence of competitors in a new industry. Although there are multiple routes in which the technology can be developed, they are not unlimited and not equally fruitful. The earliest entrants which manage to develop successful designs preempt the most fertile lines and develop them. To the extent that the technologies are appropriated and protected through patenting, secrecy, and other forms of protection, the conditions will be more difficult for late entrants seeking to develop proprietary technology. One of the major barriers to entry in technologically dynamic industries is the continuous progress, which builds on existing proprietary knowledge. In such cases, direct foreign investment or licensing may be the only feasible ways in which production facilities can be built in other countries.

As it was pointed out in chapter 3, generalized gaps between countries in technology and wealth, and the institutional differences that are at the basis of the different national competitiveness of the countries, will be a determinant of the availability of capabilities to enter specific industries. Equally important for this are the particular trajectories followed by the countries in terms of the type of activities in which local firms are engaged.

With the passage of time technology diffuses. This diffusion and the rate at which it occurs is related to changes in the technology and in the industry. As the technology matures, innovation-led growth and the profits derived from the exclusive property of the technology, associated with those innovations, diminish in importance. Thus, it is not only a matter of patents expiring and information leakages that make knowledge public. It is also that the value of monopolising the technology diminishes and the attitude of firms towards the technology changes. Royalties from licensing, for instance, become relatively more attractive as a way to capture profits from the activities of other manufacturers. The active licensing of LLDPE technology by Union Carbide, for instance, can be seen, to some extent, in this context.

The main insight of the technology life cycle idea is that, as the technology matures, the weight of different factors affecting the decisions of location of production changes. To this idea, one needs to add various qualifications: first, the implications for entry of the diffusion of knowledge associated with the technology; second, the changes in the attitude of the firms with proprietary technologies about how to profit from them; and, third, the fact that markets are heterogenous and that national markets exert different selective pressures on firms from different countries. Distance, import restrictions and cultural factors often result in more favourable conditions for firms located in the domestic market. These differences in selective pressure are among the major reasons why the existence of large domestic markets lead to the establishment of local production facilities in late coming countries.

We have seen in the two case studies that the establishment of facilities to supply domestic markets is often the prelude for a country becoming a net exporter in an industry. This appeared clearly in the case of polyethylene trade in which we identified various instances of countries passing from deficit to surplus after many years of having a polyethylene industry. There are situations, like in Canada and Saudi Arabia in LLDPE, where, at a particular point in time, lower prices of some inputs relative to those prevailing in other countries (measured in the same currency) offer a clear case for export oriented projects from the outset. In the context of the present discussion, however, what is of interest is the fact that through their presence in the industry entrants may be able to develop comparative advantage that make them net exporters in the industry. That is, latent advantages may only be materialized through the establishment and development of the industry in the country. This is one of the points emphasized by List, which is expressed, in a limited way, in the infant industry argument for protection. A final important qualification that has to be added to the product life cycle idea is the fact that the barriers to entry in general and in terms of technological knowledge in particular, and the attractiveness of entering an industry change as the technology and the industry co-evolve.

The presence or absence of an industry in the different countries and the sizes of their industries relative to domestic markets, which are behind the patterns of trade are, thus, aspects of the diffusion of the technology. This diffusion is driven, in turn, by a competitive process which responds to the various elements mentioned above. The fundamental message of the evolutionary approach adopted in the two case studies is that in order to understand the changes in the trade flows in an industry, one ought to look at a series of interlocking factors relevant to the technology, to the firms in the industry and to the national and international environments. This allows us to look at how these factors contribute to shape the patterns of trade through the mechanisms that generate variety in the system and through the mechanism of selection. At each point in time, when a significant change in trade is identified, its origins can be traced to major changes in any of these three spheres. However, to understand the way in which such changes operate, it is essential to have some knowledge of the conditions prevailing in the three spheres. Regarding technology, one ought to know things, such as the state of development of the different designs and how they compare in performance across different techno-economic dimensions. This helps us to assess the nature of the impact on their performance of whatever major changes we have identified. Similarly, with respect to firms, it is necessary to know how they are positioned in terms of the design configurations that they champion and of their shares in different market niches. It is also necessary to know any other differences between the firms which are relevant for their competitive and trade performance. All this information is essential for the assessment of the competitive impact on firms of any major change and an understanding of how it operates. The same is true with respect to the conditions prevailing in national and international environments.

Finally, it is important to stress that the focus of the present argument on a single industry has led us to adopt a very narrow perspective. Thus, the ideas above have to be seen in the context of the more general evolutionary argument on trade and technology outlined in chapter 3. Changes in exchange rates and in the relative prices of inputs between trading countries appear here as changes in national environments which alter the relative position of firms competing in different countries. More microeconomic phenomena, like the emergence of technological opportunities in related areas, which may have major effects in the behaviour of some firms in the industry, are also largely seen here as changes in the environment.

7.5 Trade theory from an evolutionary perspective

In this final section we comment on the contribution of the evolutionary argument under the light of what traditionally have been the main questions in the theory of international trade. We place the present work in that context and suggest some directions for further research.

A major advantage of the evolutionary approach to the analysis of international trade is that it brings to the analysis a focus on historical time and on the relevance of qualitative change. A second important contribution of this approach is that it brings to the front the role of diversity both as a source of trade and as a central element of the competitive process that is behind the changes in trade flows. The evolutionary approach centres attention on the processes by which variety is created and on the operation of the mechanism of selection. This provides a basis for the construction of a framework which can deepen our understanding of the mechanisms that drive the evolution of the patterns of international trade.

Most of the thesis concentrated on the analysis of the development of individual industries. This has allowed us to look at the numerous factors that affect the development of a technology and at how these relate to the changes in trade patterns. An important limitation of this approach is that it tells us little about the interrelatedness of different industries, which is the focus of general equilibrium models. This is a major task that still needs to be tackled by the evolutionary approach. An important question in this respect is the relationship between the changes in specialization in a country and the different stages of development of the relevant technologies. Some initial progress in this direction can be made by comparative studies at industry and firm level for sectors changing from deficit to surplus and vice versa, in individual countries. A more direct extension of the present research is the exploration of the role of technological diversity as a source of international trade. Empirical research on the trade performance of individual firms in an industry would be required to assess the relative importance of this factor.

A final topic which is worth commenting upon is the question of the determinants of the patterns of specialization, which has been traditionally at the centre of the debate in trade theory. As we noted in chapter 3, this question is not addressed directly by the evolutionary approach, which is focused on change. However, the argument presented in chapter 3 and the application of the evolutionary framework to specific cases, like the ones analysed in this thesis do make a contribution to this debate. Both the theoretical arguments and the empirical studies have highlighted the relevance of the development of technology in shaping the patterns of specialization and trade in specific industries. In doing so, they cast some doubt on the validity of the proposition that specialization and trade are fundamentally determined by relative factor abundance. As we pointed out elsewhere, essential aspects of technological change are overlooked in the analysis that lead to that propositions. A fundamental message that emerges from this thesis is that technological change and the technological differences between countries associated with it, are major elements driving the patterns of international trade.

Appendix A.

Table A.1 Photoreceptor configuration of the models of some major vendors in the US market, 1993

cpm	Xerox	Kodak	Oce	Savin (Ricoh)	Ricoh	Canon	Minolta	Mita	Panasonic	Royal (Konika)	Sanyo	Sharp	Toshiba
135	O-B												
120	S-B												
100	O-B	O-B	Z-B										
	O-B												
		O-L						aS-D					
						Si-D							
80										aS-			
						O-D	O-D						
												aS-D	
										S-D			
				S-D	S-D		aS-						aS-D
70	O-B	O-B,L						aS-D		aS-			
	O-B												
60		Si-D	Z-B			Si-D	S-D		S,ST-D	S-D		aS-D	aS-D
								aS-D					
				S-D	O-D								
50	ST-D	Si-D		ST-D	S-D	Si-D			aS-D			O-D	S-D
		O-D				O-D							
									aS-D				
			Z-B	ST-D				S-D		O-D			
				ST-D									
40						O-D	O-D			S-D		O-D	O-D
						O-D							
	S-D			ST-D				aS-D		O-D			
				ST-D									
				O-D	O-D						ST-D		
						O-D	O-D		O-D			O-D	O-D
30						Si-D							
	O-c					O-D				O-D			
					O-D								
									O-D				
				S-D		O-D		ST-D			O-D		O-D
							O-D						O-D
								ST-D					
				O-D			O-D						
20						O-D		O-D		O-D	O-D	O-D	
	O-c			O-D	O-D			O-D		O-D			
							O-						O-D
								O-D	O-D		O-D		
				O-D	O-c,D	O-D	O-D			O-D		O-D	
								ST-D				O-D	
									ST-D			O-D	S,ST-D
	O-c			O-D			O-		O-D	O-D	O-D		O-D
10													
	O-c					O-D		O-D	O-D			O-D	
						O-c,D					O-D		
5	O					O-c,D							
1						O-D							

SOURCE: elaboration on data provided by Datapro.
KEYS: Material: S=Se, ST=Se-Tellurium, aS=Arsenic Triselenide, O=Organinc, S=Amorphous H Silicon, Z=Zinc Oxide.
Physical Configuration: D=Drum, B=Belt, M=Master, c=cartridge, Loop.

Table A.2a France, trade of copying equipment and duplicators

	(000 units)				(mil. US Dlls.) (d)			
	1978	1980	1986	1991	1978	1980	1986	1991
Exports								
Optical system (a)	12.3	46.6	107.7	349.8	29.2	60.6	146.1	499.0
Other (b)	3.9	131.2	6.3	9.8	3.5	4.9	8.1	16.8
Total copiers	16.1	177.8	114.0	359.7	32.7	65.5	153.9	515.8
Duplicators (c)	5.0	5.4	4.7	2.9	1.9	1.8	1.2	2.6
Imports								
Optical system (a)	62	115	207	201	163	290	280	579
Other (b)	26	40	97	5	12	16	14	13
Total copiers	89	155	304	206	175	306	295	592
Duplicators (c)	12	15	2	11	7	6	1	16

SOURCE: Ministere de l'economie et des finances; Eurostat; conversion factor IBRD.

Notes: (a) 1975 to 1984 reported as aggregate, in 1986 includes Elecrostatic copiers of direct and indirect type and other copiers incorporating an optical system.

(b) 1975 to 1984 includes hectograph and stencil duplicators, in 1989 reported as aggregate.

(c) Includes thermocopying apparatus, diazo and other copiers of a contact type.

(d) Figures converted to dollars using yearly average exchange rate.

Table A.2b Germany, trade of copying equipment and duplicators

	(000 units)				(mil. US Dlls.) (d)			
	1975	1980	1986	1991	1975	1980	1986	1991
Exports								
Optical system (a)	48.9	112.3	120.3	222.2	103.6	253.2	250.9	589.3
Other (b)	71.3	66.3	14.7	9.0	17.0	46.6	50.9	59.4
Total copiers	120.2	178.6	135.0	231.1	120.6	299.8	301.8	648.7
Duplicators (c)	8.7	6.3	2.6	0.4	5.8	5.7	2.3	1.0
Imports								
Optical system (a)	36.0	105.5	254.3	532.0	65.1	267.5	344.0	923.1
Other (b)	10.0	11.9	14.3	10.5	6.2	20.9	22.1	25.3
Total copiers	46.0	117.4	268.6	542.5	71.2	288.5	366.2	948.4
Duplicators (c)	4.2	3.1	0.9	4.9	7.2	3.2	1.4	11.7

SOURCE: Statistisches Bundesbamt; conversion factor: IBRD.

NOTES: (a) 1975 to 1984 reported as aggregate, in 1986 includes Elecrostatic copiers of direct and indirect type and other copiers incorporating an optical system.

(b) Includes thermocopying apparatus, diazo and other copiers of a contact type.

(c) 1975 to 1984 includes hectograph and stencil duplicators.

(d) Figures converted to dollars using yearly average exchange rate.

Table A.2c Netherlands, trade of copying equipment and duplicators

	(000 units)				(mil. US Dlls.) (d)			
	1975	1980	1986	1991	1975	1980	1986	1991
Exports								
Optical system (a)	55.1	40.6	114.3	202.3	219.4	289.1	378.3	968.7
Other (b)	8.5	7.6	5.7	4.4	10.0	17.2	12.5	16.3
Total	63.5	48.3	120.0	206.7	229.4	306.4	390.8	985.0
Duplicators (c)	0.3	0.1	0.1	0.3	0.4	0.1	0.2	1.4
Imports								
Optical system (a)	13.3	28.5	99.8	223.7	41.8	73.6	129.0	636.4
Other (b)	5.9	4.9	2.8	1.8	3.7	9.3	7.3	5.7
Total	19.2	33.4	102.5	225.5	45.5	83.0	136.3	642.0
Duplicators (c)	5.2	4.0	1.7	1.9	12.0	3.5	1.2	5.6

SOURCE: Centraal Bureau Voor de Statistiek; conversion factor: IBRD.
NOTES: (a) 1975 to 1984 reported as aggregate, in 1986 includes Elecrostatic copiers of direct and indirect type and other copiers incorporating an optical system.

(b) Includes thermocopying apparatus, diazo and other copiers of a contact type.
(c) 1975 to 1984 includes hectograph and stencil duplicators.
(d) Figures converted to dollars using yearly average exchange rate.

Table A.2d UK, trade of copying equipment and duplicators

	(000 units)				(mil. US Dlls.) (d)			
	1975	1980	1986	1991	1975	1980	1986	1991
Exports								
Optical system (a)	17.8	40.6	87.7	262.5	99.1	347.5	170.0	388.4
Other (b)	0.0	5.7	13.1	4.2	6.4	8.4	8.0	8.4
Total copiers	0.0	46.3	100.8	266.7	105.5	355.9	178.1	396.7
Duplicators (c)	73.9	80.9	22.8	55.9	25.1	49.0	12.4	29.4
Imports								
Optical system (a)	33.2	54.9	136.5	348.7	61.9	158.9	252.0	396.4
Other (b)	0.0	23.2	6.0	321.0	13.8	16.7	6.9	7.2
Total copiers	0.0	78.1	142.4	669.8	75.7	175.6	258.9	403.6
Duplicators (c)	5.5	1.8	7.1	10.3	1.9	1.2	3.4	14.0

SOURCE: HM Customs and Excise; Central Statistical Office; conversion factor: IBRD.
Notes: (a)1975 to 1984 reported as aggregate, in 1986 includes Elecrostatic copiers of direct and indirect type and other copiers incorporating an optical system.

(b) 1975 to 1984 includes hectograph and stencil duplicators, in 1989 reported as aggregate.
(c) Includes thermocopying apparatus, diazo and other copiers of a contact type.
(d) Figures converted to dollars using yearly average exchange rate.

Table A.3a France, trade of copying equipment (000 units). Shares of main countries of destination and origin (%)

Exports		1978		1980		1986		1991
Optical system		12.3		46.6		107.7		349.8
Destination (%)								
	Nether.	28.2	Germany	73.9	Nether.	46.6	Germany	46.4
	UK	27.4	Sweden	7.1	Germany	21.5	Nether.	33.1
	Germany	8.4	Nether.	6.4	UK	18.3	UK	8.6
	EEC	77.5	EEC	88.6	EEC	93.7	EEC	96.5
Imports								
Optical system		62		115		207		201
Origin (%)								
	Japan	34.8	Japan	36.5	Japan	54.9	Japan	34.5
	Germany	29.9	Nether	26.6	Nether	28.2	UK	17.5
	Nether.	16.6	Germany	16.1	UK	8.1	Germany	11.0
	EEC	63.0	EEC	60.7	EEC	42.2	EEC	48.4

SOURCE: Ministere de l'economie et des finances, and Eurostat.

Table A.3b Germany, trade of copying equipment (000 units). Shares of main countries of destination and origin (%)

Exports		1975		1980		1986		1991
Optical system		48.9		112.3		120.3		222.2
Destination (%)								
	France	20.9	France	18.4	France	28.0	Italy	35.6
	Nether.	11.2	Nether.	16.5	UK	18.2	UK	27.2
	UK	11.1	UK	12.8	Nether.	17.5	France	21.7
	EEC	60.8	EEC	65.9	EEC	90.5	EEC	88.7
Imports								
Optical system		36.0		105.5		254.3		532.0
Origin (%)								
	Japan	44.9	Japan	72.1	Japan	78.2	Japan	34.3
	Nether.	20.0	Nether.	6.3	France	7.8	France	28.6
	US	13.6	UK	6.2	UK	7.8	Nether.	15.3
	EEC	40.7	EEC	22.2	EEC	19.7	EEC	55.4

SOURCE: Statistisches Bundesbamt.

Table A.3c Netherlands, trade of copying equipment (000 units). Shares of main countries of destination and origin (%)

Exports	1975		1980		1986		1991
Optical system	55.1		40.6		114.3		202.3
Destination (%)							
Germany	19.4	France	22.6	US	26.0	France	22.7
France	16.9	UK	16.1	France	15.5	Germany	20.1
UK	14.8	Germany	15.2	Germany	12.5	UK	15.3
EEC	66.1	EEC	70.6	EEC	58.8	EEC	82.7
Imports							
Optical system	13.3		28.5		99.8		223.7
Origin (%)							
Japan	35.2	Japan	43.1	Japan	50.0	UK	45.5
UK	29.8	France	26.9	France	15.4	France	19.5
Germany	20.0	UK	9.1	UK	14.5	Japan	11.3
EEC	60.5	EEC	51.5	EEC	44.4	EEC	78.8

SOURCE: Centraal Bureau Voor de Statistiek.

Table A.3d UK, trade of copying equipment (000 units). Shares of main countries of destination and origin (%)

Exports	1975		1980		1986		1981
Photocopiers (a)	17.8		46.3		100.8		262.5
Destination (%)							
Nether.	28.9	France	20.1	France	21.3	Nether.	71.5
France	12.9	Germany	15.0	Nether.	18.4	Germany	8.8
Soviet U.	9.0	Italy	8.8	Germany	13.5	Other	0.0
EEC	58.0	EEC	58.0	EEC	74.3	EEC	90.5
Imports							
Photocopiers (a)	33.2		78.1		142.4		348.7
Origin (%)							
Nether.	23.7	Germany	33.3	Japan	46.6	Nether.	22.2
Japan	14.2	Japan	29.6	Nether.	16.8	Germany	21.3
US	6.7	Nether.	18.1	Germany	16.5	France	12.9
EEC	36.1	EEC	60.2	EEC	49.7	EEC	152.2

SOURCE: HM Customs and Excise; Central Statistical Office.
Note: (a) For 1975 and 1991 only includes photocopiers with optical system

Appendix B

Table B.1 Polyethyelene production, consumption and net trade: US, Japan and Western Europe, 1965-1991 (000 mt) (1)

	1965	1971	1976	1981	1987	1991
United States(2)						
LDPE						
Production	1011 b	2038 c	2568 c	3491 f	4223 f	5216 h
Consumption	889 b	1896	2341	3067	4299	4795
Trade balance	122	142 c	227 c	424 f	-76 f	421 f
HDPE						
Production	356 a	857 c	1412 c	2226 f	3628 f	4253 h
Consumption	300 b	753	1262	1981	3313	3844
Trade balance	56	104 c	150 c	245 f	315 f	409 f
Total PE						
Trade balance	178	246	377	669	239	830
Bal./Prod. (%)	13.0	8.5	9.5	11.7	3.0	8.8
Bal./Cons. (%)	15.0	9.3	10.5	13.3	3.1	9.6
Japan						
LDPE						
Production	305 b	951 d	957 d	1033 d	1301 d	1831 d
Consumption	233 b	NA	737	939	1289	1682
Trade balance	72	NA	220 e	94 f	12 f	149 f
HDPE						
Production	92 a	389 d	436 d	638 d	880 d	1151 d
Consumption	81 b	NA	301	500	694	1016
Trade balance	11	NA	135 e	138 f	186 f	135 f
Total PE						
Trade balance	83	455 e	354	232	198	284
Bal./Prod. (%)	20.9	34.0	25.4	13.9	9.1	9.5
Bal./Cons. (%)	26.4	NA	34.1	16.1	10.0	10.5
Western Europe(3)						
LDPE						
Production	709 b	2450 j	3800 g	3729 g	5088 c	5529 g
Consumption	706 b	2230 h	3200 h	3433 h	4967 c	5419 h
Trade balance	3	220	600	296	116 c	110
HDPE						
Production	203 a	835 k	1400 i	1559 g	2468 c	2896 g
Consumption	188 a	710 h	1180 h	1365 h	2308 c	3019 h
Trade balance	15	125	220	194	131 c	-123
Total PE						
Trade balance	18	345	820	490	252	-13
Bal./Prod. (%)	2.0	10.5	15.8	9.3	3.3	-0.2
Bal./Cons. (%)	2.0	11.7	18.7	10.2	3.5	-0.2

SOURCES: (a) Pearce and Smith (as quoted in Cleg, 1967); (b) Predicasts *Chemical Market Abstracts* (1966), pp. 1121-1123.; (c) SRI, *Chemical Economics Handbook* (1989, 1990); (d) Ward (1992); (e) Japan Tariff Association; (f) CIS (1987, 1993); (g) APME (1983, 1993); (h) Modern Plastics (various years); (i) Predicasts *Chemical Market Abstracts*, August (1977), section 282,827; (j) European Chemical News, 12 October (1973); (k) Predicasts (1982).

Notes: (1) The source is indicated to the left of each figure. Figures without a source are own calculations. Except when indicated, for the US and Japan consumption is apparent consumption, and for Western Europe the trade balance is obtained as a residual.

(2) In 1991, US data are not production but sales of domestic resin.

(3) In 1981 and 1991, West European data are not production but sales of domestic resin. In 1965 Western Europe refers to EEC and EFTA countries. For other years includes: Austria, Belgium, Denmark, Finland, France, Greece, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, UK and West Germany. 1987 data include Turkey.

Table B.2 Major polyethylene technologists number and location of plants using their technologies, 1992

	Total Operating	North America	Western Europe	Eastern Europe	Far East	Latin America	Middle East	Africa
North American	83	23	20	6	21	7	5	1
Dow	13	4	4	-	4	1	-	-
DuPont	6	1	1	1	2	1	-	-
Phillips	19	5	7	1	5	-	1	-
Quantum	12	2	3	1	3	2	1	-
U.C.	33	11	5	3	7	3	3	1
West European	105	10	40	15	29	9	1	1
Solvay	6	3	2	-	-	1	-	-
Atochem	11	-	5	3	2	1	-	-
Enichem	17	-	9	1	5	1	1	-
Basf	11	2	5	1	3	-	-	-
Hoechst	13	1	5	-	5	2	-	-
Stamicarbon	3	-	1	-	2	-	-	-
BP	13	2	3	-	8	-	-	-
ICI	31	2	10	10	4	4	-	1
Japanese	20	1	3	4	10	2	-	-
Mitsui	15	1	3	4	6	1	-	-
Sumitomo	5	-	-	-	4	1	-	-
Total	208	34	63	25	60	18	6	2

SOURCE: elaboration on CIS (1993).

Table B.3 Polyethylene capacities in developing countries from plants that have started to operate in 1979 or later (000 mt/y)

Company	Location	Capacity in 1992	Resin Types	Start up (approx.)	Licensor
ENIP Polymed	Algeria	48	LDPE	1979	Phillips
Petropol	Argentina	62	HDPE	1982	Hoechst
Polisur	Argentina	120	LLDPE	1981	Union Carbide
USI Australia	Australia	86	LLDPE	1992	Union Carbide
Polialden	Brazil	100	HDPE	1979	Mitsubishi Chem.
Poliolefinas	Brazil	130	LL-HDPE	1992	Union Carbide
Poliolefinas	Brazil	160	LDPE	1982	National Distillers
Polisul	Brazil	220	HDPE	1982	Hoechst
Politeno	Brazil	135	LDPE	1979	Sumitomo
Politeno	Brazil	130	LL-HDPE	1992	DuPont Canada
Daquing Petroch.	China	140	HDPE	1982	Mitsui Petroch.
Daquing Petroch.	China	60	LDPE	1981	Imhausen
Daquing Petroch.	China	60	LLDPE	1988	Union Carbide
Lanzhou Chem. Ind.	China	60	LL-HDPE	1992	British Petroleum
Panjin Complex	China	125	LL-HDPE	1992	British Petroleum
Yangzi Petroch.	China	140	HDPE	1983?	Mitsui Petroch.
Indian Petroch.	India	135	LL-HDPE	1992	British Petroleum
Indian Petroch.	India	80	LDPE	1991	Enichem
Indian Petroch.	India	130	LL-HDPE	1992	British Petroleum
Reliance Petroch.	India	160	LL-HDPE	1992	DuPont Canada
IPE	Israel	96	LDPE	1979	-
Pemex	Mexico	240	LDPE	1980	ICI
Qapco	Qatar	180	LDPE	1980	Enichem
Daelim Industrial	S. Korea	150	HDPE	1988?	Phillips
Han Yang Chem.	S. Korea	80	LLDPE	1983?	Union Carbide
Honam Petroch.	S. Korea	180	HDPE	1980?	Mitsui Petroch.
Hyundai Petroch.	S. Korea	110	HDPE	1991	Phillips
Hyundai Petroch.	S. Korea	60	LLDPE	1991	Stamicarbon(DSM)
Hyundai Petroch	S. Korea	100	LDPE	1991	Basf
Korea Petroch.	S. Korea	120	HDPE	1980	Amocco/Chiso
Lucky	S. Korea	100	LDPE-LL	1988?	Hoechst
Samsung Gen. Chem.	S. Korea	120	HDPE	1991	British Petroleum
Samsung Gen. Chem.	S. Korea	80	LLDPE	1991	British Petroleum
Samsung Gen. Chem.	S. Korea	92	LDPE	1991	British Petroleum
Yukong	S. Korea	136	LLDPE	1990	DuPont Canada
Kemya	Saudi Arabia	340	LL-HDPE	1984	Union Carbide
Sharq	Saudi Arabia	140	LL-HDPE	1985	Union Carbide
Yanpet	Saudi Arabia	430	LL-HDPE	1985	Union Carbide
Polyolefins Co.	Singapore	160	LDPE	1982?	Phillips
Asia Polymer	Taiwan	100	LDPE	1979	Gulf Oil
Formosa Plastics	Taiwan	144	HDPE	1983	Nissan Chemical
Petkim	Turkey	40	HDPE	1985?	Mitsui Petroch.
Petkim	Turkey	165	LDPE	1985?	ICI
Plastilago	Venezuela	60	HDPE	1982	Mitsui Petroch.

SOURCES: *Modern Plastics International*, various issues; CIS (1993); CDS (1982-1984); Longley (1991).

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