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EVOLUTIONARY AND HETERODOX INNOVATION ANALYSIS -

A STUDY OF INDUSTRIAL AND TECHNOLOGICAL DEVELOPMENT IN PROCESS CONTROL AND INFORMATION TECHNOLOGY

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Rijksuniversiteit Limburg te Maastricht, op gezag van de Rector Magnificus, Prof. Dr. F.I.M. Bonke, volgens het besluit van het College van Dekanen, in het openbaar te verdedigen op donderdag, 1 december 1988 om 16.00 uur

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1. INTRODUCTION

Judging by the number of recent publications in economics in which technological development is an important subject of either empirical or theoretical study one would suspect that the economic profession has re-discovered technology as a major issue to be studied seriously. In so far as this discovery has led to a growth in the quantity of research coupled with a search for new departures of both theoretical and empirical research, the qualitative yield so far has been moderate. With few exceptions, the present research agenda of mainstream economics has not been changed with respect to basic ideas about technological change and innovation, the character of issues to be studied, the complexity of the subject and the consequences to the measurement of innovation and technology and empirical research.
It is this orthodoxy which led some economists, e.g. Nelson and Winter, to emphasize the need for a widening of the scope of economic analysis, in particular to the understanding of the relationship between technological and economic change[1]. This study is an attempt to contribute to an alternative analysis of technological change in its dialectical relation to changing industry structures. It builds on some older and some more recent contributions to innovation theory and industrial economics which share a common background in their heterodoxy. The emphasis in this study is on some elaborations to these alternative contributions and more particularly on some new departures in empirical research.

This publication is also one of the results of a larger research program at the Centre for Technology and Policy Studies TNO in which technological, economic and social aspects of sophisticated automated manufacturing have been studied. The research program focused in particular on the empirical analysis of this field of

1) See R.R. Nelson and S.G. Winter. An evolutionary theory of economic change, 1982, and also e.g. N. Clark, Introduction: economic analysis and technological change - a review of some recent developments, in: R. MacLeod, 1986.

technological development. Due to the empirical and applied character of the research, theoretical and conceptual elaboration was not an objective in itself. If such elaborations were performed, their function within this research program was narrowly related to the empirical research being undertaken[1]. In the present study attention is paid to both theoretical developments in innovation theory and the testing of an alternative approach to innovation research. The major topics in this research are developments in information technology, process technologies and process control and their interrelationships. The research focuses not only on the analysis of technological development but also on changes in the relevant industry structures and the innovative performance of companies involved in this field.

The research is somewhat experimental reflecting contributions to economic theory made by so-called evolutionary approaches and the interdisciplinary study of technology measurement. The emphasis in this study will be on some heterodox contributions to innovation theory in which the investigation of technological development itself is at the core of the research agenda. In such evolutionary approaches elements of a non neo-classical theoretical framework are found in an analytical framework in which technological development is studied in terms of technological paradigms, basic designs and technological trajectories. Changes in technology and industry structures, disequilibrium, asymmetry of companies, endogenous selection mechanisms and explicit attention to the consequences of technological development are important features of these contributions to an alternative theory.

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1) See e.g. J. Hagedoorn, P. Kalff and J. Korpel, Technological development as an evolutionary process, 1988, R.H. Bilderbeek and B.C.M. Alders, Advanced production systems and training implications, in: W.L. Buitelaar (ed.), 1988 and F. Prakke, Introducing CIM in the factory organization, 1987 for examples of empirical studies within this research program focusing on the in-depth study of technological development.

Such an alternative approach is quite distinct from one taken by the traditional theory of innovation and industrial development. The traditional theory of innovation is to a large extent related to the orthodox theory of the firm based on the paradigm of profit maximization by economic subjects as a behavioural hypothesis. The roots of this neo-classical theory of the firm can be traced back to the theory of value which dominated the second half of the 19th and the early 20th century. Basic notions of the theory of the firm at this early stage were perfect competition and perfect knowledge which together led to the assumption of general equilibrium. Technological change was an exogenous factor and characterized as a smooth process of adoption with gradual changes and universal availability. At the end of the 1920's the Marshallian variant to the classical theory of the firm, which included partial equilibrium, was fundamentally questioned by many economists and in particular by Sraffa, Robinson and Chamberlin. Despite the criticism and alternative theories put forward since then, the basic idea of the present neo-classical theory of the firm, as found particularly in textbooks, has remained largely unchanged as a partial equilibrium analysis assuming profit maximization in an exogenously given environment. The general framework of such assumptions builds on the notions of the company as a "... holistic firm maximizing profits under conditions of complete certainty"[1]. Uncertainty about the outcome of innovative activities, asymmetry of companies regarding the appropriation of returns on innovative inputs and disequilibrium effects of changing market structures are far removed from the basic assumptions of this orthodox theory of the firm.

Within the traditional theory criticism has been countered by technical elaborations and the introduction of theories with more complex configurations of for example multi-product companies and oligopoly. At the same time the assumption of profit maximization has been modified by the introduction of the behavioural assumption of profit maximization in the long run.

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1) D.A. Hay and D.J. Morris, Industrial economics, 1980, p. 232.

At the fringes of the theory of the firm several theoretical contributions were made which culminated in behavioural and managerialist theories. Although technological development and innovation are sometimes mentioned in such approaches they have never been at the core of these particular alternative theories of the firm. In recent years a number of contributions to economic theory have been made in which assumptions from neo-classical inspired theories of technology and economics have been criticized. Contributions such as those made by Nelson and Winter, Rosenberg, Dosi and Freeman and his colleagues, to name but a few contributors to the debate, are not only interesting with respect to theoretical issues but they also provide some analytical tools for empirical research on technological development. It is in particular in the context of the empirical research undertaken in this study that such contributions will be analyzed and, if necessary, elaborated upon.

In any study, choices have to be made regarding the theoretical background and whether to incorporate particular theorems. In this study a choice is made for contributions which are somewhat off mainstream economics. Making such a choice does not imply that there are no interesting theoretical developments being generated within particular schools from more conventional economic theory. Many modern theories of innovation, which are still influenced by neo-classical theory, go beyond some of the more simplistic assumptions of orthodox theory mentioned before. In modern theory of innovation a substantial share of the analytical-theoretical contributions is based on game-theoretic approaches[1]. Analytical and mathematical rigour is characteristic of such approaches and empirical analysis is usually not a major effort as the analytical structure is central to this approach. Applied and also empirical research have recently been put on the agenda of such approaches but the analytical content sets certain standards to the 'quality' of empirical material which will sometimes appear to be too

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1) See e.g. M.I. Kamien and N.L. Schwartz, Market structure and innovation, 1982 and A. Jacquemin, Sélection et pouvoir dan la nouvelle economie industrielle, 1986.

high for particular categories of empirical research. In this study an attempt is made to apply empirical research with an experimental, analytical framework in a relatively unknown, and in a sense, new industry which lacks official statistical data. Under those circumstances in which the discovery of elementary empirical facts and data were essential certain standardized methods of empirical research such as survey research seemed more appropriate.

In many of the contributions to innovation theory to be discussed an effort is made to widen the scope of research and theory. As such an effort is made to pay attention to some heterodox theories of technological and industrial development. In particular, theories and research inspired by Schumpeter and Marx are truly unorthodox in the sense that they diverge from conventional approaches. Both these approaches stand out in the history of economic theory as contributions in which innovation plays a more than complementary role. From the perspective of a search for new departures as they appear in the innovation literature it will be useful to discuss both the original contributions by Marx and Schumpeter and the debate that followed the neo-Schumpeterian and neo-Marxist traditions, as well as some other heterodox contributions labelled as evolutionary approaches.

Whereas Schumpeter's contribution fell largely within the accepted academic tradition of economic theory much of his work was nevertheless largely neglected until a decade ago. As will be explained in chapter 2, his contribution stands out with respect to the attention paid to the effects of technological development on the dynamics of a capitalist economy. Although Schumpeter is often referred to as one of the economists who paid considerable attention to innovation one sometimes gets the impression that few have actually read a substantial share of his contributions to the subject. His theory is still intellectually stimulating and relevant to modern analysis of technological development. I believe that the elaborations upon his work as undertaken in the following chapters will demonstrate the legitimate character of such an exercise. Of course, Schumpeter's theory has certain flaws, but

I believe it goes too far to accept Thirtle and Ruttan's recent criticism that "... the Schumpeterian system has remained an obstacle to the efforts by economists to understand the process of technical innovation"[1]. A more subtle appreciation of the Schumpeterian system will enable me to assess some modern neo-Schumpeterian contributions, relevant to analyzing changing industry structures and the innovative performance of companies, in the light of their antecedents.
Many of the present issues in the debate on innovation and its economic consequences were already discussed by Schumpeter although their presentation is not always very convenient. Schumpeter discussed innovation with respect to the role of the entrepreneur but also as an endogenous factor effecting economic change through large science based companies. As will be demonstrated in the analysis of the Schumpeterian system, Schumpeter's theory leaves more opportunity for subtle theorizing than could be concluded from many superficial interpretations of his contributions. In particular Schumpeter's advice to study the destruction of the older and the creation of new industry structures coupled with the analysis of company behaviour appears fruitful for any attempt to analyze industrial change.
Contrary to Schumpeter, Marx has hardly been accepted within the economic profession although his name is frequently mentioned when the relationship between economic and technological development is discussed. Marx's theory can be seen as one of the earlier contributions to evolutionary theory of economic change in which technological development played a substantial role. In his theory technological development acted as a disequilibrium force generating at least part of the causes of economic crises. Marx was also one of the first to stress the growing importance of the interaction of science and technology in modern capitalist society. And like Schumpeter he discussed transient monopoly and incidental extra profits as a stimulus to innovation.

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1) C.G. Thirtle and V.W. Ruttan, The role of demand and supply in the generation and diffusion of technical change, 1987, p. 5.

In this study I can only assess the relevance of Marxist contributions to some major issues in industrial economics and innovation theory. It is definitely not an objective of this study to contribute to a general theory of radical economics. From the perspective of radical economic theory the objectives of this study are rather pragmatic. Just as much as it could be helpful to conventional theory to widen its scope it could be useful to a neo-Marxist approach to consider some innovative changes in its theoretical background.

The choice for a study of contributions from such unconventional theories in order to widen the scope of the present research agenda does not necessarily lead to the acceptance of the complete theory of such schools of thought and neither does it have to lead to a superficial synthesis of particular aspects. What it can do is to demonstrate that particular issues in innovation theory are not as new as one is sometimes inclined to assume. Going back to the classics can also prove to be useful to understanding the theoretical background of modern theories.
In some neo-Marxist theories as well as in some neo-Schumpeterian theories economic and technological development is analyzed in the context of the role large, multinational companies play. In such approaches monopoly is no longer size-independent and short-run but a long-run and static phenomenon and technological development is no longer a dynamic factor but subordinate to the strategy of a small number of dominant companies.
In some other attempts to analyze and theorize the relationship between technology and the development of markets and companies, the relationship between company size, market structure and innovation has been a major focal point of research in the past decades. The results have been somewhat disappointing compared to the intellectual investments made. Some advantages have been made by including technological opportunity as a factor explaining sectoral differences. In this study the scope of the analysis is widened by including not only technological opportunity but also a categorization of companies and a set of different innovation strategies. Such an approach allows one to take into account the

complexity and differences in technological developments, the non-uniformity of companies and the alternatives in company-behaviour. Such a more differentiated analytical setting in which a number of behavioural alternatives are introduced is an immanent criticism of the Marshallian theory of the 'representative firm' typical for a particular industry. It is also different from attempts to analyze company behaviour and industry structures form a theory of successful firms as e.g. advocated by Arnold[1]. I agree that "... a theory which describes the whole universe of possible firm behaviour is likely to be so broad as to be of little use ..."[2]. However, I fail to see why the analysis should be restricted to successful firms which 'survive major technical changes in a similar market as before'. First, as will be demonstrated below, it is possible to abstract from the whole universe of firm behaviour into a number of relevant strategies. Second, the search for a theory of only successful firms is a too restrictive objective which could be compared to e.g. medical science studying only healthy people and psychiatry to theorize sanity without reference to other mental conditions. Third, in such an approach the dynamic perspective is lost because todays success is no guarantee for success during the day-after-tomorrow. Fourth, technology becomes an exogenous factor if success is studied in terms of surviving technical change quite passively while, if technical change is taken to be more endogenous, different strategies have various effects on introducing technical change. And finally, a study of the effects of technical change on company success has to been seen within the interaction of different categories of companies in the wider context of competition and changes in industrial structures.

The alternative analysis of technological development in evolutionary theory is reflected in an analytical framework which features concepts which are quite different from those applied in more conventional research. Technological development can be analyzed in terms of changes within or from existing technological

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1) See E. Arnold, Competition and technological change in the television industry, 1985.
2) idem, p. 9.

paradigms of major fields of technology. Such an analysis provides the very first insights into changes in technology. For a more applied economic understanding of these changes it will be necessary to achieve a more concrete understanding of changes in so-called technological trajectories and basic designs.
In such a framework, to be elaborated upon below, it is possible to pay attention to both gradual and more radical changes which characterize technological development. Another feature of the analysis in this study is the integration of diffusion and innovation as different aspects of technological development. In this integrated approach concrete innovative aspects of technological development are seen as a process of both the creation of new products or processes and the incremental change of technology in a process of diffusion which is not just a matter of adoption but of gradual change during the dissemination of an innovation or a new technology.

The emphasis in this study is on the feasibility of empirical research on technological development and changes in industry structures with an alternative analytical framework. Such an approach places certain limitations on the number of technologies and sectors of industry to be studied. In the research program of which this study is a part, process control technology was chosen as a core technology. Studying this field of technology enables me to pay attention to a number of other technologies which interact with modern control technology, i.e. information technology and process technologies. Furthermore, the economic setting of the industry producing process control systems can be related to economic and technological developments in adjacent fields of production.
Process control is a field of technology in which systems and stand-alone equipment are applied to regulate, determine and maintain the desired values and conditions of production processes. In the past hundred years the technology has changed from simple manual process regulation to advanced automatic control. There are still some differences between control in so-called discrete manufacturing with CAD/CAM systems and process control systems, but in

particular the system architecture and general features of control in both forms of production demonstrate similar trends in control technology.

As mentioned before, process control technology is at the intersection of a number of technological developments in process industries and information technology. Due to this interaction attention can be concentrated on a larger number of trends in technological development than would be the case in a straightforward single-sector study. Both the sectoral and technological developments are studied in the wider context of related sectors and technologies.
Another feature of this study is the choice of a sector of industry in its international setting which is neglected in official economic statistics. The sector emerged from the traditional measurement equipment sector and developed into a sector closely related to the electronics and information processing sector. One of the objectives of this research is to demonstrate the possibilities of economic research on 'new' sectors before official statistical information has caught up with changes in the industrial structure. The lack of such official information sets certain limitations to the quantity of information. This shortcoming can only be countered by developing one's own material. In this study survey research was chosen as the major source of information on the industry structure and innovative performance of companies. As far as the information on innovative performance is concerned survey research has had particular advantages for the present research, in which indicators of innovation have been applied which differ to a large extent from those applied in most other studies. This approach enabled me to study the actual companies producing process control systems and devices and to develop original indicators of technological development and innovation which suit the analytical framework and the complexity of the specific sector. The size of the survey is rather limited since it refers to 56 companies. Despite the small number of companies the survey has some important features which increases the relevance of the information and go beyond the significance in terms of

sheer numbers. First, the survey is not restricted to a national sector but it covers the international process control industry. Second, more than 80% of the world-leading companies in de industry participated in the survey.

In the following chapters the theoretical background of the present study will first be developed and the empirical analysis will then be presented in relation to this background.
Chapter 2 focuses on the classical contributions to innovation theory made by Marx and Schumpeter. The general background of their theories and some major issues with respect to economic and technological development will be the subject of a critical review. Particular attention will be paid to those subjects which are still discussed in the modern literature such as the role of different categories of companies, innovation and monopoly, the endogenous or exogenous character of technical change, and the attempts made to understand technological development as a process of evolutionary change.
In chapter 3 the 'offspring' of Marxist and Schumpeterian theories is discussed in order to investigate whether some dead-ends in the original theories have been overcome in modern versions. A part of the debate in these theories concentrates on the subject of the relationship between size of companies, monopoly and innovation. The impact of both theoretical and empirical studies will be discussed. In both neo-Schumpeterian and neo-Marxist theories there are static as well as more dynamic interpretations of the above mentioned relationship. The dynamic approach is extended into a new theoretical framework in which changes in technological opportunities, a differentiation into categories of companies and a set of alternative innovation strategies are incorporated.
At that stage of the analysis the focus of the study switches to one which will pay extensive attention to the analysis of technological development. The objective of chapter 4 is to provide some analytical tools to the understanding of technology and technological opportunities. Major building blocks in such a framework are 'technological paradigms', 'basic designs', 'key-elements' and 'technological trajectories', concepts which can be applied to the

analysis of technological development at several levels of abstraction and in different degrees of generality and particularity. Technological change will be analyzed not only as a development of forward moving frontiers of so-called 'best practice' technologies but also in terms of the pattern of diffusion. That specific context enables me to criticize the traditional static theory of diffusion. In order to limit the abstract character of such a discourse the analysis is applied to the study of technological change and patterns of diffusion of information technology in process control.

Parts of the empirical analysis in chapter 4 are based upon the survey of the international process control industry. The results of the survey and some other empirical inputs are extensively reported and analyzed in chapter 5. This chapter concentrates on the character of industrial change in this sector during the past decades and the role different categories of companies play in generating innovation and technological change. The content of innovation strategies in this sector of industry are analyzed as well. The feasibility of an alternative theoretical and analytical framework in empirical research is demonstrated in particular in chapters 4 and 5.

The general results of this study and the theoretical notions which support the approach chosen are briefly iterated and evaluated in a concluding chapter.

2. MARX'S AND SCHUMPETER'S THEORIES OF INDUSTRIAL AND TECHNOLOGICAL DEVELOPMENT

2.1 INTRODUCTION

The main objective of this chapter is to present an outline and assessment of some of the major issues in the theories of Marx and Schumpeter. In the following I will pay attention to those elements of their theories which are related to issues in modern industrial economics and innovation theory. Both Marx and Schumpeter studied many subjects in social sciences - economics, sociology, political science, economic history - and many of these subjects are far removed from the issues touched upon in this study. It is not my intention to reconstruct the wide bodies of social theory laid out by both. I can only evaluate certain elements of their theories and as such I do not intend to assess all the contributions Marx and Schumpeter made to social science or even just economics.

I will start off with a somewhat broader scope to place both Marx and Schumpeter in their 'theoretical setting'. In reference to their theoretical context it is clear that Marx and Schumpeter came from completely different theoretical backgrounds and eras in the history of economic thought. Marx's writings on economic issues were connected with both theoretical and empirical developments in the second half of the nineteenth century. His theoretical work critically reflected the classical political economy, while the empirical counterpart dealt with the consequences of the industrial revolution and the development of a modern industry, contrasting a previous system which was based upon manufacture.

Compared to Marx Schumpeter's background in economic theory was more diverse and influenced by economists from different schools of thought. It was far removed from classical political economy and clearly embedded in the marginalist tradition. However, Schumpeter's attention to disequilibrium-effects of innovation makes his work distinctly different from orthodox neo-classical economic theory. The attention paid to supply-side factors in economic development, the absence of demand as a major issue, and

the abstraction from the state in most of his considerations places Schumpeter, like Marx, far from the Keynesian tradition. If one is to typify Schumpeter's theory in one word then 'evolutionary' will probably be most appropriate.
Despite differences between Marx and Schumpeter their work does indicate many similar interests. For both, technological development, in Schumpeter preferably innovation, was at the core of their theories. And most important, technological development played an important role in their understanding of evolution in capitalist society. In some of the following sections I will discuss the role technology played in both theories as well as pay attention to the conceptualization of technology by Marx and Schumpeter.

It is well-known that technology in its interaction with economic development still plays a minor role in most of modern economic theory and analysis. Technology is frequently either completely neglected, modelled as the unknown factor, or otherwise 'maltreated'. In both Schumpeter and Marx one finds clear attempts to understand some of what is nowadays known as the 'black box' of technology. In these attempts both paid attention to macro-economic issues as well as issues more closely related to industrial economics and innovation theory. This study focuses on the latter two fields, and in particular on the theories of competition, industrial structure and innovation. It is also in these particular fields of theory that Marx and Schumpeter demonstrated some clear similarities. Here convergence is more vivid than Schumpeter sometimes seemed willing to admit.
It has to be stressed that the objective of this part of my study is not only to point out similarities and achievements of the contributions made to economic theory of Marx and Schumpeter. It is much more intended to assess where both theories are complementary, which elements are in a clear need of elaboration and where 'dead-ends', from the perspective of innovation theory and industrial economics, are to be found. Through this assessment of the works of two of the most influential economists theorizing technological development, the general framework for understanding some modern heterodox economic theory of innovation is set.

In order to get that far in the following sections I will proceed from the more general perspectives of Marx and Schumpeter to specific subjects related to what is nowadays known in industrial economics as 'the continuing debate on market structure, firm size and innovation'. I will first present a short discussion of the theoretical 'antecedents' of Marx and Schumpeter, followed by their theories of technological and economic development. The attempts made by Marx and Schumpeter to conceptualize technology and innovation are also discussed because both stand out as two of but few economists who have something to say about the inside of the 'black box' called technology. From there I will proceed with a comparison and interpretation of both theories with respect to competition, differentiation of company-size and industrial concentration. The final section of this chapter is devoted to an assessment of dead-ends and possible new departures from Marx and Schumpeter.

2.2 MARX AND SCHUMPETER: THEIR THEORETICAL 'ANTECEDENTS'

Some authors, notably Rosenberg and Elliott, stress similarities between Marx and Schumpeter in their common vision on economic progress[1]. Rosenberg mentions that both had similar research agendas which addressed issues such as:

- growth of size of companies and industrial concentration;
- instability and crises within capitalism,
- the destruction of capitalism and arrival of a socialist form of economic organization[2].

Despite such general similarities it must however be made clear from the outset that the works of Marx and Schumpeter are also quite different. Not only do some basic notions have different meanings but their theories and analyses also refer to different periods of economic development and theory.

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1) See e.g. N. Rosenberg, Schumpeter and Marx: how common a vision? in: R. MacLeod, Technology and the human prospect, 1986 and J.E. Elliott, Marx and Schumpeter on capitalism's creative destruction: a comparative restatement, in: Quarterly Journal of Economics, August 1980.
2) See N. Rosenberg, 1986, p. 199.

Marx's theory had been influenced to a large extent by three different social and scientific movements in the late eighteenth and first half of the nineteenth century. Marx's philosophical basic ideas on dialectics and materialism had been formed in a critical reflection of German philosophical idealism and materialism. His socialist political 'praxis' was influenced by French utopian socialism. Marx's theory of economic development and his critique of classical political economics was in particular related to a concrete understanding of economic development in the most advanced capitalist society of the nineteenth century, the United Kingdom, and the to works of English/Scottish classical political economists.

From all the classical political economists it was Ricardo who has had a far-reaching influence on Marx's theory of socio-economic development. Ricardo's contribution to Marx's theory is in particular related to such issues as income distribution between different social classes and the labour theory of value. There is also a line from Ricardo to Marx regarding the understanding of technical progress although Ricardo paid but limited attention to technical development as demonstrated in the earlier editions of the Principles of Political Economy and Taxation. The issue of mechanization was only briefly mentioned by Ricardo in his debate with Malthus on the effects of machinery and accumulation on the rate of profit[1]. It was not until the third edition of the 'Principles ...' that the well-known chapter On Machinery was included. Here Ricardo stressed the consequences of mechanization on the composition of capital, on a constantly rising ratio of machinery to labour, and on the level of employment. Ricardo's chapter on machinery remained somewhat like a 'blank spot' in his general theory. E.g. the substitution of capital for labour contradicted Ricardo's general assumption that capital and labour would grow at equal rates[2].

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1) See G. Claeys and P. Kerr, Mechanical political economy, in: Cambridge Journal of Economics, no. 3. 1981, pp. 253, 254.
2) See A. Heertje, Economics and technical change, 1977, pp. 14-20 and M. Blaug, Economic theory in retrospect, 1983 (1962), for neat 'summaries' of Ricardo's chapter 'On Machinery'.

So Ricardo did pay some attention to technical change but it was examined within a theoretical framework which left little room for technical change. Since Ricardo's theory was based upon his understanding of laws of nature-like developments in the growth of the population and the conditions of production within agriculture, technical development could not be easily integrated into this theory. Technical change is in a sense an irregular process and as such it contradicts Ricardo's understanding of economic development as a universal law-like process[1].

The dynamics within the capitalist system caused by changes in the ratio of labour to capital goods, only slightly touched upon by Ricardo, became a central theme in Marx's theory. In his attempt to elaborate upon Ricardo and understand the dynamics of technical change Marx developed his theory of dynamics within the proportional relation of the elements of the so-called organic composition of capital, a subject to which I will briefly return in a following section.

An earlier classical economist with whom Marx shared an interest in technical change as the development of the process of production and division of labour is Adam Smith. Despite this common interest Marx's appreciation of Smith was rather limited. Marx described Smith as the political economist par excellence of the period of manufacture who "... has not established a single new proposition relating to the division of labour"[2]. Despite these and similar cruel remarks Smith is still generally accepted as the classical political economist whose work on the division of labour has been pathbreaking.

It is well-known that it was Smith's major objective to analyze the 'nature and causes of the wealth of nations'. In this analysis he developed his main argument in which "... changes in productive technique (are) built around the division of labour, both in production and in society as a whole. The division of labour depended on the extent of the market, and the extent of the market depended in turn on the accumulation of stock"[3]. Smith defined this division of labour in such a broad sense that it became identical to

1) See K. van der Pol, Marx contra Ricardo, 1981, pp. 96, 97.
2) K. Marx, Capital I, 1983 (1867), p. 329.
3) G. Claeys and P. Kerr, 1981, p. 251.

technical progress. It referred to both specialization within a particular factory and specialization of companies as single product-line firms. Both aspects of the division of labour were seen as important factors influencing economic growth. He also underlined the relation between technical progress, embodied in new machines, and the division of labour. In Smith's theory extensive attention was paid to the interrelatedness of technical change, division of labour, the growth of production, competition and the role of large production facilities[1)]. Unemployment caused by technical progress was largely neglected in Smith's economics. He assumed that new techniques were biased toward capital-saving. It was acknowledged that in a period of economic growth labour-saving techniques were introduced but these were thought to be primarily introduced to enlarge production while retaining the former level of employment. So, within a general economic equilibrium negative employment effects of technical change are, according to Smith, 'smoothened' by a macro-economic growth of demand.
As mentioned before, Marx was very critical of Smith's theory of the division of labour as a central initiating factor of economic development. According to Marx, Smith neglected the particular historical and economic setting of capitalist society and its relation to the division of labour. Marx also stressed the importance of the division of labour to the production of commodities and economic growth, but he denied the causal relationship between them as is found in Smith's theory[2)]. As far as Marx reflected Smith's theoretical statements on technical change he was in particular addressing Smith's analysis of the manufacture and the division of labour in the narrow sense.

Apart from the critical perception of classical political economics Marx's theory of industrial development and the origin of modern industry has also, to a large extent, been influenced by the

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1) See A. Smith, The wealth of nations, 1985 (1776) and for a summary e.g. M. Dobb, Theories of value and distribution since Adam Smith, Ideology and economic theory, 1981 (1973), H.W. de Jong, Dynamische markttheorie, 1981, pp. 40-42 and M. Blaug, 1983 (1962).
2) See e.g. K. Marx, 1983 (1867), p. 49.

work of contemporary writers on technical development such as Babbage and Ure. In Capital and other publications one has to notice Marx's thorough study and understanding of technological development at a level of detail and in-depth knowledge which probably no economist, including Schumpeter, has been able to meet since. Marx apparently studied a large number of publications on the history of technical change and new developments of technology and science in his time[1]. Those reflections, despite their possible shortcomings, made Marx one of the first economists to understand the importance of the growing interaction between technical and scientific knowledge leading to technology as an important feature of modern capitalism.

Schumpeter's work, like that of Marx, covers a wide body of interrelated fields of social sciences including economics, economic history, sociology and political science. And like Marx, Schumpeter presented his main arguments quite elusory as general laws, exceptions and the wider context are discussed shortly after each other, reflecting his continuous struggle with complexity. In the particular field of Schumpeter's theory to which I will pay attention - his contribution to industrial economics and the theory of innovation - some influences of other economists are worth mentioning.

In Schumpeter's early economic theory, as e.g. laid down in his Theory of Economic Development, the economic system was pictured as a 'circular flow' in which the system would be in a stationary situation with an equilibrium under conditions of perfect competition. Some details of this model will be dealt with below, but here it will suffice to point at its theoretical background. It is important to note that the circular flow is not identical with the stationary state in classical political economics. In particular Smith, Ricardo and Mill had developed, albeit quite different,

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1) See K. Marx's, 1983 (1867), in particular Ch. XV, and K. Marx, Die technologisch-historischen Excerpte, 1981 and Excerpte über Arbeitsteilung, Maschinerie und Industrie, 1982 in which Marx's excerpts on Babbage, Ure, Poppe and others have been published.

theories of stationary state as the far or nearby 'ultimate' destiny of the economy[1]. Contrary to classical theories the stationary state in Schumpeter's circular flow is far from any ultimate destiny of the economy. Schumpeter's theory of the circular flow is in fact a particular treatment of Walras' theory of general equilibrium applied to contrast and explain economic development after a change in existing routines took place through innovation. It has been generally accepted that the influence by Walras on Schumpeter has been decisive in particular on Schumpeter's early writings on economic development and innovation[2]. This influence by Walras gives Schumpeter a certain neo-classical flavour. However Schumpeter's theory is clearly of a non-neo-classical character as price taking and an infinite number of small companies are not relevant. Even the characterization of Schumpeter as a 'non-neo-classical general equilibrium theorist' becomes doubtful in the light of Schumpeter's later works[3].

The influence of the Austrian School on Schumpeter has been moderate in the sense that the latter can by no means be seen as a representative of the Austrians. Schumpeter shared their subjective theory of value and criticism of the classical labour theory of value but the influence of Walras is much more dominant. Schumpeter's theory of a zero rate of interest due to the absence of systematic time preference is an example of his deviation of the Austrians inspired by Von Böhm-Bawerk's theory of interest[4].

Schumpeter's attention to the role of the entrepreneur can be seen in a longstanding tradition of economists. In Schumpeter's (early) theory, the entrepreneur can be described as the change-agent in the circular flow. Classical economists such as Smith, Ricardo and also Marx did not pay too much attention to the role of entrepreneurs as a distinct factor in their analysis. Schumpeter's ideas on the role of entrepreneurs had been influenced by a different

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1) See e.g. M. Dobb, 1981 (1973), passim.
2) See e.g. A. Smithies, Memorial: Joseph Alois Schumpeter, 1883-1950, in: S.E. Harris (ed.), 1951 and R.V. Clemence and F.S. Doody, The Schumpeterian system, 1966.
3) See J.A. Kregel, Is the invisible hand a 'Falacy of composition'? - Smith, Marx, Schumpeter and Keynes as economic orthodoxy in: Cahiers d'Economie Politique, no. 10-11, 1985, p. 48.
4) See J.A. Schumpeter, History of economic analysis, 1986 (1954), passim, for his appraisal of the Austrian School.

tradition with a wide variety of economists like Marshall, Wicksel, Clark, Bentham, the Austrians, Say, Walras, and early French economists[1].

Apart from Walras, one theorist stands out as having had a major influence on Schumpeter's work. At first sight one might not expect Marx to be this theorist who would influence Schumpeter, an economist in the marginalist tradition, to such an extent. Let there be no misunderstanding, there are many differences between Marx and Schumpeter, but they also reached quite similar conclusions e.g. on the future of capitalism albeit from an opposite line of reasoning and conflicting analyses. Here it will suffice to point at (close-)similarities in their theories on industrial evolution, the importance of technological development, monopoly and extra-profits and industrial concentration.

Schumpeter stressed the success of capitalism which would lead to a future of capitalism in which the economic and ideological role of the entrepreneur would become obsolete. Contrary to Marx, Schumpeter prophesized that capitalism would suffer from its success. He did not deny social inequalities, alienation, cyclical crises or unemployment but these dysfunctions are set against the overall economic 'success' of capitalism and unlike Marx they were not seen as causes of the 'decomposition' of capitalism[2].

The differences and similarities between Marx and Schumpeter will be discussed at greater length in the following sections. Here I will only indicate some facets of Schumpeter's theoretical relationship to Marx. To understand Schumpeter's interest in Marx it is probably more accurate to think of the latter as Schumpeter's intellectual 'sparring partner'[3]. In discussing Marx as a sociologist Schumpeter's criticism has been remarkably moderate

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1) See J.A. Schumpeter, Economic theory and entrepreneurical history, in: Change and the entrepreneur, Postulates and patterns for entrepreneurical history, 1949, p. 64 ff., P. Johnson, New firms, an economic perspective, 1986 and L.V.A. Marco, Entrepreneur et innovation: les sources francaises de Joseph Schumpeter, in: Economies et societés, Vol. 19, no. 10, 1985 in particular the latter stresses the nuances in the 'French connection' of Schumpeter regarding the role of entrepreneurs.
2) See e.g. J.E. Elliott, 1980, p. 54 ff.
3) This role is most clear in J.A. Schumpeter, Capitalism, socialism and democracy, 1975 (1942).

demonstrating an almost neo-Marxist reinterpretation of Marx's 'laws of economic history' as also found in contributions by e.g. Gramsci and the Frankfuter Schule. In that context Schumpeter presented an interesting modification of the mechanistic interpretation of Marx's theory of the dialectic relation between the well-known base and superstructure incorporating more complex relations between classes and subclasses[1]. Also, Marx's economic theory was valued as "... the only genuinely evolutionary economic theory that the period (of classical economic theory, J.H.) produced"[2].

Despite the admiration for Marx's economic writings, which one senses throughout Schumpeter's works, he has been very critical about particular elements of Marx's theory. Schumpeter was very negative about the labour theory of value as an economic theory[3]. It would take too long to discuss the issue as such but is clear that Schumpeter was well familiar with the 'weak spots' in this theory as a theory of value and price, the law of the tendency of the rate of profit to fall and the explanation of so-called primitive accumulation. He apparently could find more appreciation for Marx's theory of the dynamics of accumulation and innovation although he emphasized that Marx "... had no adequate theory of the enterprise and his failure to distinguish the entrepreneur from the capitalist ..."[4].

Also Marx's theory of industrial concentration and centralization was generally accepted by Schumpeter. This theory has some similarities with Schumpeter's although the latter stated that Marx's contribution overemphasized the size of individual companies and was unable to theorize both monopoly and oligopoly[5]. This criticism by Schumpeter is somewhat puzzling and can be seen as a case of 'the pot calling the kettle black'. As will be demonstrated below, Marx's treatment of monopoly (and oligopoly, for that matter) is essentially quite identical to Schumpeter's theory. For both monopoly, in particular long-run monopoly, is an exceptional case of industrial organization and not in the core of their theory.

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1) See J.A. Schumpeter, 1975 (1942), pp. 9-20.
2) J.A. Schumpeter, 1986 (1954), p. 441.
3) See idem, passim and J.A. Schumpeter, 1975 (1942), p. 23 ff.
4) idem, 1975 (1942), p. 32.
5) See idem, pp. 33, 34.

So far for a first impression of Marx's and Schumpeter's theory. Details of both theories relevant for the understanding of current industrial economics and technology will be dealt with more specifically below. Here it is important to stress that Marx and Schumpeter paid extensive attention to the dynamics of economic change and technological development.

Differences between the classical political economists and Marx can probably be explained from differences in historical and material background. 'Grosso modo' the model of classical political economics was based upon an understanding of manufacture in the early period of the industrial revolution. The manufacture was an economic system with a rather conservative character with respect to the nature of production and industrial organization. Contrary to the classical economists Marx built his theory upon his understanding of changes caused by the industrial revolution. The rise of modern industry led towards a more 'dynamic model' of economic development[1]. The dynamic aspects of Marx's political economics made him, to quote Heertje, "... the first economist to realize fully the significance of technical change for economics and society. In particular, he realized the significance of the invention and application of new machines for the division of labour, large-scale production, the creation of new products, and the phenomena of concentration and centralization"[2].

Then, if Marx was the first economist to understand the dynamics of technical change, it should be stressed that Schumpeter played an equally important role in pointing at the importance of innovation to economic development, changing market structures and the role of large companies in modern capitalism.

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1) See P.M. Sweezy, Modern capitalism and other essays, 1972, p. 139.
2) A. Heertje, 1977, p. 61.

2.3 MARX'S AND SCHUMPETER'S THEORIES OF ECONOMIC AND TECHNOLOGICAL DEVELOPMENT

Marx and Schumpeter both presented economic theories in which technological development plays a central role. In both theories technological development was introduced to explain economic development as an economic evolution. In Marx's theory there is clearly much concern about the consequences of technological development for the labour-process in general. Marx paid extensive attention to the social and economic consequences of process innovations which led him to formulate the so-called law of the average rate of profit to fall. In developing this theory Marx had some notion of business cycles but it was Schumpeter who became one of the most prominent economists theorizing business cycles and technological development. In Schumpeter's theory of economic and technological development we can observe that, compared to Marx, much more attention was paid to the positive economic effects of both product and process innovations on economic development.

Accumulation, economic crises and technology in Marx

In order to achieve some understanding of Marx's theory of technology and economic development two central concepts of his labour theory of value - surplus value and accumulation - will have to be explained very briefly first.

In Marxist economics surplus value, defined as the increment of the exchange value of labour value over the use value of labour power, can be divided into absolute and relative surplus value. The first is generated by a lengthening of the working day and technical development plays no role in the increase of this absolute surplus value. In the creation of relative surplus value, through the 'curtailment of necessary labour time' technical change is predominant[1]. Mechanization, which Marx observed as a

1) See K. Marx, Capital I, 1983 (1867), p. 477.

major technical trend in the 19th century, plays an important role in enlarging the relative surplus value through an increase of labour productivity and the intensification of labour.
Surplus value is increased if the share of necessary labour diminishes, in other words if the value of wage-commodities falls. This particular value will drop if the socially necessary labour time to produce commodities used for the reproduction of labour power is reduced by means of an increase in labour productivity. It will be clear that in that case the growth of labour productivity in the sector producing wage-commodities is compulsory.

In Marxist theory this process of surplus value creation is closely related to accumulation, which is characteristic for a capitalist economy. Marx explained the relevance of accumulation to capitalism by pointing at a comparison of so-called 'simple reproduction' and 'reproduction on an extended scale'.
In the case of simple reproduction Marx pictured a capitalist economic system which is characterized by a lack of dynamics due to so-called stationary circulation. In short, the yearly value of constant capital applied in the wage-commodities producing sector equals the value of commodities necessary for the reproduction of labour-power in the capital goods producing sector plus a revenue for luxury consumption by capitalists. Or, to phrase it in an other way, in the case of simple reproduction the total surplus value equals the revenues of 'private' capitalist income. There is no economic growth, all net income is consumed and net investment is zero[1]. Marx's description of simple reproduction is a theoretical construct to compare and explain the dynamic character of the capitalist economic system under conditions of reproduction on an extended scale. (As will be demonstrated below Schumpeter applied a somewhat similar method by introducing his concept of circular flow).
Reproduction on an extended scale is characterized by accumulation because surplus value is converted into extra capital, the realized surplus value is as it were largely 'driven back' into companies.

1) See also P. Sylos-Labini, The forces of economic growth and decline, 1984, p. 38.

Through this increased capital a capitalist, or a company, is able to appropriate extra surplus value again. The individual company can enlarge its share in the total surplus value and speed up accumulation of its capital by increasing the relative surplus value. Mechanization of production processes enables companies which apply advanced means and methods of production to gain a temporary extra-profit. Competition plays a stimulating role in achieving these extra-profits first. Marx has phrased the relation between accumulation and competition as follows: "... the development of capitalist production makes it constantly necessary to keep increasing the amount of the capital laid out in a given industrial undertaking, and competition makes the immanent laws of capitalist production to be felt by each individual capitalist, as external coercive laws. It compels him to keep constantly extending his capital, in order to preserve it, but extend it he cannot except by means of progressive accumulation"[1]. In other words accumulation is both the driving force and the cork which keeps the system 'afloat'[2].

Based upon this set of basic ideas and elaborating upon Ricardo Marx made a well-known attempt to explain the consequences of technical development and accumulation in terms of economic crises. In this theory technical development, and gradually also technological development, has to be understood primarily in terms of the growing importance of mechanization.
As such Marx's theory of economic crises goes beyond the horizon of this study. However, even in a very brief discussion of Marx's central theories on economic and technological development one can demonstrate some of his basic ideas on these issues.
In this theory, which caused a continuing debate between (neo-) Marxists, (neo-) Ricardians and the like, Marx developed his vision on the substitution of so-called living labour by so-called past labour, or the substitution of workers by machines, as an

1) K. Marx, Capital I, 1983 (1867), p. 555.
2) In Marx famous work: "Accumulate, accumulate! That is Moses and the prophets!", see idem, p. 558.

important consequence of mechanization. Marx defined this development as the change in the technical composition of capital. This technical composition of capital is determined by "... the relation between the mass of the means of production employed, on the one hand, and the means of labour necessary for their employment on the other'[1]. In terms of value the composition of capital is determined "... by the proportion in which it is divided into constant capital or value of the means of production, and variable capital or value of labour power, the sum total of wages"[2]. According to Marx there is a 'strict correlation' between the technical and value composition of capital. The value composition of capital, as far as it is determined by the technical composition and reflects its changes, is defined as 'organic composition of capital'. Since Marx considered mechanization to be characteristic for capitalism the technical composition of capital consequently rises continuously. Given the strict correlation mentioned above Marx, like Ricardo, presupposed a growing organic compostion of capital, which reflects the growing labour productivity within capitalism[3].

The thesis of the growing organic composition of capital is closely related to Marx's well-known and oft disputed 'law of the tendency of the rate of profit to fall'[4]. As surplus value is related to profit and the rate of profit is expressed in total invested capital it follows that in Marx's theory the growth of the organic composition of capital influences the rate of profit negatively[5].

Marx admits that the effects of the falling rate of profit can be diminished by counteracting influences such as[6]:

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1) idem, p. 574.
2) ibidem.
3) See idem, p. 583.
4) It is a hopeless task to list all serious contributions to the debate, but the more valuable contributions are mentioned in well-known textbooks on Marxist political economics, see also J.E. Roemer, Continuing controversy on the falling rate of profit: fixed capital and other issues, in: Cambridge Journal of Economics, Vol. 3, no. 4, December 1979, I. Steedman et al., The value controversy, 1981 and B. Rowthorn and D.J. Harris, The organic composition of capital and capitalist development, in: S. Resnick and R. Wolff, 1985.
5) K. Marx, Capital III, 1977 (1894), p. 213.
6) See idem, pp. 232-240.

- an increasing intensity of exploitation leading towards an increase of the rate of surplus;
- the depression of wages below the value of labour power;
- the cheapening of elements of constant capital;
- relative overpopulation which limits the speed of mechanisation due to low wages;
- foreign trade by which imports can reduce the value of constant capital and export commodities can, if exported to lower labour productivity countries, be sold above their value leading to higher rates of profits.

In my opinion this enumeration of counteracting influences by Marx has been somewhat arbitrary. The most relevant counteracting influence from the perspective of technological development is the cheapening of elements of constant capital. It is also this development which in collaboration with growing productivity became the 'Achilles' heel' of Marx's theory.

If one evaluates Marx's law of the tendency of the falling rate of profit, both the empirical evidence and logical consistency of the law will have to be considered. Since the growth of the organic composition of capital is the central argument of Marx one should be able to find indications of a long-term increase of e.g. the capital-output ratio[1]. However, so far only contradicting evidence of a long-term (de-)increase of the capital-output ratio has been found[2].

The relevance of this particular issue in Marx's theory has also been questioned by criticizing the logical consistency of it. Without going into any details from the ongoing debate in political economics it will suffice to mention that:

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1) It should be clear that the capital-output ratio can only be interpreted as an indicator because strictly taken the capital-output ratio is formulated in terms of market prices and the organic composition of capital in terms of value, see also J.B. Foster, The theory of monopoly capitalism, 1986, p. 13.

2) See e.g. A. Reati, The rate of profit and the organic composition of capital in West German industry from 1960 to 1981, M.J. Webber and D.L. Rigby, The rate of profit in Canadian manufacturing, 1950-1981, and A. Lipietz, Behind the crisis: The exhaustion of a regime of accumulation, in: Review of Radical Political Economics, Vol. 18, no. 1 & 2, 1986.

- Marx presupposed a very strict correlation between the technical and organic composition of capital, which led him to overlook the differences between physical and value properties.
- If one studies the major reasons for mechanization in capitalism as mentioned by Marx himself there is little reason to assume a gradual decline of the rate of profit. As Van der Pol has demonstrated the grounds for mechanization in Marx's theory can lead to both a decline or a rise of the rate of profit[1].
- Technological development in the capital goods producing sector and the continuous improvement of labour productivity will lower value and prices of capital goods[2].

The issue of a falling rate of profit is not directly related to this study but it reveals Marx's particular emphasis on mechanization, process innovations and 'capital-deepening' as major aspects of technological development. The resulting debate has had a major influence on different schools of political economics and the present mathematical elegance of the debate will ensure the controversy to continue for many decades to come.

Schumpeter on business cycles and technology

By contrast Schumpeter's theory of technology and economic development had far less theoretical pretentions than Marx's. Schumpeter also expected a decline of capitalism leading to a transition into socialism. However, the major factors at work in this process were thought to be much more related to the growing importance of large companies and, as a consequence, the obsolete function of the entrepreneur as the social and ideological 'guard' of capitalism. Technological development in Schumpeter's theory is, as will be explained in section 2.5, also related to the changing role of large companies in modern capitalism. However, I think, it would go too far to suggest a direct relationship between technological development, long lasting gradual economic decline and economic crises in Schumpeter's theory as there is in Marx's.

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1) See K. van der Pol, 1981, pp. 196-203.
2) See e.g. B. Rowthorn, and D.J. Harris, 1985.

Schumpeter's theory of economic development and technology, or innovation, is most well-known as his theory of business cycles. To understand Schumpeter's theory of economic development one has to start off with his model of the circular flow. This circular flow describes a stationary situation of equilibrium and perfect competition similar to a Walrasian state of equilibrium. Every firm is in perfect equilibrium, costs equal income, prices equal average costs and net profits are zero. The circular flow follows from continuous adaptions to small external changes which are 'absorbed' in familiar routines of company-behaviour. In other words, the economic system is characterized by stability and routine. The model of circular flow comes very close to Marx's 'model' of simple reproduction, mentioned above. The main differences between simple reproduction and circular flow appear to be related to the treatment of net profits which are zero in Schumpeter's model and Schumpeter's abstraction from capitalism in his model. The resemblance of both models becomes more obvious if it is noticed that Schumpeter simply redefined net profits into income assuming that owner-revenues are income and not profits as in Marx's theory. The main difference remains in the non-capitalist character of the circular flow, Marx's simple reproduction is also a case of static equilibrium but there labour is exploited and it has no equal access to capital.

Both models have to be seen as theoretical constructs, ideal types in the 'Weberian' sense, or 'mental pictures' in Schumpeter's own words. In Schumpeter's theory equilibrium is not so much the central norm or a direct reflection of economic reality as some authors assume[1]. Equilibrium is much more a simple theoretical norm introduced to explain the disequilibrium-effects of innovation[2]. Through innovation the economic system is driven away from the 'neighbourhood of equilibrium', Then, gradually as the effects of

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1) See e.g. A. Smithies, 1951 and W.F. Stolper, Aspects of Schumpeter's theory of evolution, in: H. Frisch, Schumpeterian economics, 1981, p. 33.

2) This holds only for Schumpeter's treatment of the subject in his early writings. In Capitalism, Socialism and Democracy, 'perfect competition' and 'equilibrium' were no longer applied to explain economic development.

innovation 'wear off' a new neighbourhood of equilibrium is restored again.
Innovation is introduced into this model to explain the consequences of discontinual, evolutionary change so characteristic for dynamic, economic development. In the circular flow Schumpeter allowed for economic growth as a continuous stream of small changes adapting to changes in the 'data' of the economic system. Schumpeter explicitly distinguished this economic growth from economic development as a difference between non-dynamic and dynamic change[1]. In his own words "... development (...) is (...) entirely foreign to what may be observed in the circular flow or in the tendency towards equilibrium. It is spontaneous and discontinuous change in the channels of the flow, disturbance of equilibrium, which forever alters and displaces the equilibrium state previously existing"[2]. This introduction of innovation as a disequilibrium force is the primary cause of cyclical movements of a two-phase cycle of prosperity and recession and a new equilibrium in Schumpeter's pure model.

Like Marx's theory of economic crises the theory of business cycles is not a subject of this study as such. Therefore only some brief remarks are made to picture Schumpeter's theory of business cycles. Schumpeter's analysis of business cycles stands out in a tradition of economic theorists like Spiethoff, Robertson, Hansen and also Marx in an earlier period. In Marx's theory business cycles were referred to in many comments. However, Marx unlike Schumpeter, had no theory of business cycles as such, but as the latter stated "... the phenomenon stood clearly before his eyes and he understood much of its mechanism"[3]. In Marx's theory of economic development business cycles have to be seen as a cyclical movement of a falling rate of profit due to a stagnating rate of accumulation within the more general tendency of the average rate of profit to fall.

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1) Schumpeter himself did not favour the term dynamics too much, see J.A. Schumpeter, The theory of economic development, 1980 (1934), p. 64.
2) idem.
3) J.A. Schumpeter, 1942 (1975), p. 41.

Schumpeter's theory of business cycles is apparent in many of his writings, even in his 'early' works, but it is most extensively, although not so conveniently, treated in his, over 1000 pages long, study on the subject[1]. The Schumpeterian model of business cycles actually exists of a framework of a multi-cycle scheme. At the outset there is the so-called 'first approximation' of the pure model of a two phases cycle with a phase of prosperity moving away from equilibrium and a period of recession moving toward a new neighbourhood of equilibrium. The pure model starts off with the circular flow which is disrupted by an innovation, financed not by savings but by bank-credit. Innovating firms are able to achieve extra gains which are reinvested and spur a growing demand for (capital) goods, which in turn will lead to a rise in prices for capital goods. Gradually, the innovators are followed by imitators in a process of diffusion. The entrepreneurs will cause some deflation by repaying their bankloans but meanwhile diffusion still increases output. Prices will tend to fall due to the increasing output and deflation which will cause a change from prosperity into recession.

The so-called 'second approximation' of the secondary wave can be seen as a more empirical construct to be added to the pure model. Here, assumptions of the circular flow such as perfect competition and equilibrium are dropped. The secondary wave comes down to a four-phase-cycle of prosperity, recession, depression and recovery. It includes economic reactions to the first wave such as a spreading of additional income and speculative operations and miscalculations of companies. Growing output leads to a decline in prices which together with excess capacity and miscalculations will create economic losses and a period of recession. A continuing recession leads to a depression, which wears off in a process of liquidation after which remaining companies find new economic opportunities.

1) idem, Business Cycles, 1939. Fortunately, there are many helpful summaries of Schumpeter's theory of business cycles, e.g. R.V. Clemence and F.S. Doody, 1966, P. Sylos-Labini, 1984, A.H. Hansen, Schumpeter's contribution to business cycle theory, in: S.E. Harris (ed.), 1951 and R. Fels (ed.), Abridged edition of Schumpeter's Business Cycles, 1964.

In the end Schumpeter's theory of business cycles leads to a 'third approximation' in a multi-cycle scheme of three cycles of different lengths: Kondratieff cycles of ± 55 years, medium term Juglar cycles of ± 9 years and ± 40 months Kitchin cycles. It is relevant to note that innovation and diffusion are important in Schumpeter's theory of business cycles as they create a 'band-wagon' effect of imitators following the initial innovators. Furthermore, the creation of new industries based upon very important innovations such as railways, electricity and automobiles are to be understood as the origins of the long-term cyclical movement of the economy.

From the above it is clear that the aspects of both Marx's and Schumpeter's theories of technological and economic development discussed above are of a fairly macro-economic nature. To a certain extent this limits the relevance of these particular aspects for this study. However, in both theories much attention is paid to technology as an important factor in economic development and as such they provide a useful background for understanding those elements of Marx's and Schumpeter's theories which are more related to industrial economics.
From the foregoing it is clear that technological development in Marx's theory was restricted to understanding socio-economic consequences of mechanization. Marx's theory led towards a theory of economic crises based upon a law of the falling rate of profit. If anything is clear with respect to this theory, it is Marx's emphasis on the labour-saving, capital augmenting character of technological development. Marx dit not deny the relevance of reverse options as such, but he clearly emphasized one side of the coin. Consequently Marx formulated a theory of technical change and economic development in which the need for accumulation, supported by the possibilities of exploiting new technologies, would in the long run lead to economic decline and recurring economic crises.
Neither Marx nor Schumpeter were too optimistic about the future of capitalism, although both stressed, in somewhat different ways, the achievements of capitalist society. The main cause for the uncertain future of capitalism in Schumpeter's theory had little to

do with technological development as such; in his theory the forces of decline are in principle related to ideological and social consequences of the obsolete role of entrepreneurs. Schumpeter's general theory of economic development and technical change did emphasize the importance of business cycles for understanding long-term economic development. Most relevant issues in Schumpeter's theory of business cycles for the present study are related to the importance of major innovations with their 'bandwagon' effects on the industrial structure and disequilibrium effect of technological change.

2.4 MARX AND SCHUMPETER ON TECHNOLOGY AND INNOVATION

So far, no attention was devoted to Marx's and Schumpeter's conceptualizations of technology. In the foregoing concepts such as technology, technical change and innovation are merely treated as synonyms. In a strict sense this is not correct as each of these concepts, although clearly related to each other, refer to different aspects of the same process of changing or creating products and processes. In this section I will comment on Marx's and Schumpeter's understanding of technical change itself. Both paid extensive attention to this complex subject and the complexity is reflected in their struggle to conceptualize and operationalize their understanding of both organizational and technical aspects of this core-element of their theory. In both theories technical change as such is not explained unambiguously. Marx made an attempt to explain technical change within a systematic explanation of the 'laws of history'. Schumpeter was definitely less ambitious but even this restricted attempt to conceptualize technical change in the context of markets and company-behaviour has left some questions unanswered with a clear need for further clarification.

Marx on the forces of production and technology

Each attempt to understand Marx's theoretical exposition of technical development will have to go back to basic concepts such as 'productive forces' and 'relations of production'. Marx's conceptualization of technical development can be placed under the basic category of productive forces. He applied the concept of productive forces as a synonym for means of production, but also in a wider context where the concept was applied to indicate the 'intercourse of man with nature'. In that wider context the concept of forces of production refers not only to concrete means of production, but also to technique, science and the organization of the production process[1]. Marx's concept of productive forces has to be seen in the light of his thoughts about the growing ability of human beings to control nature. In order to control nature it is not only technique which is applied extensively, but also particular social relations which are established to organize this control[2]. Production relations, or 'formations of social intercourse' in Marx's earlier works, refer to the social organization of the interaction of human beings and nature. Therefore production relations are more than just relations of property, they also comprise relations of (groups) of workers and relations between capitalists.

In this context the oft disputed issue of technological determinism in Marx's theory can be raised. In a simple construct technological development can be seen as the most important element in the development of productive forces as they determine the production relations thereby acting as the 'motor of history'[3]. The popular view of Marx as a technical or technological determinist is frequently 'proved' by pointing at an oft quoted passage in which he writes: "In the social production of their existence, men inevitably enter into definite relations, which are independent of their will, namely relations of production appropriate to a given stage in the development of their material forces of production. The totality of these relations of production constitutes the economic structure of society, the real foundation, on which arises a legal and political superstructure and to which correspond definite forms of social consciousness (...). At a certain stage of development, the material productive forces of society come into

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1) See e.g. K. Marx and F. Engels, 1982, passim, and K. Korsch, Karl Marx, 1972, pp. 167-171.
2) See K. van der Pol, 1981, pp. 121, 122.
3) See M. Pieterson (ed.), Het technisch labyrint, 1981, p. 126.

conflict with the existing relations of production (...). From forms of development of the productive forces these relations turn into their fetters. Then begins an era of social revolution. The changes in the economic foundation lead sooner or later to the transformation of the whole immense superstructure"[1]. A somewhat similar 'example' of technological determinism is found in a passage where Marx states that "... social relations are closely bound up with productive forces. In acquiring new productive forces men change this mode of production; and in changing their mode of production, in changing the way of earning their living, they change all their social relations. The hand-mill gives you society with the feudal lord; the steam-mill, society with the industrial capitalist"[2].

The issue of technical determinism in Marx's analysis led to a long lasting debate and much 'close reading' and few fruitful contributions. An exception is found in Rosenberg's contribution where one learns that in Marx there is little evidence of technical progress as an independent variable in explaining social development. Rosenberg explains that in several passages in the Communist Manifesto, the Grundrisse and Capital one will find anything but determinism on technology. Rosenberg, in my opinion, properly states that the essence of Marx's view is that "... the class struggle, the basic moving force of history, is itself the product of fundamental contradictions between the forces of production and the relations of production. At any point in historical time, new productive forces emerge, not exogeneously or as some mysterious <u>deus ex machina</u>, but rather as a dialectical outcome of a larger historical process in which <u>both</u> the earlier forces and relations of production play essential roles"[3].

By referring to a passage from the Communist Manifesto Rosenberg demonstrates that Marx (and Engels) describe how the discovery of America and other colonies resulted in an expansion of demand, and

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1) K. Marx, Critique of political economy, 1971, pp. 20-21.
2) K. Marx, The poverty of philosophy, 1973 (1847), p. 95.
3) N. Rosenberg, Marx as a student of technology, in: Monthly Review, 1976, no. 3, p. 60, reprinted in: Inside the black box: technology and economics, 1982, p. 38.

how such a growth of the market caused a change from the guilds, through the manufacture, to modern industry. Technical change which played a part in this development is not described as a prime mover by Marx but is much more seen as a derivative of growing markets and needs[1]. Also, the analysis of the origin of the manufacture in Capital I provides little evidence of any sort of technological determinism. Marx explained how the manufactures differ from the old guilds at first only by the larger number of workers in each unit of production. Then he continued to describe how changing relations of production gradually leads towards a new form of division of labour in which technical development is characterized by a 'differentiation of the instruments of labour'[2]. So, in the analysis of the origin of manufacture Marx described a change of relations of production within which the methods of production did not change at first. Then, influenced by the changes of relations of production, there has been a gradual change in techniques.

The issue of technological determinism by Marx is relevant in the light of modern, evolutionary, contributions and the analytical framework which will be discussed in chapter 4. There it will be demonstrated that technological development and company behaviour can be analyzed as changes within or changes of so-called technological paradigms. Within technological paradigms heuristics will lead to basic designs or technological guide posts. These basic designs do not follow deterministically from a given set of technological possibilities. In industrial technology a selection environment of companies, labour relations and the technological community selects particular options. Once a particular design has become dominant trajectories aimed at technological improvements will follow pre-determined lines of development until technological opportunities have been exploited or changes in the selection environment have created other technological options.

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1) ibidem, pp. 59-60 (1982, pp. 37, 38); K. Marx and F. Engels, Communistisch Manifest, 1968 (1872), pp. 41-42 (Dutch edition).
2) See K. Marx, 1973 (1867), pp. 317-347.

It is in that context that Marx's dialectical relation between forces of production and production relations is quite identical to an analysis based upon the dialectical relation between technological paradigms and basic designs, and a selection environment.

If Marx was not a technological determinist one can still wonder whether he did show some technological optimism. In a sense Marx was a technological optimist stressing the importance of science and technology for modern industry as it 'resolved' the old manufacture based economic system. Marx described the 'revolutionary' character of modern industry, its continuous change of technology and its far reaching potentials for modernizing the entire economy. Taken out of its context Marx well-known grandiloquent language in the description of the revolutionary character of modern industry can easily be misinterpreted. However, placed within its context we see that Marx continued to describe the other side of the coin, the social and economic consequences of modern industry to the working class[1]. These social and economic consequences were thoroughly understood by Marx as can be seen from his great emphasis on understanding technological development itself. All this is clearly shown in his analysis of developments of the manufacture, the changed application of machinery and the growth of modern industry. In a particular section of Capital Marx presented an analysis of a process in which changes in the social organization of the labour process and the development of the productive forces gradually introduced a transition of the economic structure of control from guilds to co-operation to manufacture to finally modern industry. In this development, which took place in a relatively short period, there had been an industrial revolution in the continuous mechanization of production. This industrial revolution was situated by Marx in the transition from manufacture to modern industry. A particular feature of this transition from the technical perspective is the substitution of handicraft by

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1) See e.g. K. Marx 1973 (1867), pp. 456-457.

machine-related labour[1]. Such a process of mechanization which began within certain sectors of industry lead to a chain-reaction with further mechanization in various other sectors of industry. Marx placed emphasis on the role that mechanization of the machine producing sector played in the general mechanization process. If the machine producing sector would finally have been mechanized the manufacture itself became completely outlived because at that particular stage even the handicraft-production of machines would be replaced by modern industry[2]. (In a historical comparison this situation is analogous to modern developments in manufacturing whereby robots are building robots, and the circle of automated manufacturing is closed.)

In analyzing the empirics of mechanization Marx mentioned several consequences of this development such as:

- a further division of labour which involves intensifying the labour process;
- the expulsion of 'redundant' workers and the origin and growth of an industrial proletariat;
- the expansion of employment of women and children;
- the growing importance of scientific knowledge to the labour process within modern industry.

The diffusion of mechanization throughout manufacturing led to Marx to formulate his already mentioned alternative political economics in an attempt to assess the far-reaching consequences of the industrial revolution. It will, however, not be necessary to point at the weakness of this attempt once again. It is more relevant to indicate Marx's success in understanding the role of industrial technology and advanced methods of manufacturing in his

1) In this context Heertje mentions the change "... from equipping the men to manning the equipment", A. Heertje, 1977, p. 41, 'Manning the equipment' can be seen as an 'unfortunate' choice of words; Marx and others have demonstrated that in this particular era of industrialization child and woman-labour was frequently misused at an extremely large scale, see K. Marx, 1973 (1867), pp. 372-380.
2) See K. Marx, 1973 (1867), p. 363; see also N. Rosenberg, 1976, p. 66 (1982, p. 44).

time. With this in-depth knowledge of not only economic but also technical and scientific aspects of the major trends in manufacturing he was well ahead of his contemporaries. It enabled Marx to present a powerful economic analysis of the most pervasive technological paradigm of the 19th century.

Innovation and new combinations

In the above I have already stated that Schumpeter was less ambitious in developing his theory of economic development than Marx who attempted to understand social development in all its facets in a 'closed system'. But like in Marx's writings technological development, or more appropriate innovation, played an important role in Schumpeter's economic theory from his early publications to those writings which have been published posthumously. Unlike Marx, who studied technology itself in great detail, Schumpeter appeared satisfied with less understanding of technological development itself. This attitude becomes most clear in the distinction Schumpeter made between invention and innovation. For understanding the economic impact of technology Schumpeter separated the process of invention as an exogenous factor from the endogenous character of innovation. One could state that Schumpeter was not interested in understanding technological development unless it entered into the sphere of circulation or market exchanges[1]. However the picture becomes somewhat more complicated if notice is made of a shift in Schumpeter's theory of innovation from an early interpretation in a model of largely entrepreneurial innovation to a model of large firm managed innovation where technological knowledge including invention becomes endogenous to large companies[2]. In his early works, Schumpeter introduced the concept of innovation to explain the change-over from routinized economic growth in the circular flow to economic development through the carrying

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1) See e.g. J.A. Schumpeter, 1939, p. 84 ff.
2) See also C. Freeman, J. Clark and L. Soete, Unemployment and technical innovation, 1982, pp. 38-43, A. Philips, Technology and marketstructure, 1971, E.S. Mason, Schumpeter on monopoly and the large firm, in: S.E. Harris (ed.), 1951 and N. Rosenberg, 1986, p. 211.

out of new combinations. The description of innovation as carrying out new combinations has been given in most of the literature on Schumpeter; here, the original text will be reproduced to demonstrate the 'width' of his concept as:

"... (1) The introduction of a new good - that is one with which consumers are not yet familiar - or a new quality of a good.

(2) The introduction of a new method of production, that is one not yet tested by experience in the branche of manufacture concerned, which need by no means be founded upon a discovery scientifically new, and can also exist in a new way of handling a commodity commercially.

(3) The opening of a new market, that is a market into which the particular branche of manufacture of the country in question has not previously entered, whether or not this market has existed before.

(4) The conquest of a new source of supply of raw materials or half-manufactured goods, again irrespective of whether this source already exists or whether it has first to be created.

(5) The carrying out of the new organisation of any industry, like the creation of a monopoly position (for example through trustification) or the breaking up of a monopoly position"[1].

Compared to e.g. Marx's concept of forces of production Schumpeter's concept seems to be more of an operational character. Nevertheless, it is still very broad since it encompasses both technical change, diversification and a change in elements of the market structure. Innovation in the Schumpeterian sense deals with new products and processes, product differentiation, new markets, diversification, new raw materials and new market structures. Furthermore, these new combinations will be carried out by new companies replacing the older ones. However, Schumpeter also noted that in modern capitalism large companies become more and more important

1) J.A. Schumpeter, 1980 (1934), p. 66, and also 1939, pp. 84-86.

as innovators. The difference in the role of the innovating new company and the growing importance of 'great combines' in stimulating innovation was seen by Schumpeter as "... the water-shed between two epochs in the social history of capitalism"[1).

Throughout most of his writings Schumpeter referred to innovation as new combinations, but in some publications he also defined it "... as the setting up of a new production function"[2). Whether this reference to production functions was helpful is in my opinion doubtful. As Heertje recalls, Schumpeter introduced different definitions of production functions such as:

a. "(...) the given technological possibilities within the horizon of producers;
b. (...) blue prints, where every element that is technologically variable at all can be changed at will without any expense;
c. (...) a 'realistic' production function, to be constructed on the basis of factual observations of production and factors of production, distinct from the 'logically pure' production function"[3).

All definitions of innovation given by Schumpeter whether related to new combinations or production functions are clearly rather broad and vague. It is obvious that all this reflects his difficulty in 'struggling' with the complexities of technological development.

It should not be a surprise that Schumpeter's attempt to define innovation has been criticized by many authors. These criticisms of his definitions range from 'fuzzy' and too broad on one extreme to too narrow, as it only relates to new firms and new entrepreneurs, on the other[4). The latter criticism 'cuts no ice' if we

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1) J.A. Schumpeter, 1980 (1934), p. 67.
2) idem, 1939, p. 87, see also 1986 (1954), p. 1026-1053.
3) A. Heertje, 1977, p. 100; see also J.A. Schumpeter, 1986 (1954), p. 679, p. 1031 and p. 1031, 1032, for each of these definitions of production functions.
4) See R.V. Clemence and F.S. Doody, 1966, pp. 39-50 for an overview of criticisms.

consider Schumpeter's description of innovation in the broader context of his subsequent writings. The criticism might appear to have some relevance to his concept of innovation in the Theory of Economic Development where he referred to the role of new firms as innovators. Although, as mentioned before, even there Schumpeter explicitely referred to that role in so-called 'competitive capitalism' and not to the later stages of capitalist development. In his subsequent publications large, existing, companies became more important as innovators in modern 'trustified' capitalism. So, in general Schumpeter referred not only to new companies as the main source of innovation.

The objection against the broad character of Schumpeter's definition is to be taken more seriously. In that context one can criticize both the production function and the new combinations sort of approach. A well-known criticism of Schumpeter's definition of innovation as the setting up of a new production function has been made by Lange. Lange argued that there is always a large number, even a possible infinite number, of ways of changing existing production functions. Relevant are only those changes which will lead to an increase in the maximum effective profit[1]. But then Lange proposed in a sense to understand the issue precisely the way Schumpeter apparantly meant to avoid. The latter stressed that his definition is not "... equivalent with 'change in method' or 'change in technique' of production"[2]. In other words Schumpeter's definition of innovation did not refer to a shift along but a shift of the production function itself. Lange is clearly mistaken in assuming the availibility of an almost infinite number of changes of production functions. As will be discussed at greater length in some following chapters, technology does not refer to infinite set of options and solutions to technical problems. In practice these options are limited in general and even more limited to individual companies.

Nevertheless, I think that Schumpeter's reference to new production functions as an illustration of innovation was a bad choice.

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1) See O. Lange, A note on innovations, in: Review of Economics and Statistics, Vol. 25, February 1943, p. 21.
2) J.A. Schumpeter, 1939, p. 87.

Whatever the benefits of production functions for economic analysis may be, it is not a concept which has been very successful in both explaining or understanding the character of technical change in process innovations, let alone product innovations. Furthermore, Schumpeter's definitions of production functions are somewhat vague compared to more generally accepted definitions, which only adds to the confusion in attempting to understand innovations as new production functions.
As mentioned before, also Schumpeter's definition of innovation as new combinations is also very broad as it relates to technical, market and organizational aspects of the subject. All three aspects are important for understanding the complexity of innovation. However, it could be useful to distinguish between them. A preliminary qualification can be made by 'narrowing' the concept in abstracting from organizational and market structure related elements. Then, innovation would be limited to new goods or an improvement of the quality of a good, new or improved methods of production, in other words, product and process innovations. These 'technical' innovations have to separated from organizational innovation and changes in the market structure, although it is obvious that they are related and influence one another.

Another issue which needs some clarification is the role that minor technological changes played in Schumpeter's theory of innovation. It is clear that Schumpeter frequently referred to innovations as more or less radical changes with a great impact on sectors of industry and business cycles . Minor day-to-day technical improvements are apparently less important. In particular in the Theory of Economic Development technical changes based upon existing routines was seen as irrelevant. However, in Capitalism, Socialism and Democracy routinized innovation becomes an important factor in the role large companies play, but the issue as such is not discussed thoroughly. In that sense, Schumpeter's concept of innovation is also too restricted as it abstracts form the subsequent steps of technical improvement once an innovation has been introduced. Therefore modern theories of technological development including learning by using and/or doing are relevant supplementaries to Schumpeter's theory[1].

Both theories, Marx's and Schumpeter's, were early contributions to the social scientists' attempt to conceptualize technological development. No matter which successes have been made in analyzing the effect of technology on economic development since then, the conceptualization itself has been troublesome ever since. The conceptualizations by Marx and Schumpeter provide some useful elements which will be elaborated upon in chapter 4. Here, it will suffice to notice that:

Both Marx and Schumpeter paid attention to the social and economic environment of a technical change. Marx saw technical change in the context of dialectical relationship between the forces of production and production relations. Process innovations (mechanization) were theorized with respect to their consequences to the labour process in general and their relation to both class struggle and competition as inter-capitalist rivalry. Although product innovation was recognized as relevant to economic development, Marx paid relatively little attention to it.

In Schumpeter one observes that both process and product innovation are stressed as important aspects of technical change, which is certainly a 'gain' compared to Marx. However, Marx's theory is of greater use in its conceptual distinction between technical development as such and its economic environment. Schumpeter's definition of innovation including technical, market structure and organizational aspects has made the concept too broad.

Also in another respect Marx's conceptualization is superior to Schumpeter's. Schumpeter paid little attention to technology itself, as it was seen as an exogenous factor until it became endogenous as an innovation. In some of his later work Schumpeter did pay more attention to technological development as an endogenous factor in the development of larger, science-based, companies. In

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1) See e.g. N. Rosenberg, Inside the black box: technology and economics, 1982, pp. 120-140.

Marx, attention to technological development has been more explicit throughout his theory. He has made serious attempts to understand technology, as the application of scientific knowledge to technical development, in its relation to socio-economic development. In that sense Marx's conceptualization of technological development is close to a theory in which an attempt is made to understand innovation, in a narrow sense, as an element of technological development which is influenced by a selection environment.

2.5 COMPETITION, DIFFERENTIATION OF COMPANIES AND TECHNOLOGICAL DEVELOPMENT

As this study of Marx and Schumpeter proceeds to their contributions to industrial economics and innovation theory their theories show more and more convergence. Many differences remain, but on issues such as competition, monopoly, concentration, large companies and corporations the differences are not as fundamental as Schumpeter himself apparently wanted us to believe. Even a major source of theoretical distinction - Schumpeter's emphasis on the critical role of the entrepreneur to economic development - is qualified in favour of the role of large corporations in his later writings to such an extent that the 'gap' between Marx and Schumpeter is not as large as it appears at first.

Competition, monopoly and technical change

Marx's theory of competition has to be understood in the context of the classical economic theory and his own theory of accumulation. In classical economic theory competition, profits and price-determination were related to each other in a way which is quite different from for example present neo-classical economic theory. In Marx's theory, but also in Smith's and in Ricardo's, demand and supply played but a minor role in price determination although they were thought to have a function as a signalling mechanism for changes in the industrial structure. In classical political economics and in Marx's theory price determination has to be seen in the light of the concept of 'centre of gravity'. Smith had chosen the 'natural price', composed of the normal wage, normal rent and normal profit as rewards for production factors, as the 'centre of gravity'. The market price, the actual trading price, could of course deviate from the natural price[1]. In Smith's theory the natural price is a sort of guide-post for competition[2]. For Marx and Ricardo the value of present labour and past labour incorporated in capital goods, which are both applied in production, form the basis for the 'centre of gravity'. So, production prices form the 'centres of gravity' for market prices. Competition and numerous other 'accidental' circumstances such as demand and supply, speculation and temporary monopolies determine the transient changes in market prices[3]. Competition amongst companies is aimed at achieving temporary extra profits in the process of accumulation.

For Marx competition is but a derivative of the process of accumulation, a manifestation of it. Competition has, according to Marx, no impact on the essential features of capitalism[4]. Marx saw competition above all as the result of the development of companies. Competition does not only refer to market relations, the circulation of commodities, but also to the production, realisation and distribution of surplus value. The role of competition in the production of surplus value is in particular related to the capitalist's propensity to increase labour productivity through which a transient extra surplus can be realized by those firms which apply the most advanced methods of production at first.

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1) See A. Smith, 1985 (1776), pp. 160, 161.
2) See e.g. H.W. de Jong, 1981, p. 36, J. Eatwell, Competition, in: I. Bradley and M. Howard, 1982, and P.L. Williams, Monopoly and centralization in Marx, in: History of Political Economy, Vol. 14, no. 2, 1982.
3) See O. Demele and W. Semmler, Konkurrenz und Monopol, in: idem Monopoltheorie, Kontrovers, 1980, p. 13, and W. Semmler, Competition, monopoly and differential profit rates, 1984.
4) See e.g. '... a scientific analysis of competition is not possible before we have a conception of the inner nature of capital...", K. Marx, 1973 (1867), p. 300, and idem, Grundrisse der Kritik der politischen Oekonomie, 1974 pp. 637, 638 and 450, see also S. Kuruma, Marx Lexikon zur politischen Oekonomie, Konkurrenz, 1973 for an overview of all relevant passages in Marx.

Within the circulation of surplus value marketshares of companies and differences in conditions of realization are determined by competition. The distribution of total surplus value is determined by the intersectoral competition of companies which, according to Marx, will lead to a long-run tendency of equal rates of profit in all sectors[1].

Closely related to Marx's theory of accumulation and competition is his explanation of the development of companies or separate units of capital. This refers to the discourse on concentration, centralization and differentiation as different momenta of capitalist development[2]. The nature of the relation of each of these subjects in their dealings with competition and accumulation differs to some extent. Differentiation and concentration are concepts which can be explained by the following quotation of Marx's own explanation of concentration: "With the increasing mass of wealth which functions as capital, accumulation increases the concentration of that wealth in the hands of individual capitalists (...). The growth of social capital is effected by the growth of many individual capitals, and with them the concentration of the means of production, increase in such proportion as they form aliquot parts of the total social capital (...). With the accumulation of capital, therefore, the number of capitalists grows to a greater or less extent"[3]. Marx continued with remarking that concentration is actually identical to accumulation and characterized by two features. "First: The increasing concentration of the social means of production in the hands of individual capitalists is, other things remaining equal, limited by the degree of increase of social wealth. Second: The part of social capital domiciled in each particular sphere of production is divided among many capitalists who face one another as independent commodity producers competing with each other"[4].

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1) See also W. Semmler, Competition, monopoly and differentials of profit rates: theoretical considerations and empirical evidence, in: Review of Radical Political Economics, Vol. 13, no. 4, Winter 1982, p. 41, and W. Semmler, 1984.
2) See H.W. de Jong, 1981, pp. 50-51, and K. Kühne, Economics and marxism, 2 Volumes, 1979, pp. 267-278.
3) K. Marx, 1973 (1867), pp. 585-586.
4) idem, p. 586.

Differentiation, the growth of the number of individual capitals, and concentration are in this manner limited by the growth-rate of the process of accumulation. On the other hand, centralization takes place more or less independently of accumulation and is therefore much more a stimulus for accumulation. Marx has distinguished centralization from concentration as follows: "This process differs from the former (concentration, JH) in this, that it only pre-supposes a change in the distribution of capital already to hand, and functioning; its field of action is therefore not limited by the absolute growth of social wealth, by the absolute limits of accumulation. Capital grows in one place to huge mass in a single hand, because it has in another place been lost by many"[1]. In other words, Marx's definition of centralization is identical to what modern economics somewhat confusingly refers to as aggregate concentration. Competition amongst companies determines the speed and the range of the process of centralization. Companies which have not been able to sell their commodities, usually at the lowest prices, will be taken over or will remain as small companies in certain sectors of industry where centralization has not yet taken place. Centralization in its turn stimulates accumulation of capital. "The means of capital fused together overnight by centralization reproduce and multiply as the others do, only more rapidly, thereby becoming new and powerful levers in social accumulation. Therefore, when we speak of the progress of social accumulation we tacitly include - today - the effects of centralization"[2]. This growth of large combined capitals offers, according to Marx, a base for further development of 'scientifically arranged processes of production'.

Centralization played thus a central role in Marx's theory. The development of joint-stock companies and the increased importance of the credit system are extra stimuli for this process of centralization. In the end centralization could reach the 'theoretical' upper limits in a particular sector if "... all the individual capitals invested in it were fused into a single capital. In a

1) ibidem.
2) idem, p. 588.

given society the limit would be reached only when the entire social capital was united in the hands of either a single capitalist or a single capitalist company"[1]. Such remarks which can also be found at other places in Marx's analysis, have contributed to the development of Marxist theories of monopoly based upon specific interpretations of Marx's discourse on centralization.

Marx himself however paid relatively little attention to monopoly. Monopolistic pricing, as explained above, was seen by Marx as an incident which causes a deviation of the market price from the production price. Such a monopoly was termed 'incidental monopoly', "... which a buyer or seller acquires through an accidental state of supply and demand"[2]. All other references made to monopoly by Marx are also discussed as deviations. Comments on monopoly, trusts and cartels have been added to the original text by Engels[3].

More than monopolization it seems important to note that in Marx's theory disequilibrium effects of competition and accumulation are reflected in concentration and centralization, or internal and external growth of companies, and even the possible growth of the number of companies.

Schumpeter's ideas on competition are not fundamentally different. He did assume perfect competition and equilibrium in the model of circular flow, but these assumptions were dropped in the extended model of the second approximation which allowed for innovation. There, innovation introduces imperfect competition and disequilibrium into the economic system. The introduction of innovation renders entrepreneurial profit to early introducers. This entrepreneurial profit has to be understood as a surplus over cost[4]. The

1) idem, pp. 587, 588.
2) K. Marx, 1977 (1894), p. 178.
3) See e.g. idem, p. 120 and pp. 437, 438.
4) It has to be stressed that Schumpeter considers the income of management and company-owners as wages or costs and not as profits, see J.A. Schumpeter, 1980 (1934), p. 128.

diffusion of an innovation gradually destroys the surplus of entrepreneurial profit in a process of 'progressive diminution'. The entrepreneurial profit, extra profit in Marx's terms, disappears when the innovation becomes part of the circular flow again and price and costs are in a normal relation again[1].

Like Marx, Schumpeter paid but little attention to monopoly as such. In his early writings, in particular in the Theory of Economic Development, it is excluded from the circular flow, although as Chamberlin mentioned it could have been introduced without changing the static character of the model[2]. Once innovation is introduced it has a disequilibrium effect with short-term monopoly revenue until diffusion restores a neighbourhood of equilibrium again. So innovation is in a sense related to monopoly. In Schumpeter's own words: "Since the entrepreneur has no competitors when the new products first appear, the determination of their price proceeds wholly, or within certain limits, according to the principles of monopoly price. Thus there is a monopoly element in profit in a capitalist economy"[3].

In Capitalism, Socialism and Democracy Schumpeter's treatment of monopoly has to be seen in the light of the well-known process of 'creative destruction'. This creative destruction pictures the truly dynamic and evolutionary character of capitalism. Capitalism is seen as "... by nature a form or method of economic change (...which...) not only never is but never can be stationary"[4]. Schumpeter stressed the dynamic element in competition related to innovation which goes further than price competition or quality competition or competition in sales efforts because this form of competition stems from new commodities, new technologies and new forms of industrial organization. Economic change is induced by these new combinations which lead to creative destruction as a process of destroying and reshaping of older into new industrial structures. In that context Schumpeter emphasized that economic

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1) See idem, p. 136.
2) See E.H. Chamberlin, The impact of recent monopoly theory on the Schumpeterian system, in S.E. Harris (ed.), 1951.
3) See J.A. Schumpeter, 1980 (1934), p. 152.
4) idem, 1975 (1942), p. 82.

analysis should not study industrial structures as such, but concentrate upon the investigation of the creation of new and the destruction of existing structures and the role of competition, monopoly and company behaviour in this process.

Monopoly, both short and long-run, is theorized by Schumpeter as an element in the process of creative destruction, as the latter sets theoretical limits to monopolistic behaviour. Short-run monopoly is accepted as a necessity for innovation and technological development. Mason correctly stated that "... the essence of Schumpeter's position is that market power is necessary to innovation and that innovation is the core of effective competition"[1]. The well-known classic Cournot-Marshall theory of monopoly is irrelevant to Schumpeter's theory. If the strict Cournot-Marshall condition of fixed demand for a monopolist is set aside short-run monopoly can be integrated into Schumpeter's model. Then innovation has some features of monopoly but a new combination still has to compete with existing products and demand for it is not given. However, lasting, long-run monopoly will be a rare occasion, according to Schumpeter. The process of creative destruction changes existing structures and new industries are created which surpass existing industrial, structures including monopoly.

In that sense competition and monopoly were not so much opposites in Schumpeter's theory but much more two sides of the same coin.

The above demonstrates that in both Marx's and Schumpeter's theory monopoly, in the sense of long-run monopoly, is considered to be of little relevance to the analysis of economic structures. Economic change, accumulation and competition is much more relevant to both analyses. Marx's theory allows for a distinction of companies into larger and smaller companies within the process of accumulation. The main differences between Marx's and Schumpeter's theory of the subject are related to changing industrial structures and to a certain extent to the centralization of companies.

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1) E.S. Mason, 1951, p. 89.

Schumpeter made a valuable contribution in stressing the relevance of creative destruction to understanding the evolution of industrial structures, a subject to which Marx paid little attention. Marx stressed the importance of centralization, or industrial concentration in modern economic theory, for economic and technological development. As will be demonstrated below Schumpeter paid less attention to the issue in his early writings, but it gained much more attention in later publications.

Entrepreneurs, new companies and large corporations

In modern innovation theory, of which I will address some issues in chapters 3 and 4, much attention is paid to the role played by entrepreneurs, new companies and companies of different sizes. Both Marx and Schumpeter had something to say about the role of each of these 'actors'. Having discussed Marx's theory of centralization it will not be a surprise that in his theory the emphasis has been on the role of large companies. But Marx also mentioned new companies, to which he referred as additional capitals, as creators of innovations in particular in their role of 'incubators' of process innovations. These new companies would serve as an example to existing companies. In the long-run, older companies were expected to develop either into a more 'perfected technical form' or gradually disappear under competitive pressures[1].

Compared to Marx's thoughts on the 'example-setting' relevance of new companies, the role of entrepreneurs was less relevant to his theory.

Like Schumpeter Marx understood the difference between invention and innovation and the different roles inventors and entrepreneurs play. However, both inventors and entrepreneurs receive relatively little attention in his theory. As Rosenberg has remarked "... for Marx invention and innovation, no less than any other socio-economic activities, were best analyzed as social processes rather than inspired flashes of individual genius. The focus of Marx's discussion of technological change is thus not upon individuals,

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1) See K. Marx, 1973 (1867), pp. 588, 589.

however heroic, but upon a collective, social process in which the institutional and economic environment play major roles"[1].

The limited role individual inventors played according to Marx is clearly demonstrated by his remark that a "... critical history of technology would show how little any of the inventions of the 18th century are the work of a single individual"[2].

An equal qualification was dedicated to entrepreneurs. In Marx's theory the dynamics of economic development, technical development included, is not a prime result of entrepreneurial activities. For Marx there is no real difference between the entrepreneur and the capitalist the former only gained his interest as a capitalist. From a Schumpeterian perspective it seems accurate to state that Marx made no clear distinction[3]. However such a distinction would have been inconsistent with Marx's own theory. In Marx's perception of capitalist society economic dynamics result from a process of accumulation which is based upon the contradiction between capital and labour. The efforts of an individual capitalist to introduce process or product innovation become only of some importance to Marx if this development, through a process of diffusion, surpasses the level of pure incidents.

Marx did understand that the original innovators, troubled with high initial costs, could frequently make but little benefit of their efforts. In that context Marx has commented, in his well-known somewhat exaggerated wording, on "... the far greater cost of operating an establishment based on a new invention as compared to later establishments arising ex suis ossibus. This is so very true that the trail-blazers generally go bankrupt, and only those who later buy the buildings, machinery etc., at a cheaper price, make money out of it. It is, therefore, generally the most worthless and miserable sort of money-capitalists who draw the greatest profit of all new developments of the universal labour of the human spirit and their social application through combined labour"[4].

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1) See N. Rosenberg, 1976, pp. 57 and 70 (1982, p. 35 and 48).
2) See K. Marx, 1973 (1867), p. 352.
3) See A.C. Taymans, Marx's theory of the entrepreneur, in: The American Journal of Economics and Sociology, 1951, p. 83, J.A. Schumpeter, 1975 (1942), p. 32..
4) See K. Marx, 1977 (1894).

Schumpeter's theory of the role of entrepreneurs and also his definition of entrepreneurship reveals what is probably the most striking difference with Marx. But also in Schumpeter's own theoretical development there is a gradual but clear change in the role entrepreneurs play. As mentioned before his theory of capitalist and technological development can be categorized into two periods: a period of entrepreneurial capitalism and a period of modern, trustified capitalism. The distinction, frequently made in the literature, is useful and acceptable as long as it 'admits' that Schumpeter paid attention to both entrepreneurial and large company activity in capitalist society. The distinction could be interpreted in terms of different points of emphasis and not so much as a dichotomy[1)].

Schumpeter presented his theory of capitalist development of the entrepreneurial era, which probably coincided with the 19th century, most clearly in his Theory of Economic Development. There, entrepreneurial activity was seen as a third factor of production, next to labour and land. In the explanation of the circular flow land and labour are set in equal terms. Labour, however, is differentiated in directing, creative labour of a higher order and directed labour. Differences between other categories of labour such as productive and unproductive labour, direct and indirect labour, mental and manual labour or skilled and unskilled labour are all neglected as irrelevant to Schumpeter's economic analysis. The decisive element of directing, creative labour is embodied in the entrepreneur. The entrepreneur was defined as the individual who carries out new combinations. In a sense the entrepreneur is the personification of innovation. It is important for understanding Schumpeter's definition to note that the entrepreneur can be both an independent entrepreneur or an employee of a large company with an entrepreneurial function[2)]. A major difference with Marx's

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1) See also F. Chesnais, Schumpeterian recovery and the Schumpeterian perspective - Some unsettled issues and alternative interpretations, in: H. Giersch (ed.), Emerging technologies: Consequencies for economic growth, structural change, and employment, 1982, p.63.

2) See J.A. Schumpeter, 1975 (1942), pp. 74, 75.

thoughts on the entrepreneur as a capitalist is that entrepreneurs are by definition neither inventors, capitalists or a social class. In practice all three can be combined in one person but definitely not necessarily so[1]. In my opinion Elliott is mistaken in stating that "... successful entrepreneurs 'become' capitalists in Schumpeter's analysis" [2]. According to Schumpeter succesful entrepreneurs might become capitalists but they stop being entrepreneurs once they fail to continue to innovate and (re-)return to capitalist routines.

In this early version of Schumpeter's theory capitalists are owners of companies which maintain their existing routines and bankers who provide credit to the entrepreneur. The role of credit for innovative investments is also one of the key differences with Marx's theory in which credit is merely seen as a function in the process of centralization[3]. In Schumpeter's system innovations are introduced by entrepreneurs and financed through bank-credit and not savings. Credit is essential to economic development as a change from the circular flow. It enables the potential entrepreneur to actually become one and, as 'the typical debtor of capitalist society' to reorganize the existing combinations[4]. In stressing the role of the entrepreneur as innovator and debtor Schumpeter presents a definition of the entrepreneur in which risk-taking is less essential as in other well-known theories, in particular those in the tradition of Say and Knight[5].

1) E.g. Thirtle and Ruttan are mistaken if they understand Schumpeter's entrepreneur as inventor, see C.G. Thirtle and V.W. Ruttan, The role of demand and supply in the generation and diffusion of technical change, 1987, p. 3.
2) J.E. Elliott, Schumpeter and the theory of capitalist economic development, in: Journal of Economic Behavior and Organization, Vol. 4, no. 4, 1983, p. 286.
3) See e.g. R. Bellofiore, Marx after Schumpeter, in: Capital and Class, no 24, Winter 1985.
4) See J.A. Schumpeter, 1980 (1934), p. 95 ff.
5) See e.g. L.V.A. Marco, 1986, p. 104.

In Schumpeter the entrepreneur is the true and only economically relevant change-agent of a pre-trustified capitalist society. Elster has characterized Schumpeter's entrepreneur as both a rational and irrational motivated agent. The entrepreneur's behaviour "... is rational in the sense of successfully exploiting the objective possibilities of innovation, yet irrational in that he is ridden by a demon who never lets him be satisfied by results"[1].

For understanding Schumpeter's perception of modern capitalism the later version of his theory of the firm is more appropriate. In Capitalism, Socialism and Democracy Schumpeter pictured the diminishing importance of the entrepreneur who loses his function as the agent who changes existing routines. Economic development gradually becomes 'depersonalized' and 'automatized'. Consequently, "... innovation is being reduced to routine. Technological process is increasingly becoming the business of trained specialists who turn out what is required and make it work in predictable ways"[2]. This routinization does not only take place in large companies but it is clear that Schumpeter also acknowledged the growing importance of incremental technological change pursued by these large companies. In one of his last and relatively unknown publications Schumpeter returned to the subject of routinized innovation in large companies. There the role of entrepreneurial activity is stressed again but now in the importance of co-operative entrepreneurship in large companies. Somewhat surprisingly Schumpeter even mentioned the possible role of entrepreneurial change-agent for other organizations than companies, e.g. the role of state agencies[3].

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1) J. Elster, Explaining technical change, 1983, p. 120.
2) See J.A. Schumpeter, 1975 (1942), p. 132.
3) See J.A. Schumpeter, Economic theory and entrepreneurial history, 1949, p. 71, where the role of state agencies such as the US Department of Agriculture is discussed. As a side step I would like to point at the political economic consequences of this attention for creative labour other than the single person entrepreneurial activity known from Schumpeter's early writings. If entrepreneurial activity has become co-operative action instead of the 'heroic' creative labour of a single entrepreneur it can also be a form of combined creativity of others than just management.

The disappearance of the entrepreneur as the only change-agent in capitalism has far reaching consequences. Schumpeter, like Weber, stressed that rationalization and bureaucratization had become major trends in modern capitalist society[1]. The final consequences of these features of modern capitalism is that, according to Schumpeter, it evolves towards a socialist society as the 'bourgeoisie' will lose its social and ideological defender. The issue as such goes beyond the aims of this study but an often quoted and clarifying passage can reveil much of Schumpeter's far reaching conclusions. There it is stated that, "... if capitalist evolution - 'progress' - either ceases or becomes completely automatic, the economic basis of the industrial bourgeoisie will be reduced eventually to wages such as are paid for current administrative work excepting remnants of quasi-rents and monopoloid gains that may be expected to linger on for some time. Since capitalist enterprise, by its very achievements, tends to automize progress, we conclude that it tends to make itself superfluous - to break to pieces under the pressure of its own success. The perfectly bureaucratized giant industrial unit not only ousts the small or medium-sized firm and 'expropriates' its owners, but in the end it also ousts the entrepreneur and expropriates the bourgeoisie as a class which in the process stands to lose not only its income but also what is infinitely more important, its function"[2].

For the study of industrial economics it is relevant to point at the role of large companies which is quite similar to their role in Marx's theory. Schumpeter acknowledged that in a world of large companies small companies can play some role. He even stressed that large companies not only destroy but also create some sub-markets for small companies[3]. However, as a whole modern capitalism would, according to Schumpeter, gradually become dominated by 'big concerns'.

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1) See also J.A. Foster, The political economy of Joseph Schumpeter: A theory of capitalist development and decline, in: Studies in Political Economy, no. 15, Fall 1984, pp. 16, 17.

2) J.A. Schumpeter, 1975 (1942), p. 134.

3) idem, p. 140.

It is in the analysis of the role of large companies in modern capitalism that one is to observe a high degree of convergence between Marx's and Schumpeter's theory. As mentioned above, both stressed the consequences of industrial concentration, or centralization in Marx's terminology, for technological development and capitalist society at large. They also demonstrated a joint belief in the remaining, albeit petty, role of small companies next to large companies in some market-niches.

Schumpeter's theory on the role of large corporations in modern capitalism led him to formulate its far reaching consequences for capitalist society in its transition to a socialist economy. In a sense Marx's theory has some similar aspects referring to the declining function of the entrepreneur as a capitalist in a capitalist society. In one of the, in my opinion, most remarkable and inconsistent parts of Marx's theory there is a discourse on centralization and joint-stock companies. In a short paragraph on the 'historical tendency of capitalist accumulation' it is outlined how the expropriation of capital will be executed by "... the action of the immanent laws of capitalist production itself, by the centralization of capital"[1]. Marx explained how the number of 'magnates of capital' is constantly reduced by competition, economic crises, and the process of concentration and centralization. This leads towards a critical limit within capitalism as the "... monopoly of capitalism becomes a fetter upon the mode of production, which has sprung up and flourished along with, and under it. Centralization of the means of production and socialization of labour at last reach a point where they become incompatible with their capitalist integument. Thus integument is burst asunder. The knell of capitalist private property sounds. The expropriators are expropriated"[2]. Even if one takes into consideration that Marx thought in terms of 'tendencies' if referring to 'laws', and his theory at this point was not well developed, it all remains dubious. Apart from the fundamental criticism of the deterministic

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1) K. Marx, 1973 (1867), p. 714.
2) idem, p. 715.

and mechanistic character of Marx's exposition one can add more detailed criticism to his conception of capitalist economic development. Marx presupposed that concentration and centralization would lead towards an antithesis of the capitalist mode of production and the existing production techniques and organization of production. It is evident that for many technological developments predominated by large-scale production a certain minimal plant-size and probably also company-size is indispensable. Apparently there is some relation between concrete forms of centralization and the development of forces of production in those companies, but it is unclear why this should have such far reaching consequences as the transition of capitalist society as a whole into socialism.

Marx based himself on the assumption that the development of 19th century modern production technology and the organization of production developed by capitalist companies themselves would eventually contradict private property of capital.

Marx also presupposed that concentration and centralization occur in all sectors of industry to a similar extent or these tend to converge to an equal rate across the economy. There are, however, structural differences between branches which leads towards a sectoral differentiation of capital. The growth of large-scale production with but a few companies in some sectors does not imply that this process takes place to an equal degree in all other sectors. Furthermore, large-scale production does in some cases create favourable conditions for establishing small independent suppliers which can operate along-side large companies.

The immanent tendency which Marx discussed while analyzing concentration and centralization appears to be the fruit of an exaggerated deterministic interpretation of one aspect of social history. In this interpretation concentration and centralization have been ill-expressed as a linear and irreversible process which would also contradict the nature of the capitalist mode of production[1].

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1) Similar reservations about these aspects of Marx's theory are found in A. Cutler, B. Hindess, P. Hirst and A. Hussain, Marx's Capital and Capitalism Today, Vol. 1 and 2, 1977 and 1978, p. 148 ff.

Marx exposé on the role of corporation and joint-stock companies has to be seen in the context of the above mentioned. The role of corporations and joint-stock companies in Marx's theory is closely related to both competition and the growing importance of credit which are described as the two 'most powerful levers of centralization'[1]. In the above it has already been stressed that accumulation is a slow process compared to centralization; in centralization the 'economic time' is reduced substantially[2]. Marx mentioned corporations which have brought about large projects such as in shipbuilding, railroads and harbours through their financing in a much shorter period than would have been possible in the case of accumulation of distinct capitals[3].

In Marx's brief remarks about the credit-system the following three developments resulting from the creation of corporations or joint-stock companies were specified:

- "An enormous growth of the scale of production and of enterprises, that was impossible for individual capitals"[4].
- Capital as a corporation would cease to be private capital and become based upon a 'social mode of production'. Marx referred to 'social undertakings' and went as far as to state that such corporations are to be understood as "... the abolition of capital as private property within the framework of capitalist production itself"[5].
- Capitalists are separated into two social categories: managers, administrators of capital, and capital-owners as money-capitalists. Here Marx showed himself as a radical 'managerial economist avant la lettre'. The divorce of ownership and management is, according to Marx, the ultimate development of capitalism and a prerequisite transitional phase into socialism of associated producers. It is worth mentioning that also Schumpeter

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1) See K. Marx, 1973 (1867), p. 587.
2) See H.W. de Jong, p. 92 ff.
3) See K. Marx, 1973 (1867), p. 588 and idem, Capital II, 1977 (1885), p. 481.
4) K. Marx, 1977 (1894), p. 436.
5) ibidem, I think the original German text on this issue is much more strongly phrased than the English translation.

stressed this separation of ownership from management in large companies as important steps in the 'depersonalization' of capitalism[1].

Marx understood the corporation as the abolition of the capitalist mode of production within capitalism, 'a self-dissolving contradiction', which can be described as a phase of social transition. However, it is also noted by Marx in his turged way of phrasing that it "... reproduces a new financial aristocracy, a new variety of parasites in the shape of promotors, speculators and simply nominal directors; a whole system of swindling and cheating by means of corporation promotion, stock issuance, and stock speculation. <u>It is private production without the control of private property</u>"[2] (e.a. J.H.).

Marx's treatise on the corporate and joint-stock company does illustrate his understanding of the role corporations play in the process of centralization and the effect of 'tempo profit' due to corporate organization of capital. On the other hand Marx's analysis of corporations also demonstrates a number of serious shortcomings and fundamental errors. As mentioned before, Marx did not explain why the corporate organization should contradict the capitalist mode of production. The introduction of the predicat 'social' to corporations and the attention paid to the separation of property and management are too easily interpreted as a necessary 'overriding' of the capitalist mode of production. The description of the financial structure of the corporation, in which an 'exaggerated' terminology is applied in order to picture both parasitic relations and fraud, does not capture the essential intertwining of corporate power in present capitalism. I think Cutler et al. are right as they state that "... in his treatment of stock-companies and financial markets Marx reveals his failure to theorize the enterprise, rather than the 'capitalist', or to conceive of finance capitalist enterprises"[3]. Marx's analysis of the enterprise as a structural element of the capitalist mode of

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1) See J.A. Schumpeter, 1975 (1942), pp. 141, 142.
2) K. Marx, 1977 (1894), p. 438.
3) Cutler et al., 1977, p. 154.

production remains largely limited to 'the' capitalist as 'ideal-type'. Consequently the change from the classical to the corporate enterprise is overstated as a step towards a socialist mode of production, instead of stressing its importance as an essential change within capitalism.

From the above it becomes clear that Marx and Schumpeter shared many aspects of their views on the role of different categories of companies. Even though they had different conceptions of 'the' entrepreneur, the future of either the entrepreneur/capitalist or the entrepreneur/innovator was foreshadowed in both theories as dim. Both were correct to see a diminishing role of owner-capitalists or owner-entrepreneurs in modern capitalism. But I fail to see why this would lead to a fundamental transition from capitalism into socialism. In that context Schumpeter and, in particular, Marx overemphasized the change-over to corporate company structures. If both Marx and Schumpeter had paid more attention to their own arguments and analyses of dynamic development in capitalism their theories would not have had that particular 'teleological' character. Without this superfluous part of their theories the dynamic elements in their analyses are most valuable. Then it is relevant to point at their, albeit somewhat different, analyses of the separate roles played by large, powerful companies, small companies and/or new firms in a process of accumulation, restructuring and competition.

2.6. DEAD-ENDS AND ROADS TO PURSUE

The issues discussed in the previous sections are those which I perceive as most relevant in the light of what is to follow. Both, Marx and Schumpeter, have dealt throughout their work with many issues still relevant to modern economics. E.g. issues related to industrial concentration, size of companies and technological development have been theorized in their work. During the development of their theories changes in emphasis, in particular in Schumpeter's theory, did occur. Such changes provide opportunity for several interpretations of their work. It is no surprise that

one finds several interpretations of both Marx and Schumpeter in the literature. Furthermore, both presented their theories without the rigour which we have come to know in present industrial economics. However, the very strict formulations in economics can also redefine complexity in an artificial manner[1]. To a certain extent Marx's and Schumpeter's treatment of technological and economic development reflects both the complexity of the issue itself and their struggle in combining theory and empirics.
The fact that Marx and Schumpeter have reached similar or very close conclusions on many topics is still somewhat surprising since they came from such different traditions in economic theory. After all, Marx's theory was, despite his criticism, deeply rooted in classical political economics. Schumpeter, the 'bourgeois' Marx, came from a completely different background and was influenced by the marginalist school. The (close) similarities and the differences will be discussed as far as they lead to conclusions relevant to understanding modern, heterodox, thoughts in industrial economics. In particular starting-points for the study of technological development and industrial change will be disclosed.

A major shortcoming of Marx's theory of economic and technological development, and also a dead-end for innovation theory, is the emphasis Marx laid upon the far-reaching consequences of process innovations. Technology played an important role in Marx's theory of the value-composition of capital, elaborating upon classical economic theory, in particular Ricardo. Mechanization, undoubtedly the major technical development in the second half of the eighteenth century, was theorized by Marx not only in terms of the technical composition of capital but also in terms of the value-composition. It led Marx to formulate law-like theories on the organic composition of capital and a tendency of the rate of profit to fall and consequently to a theory of economic crises. Marx emphasized the labour-saving character of process innovations and although capital-saving was not denied, the consequences of it

1) The well-known controversy over the so-called Schumpeter-hypotheses and the modelling and empirical research on that topic provides some examples of simplification, see chapter 3.

as such played no role in his considerations. The same can be said about the role product innovations played in his theory. Throughout Marx's works one can find remarks about the relevance of product innovation, but, unlike in Schumpeter's theory, they are neglected within the general framework.

A positive feature of Marx's theory is his attempt to understand technology as an endogenous factor. The theoretical framework of the forces of production and relations of production might be somewhat broad of scope but the dialectical relation between both is important to note. In this theory one can notice that forces of production and relations of production influence each other constantly. In modern economic 'lingo' the above mentioned categories could be translated into technological development and socio-economic selection environment. Within the socio-economic environment Marx stressed that there is not only a relation between capital and labour but also one between capital-to-capital. This leads to an understanding of the economic environment of technological development in terms of a differentiated composition of a group of companies. The notion of the relation between technological development and a socio-economic selection environment is quite identical to Marx's ideas on forces of production and production relations. In the context of this study the relation between technology and economic development can, at first, be interpreted in terms of a classical Marxist relationship. Then, technological development has a twofold character. In itself it is largely influenced by the possibilities and restrictions set by laws of nature. The concrete applications of technology is, however, largely influenced by its socio-economic acceptability and choices made by competing companies. The economic selection environment, relevant to this study, is generated by the complexity of producers and users of particular technologies.

Another feature of Marx's theory worth pursuing is his thorough attempt to understand technology, i.e. the coupling of scientific knowledge to practical production-related problems. In modern industrial economic analysis technological development is frequently abstracted from or reduced to simple indicators. However, the economic study of industrial and technological change could benefit from more in-depth knowledge of technology as such.

Although Marx went as far as to formulate almost his entire theory of economic crises on his understanding of mechanization, it remains relevant to note that, despite his jumping to conclusions, Marx nevertheless attained an unprecedented knowledge of technological development. In the above I have already mentioned that Marx's understanding of the process of mechanization during the Industrial Revolution can be seen as an attempt to understand the consequences of the major new technological paradigm in the 19th century. His study engaged both scientific sources of technological development as well as the technical details of concrete applications. Modern technological development has, of course, become much more complex and more pervasive than in Marx's time. Integrating knowledge of a technological character into economic studies can, by consequence, only be realized through multi-disciplinary co-operation. Attempts to integrate technological knowledge into those fields of industrial economics in which innovation is studied can enrich the analysis and provide the necessary background for interpreting indicators of technological development.

In this context Schumpeter's conceptualization of technological development or innovation can be discussed. Schumpeter demonstrated some interest in technological development but he never went as far as Marx to understand technology specifically. In his theory of economic development technology is both an exogenous and an endogenous factor. Schumpeter was not interested in the 'early' phases, the pre-market developments of technology. In particular in his early writings technology is exogenous and innovation was only theorized as a new combination. In stressing the relevance of large science based companies Schumpeter allowed for technology to become more endogenous to his theory.

Compared to Marx, Schumpeter came definitely closer to economic reality stressing the importance of both product and process innovation. The definition of innovation itself, however, is not too clear. Schumpeter referred to innovation both in terms of new combinations and new production functions. The reference made to a shift of production functions is, in my opinion, not very successful as Schumpeter defined production functions in several ways and the reference remained quite 'fuzzy'. The definition of innovation

in terms of new combinations is also too 'broad', but it can be 'tightened' by separating technical or technological innovation from social innovations such as changes in market structures and corporate organizations.
Schumpeter's focus on innovation as a new combination without too much attention for technological development as such did not only result in the abstraction from early phases of technology, it also meant that minor technological changes were neglected. As with the early phases, the importance of later phases of technological development became somewhat more important in Schumpeter's later work.

Both Marx and Schumpeter presented economic theories of technological development in which the dynamic and evolutionary character was stressed. Marx paid extensive attention to accumulation as dynamic evolutionary economic development in a model of reproduction at an extended scale which was characteristic for modern capitalism. Economic growth, of both individual companies and the economic system at large, through accumulation is essential in Marx's theory. Within this process of accumulation competition amongst individual companies regulates the distribution of profits. Extra-profits are gained by those companies which are the first to introduce new technologies successfully until the effect wears off as other companies benefit from the gradual diffusion. Some companies will not be able to catch up in time. In a process of gradual decline they will disappear, some will be taken-over and some might continue for long periods due to particular circumstances. In general it will be a 'game of winners and losers'.
Schumpeter's theory, although differently phrased, is quite similar. In his early theory Walrasian equilibrium is applied in the construct of the circular flow as a theoretical norm. Innovation is a change from existing routines. In later versions of Schumpeter's theory the dynamic character of capitalism and the disequilibrium effects of innovation are stressed even stronger. Throughout his theory Schumpeter paid attention to the profit-seeking stimulus for innovation which through diffusion would cause a bandwagon-effect after the first successful introduction.

The attention paid to evolutionary change, disequilibrium, competition through innovation and the process of diffusion which is to be found in both Marx and Schumpeter has, in my opinion, most valuable elements for understanding present industrial development.

In Schumpeter one can find a useful elaboration upon Marx's thoughts on monopoly and the more general idea of monopoly and innovation or technological change. Marx paid little attention to monopoly, which was considered as an incident, but I suspect that Marx would not object against Schumpeter's notion of an element of monopoly in innovation. Both Marx and Schumpeter paid little or no attention to a relation between long-run monopoly and innovation. In Schumpeter's earlier writings the entrepreneur is able to gain profits, extra-profits in Marx's terminology, through the introduction of an innovation. There is an element of short-run monopoly or market-power in innovation until this short-run monopoly is destroyed through diffusion. In later versions of his theory Schumpeter introduced the concept of creative destruction. Through creative destruction the dynamic and evolutionary character of capitalism is exposed in competition with new technologies and new commodities as a process of restructuring older and creating new industrial sectors. Schumpeter's ideas on creative destruction are most valuable as they surpass the notion of static monopoly. Even if there is an element of monopoly in an innovation it still has to compete with existing products and demand for it is not given. The dynamic character of capitalism with its continuous restructuring and the creation of new sectors makes long-run monopoly a less relevant notion, only applicable under exceptional circumstances.

Industrial concentration and the dominance of large companies in relation to technological development are frequently mentioned within Marxist or Schumpeterian perspectives. It has to be acknowledged that both Marx and Schumpeter provided the arguments themselves, although not always as straightforward as the interpretations of their 'followers'. I would like to broaden the scope again in order to differentiate between several categories of companies.

Marx stressed the importance of internal growth of companies. This process was labelled concentration and the speed of this process depended on the process of accumulation. In this process of concentration Marx also saw the appearance of new companies. His concept of centralization is of a different order since it is not accumulation which sets the limits of company-growth. Centralization is found in the process of mergers and take-overs and is much more a stimulus to accumulation. Marx also noted the growing importance of science based large companies in centralization.

It has been mentioned before that all this led Marx to see centralization, in combination with the appearance of joint-stock companies, as an important step in the process of a transition to socialism. I think it is more relevant to go back one step, as it were, and to retain some relevant notions of different categories of companies which follow from Marx's theory.

The emphasis Marx laid upon concentration and centralization together with large-scale production made him point at the importance of large companies. In my opinion Marx was right in his analysis of the modern large corporation as a large joint-stock company which is able to stimulate technology by shortening the 'economic time' of innovative projects. Had he paid more attention to sectoral differences in centralization and economies of scale Marx could also have articulated the relevance of smaller companies complementing large companies more adequately. But it has to be acknowledged that Marx apparently did see the importance of new companies, and in particular in their rôle of risk-bearing, early introducers of innovations.

Schumpeter's analysis of the role of different categories of companies resembles Marx's theory to a certain extent. At first Schumpeter stressed the almost heroic role of the entrepreneur as the innovator of capitalism, but even in his early works he pointed at the particular importance and relevance of this role in nineteenth century capitalism. In a sense Schumpeter's attention for 'the' entrepreneur is as much a simplification of technological or innovative capabilities of a company as is Marx's reduction of the company to 'the' capitalist. However, Schumpeter also pointed at the growing importance of entrepreneurship within large companies where innovative activities would come from joint-efforts. In many sectors of industry innovation would gradually be generated by large science based companies with formalized R&D-departments where innovation would become routinized.

These considerations led Schumpeter, like Marx, to pay almost exclusive attention to the growing role of large, science based, corporations. And also like Marx he acknowledged that smaller companies did continue to play a role in some sectors of industry and in certain market-niches, although the issue was not central to his main argument. If Schumpeter would have regarded his own ideas on creative destruction more carefully his theory of the firm could have been less deterministic and more differentiated.

Such a differentiated framework of categories of companies, based upon those distinguished by Marx and Schumpeter, would consist of:

- large dominant corporations, frequently science based;
- smaller companies of different sizes which have either found particular market-niches or provide supplementary services to the large dominant companies;
- new companies and cross entry.

All these companies have to be seen in the light of two important aspects of industrial development:

- competition changes the relative positions of companies over time within each sector of industry;
- in the process of creative destruction sectors of industry are reorganized and new sectors are created through which the existing market structure and relations are fundamentally changed.

3. RADICAL AND NEO-SCHUMPETERIAN THEORIES OF INNOVATION

3.1 INTRODUCTION

Despite shortcomings and flaws in Marx's and Schumpeter's theories it has become clear that, in my opinion, both contributions are noteworthy and could still have some relevance to the understanding of present capitalist society. In particular in Marx's theory the attention paid to technological change did not only appear in abstraction but Marx developed his theory from a thorough understanding of technology itself. With few exceptions, such as e.g. Bernal, most Marxists and neo-Marxists have not followed Marx in this tradition. In particular (neo-)Marxist political economists have paid little attention to technological development unless it could be incorporated at a high level of theoretical abstraction. Marx's own understanding of technological development was embedded in this theory of the dialectical relation between productive forces and relations of production of which the latter can be seen as the selection environment of technological development. Within this selection environment it is not only the capital-labour relation but also intercapitalist rivalry which is important. Technological development plays a crucial role in competition generating 'winners and losers'. The dynamics of competition become clear in the process of accumulation which generates both concentration and centralization, but also the establishment of new companies. In the analysis of accumulation Marx paid most attention to large companies and their ability to create large innovative projects. Other categories of companies were mentioned 'in passing' without much attention being paid to them in the central argumentation.

Like Marx, Schumpeter stressed the relation between competition, technological change and disequilibrium. In his analysis of so-called trustified capitalism the role of large science based companies as major innovators is emphasized. From the reconstruction of Marx's and Schumpeter's theories in the previous chapter it follows that in the analysis of industrial development attention should be paid to changes in the competitive environment of companies due to the effects of creative destruction. Furthermore, both Marx and Schumpeter provide elements of a classification of companies in such categories as large, frequently science based, companies, small and medium sized companies and new companies.

In the following sections two central themes will be addressed: First, the implications of Marx's and Schumpeter's theories will be studied for the so-called neo-Marxist contributions to industrial economics and the so-called Schumpeter controversy regarding market structure, firm size and innovation. The attention paid to the role of large companies in both Marx's and Schumpeter's theories have led many economists, influenced by these theories, to draw direct linkages from monopoly to technological development. As explained above the original contributions hardly led to such conclusions. Long run monopoly is not connected to innovation in either theory. Short run monopoly is relevant but then monopoly is seen as a transient feature of early introduction.
In section 3.2 some neo-Marxist contributions to the analysis of capitalist and corporate development will be subject to a critical assessment. It is followed by two sections in which the so-called Schumpeter-controversy over the relation between firm size, industrial concentration and innovation, a major theme in the past decades of industrial economics, will be discussed.
The second theme of this chapter covers an elaboration upon contributions in which innovation is analysed in the context of different categories of companies according to size and organization. This categorization of companies will be complemented by a brief discussion of the relevancy of understanding corporate strategies in terms of (changes of) routines and alternative strategies. This enables me to stress the necessary dynamic aspects of the relation between industry structure and innovation if corporate strategies are taken into consideration.
Both central themes provide materials for analysing an industrial sector and technological development. At the end of this chapter I will be able to establish such a framework in which the complexities of different categories of companies, innovation strategies and technological opportunity are taken into account. It has to be

seen as a necessary improvement of orthodox Marxian and Schumpeterian analytical tools. It also serves as an analytical setting for the analysis of technological change and the economic analysis of a concrete sector of industry in the two following chapters of this study.

3.2 NEO-MARXIST THEORIES OF COMPETITION, DIFFERENTIATION OF COMPANIES AND TECHNOLOGY

If one has decided to search for new insights in so-called neo-Marxist theories one appears bound to dig through a vast 'pile' of Marxist literature in which 'Capital' is explained and re-explained. According to e.g. Mishra and Braverman little attention has been paid to the further understanding of technological development within the Marxist traditon[1]. There are not too many contributions which go beyond 'Marxology' and in particular empirical research related to industrial economics and technological development is scarce. In the following I will focus on some contributions which either go beyond Marx's original theory or which stress some neglected aspects of it.
I will briefly discuss a controversy within neo-Marxist economics over the (non-)existence of monopoly capital and its far reaching consequences to the analysis of present capitalism. The debate is sometimes pursued at a level of high, mathematical, abstraction, its consequences, however, are also relevant to empirical research. If competition in modern capitalism would be (partially) surpassed by large monopoly capitals this could have far reaching effects on technological development as well. It would lead to a situation in which a few companies would dominate industries and all other companies would be doomed to stay in a longlasting position of inferiority. For the analysis of industry structures this would lead to a differentiation of companies in a static world in which there are but two categories: monopoly capital and non-monopoly capital.

1) See R. Mishra, Technology and social structure in Marx's theory: an exploratory analysis, in: Science and Society, Vol. 43, no. 2, 1979, p. 154 and H. Braverman, Labor and monopoly capital, 1974, p. 9.

In order to clarify some of the issues related to monopoly capitalism and technological development from a neo-Marxist point of view I will discuss the contribution made to industrial economics by P.M. Sweezy at some length. His contribution is clearly representing the theory of monopoly capitalism. His seminal contributions deserve special attention not only due to their large influence on radical economics but in particular because of its Schumpeterian flavour and the attention paid to technological development.

Competition and monopoly or oligopoly

In radical but also in some other heterodox, Keynesian inspired, contributions to economic theory one can distinguish two broad categories of theories on competition and oligopoly or monopoly. The debate between such theories, in particular the one within Marxist political economics, is sometimes characterized as a true 'tribal war' where nuances are discussed as fundamental controversies[1]. Nevertheless it is useful to see some differentiation between heterodox theories of competition and monopoly.
The first group of related theories stresses the development of capitalist economies with a (partial) disappearance of competition through the discretionary power of oligopolies over profits, prices and sometimes the introduction of new technologies. The dominance of oligopolies, or what is sometimes loosely defined as monopolies, is reflected in a hierarchy of profit rates. Well-known (political) economists within this tradition such as Lange, Sweezy, Dobb, Kalecki, Sylos-Labini, Steindl and representatives of the 'official' theories on state monopoly capitalism of communist and some socialist parties might be 'bien étonnés de se trouver ensemble'. Indeed, they differ with respect to many particular aspects and theoretical roots of the issue. However, the hierarchy of profits and the assumed discretionary power of oligopolies build a common element in these theories. In many straightforward Marxist contributions the existence of monopoly

1) See e.g. H.J. Sherman, Monopoly capital vs the fundamentalists, in: S. Resnick and R. Wolff, 1985.

profits and monopoly capitalism is frequently mentioned by referring to concentration within and centralization across industries, coupled with constraints on the mobility of capital due to high proportions of fixed capital and the collusive behaviour of large corporations. In that particular context 'classical' texts by Hilferding and Lenin build the foundation of many Marxist theories of monopoly capitalism[1].

In some of the more 'academic' contributions oligopoly and monopoly are treated in the context of theories on industrial pricing and profits. In these theories, to which Semmler refers as post-Keynesian or post-Marxian, "... prices do not react in the short run to quantity disequilibria in the market. Prices are constituted by the cost of production (...) and a mark-up determined by the degree of monopoly"[2]. Such mark-ups are in general determined by market structures, entry barriers and corporate power which leads to above average prices and consequently above average profit rates for oligopolies.

Oligopolies, or monopolies as they are frequently referred to, and their price-setting policies have, according to such theories, changed capitalism into a new stage of monopoly capitalism. This stage of monopoly capitalism is not seen as 'non-competitive' but "... the nature of competition is radically transformed, with price competition, in particular playing a much smaller role"[3]. Oligopolistic rivalry, industrial concentration and the growth of firms in absolute size are seen as indicators of monopoly power in

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1) See R. Hilferding, Das Finanzkapital, 1968 and V.I. Lenin, Het imperialisme als hoogste stadium van het kapitalisme, 1973. Two qualifications are worth mentioning:
   - Hilferding did not present a theory of monopoly or oligopoly stricto sensu but he referred to finance capital resulting from mergers, cartels and trusts.
   - Lenin wrote a 'popular' and political text in which he frequently referred to Hilferding and stressed the importance of, what he somewhat confusingly labelled as, increased monopolistic competition.

2) W. Semmler, Competition, monopoly and differential profit rates, 1984, p. 59.

3) J.B. Foster, The theory of monopoly capitalism, 1986, p. 69.

present capitalism[1]. As a consequence of such theoretical elaborations it follows that there are two categories of companies: price-setting monopolies and price-taking non-monopoly companies. Competition can take place either between such 'monopolies', or between monopolies and non-monopoly capitals in one industry or in case of absence of monopoly capital in a particular industry, between 'normal' companies[2]. I will return to some of the basic assumptions and consequences of theories of monopoly capitalism in a critique of Sweezy as one of the most influential political economists and representative of this line of thought. Here it will suffice to note that such an approach leads to a simple dichotomy of companies into monopolies, or oligopolies, and non-monopoly companies.

In another attempt to theorize these issues from a radical perspective competition and rivalry are still seen as important aspects of capitalist economic development. Consequently, the structural hierarchy of differential profit rates resulting from discretionary power of some companies is denied. Such theories of competition, profit rates and industrial pricing elaborate upon classical political economists and Marx's theory of profits and pricing. As mentioned in the foregoing chapter, from this point of view, temporary and natural monopolies and many other 'accidental events' can effect industrial prices and profits but, within the context of classical political economics such disturbances will not create a structural hierarchy of profits for different units of capital. In classical and Marx's theories of production prices mark-ups are not determined by market structure related factors such as those mentioned above. Mark-ups in classical theories of production prices "... are not arbitrary but determined by the structure of production and the cost of reproduction of labor power"[3]. Semmler and Clifton representing this second group of

1) See e.g. idem, and H.J. Sherman, Monopoly power and profit rates, in Review of Radical Political Economics, Vol. 15, no. 2, Summer 1983, and idem, 1985, and Sweezy's contribution.
2) See e.g. J. Wheelock, Competition in the Marxist tradition, in: Capital & Class, no. 21, 1983.
3) W. Semmler, Marxian conception of competition, 1985, p. 64.

theories, have shown that cost-plus or mark-up pricing in modern corporations is applied to control normal expansion of companies. As a rule it should not be seen as determined by market power but as consistent with a normal or average rate of return[1]. Such an approach is quite compatible with Morishima's theory of industrial pricing as the full cost principle for manufactured products[2]. In an attempt to falsify the first group of theories on oligopoly and mark-up pricing Semmler is able to illustrate that many studies show that mark-up pricing is found in both concentrated and non-concentrated industries. Furthermore it is demonstrated in a valuable overview of many older and recent studies of market power and differential profit rates that there is no clear-cut evidence of a relation between concentration and persistent higher profitability[3].

In this group of traditional Marxist and classical interpretations competition is seen as the movement of equalization of profit rates with disequilibrium in an unstable and uneven development both within and between industries. It leads to a, in my opinion, valuable criticism of the distinction between monopoly and competition or large and small firms in a static approach which is of little use since the growth factor is neglected. Monopoly, in the meaning of the appropriation of a rent e.g. for a new product, does not have to be excluded but then monopoly is not necessarily related to the size of companies. In this classical notion of monopoly it is, in principle, both short run and size independent even if transient monopoly can influence the growth potential of a company[4].

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1) See idem, p. 165, 1985, and J.A. Clifton, Competition and the evolution of the capitalist mode of production, in: Cambridge Journal of Economics, Vol. 1, no. 2, 1977 and idem, Administrered prices in the context of capitalist development, in: Contributions to Political Economy, Vol. 2, 1983.
2) See M. Morishima, The economics of industrial society, 1984, pp. 27-31, 68-98
3) See W. Semmler, 1984, pp. 89-103 and pp. 111-128, see also M. Glick, Monopoly or competition in the U.S. economy, in: Review of Radical Political Economics, Vol. 17, no. 4, 1985, for a critical assessment of Semmler's analysis.
4) See also R. Bryan, Competition and monopoly: a reply, in: Capital and Class, no. 30, 1986, p. 87 and J.A. Clifton, 1977, p. 150.

Sweezy's theory of monopoly capitalism and technological development

In order to clarify some of the issues mentioned above it appears useful to pay some extra attention to Sweezy's theory of monopoly and related issues. In the past forty years P.M. Sweezy has become one of the most outstanding political economists and one who has paid extensive attention to oligopoly (or monopoly), rates of profit and, although to a lesser extent, to technological development. Furthermore, Sweezy, who was Schumpeter's assistant at Harvard for some years, has to a large extent been influenced by both Marx and Schumpeter. Unfortunately, it was in particular Schumpeter's and Marx's emphasis on large corporations and not so much the dynamics in their theories that have been synthesized in Sweezy's theory.

In the following I will attempt to demonstrate, what I consider to be, some major shortcomings in Sweezy's theory which can be seen as an example of some popular views in modern neo-Marxist political economics[1].

I will concentrate upon three issues in this theory:

- the monopolization and categorization of private capital;
- the structural differentiation of profit rates into a hierarchy;
- the role of technology in the issues mentioned above.

Sweezy has frequently applied the analysis of monopoly and so-called monopoly capitalism to indicate, what is seen by him, as fundamental changes in the economy and the firm. In this theory monopoly is presented as a transformation of the firm as a result of both concentration and centralisation. If monopoly occurs there is, according to Sweezy, no longer profit maximization to the point where marginal costs equal marginal revenue or marginal rate

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1) I am aware that Sweezy's particular interpretation and modification of the labour theory of value and the law of the tendency of the rate of profit to fall have been subject to a lively debate in the past decades. These issues, however, have but little to no effect on the specific subjects discussed here. See J.B. Foster, 1986, for a full coverage of (Baran's and) Sweezy's theory of monopoly capitalism.

of profit[1]. Further expansion of this monopoly capital can only be found in new markets searching for new products, other companies (conglomeration) or new regions (multinationalization).
In an empirical analysis in his study on Monopoly Capital Sweezy has, together with Baran, made an attempt to operationalize this concept of monopoly capital[2]. In this analysis private capital is divided into two broad categories or sectors. One sector consists of small business, price takers, which is frequently coupled to calculations and strategies of 'Big Business'[3]. The other sector, monopoly capital, is qualified in terms of (quasi) synonyms such as giant corporations, large-scale enterprises, big business or oligopolies. This monopoly capital is seen as somewhat risk aversive in its strategies but well equiped for exploiting the innovative activities of small business companies. Innovations are often 'pioneered' by entrepreneurs and small business while 'large companies' take over such activities once success has been proven[4]. As demonstrated in some of the following sections these latter observations are not too far from what is accepted by many economists. However, the operationalization of monopoly capital and the categorization is too impressionistic, 'fuzzy' and 'popular' to enable the construction of a workable classification for empirical research. Whatever the usefulness of dichotomies for didactic reasons the complexity of economic structures can not be expected to fit into a simple division in two. As will be demonstrated in the empirical sections of this study and some theoretical elaborations in the following a further categorization of companies is more suited for empirical research.

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1) See P.M. Sweezy, The theory of capitalist development, 1968 (1942), pp. 275, 276 and idem, Modern capitalism and other essays, 1972, p. 44.
2) See P.A. Baran and P.M. Sweezy, Monopoly capital, 1966.The general aim of their study was to demonstrate that monopoly capitalism will lead to a tendency of the economic surplus to rise from which the refutation of Marx's law of the falling rate of profit follows.
3) See idem, p. 62.
4) idem, p. 59.

In the above Sweezy was mentioned as one of the theorists of 'a hierarchy of differential rates of profit'. In his theory the establishment of a hierarchy of profit rates is related to the transition from competitive capitalism to monopoly capitalism, as discussed by Schumpeter, and changes in forms and methods of competition. Monopolization following from concentration and centralization is said to lead to a rise in the rate of surplus value and a skewed distribution of profits in favour of larger companies. There is no tendency for profits to converge to an average rate of profit, but instead a hierarchy of profits will emerge. Due to high barriers for the mobility of capital in some sectors and low barriers in others there will be a "... hierarchy of profit rates ranging from highest in the industries of large-scale production where close well-protected combinations are relatively easy to establish, to lowest in the industries of very small-scale production where numerous firms co-exist and the case of entry precludes stable combinations"[1]. So the hierarchy of profit rates is determined by the degree of monopoly or centralization in industries. According to Sweezy empirical evidence is found in the "... rough correlation between the height of the profit rate and number and size of firms in a given industry"[2]. A major problem with 'rough' correlations, I find, is that these are often multi-interpretive and by definition not too strong. Furthermore, as already mentioned above, some recent surveys of a large number of studies on industrial concentration, market shares and differential profit rates do not suggest an overwhelming evidence of the above mentioned correlation[3].

A complicating factor in Sweezy's theory of a 'structural differentiation' into a hierarchy of profit rates, is that it does not imply that "... the industries (or firms) at various levels of the

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1) P.M. Sweezy, 1968, p. 274.
2) idem, Four lectures on Marxism, 1981, p. 66.
3) See e.g. M.A. Utton, The political economy of big business, 1982, pp. 96, 97, and W. Semmler, 1984, pp. 111-128, and N. Rosenberg and L.E. Birdsell Jr., How the West grew rich, 1986, pp. 289-295.

hierarchy must always be the same. There is constant movement within the hierarchy in response to both internal and external factors"[1]. Apparently the hierarchy is not too structural and one could even wonder why the notion of hierarchy has to be introduced in the case of constant movement. In fact a distribution of profits with changing positions over time comes very close to the classical concept of 'center of gravity' for profit rates.

The final subject of this critique of Sweezy's work relates to his perception of the role of technology in capitalist development. As with so many other neo-Marxists technology itself is not at the core of Sweezy's work but is scattered troughout his contributions. Sweezy, and also Baran, claim that under present monopoly capitalism there will be a slower rate of introduction of innovations than under competitive capitalism. In competitive capitalist circumstances innovation brings extra profit for the first innovative companies as others lose their share of the market. Under monopoly capitalism, according to Baran and Sweezy, labour saving process innovations but also product innovations are introduced or regulated at a pace which does not disturb the existing capital values. Price cutting policies in order to 'smoothen' the absorption of the output of both old and new methods of production is ruled out as unrealistic "... given monopoly capitalism's strong bias against price cutting ..."[2]. Following Joan Robinson it is assumed that a monopolist will not introduce new capital equipment and scrap existing equipment unless cost savings on new equipment plus interest is less than the costs of maintaining the existing equipment[3]. This does not necessarily imply that there will be a dramatic decline in the rate of invention itself under monopoly capitalism. The intensive use of science and technology by large corporations can even speed up the rate of discovery and

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1) P.M. Sweezy, 1981, p. 66.
2) P.A. Baran and P.M. Sweezy, 1966, p. 100, this, in my opinion, mistaken conception of competitive strategies is supported by many radical economists, see e.g. M. Aglietta, A theory of capitalist regulation, 1982, pp. 304-313.
3) See P.A. Baran and P.M. Sweezy, 1966, p. 101, see also P.M. Sweezy, 1968, p. 276.

potential innovations. However, as Baran and Sweezy claim "... under monopoly capitalism there is no necessary correlation (...) between the rate of technological progress and the volume of investment outlets"[1]. In general the introduction of innovations is planned by monopoly capital itself and Schumpeter's creative destruction will not occur under these circumstances.

The main shortcoming of Sweezy's treatise on monopoly and technological development is the jumping to conclusions from a highly abstract and theoretical discourse to a concrete analysis without taking the intermediate steps. The result is a typical case of 'economics with blinded windows'. In abstract theory Sweezy's statements and derivations could hold in case of pure monopoly, the absence of creative destruction, and unchanged demand conditions. However, this does not permit conclusions for empirical situations, unless concrete monopolization in strict terms has been adequately demonstrated. As mentioned before, Sweezy switches from a 'tight' definition of monopoly in abstract theory to a very 'loose' description of monopoly when analyzing current capitalism where large corporations, oligopolistic market structures, etc. are defined as monopoly capital. All this leads to conclusions e.g. for the relation between monopoly capital, large companies, and the rate of the introduction of innovations which are not supported by any evidence from empirical research. Furthermore, at the present stage of capitalist and technological development both fierce competition with price-wars, shortened product-life cycles, changing market structures and technological change induced by many companies provide clear objections to this element of Sweezy's theory.

The world of technology and capitalist development shows a differentiated picture with many categories of innovative companies and change in technological progress, as such it appears to be a far cry from the world pictured in Sweezy's system of monopoly capitalism.

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1) P.A. Baran and P.M. Sweezy, 1966, p. 103.

Dead-ends in neo-Marxist theories

Marxist and neo-Marxist political economics has paid little attention to technological development in present-day capitalism as we search for new ideas and new analyses. But few have made an attempt to go beyond or even expand the field of research laid out by Marx himself. This does not mean that there has been no theoretical development in radical economics itself but most attention has been paid to other developments than those related to industry and technology. In some Marxist and other heterodox theories attention was paid to rather abstract elaborations upon monopolization. Theories on oligopolization or monopolization, although sympathetic at first sight, have not been too persuasive in presenting an unambiguous support for the thesis of a structural differentiation of companies into persistent different levels of profit. So far, no evidence of high correlations of industrial concentration and persistent difference in profitability have been found unanimously. In other words, there is little evidence of the existence of a monopoly capital leading to structural monopoly profits other than in exceptional cases.

Sweezy's work can be seen as an example of a popular misunderstanding of present-day capitalism amongst neo-Marxists. Abstract theorizing of monopoly, technological development and strategy is 'translated' into an empirical analysis assuming the correspondence of 'monopoly' and large companies. In abstracting from competition, technological development and diffusion capitalism is misunderstood as a non-dynamic economic system.

Such criticism of neo-Marxist theory is in my opinion, more fruitful than the approach chosen by some orthodox Marxists who have criticized the theory of monopoly capitalism as a deviation from Marxist political economics. In that context Foster has correctly stated that for the logic of the argument it is completely irrelevant whether Marx had a theory of monopoly capitalism or not[1].

1) See J.B. Foster, Is monopoly capitalism an illusion?, in: Monthly Review, Vol. 33, no. 4, 1981, p. 37.

Criticism cannot be based upon any reference to the absence of such a theorem in Marx's theory. Orthodox criticism based upon 'purism' is fallacious indeed, as too many elements in Marx's general theory are outdated and inconsistent. It is much more fruitful to discuss neo-Marxist contributions with respect to their applicability and empirical relevance. Then, contrary to e.g. Foster, I think neo-Marxist theories of structural monopoly are of little relevance. This does not mean that concepts such as monopoly and oligopoly have no purpose in economic analysis. In concrete analysis monopoly and oligopoly, if properly defined and understood, could be applied to describe and analyze production and market structures. Applied as a base for classifications of companies or a theory of technological development under a capitalist mode of production they are of little use.

3.3 THE SCHUMPETER CONTROVERSY

Within the more traditional, academic, school of modern industrial economics and innovation theory one important issue has attracted much attention during the past decades. It has become well-known as the on-going debate on the so-called Schumpeter controversy on market structure, firm size and innovation[1]. The issue is related to two questions:

- which level of industrial concentration is most conducive to innovation; and
- what size of firm is most appropriate to stimulate innovation?

It is clear that these questions are not only of a theoretical relevance but they are also very important will respect to the implementation of (state) policies. In the public debate on innovation policies in the past decades one observes a somewhat cyclical movement in the argument. In the fifties and sixties industrial concentration and the supremacy of large companies were accepted by many as most suitable for generating new products and industrial processes. In the seventies and early eighties a change in

1) In the following I will refer to industry and market structures as synonyms, although strictly taken the latter concept is broader and encompasses the first.

the debate can be observed in the sense that small, and often new, firms are seen by many as the true innovative change agents of industry. The public debate so far has, in my opinion, largely been influenced by populist and ideological beliefs about what innovation policy should be pursued. However, this does not mean that economic research and theory has not been mediated to a certain extent within the public debate. So far, any point of view on this matter can be backed by bits and pieces of research and theory.

In academic economic theory the debate can be traced back to a long-standing controversy over the efficiency of large (or small) companies[1]. It goes back to Marshall's theory of decreasing returns to scale expressed in the rising portion of the long-run average cost curve. This theorem has been countered in later years by those who point at improved information control and co-operation within the so-called M-divisional structure of large companies. The proclaimed inefficiency of large companies has also been discussed in the debate on their lack of control over cost levels (X-efficiency), which others claimed were countered by competition and improved organization. As far as the (in-) efficiency of large companies in their innovative performance is concerned both sides have generated evidence supporting their point of view.

If reduced to straightforward dichotomies the complexity of economic performance, of which innovative capability is an important aspect, is frequently simplified to statements such as: large companies/small companies or concentrated industries/ atomistic industrial structures are most efficient and stimulating for innovation.

Many will agree that such plain dichotomies are even at first sight probably too simple for understanding what everyone can expect to be a very complex aspect of economic reality. Economic theory so far has advanced in the past decades in the sense that the complexity of the issue is recognized in more subtle explanations. That is not to say that the 'truth' lies in the middle but in many contributions one part of the coin is represented with at least some reference being made to certain features and relevance of the other part.

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1) See e.g. M.A. Utton, 1982, pp. 5-15.

Schumpeter and Galbraith: large companies and industrial concentration

In their outstanding review of studies on market structure and innovation Kamien and Schwartz have summarized the set of Schumpeter, or probably more convenient Schumpeter inspired, hypotheses as follows:

"1. Innovation is greater in monopolistic industries than in competitive ones because
   (a) A firm with monopoly power can prevent imitation and thereby can capture more profit from an innovation.
   (b) A firm with monopoly profits is better able to finance research and development.
2. Large firms are more innovative than small firms because
   (a) A large firm can finance a larger research and development staff. There are other economies of scale in this activity also.
   (b) A large diversified firm is better able to exploit unforseen innovations.
   (c) Indivisibility in cost-reducing innovations makes them more profitable for large firms.
3. Innovation is spurred by technological opportunity.
4. Innovation is spurred by market opportunity (demand-pull)"[1].

The third and fourth hypotheses are not necessarily Schumpeter-inspired but they are relevant for adjusting studies on innovation for differences in technological and market opportunity. The first two sets of hypotheses can be accepted as what is generally seen as the core of a Schumpeter-inspired theory of innovation.
Whether these hypotheses can also be attributed to Schumpeter is of course a matter of debate. From my perception of Schumpeter's theory there are at least some modifications for this set of hypotheses to be made. These reservations will become clear when I briefly recall some of the important subjects in my view of Schumpeter's theory of innovation.

1) M.I. Kamien and N.L. Schwartz, Market structure and innovation, 1982, p. 47.

For Schumpeter innovation, the creation of new combinations, is the motor of economic development creating disequilibrium and imperfect competition in the economy. Schumpeter's own perception of disequilibrium and imperfect competition might have changed slightly in the course of his theoretical development, but at all stages their relevance for understanding the dynamics of economic change was stressed.
In Schumpeter's earlier works innovation is understood within the world of entrepreneurial capitalism in which 'heroic' entrepreneurs, and not capitalists as such, introduce innovations to gain profits or extra-profits. Transient, short-run, monopoly on new products or processes triggers imitative reactions in other companies and through this imitation and diffusion the monopoly position of early introducers wears-off. In this picture of classical 19th century capitalism entrepreneurs in existing but also in new companies set the scene for innovation.
In his later works Schumpeter referred to modern, trustified capitalism as 20th century capitalism. Here, large companies, which are frequently also science-based with formalized R&D departments, dominate the process of innovation. In these large companies innovation has become routinized. Small companies do not play a very distinct role in generating innovations, their economic role is 'restricted' to market-niches and the provision of services to large companies.
Schumpeter discussed monopoly in particular in terms of short-run, transient monopoly which disappeared through the diffusion of an innovation. Long-run monopoly was seen as an exceptional case. The actual limits to both forms of monopoly was set by the effects of creative destruction. In short, this notion of creative destruction was introduced by Schumpeter to stress the importance of the creation of new and the destruction of older industrial structures. In other words industrial development is marked by the growth of new sectors and other companies than the existing dominant companies.
Returning to the set of Schumpeter inspired hypotheses mentioned by Kamien and Schwartz the following qualifications, in particular with reference to the first two sets of hypotheses, are to be made:

It will be clear that hypotheses regarding the greater innovative potential of large companies can be seen as Schumpeter-like hypotheses. (But then one refers in particular to his later works). The first set of hypotheses about monopolistic market structures is, so to speak, more 'inspired' than related to Schumpeter's theory. Schumpeter referred much more to large firms and market power than to lasting monopoly as a structural phenomenon of industrial development. A concentrated market structure is not necessarily conducive to innovation according to Schumpeter's theory[1).

One of the most popular advocates of the supremacy of large firms is the American economist Galbraith. In two of his famous texts this supremacy of large companies in many aspects of their business operations is frequently mentioned[2). In his work the whole set of arguments in favour of large firms and concentrated markets, firm size and market structure, are usually intertwined. Although he clearly states that he comes from a different tradition in economic theory Schumpeter is mentioned by Galbraith as the main inspiration of his thoughts on firm size, industry structure and innovation. In the broader context of his general theory Galbraith pictures a world of modern capitalism in which large companies act no longer as price-takers. These large companies with oligopolistic features pre-empt the market before maximum output equals lowest prices. This form of inefficiency is offset by the benefits of technical change leading to a host of new products from these large companies. Competition is no longer

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1) See e.g. also R.R. Nelson and S.G. Winter, An evolutionary theory of economic change, 1982, p. 279, and F. Chesnais, Schumpeterian recovery and the Schumpeterian perspective - Some unsettled issues and alternative interpretations, in: H. Giersch (ed.), Emerging technologies: Consequencies for economic growth, structural change, and employment, 1982, p. 61.
2) See J.K. Galbraith, American capitalism, 1970 (1952) and idem, The new industrial state, 1985 (1967).Although Galbraith changed his views on some subjects discussed in these publications, his thoughts on the role of large companies in technological change apparently has not changed over the past thirty years.

determined by prices but oligopolistic rivalry is determined by advertising, sales efforts and innovation strategies of these companies. According to Galbraith "... modern industry of a few large companies (is) an excellent instrument for inducing technical change. It is admirably equipped for financing technical development. Its organization provides strong incentives for undertaking development and for putting it into use"[1]. Like Schumpeter he admits that small companies and entrepreneurs have played an important role in 'competitive capitalism'. However in modern capitalism and "... with the rise of the modern corporation, the emergence of the organization required by modern technology and planning and the divorce of the owner of capital from the control of the enterprise, the entrepreneur no longer exists as an individual person in the mature industrial enterprise"[2]. In that context Galbraith asserts that competition and competitive markets are not very well suited for innovation as diffusion and imitation destroys the profit of innovation because imitators are quickly to take advantage of the inventive activities of the original innovators. Furthermore, most cheap inventions have already been made and modern technology has become very expensive, which diminishes the likelihood of recovery of those costs in a truly competitive market. According to Galbraith, larger firms, with substantial market power, can control the length of time of the benefits of their innovations. "Thus, in the modern industry shared by a few large firms, size and the rewards accruing to market power combine to insure that resources for research and technical development will be available. The power that enables the firm to have some influence on prices insures that the resulting gains will not be passed on to the public imitators (who have stood none of the costs of development) before the outlay for development can be recouped. In this way market power protects the incentive to technical development"[3].

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1) J.K. Galbraith, 1970 (1952), p. 100.
2) idem, 1985 (1967), p. 64.
3) idem, 1970 (1952), p. 102.

In other words: large firms and concentrated market structures are favourable to technical change. The relation between these goes either way as the expensive character of science based technical change also influences the existence of concentrated markets and large firms.

In that context Galbraith mentions six consequences of modern technology for individual companies[1]:

- with the sophistication of technology there is an increasing span of time from beginning to completion of an innovation;
- capital investments increase;
- there is a larger division of tasks and means of production;
- more specialized manpower is needed;
- more organizational efforts have to be made;
- and by consequence more planning is compulsory.

It is clear that in Galbraith's view of the consequences of technological development there is little left for small companies. His theory is doubtlessly one sided in the sense that he pictures a world dominated by oligopolistic companies. Apart from the fact that I disagree with Galbraith's theory on industrial pricing and oligopolistic rivalry, because full cost theories are more plausible, the Schumpeterian aspects in his theory still have to be qualified. Galbraith discusses concentrated market structures and large companies almost as synonyms, which is, I think, not allowed without explaining particular conditions under which the two are closely related. In general, Galbraith's theory on the dominance of large giant companies, the 2000 leading companies in the USA, is, if restricted to technological development, of a clear Schumpeterian character. Other aspects of Schumpeter such as 'creative destruction' and the growth of companies which are relevant in understanding the dynamics of market structure and innovation are not discussed in Galbraith's theory. In particular the absence of some understanding of changes in industry structures, the growth and decline of industries and the changes within industries, makes Galbraith's theory to a static variant of Schumpeterian theory. In that sense it has a close resemblance to some neo-Marxist theories of monopoly capitalism, such as Baran and Sweezy's.

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1) idem, 1985 (1967), pp. 12-16.

Small companies, some nuances and neo-Schumpeterian approaches

The supremacy of large companies, as theorized in the Schumpeter-inspired theory of innovation has been questioned by many. In response to e.g. Galbraith's theory a debate on the proclaimed efficiency of large companies and the role of giant corporations as great innovators started in the early fifties and the debate has lasted ever since[1]. A well-known adversary of the Schumpeter-Galbraith theory is Blair. In his contribution Blair put forward exactly the opposite of what has been discussed above. In his theory of the so-called 'creative backwardness of bigness' Blair attributes this backwardness amongst other things to:

- the desire to protect the investment in an older technology;
- indifference to technological advance;
- underestimation of the demand for new products;
- neglect of the inventor;
- misdirection of research and incompatibility between organization and creativity[2].

Although definitely not identical, many aspects of this proclaimed backwardness are related to what is also known as dynamic X-inefficiency[3].

Others have paid more attention to industry specific conditions which influence the position of large or small companies. E.g. Freeman states that both Galbraithian and opposite theories represent only a part of the picture. There are some industries like aerospace, vehicles and pharmaceuticals where small firms make no or almost no contribution to innovation. In other sectors such as scientific instruments, textile and construction small firms do make an important contribution to technical change[4].

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1) See e.g. W. Adams, Competition, monopoly and countervailing power, in Quarterly Journal of Economics, Vol. 67, no. 4, 1953 as an 'early' contribution and e.g. M.I. Kamien and N.L. Schwartz, Market structure and innovation: a survey, in: Journal of Economic Literature, Vol. 13, 1975, and idem, 1982, and C. Freeman, The economics of industrial innovation, 1982 for an overview of many contributions.
2) See J.M. Blair, Economic concentration, 1972, pp. 228-257.
3) See e.g. A. Heertje, Economics and technical change, 1977, pp. 215-219.
4) See C. Freeman, 1982, p. 141.

Some authors stress the importance of a balance between large and small firms, or a mix of both companies in the economy[1]. In that context Rothwell and Zegveld mention the advantages and disadvantages of small and medium sized firms, which can also be seen as the mirror image of large companies. Advantages for smaller companies are, according to Rothwell and Zegveld, in particular found in[2]:

- their able marketing for particular niches;
- dynamic, entrepreneurial management;
- internal communication. (Their argument supporting the idea of resulting excellence of labour relations in small companies is probably too optimistic.);

They also mention a considerable number of disadvantages for small companies such as:

- their lack of qualified R&D personnel;
- shortcomings in external communication, in particular a lack of information on technology and markets;
- lack of management skills;
- constrained financial resources;
- problem related to economies of scale and selling of turnkey projects and complete systems;
- disability to take advantage of government measures;
- problems related growth of the firm.

Many of these (dis)advantages can also apply to new companies. In particular in some of the earlier works of Schumpeter new companies were seen as innovative. From the literature one learns indeed that new firms share many of the advantages of small companies. Whether new companies also play an important role in generating innovations still has to be seen. E.g. Johnson concludes, after having reviewed the literature, that "... it seems that most

1) See D. Sahal, Technology, productivity, and industry structure, in: Technological Forecasting and Social Change, Vol. 24, 1983, pp. 11, 12 and R. Rothwell and W. Zegveld, Innovation and the small and medium sized firms, 1982, p. 75, and R. Rothwell, The role of small firms in technological innovation, in: J. Curran et al., 1986.

2) See R. Rothwell and W. Zegveld, 1982, pp. 45-54, see also R. Rothwell, 1986, pp. 116, 117.

of new firms are not innovative in the Schumpeterian sense (i.e. 'early' Schumpeter, J.H.), although many of them may have some marginal advantage over competitors"[1]. However, a study by Dorfman to be discussed in the next section suggests the opposite for some 'high-tech' sectors[2].
So far, the literature on market structure, size of firm and innovation demonstrates that in between the 'extremes' there is a field of nuances and second thoughts. Arguments in favour of either side of the Schumpeter controversy can be countered with some reservations[3].

Some attempts have been made to develop a theory in which the different roles of small and large companies are emphasized. E.g. Scherer has made an interesting attempt to generalize research on the relation between both market structure, firm size and innovation. Scherer's theory can be summarized as follows[4]:
Small and medium sized firms contribute significantly to the initial stages of innovations, but large corporations appear to have a particular task of developing inventions into the stage of commercial success. In that context three generalizations are made:

- small firms play a 'disproportionate' role in developing new ideas;
- the further development usually requires investments which cannot be met by small and medium sized firms;
- these private investments can be undertaken by (very) large corporations or by medium sized firms with a 'high tolerance for risk'.

Furthermore, for both R&D input and output it is said that these tend to rise less than proportionally to size once a threshold has

1) P. Johnson, New firms, an economic perspective, 1986, pp. 36, 37.
2) See N.S. Dorfman, Innovation and market structure, lessons from the computer and semiconductor industries, 1987.
3) See R.W. Shaw and C.J. Sutton, Industry and competition, 1976, p. 203 for an overview of arguments in favour of high concentration and large firms and major reservations.
4) See F.M. Scherer, Firm size, market structure, opportunity, and the output of patented inventions, in: American Economic Review, Vol. 15, no. 5, 1965 and idem, Industrial marketstructure and economic performance, 1980.

been passed. This leads towards the so-called 'humpback' or 'inverted U-shape' distribution. This 'inverted U-shape' distribution is also mentioned for the relation between market structure and innovation.

Williamson arrives at somewhat similar conclusions for size of firms and innovation stating that "... R&D expenditures (expressed in relation to firms size) are not usually greater and are often lower for the very largest firms in an industry by comparison with its large but somewhat smaller rivals; the productivity of research expenditures follows roughly the same pattern; (...); research conducted in most large industrial laboratories favors minor improvement inventions rather than new inventions ..."[1].

These complementary roles of small and large firms in a situation in which small firms invent new products and processes and larger companies take care of the further development and subsequent stages such as marketing is accepted and stressed by many authors[2]. Theories of Williamson, Mueller and in particular Scherer can be seen as examples of neo-Schumpeterian inspired theories of innovation. The importance of small companies to the process of invention and innovation, as partly featured in Schumpeter's early theory, is stressed. The growth of research intensity of larger companies and concentrated markets as mentioned in the Schumpeter inspired hypotheses mentioned before is emphasized, as well. However, such neo-Schumpeterian theories also mark the less than proportional to size contribution of the largest companies once a threshold has been passed.

Two other relevant contributions from a neo-Schumpeterian perspective to this field of economic theory are worth mentioning. The first contribution to be discussed is the attempt made by Nelson and Winter to theorize and model Schumpeterian aspects of competition and innovation[3]. The theory of Nelson and Winter and their

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1) O.E. Williamson, Markets and hierarchies: Analysis and antitrust implications, 1975, p. 196.
2) See also C. Freeman, 1982, p. 137 and D.C. Mueller, The modern corporation, 1986, pp. 108-118.
3) See e.g. R.R. Nelson and S.G. Winter, 1982, and R.R. Nelson, Understanding technical change as an evolutionary process, 1987, pp. 37-43.

simulation models touch upon many subjects ranging from macro-economics to the theory of the firm and the dynamics of technological development. The richness of their contribution enables me to come back to their contribution in another chapter, in particular with respect to the dynamics of technological development. Here, I will restrict myself to a brief discussion of some theoretical conclusions from their modelling of Schumpeterian competition. Central to Nelson and Winter's models is disequilibrium which is featured as an important characteristic of economic development. Furthermore market structure and innovation are seen as interdependent, hence market structure is endogenous. Competition is not a static phenomenon but a process in which winners and losers are generated. Winners are those companies which make better use of technological opportunities which enables them to grow. Losers are those companies which take less advantage of technological opportunities after which they gradually decline into a stage of technological obsolence. Losers do not necessarily disappear from the market, some of them can languish for extended periods of time. The simulations with Nelson and Winter's models generate some interesting results for the study and theory of market structure, size of firms and innovation. First of all their findings suggest that already concentrated industries remain concentrated, although "... the actual exercise of market power by the larger firms (...) may be an important factor in tending to limit the growth of concentration in the industry"[1]. Initially unconcentrated industries gradually become more concentrated as winners grow and losers decline.

Other conclusions from Nelson and Winter's models are:

- relatively concentrated industries provide a 'better shelter' for R&D than atomized industries;
- "... industries with rapid technical progress ought to be marked by high average R&D intensity and, as the industry matures, by a more concentrated industry structure than industries in which technical progress is slower ..."[2];
- skillful and agressive imitators can compete successfully with innovative R&D performers.

1) R.R. Nelson and S.G. Winter, 1982, p. 326.
2) idem, pp. 350, 351.

A shortcoming in Nelson and Winter's theory is that the long term effect of entry and creative destruction is somewhat neglected. In modelling Schumpeterian competition the role of entry is restricted to a situation comparable to an existing small company[1]. From my perception of Schumpeterian competition entry, cross-entry and diversification can have a further reaching effect on changes in existing industrial structures.

A related approach to the dynamics of market structure, size of firms and innovation has been introduced by Dosi. His theory has certain Schumpeterian features in common with Nelson and Winter in the attention paid to the asymmetry of firms in relation to technical change. It also has some features from classical economics in the treatment of competition and profit rates in a 'centre of gravity' approach, which is quite distinct from e.g. Nelson and Winter. Dosi is rather sceptical about theory and research on market structure, firm size and innovation so far. In his critique of the state-of-the-art an alternative explanation for the so-called inverted U-shaped relation between 'innovativeness' and firm size and concentration is suggested. This hypothetical explanation supposes that:

- the degree of innovativeness is a negative function of the technological age or maturity of an industry, technological maturity being the inverse measure of technological opportunity;
- concentration is a positive function of past innovativeness and technological maturity, making market structure endogenous;
- for any given technological maturity, innovativeness is a positive function of firm size.

Then, according to Dosi, there could be an inverted U-shaped relation in the economy as a whole even if innovativeness grows proportional to size[2]. From which one is to conclude that the actual shape of the relation between innovation, firm size and market structure for a particular economic system depends upon the

1) idem, p. 328.
2) See G. Dosi, Technical change and industrial transformation, 1984, pp. 92, 93.

intersectoral pattern and the 'state' of technology applied in each sector. Although Dosi himself does not mention it, such a dynamic analysis of firm size, market structure and innovation can be viewed in the light of Schumpeter's emphasis on creative destruction.

A full treatment of Dosi's theory of oligopoly would take too far, but one issue should be mentioned here. In Dosi's theory a distinction is made between two different phases of technological development and oligopolistic structures[1]. In case of the emergence of a new field of technology it is stated that there will be a high rate of birth and mortality of new companies with temporary oligopolies which can pre-empt new markets.

In case of an already established field of technology there will be a more stable oligopolistic structure and entry barriers, then technical change becomes part of oligopolistic competition as e.g. also Galbraith has argued. This differentiation is to be seen as an attempt to integrate two distinct approaches in e.g. Schumpeter's theory. The first situation is quite similar to Schumpeter's early theory of competitive capitalism, the second is more related to his theory of advanced capitalism. I think it is useful to stress that even in the latter case existing oligopolistic structures, and entry barriers will have to be seen as temporary. From a Schumpeterian perspective existing oligopolistic structures are not excluded from cross-entry, in particular not if the industry is still characterized by an above average level of growth. In case of a mature sector of industry characterized by stagnation or decline it is not so much entry barriers as exit barriers for non-diversified or specialized, companies which cause stable oligopolistic structures[2]. Such considerations lead to an approach in which the reciprocal effects of existing oligopolistic structures, mobility barriers, intersectoral competition and the 'maturity' of a field of technology have to be taken into consideration.

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1) idem, pp. 93, 94.
2) See also W. Semmler, 1984, p. 111 ff.

A major problem for applied economic research in this field is that the dynamics of (inter-) sectoral change and technological development can lead towards an irregular process of changes within an existing industry. E.g. in the case of the sector of process control equipment it can be demonstrated that a mature industry, has evolved towards a new phase of its development. Process control based upon pneumatic principles was not only a mature technology, it was also produced by a 'stable' group of manufacturers. The introduction of electronics, computer technology and at a later stage the further application of the complete range of information technology changed the industry structure. The technology applied became more sophisticated, existing companies merged or were taken over, electronics manufacturers entered the market et cetera.
In other words, a mature industry developed towards a stage where new technologies are introduced and incorporated. Side entries, take-overs of companies with experience in relevant technologies and concentration have led to a situation in which oligopolistic rivalry in that particular sector has become but a momentum within a larger 'game' of competition.

The theoretical contributions discussed above suggest that the complexity of the relation between firm size, industry structure and innovation has been recognized by many. Generalizations are hard to make. Arguments in favour of large companies such as provided by e.g. Galbraith are not completely beside reality eventhough only certain features of modern capitalist society and the role of large companies are stressed. The same could be stated for those who stress the opposite picture in which the role of the small company as the innovator is stressed. Some authors apparently choose to be on the safe side and stress that both large and small companies have certain, albeit opposite, characteristics which, if balanced, generate a successful innovative climate. Others stress the importance of intersectoral and dynamic changes in order to understand the issue. In that context it has been argued that:

- Small companies play an important role at the initial stage of innovation, this role is taken over by their large competitors at the stage of further development and commercialization.
- The contribution to innovation of very large companies is less than proportional to their size.
- Industrial concentration has a positive effect on innovation, but the effect is less than proportional once a threshold of concentration has been passed.
- Sectors with rapid technological progress become more concentrated than sectors with slow progress.
- Different forms of oligopoly, barriers to mobility, and varying industry structures and dissimilar levels of technological maturity are decisive in explaining differences in innovative performance.

3.4 EMPIRICAL STUDIES ON THE SCHUMPETER CONTROVERSY

Theoretical contributions to the Schumpeter-debate so far suggest that one can choose not only between extremes such as: high (low) industrial concentration is most advantageous to innovation or large (small) companies generate more innovations. A substantial part of the theory provides more intermediate, subtle or indistinct elaborations upon probably too crude dichotomies in the theory on the subject. Most theories mentioned previously are based upon empirical observations but it is fair to state that these observations range from circumstantial evidence to econometric research. Having stated some of the issues in economic theory it appears useful to glance at some of the more empirical studies. Fortunately several well-known surveys of empirical studies have been published which enable me to present the state-of-the-art without 'carrying too much coal to Newcastle'. This overview of these findings and the review of some recent studies explicitly does not attempt to replace these outstanding and thorough surveys. The aim of this section is much more to concentrate on what can be learned from the vast body of empirical studies in terms of generalizations or dead-ends. If the state-of-the-art would lead to dead-ends or superficial generalizations it is worth looking for new departures.

Before I turn to these studies I will first make some brief remarks about the measurement of technology, innovation and R&D. A major problem in assessing the large body of empirical research in this and related issues is that one can cast some serious doubts about the compatibility of different indicators applied in empirical research such as patents, R&D-employment or expenditures, etc. Every indicator has its specific shortcomings. E.g. R&D figures, whether measured in value or in employment, tell us only something about one aspect of the technological development, the research input. Patents as such measure only inventive output in terms of how many inventions are administred but little about their importance and their effective application. Also, differences in propensity to patent between sectors of industry and countries can be expected. The different attitudes towards formal R&D and patenting amongst categories of firms related to size can influence the 'neutrality' of variables to be measured. Research by Schmookler, Pavitt, Soete and others suggest a lower propensity to patent by large compared to small firms[1]. Furthermore, many studies apply different indicators for innovation such as R&D, patents or innovations mentioned by experts which causes some shortcomings in comparability. All of which suggests that even if some generalizations about firm size, or market structure, and innovation were to be made these will have to be interpreted with utmost care.

Market structure and innovation

Market structure and innovation, and size of firms and innovation are sometimes discussed as if these are identical or almost identical topics. Strictly taken these relations are of a different character. E.g. J.B. Rosenberg found that market share and industrial concentration, two operational definitions of market structure, had greater impact on innovation than absolute size of companies[2]. In many studies on the relation between market structure

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1) See C. Freeman, 1982, p. 136 and L. Soete, Inventive activity, industrial organization and international trade, 1978, p. 187.
2) See J.B. Rosenberg, Research and market share: A reappraisal of the Schumpeter hypothesis, in: Journal of Industrial Economics, Vol. 25, no. 2, 1976, p. 107.

and innovation the optimal configuration of companies to stimulate technological development is a central theme. Questions on the optimal size of firms with respect to innovation or the actual distribution of innovations over categories of firms' size are not necessarily related to market structure. However as soon as oligopoly is introduced and when more industry specific circumstances are considered market structure and size of firm are easily connected. Quite simply because large firms frequently play a dominant role in concentrated markets and/or oligopolistic rivalry. But even there the relationship between firm size, market power in case of oligopoly, market structure and indicators of innovation is complicated. As e.g. Culbertson has demonstrated the effect of absolute and relative firm size and market power on industry R&D expenditures is mediated by technological opportunities and individual firms' R&D[1)]. For the sake of clarity and acknowledging such objections against a simplification of the matter I will discuss the relation between innovation and market structure and firm size separately.

If one looks at the state-of-the-art in empirical research on market structure and innovation one can find some consensus, but only at a level of extreme generality. In most studies market structure is operationalized in terms of concentration ratio's. Innovation is in most cases defined in terms of either research input, R&D expenditures or numbers of R&D employees, or research output for which numbers of patents are taken. Kamien and Schwartz found little consensus in reviewing well-known research on the relation between concentration and research <u>input</u> in studies by Scherer, Comanor, Hamberg and others. Research on the relation between concentration and innovative <u>output</u> apparently led to a similar conclusion[2)]. If anything follows from these studies it is the suggestion that there might exist the previously mentioned

1) J.D. Culbertson, Econometric tests of the market structural determinants of R&D investment: Consistency of absolute and relative firm size models, in: Journal of Industrial Economics, Vol. 34, no. 1, 1985.
2) See M.I. Kamien and N.L. Schwartz, 1982, p. 86 ff.

humpback or inverted-U relationship between industrial concentration and R&D intensity. In other words, if concentration develops towards its theoretical maximum this will lead to a gradual decline of the R&D intensity again.
Having reviewed the vast body of studies on this and related issues performed in the sixties and seventies Scherer could not but conclude that "... market concentration has a favorable impact on technological innovation in certain situations. <u>How much</u> concentration is advantageous remains to be determined. Obviously, there is no general answer; the optimum depends upon the size of the overall market profit potential in relation to the cost of development in any given case"[1]. In a broader context Scherer suggested that technological progress benefits from "... a subtle blend of competition and monopoly, with more emphasis in general on the former than the latter, and with the role of monopolistic elements diminishing when rich opportunities exist"[2]. So the literature on the subject up to the early eighties tended to boil down to such general statements as "... there exists a market structure intermediate between monopoly and perfect competition most conductive to technical change"[3]. Taking into account the large intellectual investment in this issue the general statements mentioned above might be somewhat disappointing to some of us. In particular as seen from a Schumpeterian and classical economics perspective, as explained above, it can be stated that in advanced capitalist economies:

- perfect competition is but a rare occasion and not the rule;
- monopoly, in its strict meaning, is found only for some products or processes during a short period of time.

Consequently, it all could lead to the general but hardly discriminatory conclusion that an advanced capitalist economic system is most favourable to technical change. Whatever the political economic relevance of such a conclusion might be it still leaves us without more detailed knowledge about the relationship between market structure and innovation.

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1) F.M. Scherer, 1980, p. 437.
2) idem, p. 438.
3) M.I. Kamien and N.L. Schwartz, 1975, p. 30.

Recent contributions suggest that this relation between concentration and R&D could be of a spurious character because the explaining factor can be found in the specific conditions of technological opportunity within industries. Hence, this technological opportunity is associated with both R&D investment and concentration levels[1].

Such sector specific relations between concentration and R&D have also been found in a number of studies in the USA, which illustrate the relevance of this point. Shrieves found positive and significant relations for levels of concentration and R&D for sectors producing consumer goods and producers of material inputs, and a positive but weak relation for producers of non-specialized goods. A marginally significant but inverse relation between concentration and R&D was discovered for the specialized durable equipment industry[2]. Chappell et al. found industrial concentration to have a strong significant positive effect on R&D in mechanical and electronic/electrical industries manufacturing consumer goods. Concentration has a weak effect on the R&D in producer goods industries and traditional consumer goods industries[3]. Angelmar found different results for research intensity and industrial concentration depending on different technological opportunities within sectors. In industries with low R&D costs and low uncertainty of R&D, plus strong barriers against imitation (patents, trade secrets and property rights) industrial concentration is not necessary as there are sufficient incentives for innovation; if concentration already exists it will reduce the level

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1) See D.C. Mowery, Market structure and innovation: A critical survey, 1985, in which some recent studies on the issue are reviewed; see also M.I. Kamien and N.L. Schwartz, 1982, pp. 58-64, and R.C. Levin, W.M. Cohen and D.C. Mowery, R&D appropriability, opportunity and market structure: New evidence on some Schumpeterian hypothesis, in: American Economic Review, Vol. 75, no. 2, 1985, p. 21.

2) See R.E. Shrieves, Marketstructure and innovation: a new perspective, in: Journal of Industrial Economics, Vol. 26, 1978.

3) See H.W. Chappel Jr., J.T. Pietrowski, and R.P. Wilder, R&D, firm size and concentration: Evidence from the FTC Line of Business Survey, in: Quarterly Journal of Business and Economics, Vol. 25, no. 2, 1986.

of research investment. In industries with high R&D costs and high uncertainty of R&D and no barriers, increase in concentration will lead to an increase in research investment[1].

Therefore a more fruitful way to pursue could be found in the suggestion to pay more attention to differences in technological opportunities, changes over time, and their consequences for the study of market structure and innovation. In particular, as e.g. Zuscovitch has stated, any attempt to identify a market structure which favours innovation is an attempt to formulate a dynamic problem in static terms[2]. Then the study of market structure and innovation could gain in a more detailed understanding of changes in each sector of the industry or market before returning, if possible, to more subtle generalizations.

Innovation and firm size

The short review of empirical findings on market structure and innovation in the above will probably not arouse high expectations on the results of economic research into the adjacent and related issue of firm size and innovation. Here also, many studies suggest an inverted U distribution for innovation and firm size. However, there are also some studies which suggest some contrasting evidence. In short, one can confront three different groups of analyses on the relation between firm size and innovation:

- the widely accepted evidence of an inverted U distribution of R&D input and output over firm size which I will label the Scherer-variant after one of its most prominent researchers;
- the Schumpeter inspired interpretation of research and innovation concentration in large companies;
- analyses which, at first sight, could well be a synthesis of the two contrasting analyses mentioned above suggesting a U shaped distribution of innovation and firm size.

I will briefly discuss some studies which are exemplary for these different analyses.

1) See R. Angelmar, Market structure and research intensity in high-technological-opportunity industries, in: Journal of Industrial Economics, Vol. 34, no. 1, 1985.

2) See E. Zuscovitch, The economic dynamics of technologies development, in: Research Policy, Vol. 15, no. 4, 1986, p. 176.

A vast number of studies on the relationship between firm size and either innovative input or output suggests at least a non-linearity. Studies by Scherer, Mansfield, Philips, Mueller, Freeman and others all point to this non-linearity. With the exception of the chemical industry there is little support for the hypothesis that innovative input and output increases with firm size beyond some magnitude[1]. A well-known and prominent illustration of the findings of the humpback distribution of R&D intensity over firm size is found in Scherer's contribution. Scherer's theory and earlier research are well-known and have been discussed in the previous section. Also some of his more recent research supports his theory while it also offers some qualifications. Scherer maintains that small companies are still disproportionately important contributors to innovation as shown in diminishing returns in the relation between size and patents. However, it has to be acknowledged that large firms contribute more than proportionally to total R&D expenditures[2]. In his earlier writings Scherer stated that not only R&D output but also R&D input would rise less than proportionally to size once a threshold had been passed[3]. His later findings apparently suggest some modification of earlier results.

Such findings on an inverted U relation between size and innovation is partly supported in a recent study of Ettlie and Rubenstein who found that the introduction of radical new products is more than proportionally found within medium sized companies (between ± 1,000 - 10,000 employees). The largest companies with over 45,000 employees in their population were unlikely to introduce radically new products[4].

A study by Dorfman on innovation in the computer and semi-conductor industries stresses the role small and new companies have sometimes played as major innovators within these industries[5].

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1) See e.g. M.I. Kamien and N.L. Schwartz, 1975, and 1982, p. 18 ff; F.M. Scherer, 1980, p. 417 ff and many other surveys.
2) See F.M. Scherer, Innovation and growth - Schumpeterian perspectives, 1984, pp. 222-239.
3) See idem, 1965, pp. 1103, 1104 and 1980, p. 420.
4) See J.E. Ettlie and A.H. Rubenstein, Firm size and product innovation, 1986.
5) See N.S. Dorfman, 1987.

Contrary to most studies in this field Dorfman presented a more qualitative study combining analysis of relevant technological developments with changes in market structures. The study gives a differentiated picture of innovation in five related industries: mainframe computers, minicomputers, computer printers, magnetic disk storage and integrated circuits. In mainframe computers the present market leader IBM soon became the leading manufacturer. New and relatively small companies concentrated on either the very-high-performance market niche or the lower end of the market. In the other industries new and small companies played a more prominent role in particular at the early stages of technological development. However, for each industry one has to recognize the complex setting and historical perspective of larger established companies and entrants within sub-markets.

Scherer's and others' research findings on the relationship between firm size and innovation have become 'conventional wisdom' amongst students of technological development, generally accepted and but rarely disputed. So far, but few have criticized the out come of a disproportionate distribution of innovative input or output to size. A marked dissident analysis has been brought forward by Soete[1]. His alternative analysis is based upon R&D expenditures of US companies in 1975 and 1976 covering 95% of total company R&D in the USA. This research generated results which contradicted accepted evidence of the size - research input relationship. From Soete's research it follows that very large companies employing over 250.000 people had higher R&D to sales ratio than the following size classes. Also, R&D expenditure is found concentrated in the largest firms, ranked either by employment or sales. Furthermore, the results of regression analysis indicate that "... innovation effort, as measured by company financed R&D expenditure, tends to increase more than proportionately with firm size"[2]. There are differences between sectors due to

1) See L. Soete, 1978, idem, Firm size and inventive activity - the evidence reconsidered, in: European Economic Review, 12, 1979(a), and idem, Size of firm, oligopoly and research: A reappraisal, in: Reseaux, no. 35-36, 1979(b).
2) L. Soete, 1979(a), p. 337.

industry specific circumstances but most industries studied are in favour of the Schumpeter hypotheses and the humpback distribution is found in only a few industries.

These findings cast some serious doubt about the evidence of what has been described as 'conventional wisdom' on the disproportiate relation between firm size and industrial research and development. Soete's findings are, however, more in accordance with some of Scherer's later findings on size and R&D input.

The third approach, in which a U-form relationship between innovation or R&D and firm size is generated, has only been introduced recently in two studies, one by Pavitt et al. and an other study by Bound et al.[1]. These findings could contradict both the so-called Schumpeterian and the Scherer-like explanation. Pavitt's research is based upon a databank of over 4,000 innovations which have been introduced in the past 40 years in the UK. The sectoral distribution of their sample of over 4,000 innovations coincides with the sectoral distribution of patents. Some conclusions to be drawn from this research are:

- There is some evidence that the smallest companies and units of production, with less than 200 employees, and also the largest companies, with over 50,000 employees, have become more innovative in the period to which the study refers.
- There is an above average innovation intensity amongst large firms, with over 10,000 employees, and a growing innovation intensity amongst smaller companies. (The picture of the latter group is somewhat differentiated, but it holds for companies with a size between 100 and 500 employees and probably also for companies up to 1,000 employees.)

1) K. Pavitt, M. Robson and J. Townsend, The size distribution of innovating firms in the UK: 1945-1983, SPRU-paper, 1985, idem, A fresh look at the size distribution of innovating firms, SPRU-paper, 1986(a), and idem, The size distribution of innovating firms in the UK: 1945-1983, in: Journal of Industrial Economics, Vol. 35, no. 3, 1987; and J. Bound, C. Cummins, Z. Grilliches, B.H. Hall, and A. Jaffe, Who does R&D and who patents?, in: Z. Grilliches, 1984.

- Intersectoral comparisons show that there is considerable variation amongst sectors generating several distributions, which explains that the overall distribution is a result of three different trends. (Large firms domination, small firm domination and U-form distribution, each for a different group of industries.)

In a study by Bound, Grilliches and their colleagues the R&D intensity of about 2,600 US companies is studied and in particular very small and very large companies are found to be more R&D intensive than average size companies. However, their sample is strongly biased towards small firms which have been successful in R&D and interesting for investors.

As mentioned before the results of the empirical research so far have to be interpreted with utmost care. In many studies quite different indicators for innovation ranging from research inputs to innovative output such as patents and tangible innovations have been applied. As far as the relation between firm size and R&D inputs is concerned there is apparently some consensus that R&D expenditures are concentrated in the group of very large companies and that these expenditures rise more than proportionally to the size of companies. Regarding the output of research in terms of patents or innovations the situation is still unclear.

Contributions by Pavitt and Bound and their colleagues cannot be seen as a synthesis of the other two approaches. On the face of the matter this could be concluded from adding both contrasting findings generating a stylized U-relationship. No matter how elegant such a solution might seem, it has certain flaws. As mentioned above Pavitt et al.'s findings suggest that at the level of individual sectors of industry several sorts of distributions of the relation between size and innovation can be found. The overall U-relationship results from the interplay of size, innovative activities and the intersectoral pattern.

3.5 INNOVATION AND TECHNOLOGICAL OPPORTUNITY

A possible way-out for further research could be found in a broadening of the scope. It has already been stated that the debate on market structure and innovation led to few satisfying results apart from the emphasis placed upon the importance of technological opportunities as a key-issue on the present research agenda. Also, further research into the relation between firm size and innovation could benefit from more attention to e.g. technological opportunities within sectors of industry. Suppose that more of the same kind of econom(etr)ic research based on the well-known size classes and variables analyzing slightly different time-series and or data will probably not bring about completely new insights. In that case it might be useful to change our focus towards a more differentiated approach, in which innovative performance is analyzed in the context of sectoral differences and several categories of companies. Such an approach could also enable research to pay more attention to differences in technological opportunities for industrial sectors. Many authors have stressed technological opportunity as an important determinant of the relation between market structure, firm size and innovation. Technological opportunity is sometimes defined as the extent of basic scientific knowledge in the industry[1]. Levin et al. have included technological opportunity in their analysis in order to explain patterns of innovation. They mention three dimensions of technological opportunity: closeness to science, external sources of technological knowledge and industry maturity[2]. It is clear that technological opportunities vary amongst industries but also with time. Differences in the degree of innovativeness of industries and the gradual but also uneven development of technology itself causes technological opportunities to differentiate.

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1) See e.g. G. Dosi, 1984, pp. 92, 93 or R. Kaplinski, Firm size and technical change in a dynamic context, in: Journal of Industrial Economics, Vol. 32, no. 1, 1983.
2) R.C. Levin, W.M. Cohen and D.C. Mowery, 1985 and W.M. Cohen, R.C. Levin and D.C. Mowery, Firm size and R&D intensity: A re-examination, in: Journal of Industrial Economics, Vol. 35, no. 4, 1987.

A 'mapping' of technological opportunities, sectoral differences and company strategies has been introduced by Pavitt. The author has suggested a taxonomy of technical change, categories of firms and industrial sectors[1]. Within this taxonomy categories of firms such as supplier dominated, production intensive and science based firms are set against sectors of industry, technological developments and other characteristics such as product or process innovations, size of innovating firms and forms of diversification. Analyses based on such an approach can lead to more differentiated knowledge about sectoral development, technological classifications of sectors and intersectoral patterns of technological change[2].

Freeman has introduced a somewhat similar approach but more directed towards a distinction of industries and the role of small firms in innovation. In Freeman's division of industries there are:

- industries in which small firms make but little contribution to innovation, either absolutely or relatively, e.g. aerospace, motorvehicles and chemicals;
- industries in which small firms make a substantial contribution to innovation, e.g. instruments, electronics and textiles.

But also here few generalizations can be made because variations by branches of industry and other factors such as the position of the growth cycle of an industry will have to be considered. In new industries Freeman points out, in agreement with explanations stated e.g. by Dosi, Dorfman and Scherer, small innovative firms can be important but this role can gradually decrease as the industry enters into maturity and economies of scale are introduced[3].

A major achievement of such attempts to understand industrial development and innovation in the context of technological opportunities is that innovation is not reduced to indicators such as R&D

1) See K. Pavitt, Sectoral patterns of technical change: towards a taxonomy and a theory, in: Research Policy, Vol. 13, 1984.
2) See idem, and L. Soete, Sectoral and technological taxonomies: an 'integrative' analysis based on innovation statistics, in: C.P.B., 1987.
3) See C. Freeman, 1982, p. 143.

or patents but that these indicators are integrated within a wider understanding of technological development and its consequences. A more detailed outline of a theoretical framework which enables a more dynamic and concrete understanding of technological development and innovation will be presented in the next chapter. Here, it will suffice to draw some conclusions from the Schumpeter debate for understanding technological development.

Until recently the state-of-the-art of research on the Schumpeter controversy was somewhat disappointing. There has been some sort of consensus that both market structure and size of companies show an inverted U-shaped distribution with respect to innovation. For the market structure many studies suggest that growing concentration is parallelled by a growing R&D intensity upto a certain level after which R&D intensity grows disproportionately less than concentration. However, the relation between concentration and R&D intensity differs from sector to sector. Differences in technological opportunity amongst sectors has been mentioned as the intervening factor which could explain differences in the relation between concentration and innovation for industrial sectors. For firm size and innovation the distribution is frequently seen as having a similar character. A non-linearity between size and innovative output once a particular company size is reached, is accepted by many. It is thought that small companies play an important role in the early stages of a particular technology, followed by a growing importance of large companies in the further development of a technology. Then, at a particular size both innovative input and output rise less than proportionally to size. However, there is also some deviate evidence which suggests a linearity or even more than proportional growth of R&D to size. And recent studies disclose some empirical evidence which suggests a cross-sectoral pattern of small and large company dominated process of innovation. But then again the pattern is fundamentally different at the level of individual sectors of industry.
Some recent contributions to evolutionary economic theory suggest a more fruitful analysis of technological development. In the next chapter I will return to these contributions. Here it will suffice to point at the growth of attention being paid to technological opportunities both in the empirical and theoretical literature.

All this suggests that including technological opportunities for several industrial sectors could enable the analysis of market structure, firm size and innovation to develop towards a more dynamic analysis. In particular if technological opportunity is operationalized adequately in order to understand technological development itself the analysis of the dynamics of innovation, market structure and firm size for sectors industry could complement 'across-the-board' analyses.

3.6 CATEGORIES OF COMPANIES AND INNOVATION STRATEGIES

In the above it has been concluded that widening the scope of research on the subject of market structure, firm size and innovation could well complement more traditional research. The inclusion of technological opportunity, in particular if understood as a way to understand technological development itself, could provide useful insights for further study. But also a further categorization of companies can lead to a more concrete understanding of innovation and industrial development. The mere recognition of relevant differences between categories of companies is superior to the crude neo-classical theory of the firm in which a company is reduced to a production function. It also coincides with some recent developments in industrial economics deviating from the traditional school based upon Bain's 'structure-conduct-perfomance'-approach, in which there had been so little attention to different performances of companies. Since the late seventies there has been a growing attention to strategic options and categories of companies. Stressing the role of both different categories of companies and different strategies and objectives enables a more dynamic analysis of industry evolution. In short, the more static relation between structure, conduct and performance is replaced by a more dynamic approach in which there are feedback effects from performance and conduct to structure[1].

1) See also M. Porter, The contributions of industrial organization to strategic management, in: J.B. Barney and W.G. Ouchi (ed.), 1986 and P. van Cayseele and H. Schreuder, De economische inbreng in de strategiebepaling van ondernemingen: een overzicht, 1988.

In this section I will pay attention to some attempts made to differentiate between groups of companies and their innovation strategies. Before discussing such categorizations I will first briefly discuss some aspects of organizational changes of companies in modern capitalism and corporate innovation strategies.

Organizational transformations and innovation

In modern capitalism one observes a wide variety of companies from extremely large, multinational, companies to small companies with only a few employees. The growth of both companies and plant-size has been recognized as an important feature of capitalism ever since the classical economists. In particular the growth of companies has been subject to a continuous debate on (in-)efficiency and size. In that context organizational changes within companies have been discussed as 'solutions' to problems related to in-efficiency following company-growth.

Such organizational changes are also relevant for understanding innovation strategies in modern companies. These organizational and decision-making aspects of innovation strategies are frequently discussed in the literature on large, multi-product companies with a multi-divisional structure. In seminal work by Chandler and Williamson, but also in some less well-known neo-Marxist contributions, different company and management structures are identified[1]. The analysis of Chandler stresses the outlived character of the so-called unitary, departmentalized, U-form organization of a large company with respect to major issues in its strategic decision-making. The alternative was found in the so-called M-form, multidivisional, organization in which strategic and operational decision-making are separated at different levels. At the top level, the general office is involved in coordination and evaluation of strategic decision-making. Operational decision making takes place at a lower level of separate divisions.

1) See A.D. Chandler Jr., The visible hand: the managerial revolution in American business, 1977, A.D. Chandler Jr. and H. Daems, Managerial hierarchies, 1980, and O.E. Williamson, 1975, and S.H. Hymer, The multinational corporation, a radical approach, 1979 and M. Aglietta, 1979.

The classical U-form organization with vertically integrated divisions can still dominate the group of medium sized companies. Its structure is most suitable for decision making on familiar problems within a non-diversified company[1].

In this context two interesting neo-Marxist contributions, by Hymer and Aglietta, are worth mentioning. Hymer has paid extensive attention to the role of large, multinational, companies and their organizational change[2]. Aglietta has been able to take the argument somewhat further and present an interesting concept of the corporation as a global system[3]. Both authors founded their theories of organizational change of companies on Marx's theory of concentration and centralization, but they have integrated elements of modern theories of organizational change of companies in their respective theories. Hymer presented a theory of the evolution of the corporation at different stages. In short, these stages have developed from the workshop, the factory, the national corporation, the multidivisional corporation to the multinational corporation. Aglietta has analyzed changes in corporations from the former centralized, U-form, company to the decentralized multi-divisional company into a new stage of a centralized and global system.

Both typologies of corporate change can be integrated into the following framework.

Some of the 19th century 'single product-line' manufacturing companies gradually developed into the large company with a few functional departments and a separate head-office. Such companies have been described by Hymer as 'national companies', and by and large the main features of these companies coincide with Chandler's U-form. Through internal and external growth (concentration and centralization) again some companies evolved into multidivisional, diversified, companies in which the organizational top-structure changed from a head office into a general office. Many management

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1) See C.J. Sutton, Economics and corporate strategy, 1980, pp. 72, 73.

2) See e.g. S.H. Hymer, 1979.

3) See M. Aglietta, 1979.

tasks were decentralized and commissioned to division-level. In this structure the general office is engaged in strategic planning and control of divisions based upon financial criteria[1]. These companies are usually multidivisional, Chandler's M-form, but also multinational.

Hymer mentioned the planning of the product cycle as an essential feature of this modern, multidivisional, corporation. Planning of the product cycle involves the coupling of several phases of production, such as R&D, manufacturing and marketing. The development of degrees and patterns of coupling of such phases of production reached its highest level of control in the modern multidivisional and multinational corporation. The increase in information flows is a reflection of the importance and interaction of product development and marketing in the M-form company[2].

Aglietta has taken the notion of intensified integration of information flows somewhat further, introducing the concept of the corporation as a global system evolving from the multidivisional structure[3]. In this development there is a change, an organizational transformation, back to organizational centralization although under different conditions than in the situation of the U-form company. The present transformation of the organizational structure is, according to Aglietta, a movement back to centralization but based upon automated information processing and overall production control. This new organizational structure is pictured as a star-form compared to the divisional structure in the form of a pyramid. The central control unit is found in the centre

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1) Following Ansoff this strategic decision-making is directed towards:
"- monitoring the environment for changes and searching for attractive product opportunities;
- consideration of allocation of resources between current operations and possible future opportunities;
- evaluation of competitive advantages, long-term potential and possible joint effects (synergy) of opportunities;
- coping with potentially antagonistic objectives";
see Ansoff op. cit. in N.M. Kay, The innovating firm, 1979, pp. 54, 55.

2) See S.H. Hymer, 1979, p. 151.

3) See M. Aglietta, 1979, pp. 257-266.

coordinating and programming all company-activities. Furthermore, all elements of the company are interacting with each other. This new system of organization enables the company to set up semi-autonomous groups in order to improve the external 'sensitivity' of companies. Within this system the development of communication, automation of routine managerial tasks, improvement of planning and budgetary methods and production control are compulsory. Around these corporations there is 'a network of subcontracting' with legally independent companies. These firms produce no commodities in the strict sense but intermediate products within a wider production process. Although legally independent they can be considered as a part of the production process of larger companies[1].

Both Hymer's and Aglietta's contributions present some valuable thoughts on organizational transformations of corporations and the differentiation of capital. The distinction of companies into national, not widely diversified companies, and multidivisional, multinational, companies and small, economically dependent but not legally integrated firms appears to be helpful.
The remarks made by Hymer about the growing integration of information flows from and to all phases of the product cycle stress the importance of organisational control within large multi-divisional companies. This growing integration is also stressed in Aglietta's concept of the corporation as a global system. The attention paid to integration, overall production control, automation of lower-level managerial tasks is worth mentioning. Also the interrelation of companies and how it can effect technological change is relevant[2]. In that perspective the relation between large multidivisional companies and small sub-contracting firms is of importance. The present trend in sub-contracting and co-makership, widely discussed in the popular business press, supports the view of an economic and often technological link between companies. In that case large companies outsource non-critical parts of

1) See idem, p. 220.
2) See e.g. J. Hagedoorn and J. Schot, Co-operation between companies and technological development, 1988 and the literature mentioned.

their production and small firms supply intermediate products or services often within modern 'just-in-time'-lines of production. In a sense this is a trend which goes against vertical integration in the formal sense, but in practice there is a form of 'quasi' integration if suppliers depend on a small number of procuring companies.

Innovation- and corporate strategies

It will be clear that the transformation of companies into different categories is related to innovation strategy and changes of strategy. Already Schumpeter discussed innovation as a change from existing routines in a company. This notion of routine and innovation as a change of routine is also found in the evolutionary theory of Nelson and Winter. It is introduced by them to describe regular and more or less predictable patterns of company behaviour. A routine is defined as all conduct which is "... regular and predictable (...) especially if we understand that term to include the relatively constant dispositions and strategic heuristics that shape the approach of a firm to the nonroutine problems it faces."[1]. Routines include characteristics of firms regarding several policies for the organization of production and innovation strategies, manpower, investments, et cetera, the so-called operating characteristics. Companies follow routines while they are operating in the market and when they are adapting their internal strategies to their environment. These routines serve as a kind of organizational memory, representing the existing capabilities of a company. Nelson and Winter stress that "... a firm with an established routine possesses resources on which it can draw very helpfully in the difficult task of attempting to apply that routine on a large scale. Because the creation of productive organizations is not a matter of implementing fully explicit blueprints by purchasing homogenous inputs on anonymous markets, a firm that is already successful in a given activity is a particularly good candidate for being successful with new capacity of the same sort"[2].

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1) R.R. Nelson and S.G. Winter, 1982, p. 15, see also R.R. Nelson, 1987, pp. 21-23.
2) idem, 1982, p. 119.

Therefore firms are usually better equipped to do more of the same than to change their strategies on one of their characteristics. Changes in routines under uncertain conditions or just new combinations of already existing routines can be described as innovations in the Schumpeterian sense. There is also some similarity between future and present behaviour of companies because the routines that firms have employed in the recent past will have a rather strong tie to routines applied in the near future.
Innovations are not only characterized as a change in the existing routines, but innovations can also emanate from problems and irregularities within these routines. Answers to the questions being raised by these problems are probably to be found in a change of prevailing routines or in carrying out of new combinations, in the Schumpeterian sense.
New combinations may be found through either existing routines which had not been combined before or a combination of existing routines with new subroutines. Nelson and Winter stress that for the incorporation of an existing routine as a component of innovative routines it would be useful if two conditions are satisfied:

- The routine has to be reliable in order to ensure that existing routines do not cause new problems in their new setting.
- The new application of the existing routine should be unambiguously applicable.

"These two conditions suggest an important qualification to the general notion of an opposition between routinization and innovation. Reliable routines of well-understood scope provide the best components for new combinations. In this sense, success at the innovative frontier may depend on the quality of the support from the 'civilized' regions of established routine."[1].
Although innovation can largely be characterized by a fundamental uncertainty about the results, the search process involved can to a large extent be described as 'routinized'. Nelson and Winter adopt the framework of the theory of heuristic search for a better understanding of the relation between routines and innovation. As a definition of a heuristic they adopt Newell, Shaw and Simon's definition stating that a heuristic is "... any principle or

1) ibidem, p. 131.

device that contributes to the reduction in the average search to solution"[1]. Search strategies of firms adopt certain procedures for the screening of R&D projects. These R&D strategies consist of "... a quasi stable commitment to a particular set of heuristics regarding R&D project selection..."[2]. It is possible to recognize certain R&D strategies that dominate particular sectors of the economy but the total number of research projects for an R&D organization is in theory that large that in practice certain choices have to be made. Therefore, as Nelson and Winter rightly state, most firms will limit themselves to "...strategies which involve a precommitment to one or a small number of classes of R&D projects each of which has a certain similarity of broadly defined targets, procedures for reaching these targets, and R&D resources required."[3]. Even if these search strategies consist of more or less well described set of activities and decision rules, according to Nelson and Winter, "...firms cannot hope to find optimal strategies"[4]. However, even these non-optimal policies are of course aimed at a positive influence on the firm's profitability.

The understanding of innovation strategies in terms of routines and heuristics parallels theories on strategic decision-making on innovation and R&D priorities. It is accepted by many that in large companies top-level decision-making on corporate R&D budgets is generally based upon consideration of resources, not on projects. This resource-consideration instead of component projects, together with a routine of R&D funding, leads to quasi-stable R&D decision-making within large companies[5].

Kay has mentioned four general features of corporate R&D resource allocation:

- allocation is based on subjective rather than objective decision rules, applying rule of thumb methods rather than optimization techniques;

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1) ibidem, p. 132.
2) R.R. Nelson and S.G. Winter, In search of useful theory of innovation, in: Research Policy, Vol. 6, 1977, p. 52.
3) ibidem, p. 55.
4) ibidem, p. 55.
5) See also EIRMA, The role of R&D in the innovation process, 1982 and idem, How much R&D?, 1983, and R. Coombs, P. Saviotti and V. Walsh, Economics and technological change, 1987, Ch. 3.

- there are stable managerial preferences for allocation;
- the corporation behaves as an open system in which R&D at the functional level can influence managerial preferences;
- decision-making is rational in the sense that companies learn to chose an appropriate level of R&D in order to survive[1].

The practice of inter-subjective decision-making against a background of stable routines of R&D funding is quite contrary to management decision-making supported by 'scientific' methods. The impossibility for companies to overcome uncertainty in technological development by 'objective' technology forecasting methods is frequently stressed[2]. Corporate R&D decision-making at top level can be expected to be more of a general commitment to a satisficing level of resource allocation. Consequently decision-making at lower levels of management has to be more related to specific problems and component innovation projects. This level is found within the divisions or central R&D institutions of large companies[3].

So far most attention has been paid to transformations of larger companies and their innovation strategies. Small and medium sized companies have been mentioned, but only incidentally. Much of the literature on innovation strategies and related issues deals with large, in particular, the very large companies. This particular attention for large companies is understandable as they present a group of companies for which the process of decision-making and existing procedures are more readily studied.

But, as mentioned in previous sections, innovation is probably not only a matter of the largest companies. Small and medium sized companies do pull their weight although it might vary from industry to industry. Even with regard to R&D activities some small and medium sized firms play an active role. Freeman has mentioned three categories of small and medium sized firms for which R&D is essential to their existence:

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1) See N.M. Kay, 1979, p. 91, 92, and R. Coombs, P. Saviotti and V. Walsh, 1987, p. 59.
2) See e.g. C. Freeman, 1982, p. 168; N.M. Kay, 1979 and O. Grandstrand, Technology, management and markets, 1982.
3) See e.g. EIRMA, 1983, p. 67, and R. Coombs, P. Saviotti and V. Walsh, 1987, Ch. 4.

1. Firms which have recently started to develop or exploit a new invention and for which a high research intensity can be expected. The research intensity will probably fall after successful exploitation of the invention.
2. Highly specialized, often research intensive, firms which concentrate upon narrow fields of technology.
3. "Firms struggling to survive in industries in which new product competition makes R&D increasingly necessary. Here small firms can either pursue to survive with a so-called sub-threshold R&D effort, or rely on cooperative research or take high risks with an ambitious programme"[1].

In the foregoing it was stressed that large, medium and small companies all play a role in generating innovations. Their role in research might differ, there are sectoral differences and technological opportunity is to be incorporated in studies to achieve a better understanding of many issues. If these differences are recognized, then the scope of research will be broadened considerably.

It would be broadened even further if various innovation strategies, some open to several groups of companies, are incorporated. E.g. Porter, and also Nelson and Winter, discuss technology strategies in the dichotomy of technological leadership versus followership or innovative and imitative strategies[2]. Freeman had already taken the issue somewhat further in recognizing several innovation strategies. Based upon Freeman's contribution one can distinguish six alternative ideal types of innovation strategies[3]:

The offensive innovation strategy which is aimed at achieving both technological and market leadership through quick internal technological diffusion, keen exploitation of new combinations or a combination of both. An offensive strategy encompasses internal R&D facilities, information processing abilities and marketing facilities.

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1) C. Freeman, 1982, pp. 133, 134, see also R. Rothwell, 1986, pp. 125-127.
2) See M.E. Porter, Competitive advantage, creating and sustaining superior performance, 1985, pp. 181, 182, and R.R. Nelson, 1987, pp. 41-43.
3) See C. Freeman, 1982, pp. 170-186.

Defensive strategies do not imply a complete ignorance of innovative activities but companies following such strategies are more risk-averse and at some distance from the radical innovating companies. Defensive strategies by large companies can be expected in particular in mature oligopolistic market structures.

Such defensive strategies enable companies to 'keep up with the game' but imitative companies are normally lagging at considerable distance from the leading companies. In order to compete with innovating companies imitators have to rely on specific advantages for some factors of production, or concentrate at the lower end of the market.

For many large multi-product companies their overall innovation strategy will be a mixture of both offensive and defensive, and perhaps imitative, strategies for different lines of business.

A dependent strategy is usually of some sort of subcontracting character, in which no initiative toward innovation is taken unless it is done by customers.

Traditional strategies are followed by companies for which innovation is not compulsory due to specific market circumstances, e.g. in handicrafts.

Opportunist strategies reflect the search for particular market niches by so-called imaginative entrepreneurs.

The actual market structures and technological opportunities are too complicated to make a direct linkage between size of companies and innovation strategies. Also, the character of strategies will differ between sectors. E.g. a defensive strategy in a sector with many technological opportunities such as in the microelectronics industry or in other 'high tech' sectors is intrinsically more offensive than an offensive strategy in an industry with little technological opportunity. In other words, the set of alternative strategies and their concrete substance is mediated by sectoral and technological circumstances. Depending on both structure of the industry and technological opportunity a number of strategies are open to all companies. As such a classification of innovation strategies and sizes of companies does not render predictive statements but it can be useful in describing different company behaviour in a particular industrial setting. Although not identical the approach chosen has certain features in common with the analysis of 'strategic groups' in strategic management studies[1]. In particular multivariate analyses of strategic groups with reference to size of companies provide somewhat similar attempts to bridge the gap between industry and company-level analyses. In this study alternative innovation strategies could be seen as 'strategic groups' in relation to mainly one particular aspect of business strategie, i.e. innovation strategy.

3.7 AN ANALYTICAL FRAMEWORK FOR THE ANALYSIS OF INDUSTRY STRUCTURES AND INNOVATION

Having reviewed relevant theories and research in the foregoing, elements of these different theoretical contributions and conclusions from empirical research will have to be mediated into an alternative and more coherent analytical and conceptual framework.

In neo-Marxist political economics a rather static theory of monopolization has been at the forefront of this particular economic paradigm. Sweezy's contributions are typical for this approach in which companies are divided into two separate classes. One group is the group of small and probably also medium sized companies. The other group consists of so-called monopoly capital also labelled as oligopolies, large companies or big business. This theory shares its dichotomy with Galbraith's, partly Schumpeter inspired, approach. A major difference between both theories is that in the theory of monopoly capitalism a slower rate of the introduction of innovations is assumed while Galbraith assumes that very large companies and concentrated markets are a stimulus for innovation. However they share their neglect of the dynamics of capitalism through the effects of creative destruction. Both contributions arrive at a simple dichotomy of large versus small companies which is too simple for analytical purposes. The same holds for theories in which companies are seen as either small, efficient and innovative or large, inefficient and non-innovative.

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1) See e.g. J. McGee, Strategic groups: A bridge between industry structure and strategic management, 1985 and K.J. Hatten and M.L. Hatten, Strategic groups, asymmetrical mobility barriers and contestability, in: Strategic Management Journal, Vol. 8, 1987.

In between the two extreme positions there are a number of theoretical nuances. Some state the advantages and disadvantages of both small and large companies in general, in doing so they present both sides of the coin. If these (dis)advantages are related to sectoral differences, e.g. small companies face substantial disadvantages in R&D and capital intensive sectors, then the argument is taken some steps further.

Within the neo-Marxist school a deviate approach stresses the dynamic analysis of different categories of companies without a structural differentiation of companies into e.g. a structural hierarchy of profit rates. In that context competition between companies is related to both growth of industrial sectors and companies. Monopoly is seen as a transient feature of innovation which is not directly related to size.

As demonstrated, many recent contributions to innovation theory and research stress the interrelatedness of industry structure, firm size and technological opportunity/maturity. This dynamic aspect provides a basic assumption for the analytical framework from an evolutionary perspective.

In the following chapters, in particular in chapter 5, the role of size and innovation, changing industry structure, and innovative performance will be analyzed for the international process control industry.

From the literature, discussed above, some general hypotheses are to be drawn for further empirical analysis:

- Rapid technological development in an industry will lead to high average R&D intensity, as the industry reaches a level of maturity its structure will become more concentrated (e.g. Nelson and Winter).
- In new fields of technological development innovative companies will obtain temporary oligopolistic positions, as the technology and the industry matures one will find stable oligopolistic structures (Dosi).
- The relation between innovation and both industry structure and firm size can be characterized as an inverted U-relationship, innovation increases with size of firms and industrial concentration upto a particular level after which there is a relative decline. Small companies are disproportionately important to innovation (e.g. Scherer).

The third set of general hypotheses has been subject of a substantial number of empirical studies. No conclusive evidence has been found, but for firm size and innovation three 'contradicting' results have been generated:

- The relation between size and R&D output is of a stylized inverted U - relationship (Scherer and others).
- R&D input increases more than proportionately with firm size (Soete and Scherer).
- The relation between size and innovation is U-shaped, but there is a large inter-sectoral variation (e.g. Pavitt et al.).

As innovation is operationalized quite differently in many studies, either through input or output indicators, it seems sensible to analyze innovative performance applying a number of indicators. In the following chapters some indicators of innovation such as R&D-inputs, diffusion of best practice technologies, and share of new products in company turnover will be introduced.
Many studies suggest that technological opportunity is an important intervening factor. In the empirical parts of this study the process control equipment (p.c.e.) industry and its companies will be studied for their technological performance within the perspectives of a particular field of technology. By-and-large the technological opportunity is, although not identical, relevant to all companies. To study this technological opportunity it can be helpful to achieve in-depth knowledge of technological developments relevant to the understanding of innovation and technological change in the particular sector of industry. Studying technological opportunity against the background of technological change in an industry provides complementary information for the interpretation of indicators of innovation.

In the previous section it was explained that a differentiation of companies to size and their innovation strategies would enable a more subtle analysis of industry structure and technological development. From the foregoing it is possible to derive the following categories:

- small or medium sized companies which serve as subcontractors;
- small (existing or new) or medium sized 'single product line' companies;
- large companies with a small numbers of divisions;
- very large, multidivisional and multinational companies.

The actual size of these categories is to be determined in the light of the sector in question. Too often the debate about size has been mystified by fabricated size-categories which are of little relevance to the actual distribution. In other words, medium sized in one industry can easily turn out to be large in another.

Innovation strategies of these categories of companies are to be understood as a mixture of existing routines and implementation of changes in routines. In larger companies search strategies have become routinized with stable commitments to R&D and areas of innovation. Alternative strategies range from offensive, defensive, imitative, and dependent to opportunist.

There is hardly any reason to expect that, with few exceptions, particular innovation strategies will only be pursued by certain categories of companies exclusively. A dependent, subcontracting, strategy is probably most relevant for some small and medium sized companies. Almost by definition, an opportunist strategy can be expected from small and new companies. Traditional strategies are only relevant for some industries and from common sense one can expect that in those industries small and medium sized companies will follow such a strategy.

The other strategies mentioned above are less discriminatory for categories of companies according to size, beforehand.

As a sort of null hypothesis it can be expected that offensive, defensive and imitative strategies are followed by companies in all size-categories in a particular industry.

4. TECHNOLOGICAL DEVELOPMENT AND DIFFUSION AS AN EVOLUTIONARY PROCESS - INFORMATION TECHNOLOGY AND PROCESS CONTROL

4.1 INTRODUCTION

In the foregoing I pointed at the thorough understanding of technological development itself that Marx demonstrated in his analysis of capitalist development. Also Schumpeter, although not to a comparable level of detail, emphasized the understanding of innovation beyond what it usually found in economic analyses of technological development. Following this tradition of serious attempts to pay profound attention to the importance of technology, some recent interesting attempts have been made to analyze technological development as an evolutionary and dynamic process in which both technology and economic development influence each other. In such an approach technological development is analyzed as demonstrating far-reaching revolutionary changes which after successful introduction are followed by more incremental evolutionary changes. A central element in evolutionary theories of technological development is this attention paid to technological change as a process of accretion. E.g. both Rosenberg and Sahal stress this cumulative aspect of technology as a historical process in "... a series of smaller and highly tentative steps"[1]. In some analyses which stress the evolutionary character of technological development a new conceptual framework is introduced in which concepts such as technological paradigm, technological regime, basic design and technological trajectories are introduced. Such concepts can be applied without a clear definition and their 'loose' interpretation makes them extremely well-suited for suggestive descriptions of technological development. They share this particular feature with e.g. the Marxist notion of forces of production. However, a stricter interpretation of these concepts and

1) N. Rosenberg, Factors affecting the diffusion of technology, in: idem, Perspectives of technology, 1976, pp. 192, 193; see also D. Sahal, Patterns of technological innovation, 1981, p. 37, where it is stated that technological development is rather evolutionary, whereby radical break-through points are generally made possible by numerous minor innovations.

a clear distinction of different levels of abstraction can, in my opinion, offer some fruitful clarifications on the role technological change plays in economic development. Moreover it will enable a clearer identification of technological aspects of the development of the forces of production.

Before I discuss these concepts and submit a theoretical framework it would be useful to explore some ideas on what is meant by 'technology' in the context of this study. I will refer to technology as a particular aspect of what is labelled as the forces of production in Marxist theory. A useful definition has been suggested by Dosi in which technology is described "... as a set of pieces of knowledge, both directly 'practical' (related to concrete problems and devices) and 'theoretical' (but practically applicable although not necessarily already applied), know-how, methods, procedures, experience of successes and failures and also, of course, physical devices and equipment."[1]. In my view technology differs from craft based technique in its theoretically mediated character and from science in its more practical and applied character. In practice there is a 'grey area' between craft based expertise and theoretically mediated technology. Following Whitley technological research can be differentiated into:

- trial and error experimentation based upon conventional judgements and not upon deduction from general laws and principles (this trial and error experimentation is, in my opinion, an example of the 'grey area' between technique and technology);
- applied research on particular artefacts or systems redescribing practical problems to the extent that they can be analyzed, with 'established scientific knowledge' leading to feasible practical solutions; and,
- theoretically 'backed' technological research which generates some general understanding of causal relationships[2].

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1) G. Dosi, Technological paradigms and technological trajectories, in: Research Policy, Vol. 11, no. 3, 1982, pp. 151, 152; see also idem, Technical change and industrial transformation, 1984.
2) See R.D. Whitley, Types of technological research and their impact on occupational practices, 1987, pp. 4-6.

In that sense there is no general model of technological change going from science to technology to innovation. As. e.g. Thirtle and Ruttan have explained science and technology oriented research are "... two parallel but interacting paths"[1]. For some industries craft based expertise combined with trial and error experimentation such as in mechanical engineering will generate technical change. In others technological development is characterized by the application of established or new theoretical understanding. Although there are still some obvious reasons for differentiating between technology and science, it cannot be denied that, as Marx already stressed, one of the characteristics of modern capitalist societies is the growing interrelation between applied science and technology in so called science based industries[2].
Somewhat similar remarks are to be made about the interrelation between technology and innovation. Following a well accepted definition innovation is the commercial introduction of a new product or process. An innovation could therefore result from either technological research or craft based inventive activities. If one abstracts from innovations resulting from craftmanship then science, technology and innovation could be seen as overlapping, interacting, but still partly autonomous, 'stages' in changing the material world, ranked in order of market-related activity.

In the following sections I will introduce a conceptual and theoretical framework which enables the analysis of technological development at different levels of abstraction. Concepts which figure in section 4.2 are technological paradigm, basic design, key-element, technological trajectories and generations.
In order to limit the abstract character of such a treatise these concepts will be applied in the analysis of technological developments which are relevant to understanding the core-industry of this study, the sector in which information technology is transformed into process control equipment and control systems[3].

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1) C.G. Thirtle and V.W. Ruttan, The role of demand and supply in the generation and diffusion of technical change, 1987, p. 7.
2) See e.g. C. Freeman, The economics of industrial innovation, 1982.
3) The empirical data on relevant technological developments are largely based upon J. Hagedoorn, P. Kalff and J. Korpel, Technological development as an evolutionary process - the case of information technology and process control equipment, 1988.

Technological developments in process-, information-, and process control technology are analysed as changes within or changes from existing technological paradigms. Particular attention is paid to developments closely interlocking all three fields of technology. This part of the analysis is still at a level of considerable generality. The analysis will become more specific with the introduction of basic designs and key-elements as a further concretization of technological development, in this case the analysis of trends in process control technology. At the most concrete level of analysis technology is analysed in its development along trajectories leading to subsequent generations of both control devices and control systems. In short: section 4.2 pictures technological development as an evolutionary process with changes both within or from technological paradigms and their materialization in basic designs and technological trajectories.

The next section builds upon this concrete understanding of technological development connecting the analysis of technological change as an evolutionary process with diffusion. From that perspective diffusion is not a static phenomenon, the spread of a particular unchanging technology, but diffusion is a part of the evolution in technological trajectories. Some recent theoretical contributions will be confronted with more traditional theories of diffusion. Elaborating upon some criticisms on traditional research the consequencces of an alternative approach is shown in the empirical analysis of patterns of diffusion of information technology in process control. This will be studied in terms of changes in the relative importance of several generations of process control equipment and systems. In section 4.3 empirical findings on diffusion of information technology in process control are analyzed in the context of a survey of the international industry of process control equipment manufacturers. The findings of this survey will be studied extensively in the next chapter.

The present chapter 'builds a bridge' between the foregoing chapters, in which theories and research on technological and industrial development were discussed, and the next chapter where a concrete industry and innovative performance of different categories of companies are discussed.

4.2 TECHNOLOGICAL TRENDS IN PROCESS TECHNOLOGIES, INFORMATION TECHNOLOGY AND PROCESS CONTROL

In the following paragraphs I shall proceed from a general analysis of technological development in process control, information technology and process technologies to a more specific analysis of technological trajectories in process control. At an intermediate level of detail technological development can be analyzed in terms of changes of so-called basic designs. The analysis of particular fields of technology within a theoretical framework enabling descriptions at different levels of detail will concentrate upon both cumulative and divergent aspects of technological development. Such an analysis in which technology itself is studied provides some tools for the measurement of technological development which can complement more well-known indicators such as R&D inputs and outputs and patents.

Technological paradigms in process technologies, information technology and process control

The first concept I will define is technological paradigm. This notion is applied by a growing number of scholars from different disciplines such as economics, sociology, philosophy and history of technology[1]. In applying the notion of paradigm I refer to its meaning as a body of knowledge and practices which serves "... for a time implicitly to define the legitimate problems and methods of a research field of succeeding generations of practioners"[2].

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1) See e.g. G. Dosi, 1982, G. Gutting, Paradigms, revolutions and technology, in: R. Laudan (ed.), 1984, H. van den Belt and A. Rip, The Nelson-Winter-Dosi model and synthetic dye chemistry, in: W.E. Bijker, T.P. Hughes and T. Pinch, 1987, C. Freeman and C. Perez, The diffusion of technical innovations and changes of techno-economic paradigm, SPRU-paper, 1986, C. Freeman and L. Soete, Information technology and change in the techno-economic paradigm, in: C. Freeman and L. Soete (ed.), 1987, and N. Clark and C. Juma, Long-run economics, an evolutionary approach to economic growth, 1987.
2) T.S. Kuhn, The structure of scientific revolutions, 1974 (1962), p. 11 and idem, Second thoughts on paradigms, in: idem, The essential tension, 1977.

Although one has to be careful with analogies a technological paradigm can be interpreted as the technology related counterpart of Kuhn's scientific paradigm. It stresses the role a disciplinary matrix or a community of practioners "... with similar education and professional initiations ..."[1)] plays in defining a field of technology. Following Kuhn Dosi has defined technological paradigm 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; (...) a technological paradigm embodies strong prescriptions on the directions of technical change to pursue and those to neglect"[2)]. Although natural sciences are important to the building of technological paradigms it has to be stressed that social sciences can also play a role, in particular with respect to organizational aspects of production technologies. Within technological paradigms rules building both negative and positive heuristics are formulated to stimulate research in certain directions. Therefore technological paradigms have a strong 'exclusion effect' as they are focussed on certain directions, exploiting only particular technological possibilities. Also, a technological paradigm relates "... to generic tasks to which it is applied (...), to the material technology it selects (...), to the physical/chemical properties it exploits (...), to the technological and economic dimensions and tradeoffs it focuses upon (...)"[3)]. Hence, technological paradigms are to be understood as basic bodies of rules steering the process of search within technologically mediated knowledge. As in scientific paradigms most of the research within a well developed and 'mature' technological paradigm is aimed at solving 'puzzles' with existing tools. New paradigms emerge from the existing paradigms which are confronted with their boundaries when questions can no longer be answered within the existing body of knowledge and practice. Then, theories, new rules and practices have to be formulated and developed. It will be clear that the closer the achievements of a paradigm interact with the research

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1) idem, 1974 (1962), p. 175.
2) G. Dosi, 1982, p. 152.
3) ibidem, p. 153.

heuristics and innovation policies of leading companies the more a technological paradigm is 'driven' by the search strategies and objectives of these companies.
In order to understand general trends and major issues in process control one can make a first attempt by analyzing technological paradigms in process technologies and information technology which have become interlocked in process control. Process technologies to be looked at are iron and steel processing, food processing and the most important example of process technology, chemical processing. All these technologies are major fields of application of control technology, although the impact of control technology differs for each process technology. Nevertheless changes in control technology have to be seen against the background of changes in these fields of technology at the 'demand side'.

Chemical processing can be considered a mature technological paradigm since about 1960. Before 1960 both process and product innovation were generated but in retrospect it is remarkable how many product innovations were established in the first half of this century. Since the sixties only few product innovations have come about and, with the exception of the wider application of new materials, most innovations to date are process innovations. In the present state-of-the-art generic tasks in chemical processing deal with further improvements of catalysts and chemical reactor design, the development of new separation techniques, energy saving and reduction of emissions. All of which is coupled with improved and more sophisticated systems of process control. A change of paradigm can be found in the large-scale introduction of biotechnology and a divertion of feedstocks. Changes in relative prices could stimulate further development and diffusion of such technologies. However, both are not expected to have such a fundamental impact at least until the next century.
It is important to note that technological development in chemical processing has influenced industrial production to an extent which goes beyond the chemical sector itself. Developments within the existing paradigm in chemical processing have not only affected process control, for which it can be seen as a 'nursery' of many of its applications, but it also influenced industrial processing in other sectors, e.g. in food processing and the plastics industry.

Food processing has gradually changed from a traditional technique as a craft to one of industrial processing. In that process of change food processing first went through a phase of mechanization followed by automation. In this development toward industrial processing it was necessary to achieve more scientific and technological understanding of basic processes. As this understanding is still underdeveloped, food processing can only be seen as a less developed technological paradigm in which handicraft is still relevant to many sub-disciplines.
Many technological routines and new processes have been taken from other process technologies. In particular chemical and plastics processing have set examples for separation, extrusion and other techniques which are frequently applied in food processing.
Modern foodprocessing is still faced with various problems related to changing from batch to continuous processing. Technological barriers still to be overcome are due to a lack of process knowledge, the inhomogeneity of feedstocks, problems due to control of a large number of process variables and the absence of a wide range of sensors for organoleptical properties. Process control plays a role in the search for advanced processing, not only in the application of computer control but also in the introduction of automatic optical systems, quality control, a wide range of sensors and automation of weighing and packaging.
At the horizon of technological possibilities biotechnology can be seen as a future, new paradigm in food processing. So far biochemical processing has had little cost advantages. Social and economic acceptance, therefore, is not an issue yet and many technological problems still have to be solved.

A third field of process technology which is relevant to understanding changes in process control is found in iron and steel processing. The present paradigm can be seen as a mature field of technology which has materialized in incremental changes within the existing integrated coke-oven, blast furnace, oxygen steel making process. Since the seventies the search for further process innovations has been directed towards:

- efficiency of production routing;

- energy saving (energy costs count for about 25% of production costs);
- improvement of product yield and quality.

In iron making technology economies of scale have reached their theoretical upper limit. Search for further enhancement is concentrated on energy conservation, suitability of so far unapplied sorts of coal and process improvements in control of charges, blasting procedures and temperature.

Modern steel processing is based upon oxygen steel making and continuous casting which were both developed in the early fifties. Further refinement of this process is found in the improvement of blowing technology, energy conservation, and more efficient control of casting. Also in the downstream production of (semi-) finished products a search for improvement has been directed towards continuous processing and automatic control. Compared to chemical and food processing, modern iron and steel processing is more advanced in overall production control with management information systems.

As mentioned above the present dominant paradigm is found in the coke-oven, blast furnace, oxygen steel processing technology. An alternative paradigm setting new rules for production technology can be found in direct reduction in iron making technology and the wider diffusion of electric furnaces for steel making. Both technologies have passed their phase of experimentation, in particular electric furnaces are already applied in many 'mini mills' and its history goes back to the beginning of this century. So far the impact of these technologies have been, although by no means negligible, still too moderate to replace the existing paradigm at a large scale.

For a further understanding of technological change in process control it is necessary to pay some attention to developments in information technology which is beyond doubt the most pervasive technological paradigm at present. Information technology, a relatively 'young' field of technology, is concerned with information processing which is mediated through electronics and computers, software, and telecommunication. Basic trends, or general trajectories, are found in continuing miniaturization, increasing speed of data processing, increasing reliability, and, although with few exceptions, decreasing costs.

The first electronic computers were introduced shortly after the second world war. Their main information processing technology was based upon triode-circuits. Although promising the first computers had some serious drawbacks, they were expensive, 'bulky', not very reliable and difficult to operate. In the later part of the fifties transistors replaced the old triode-circuits and computers became faster but many of the existing shortcomings continued. Since the early sixties the search was directed towards further miniaturization which was made possible through the introduction of hybrid circuits. Major steps forward were made with the perfection of silicon technology in micro-processors in the seventies.

In computer technology all this led to a wide range of applications and a variety of types of computers some of which were designed in particular for process control.

In computer software major developments have been realized in the past decades as well. With the first computers programming was done by means of complicated procedures using e.g. the well-known punch-cards. Since the early fifties programming became somewhat less complicated with the introduction of alphanumeric codes. The search continued for a further development in 'languages' for computer programming resulting in a succession of well-known computer languages such as Fortran, COBOL, Basic, et cetera.

Since 1970 prices of computers have decreased substantially due to some of the main trends mentioned above. Technological development in software resulted in a continuing price-decrease for so-called standardized software but an increase in prices for 'tailor-made' sophisticated software. Present software technology is set for a move into so-called artificial intelligence, the translation of characteristics of human intelligence into computer systems. A less far-fetched attempt to develop artificial intelligence is found in expert systems.

The third element of information technology is the improved telecommunications technology, of which switching equipment, transmission systems and terminals are most relevant. It was not until the mid-sixties that older electromechanical switching equipment was replaced by electronic components although representation of signals was still analogues. The digitalization and change to fully electronic switching systems in the early seventies enabled the integration of computer and telecommunications technologies. Transmission systems were first based upon copper cable technology and micro-waves. The latter system has been upgraded by satellite communication systems, the first is being replaced by optical fibres. Terminals for computer-communication were introduced with the teletypewriter in the sixties. Since the seventies there has been considerable growth in so-called 'intelligent' equipment which is much better suited for sophisticated communication.

All these changes and searches for more 'intelligent' information technology, no matter how relevant in their own right, still have to be 'linked' to process control technology. In the following it will be demonstrated how some fundamental changes in process control led to a new paradigm which is heavily based upon the diffusion of information technology. Here it will suffice to note that computer technology has enabled more advanced and further reaching process control. Software is relevant not only for direct process control but also for upgrading of control into overall production control for which telecommunication is essential to plant-communication and intra-firm management information systems.

In the past hundred years process control developed from a very simple technology to sophisticated systems of control at all levels of production. In this development there is a clear shift of paradigm with the introduction of computer control. The older paradigm, dated before the introduction of computers, evolved from very simple local manual control at the end of the 19th century. In those early years there was little to no scientific understanding of process behaviour. Few process variables had to be controlled by the operator who made adjustments having read some instruments. Gradually process control became more complex and more automatic. Mechanical (pneumatic) devices, electrical instruments and controllers, and the first analogous controllers were introduced. In the period between 1930 and 1960 the expansion of the chemical industry and chemical processing was parallelled by an upgrading of process control. There was an increase in the number of measurement variables with a simultaneous introduction of analogous, electronic controllers at a large scale. It is the period of central control where both operators and controllers become situated in the familiar central control room.

The introduction of computerization of process control marks the shift towards a new paradigm in control technology. This new paradigm with a greater impact of information processing on control is apparent in a change in the disciplinary matrix as well. From that period the industry is in need of technologists and engineers who are capable of integrating process and advanced control technologies.

The period from 1960 to the mid seventies can be characterized as central computer control, i.e. computer control from a central control room. It is a period of search for different options ranging from off-line control, to a variety of on-line and in-line options and so-called direct digital control. Despite all efforts no option appeared unambiguously successful. Major problems were related to the reliability of existing mainframe computers and the costs of back-up facilities. A more well accepted solution was found in the introduction of a so-called 'distributed process control' which is dated from around 1975. Distributed process control meant a reversal of the trend of centralization in control with a decentralized use of several computer functions. Developments in information technology such as the introduction of microprocessors, the differentiation of computers into mainframes, mini's and micro's and computer-like controllers such as PLC's, and adequate software enabled a sophisticated systems approach to process control. Computerized control was now made possible at local, semi-local and central-control level.

Since the mid-eighties, search within the present paradigm is directed towards systems with integrated control in which there is overall production control. In integrated control the plant level is overarched into control of all aspects of production such as processing, routing, availability of raw materials, financial aspects and markets.

In the above changes, focal points, search and interrelations between several technological paradigms have been analyzed. Overviews of such developments are presented in figure 4.1 and 4.2. Although linkages between different paradigms have not been drawn in the first picture it is easily recognized how different paradigms are connected.
Sophisticated computerized control and communication have been made made possible by technological innovations in information technology. Modern industrial processing, e.g. in chemicals and steel processing, characterized by advanced control and a large number of process innovations has been aided by technical inputs from process control. Industrial processing in food technology is of a later date and influenced by other process industries.
In figure 4.2 it is shown how different stages of process control have been influenced by information technology. The new paradigm starting with central computer control and also succeeding stages could not have been developed without advanced information technology.

Basic designs and key-elements in process control technology

Other relevant concepts for the study of technological development at a lower level of abstraction than paradigm are technological regime and basic design. Nelson and Winter introduced the concept of technological regime which they compared with the concept of a meta-production function. This meta-production function, a concept first introduced by Hayami and Ruttan, has been described by Rosenberg as "... an envelope curve that goes beyond the production possibilities attainable with existing knowledge and described in a neo-classical long-run envelope curve. It describes, rather, a locus of production possibility points that can be discovered within the existing state of scientific knowledge. Points

Figure 4.1: Development of technological paradigms in process-, process control-, and information technology.

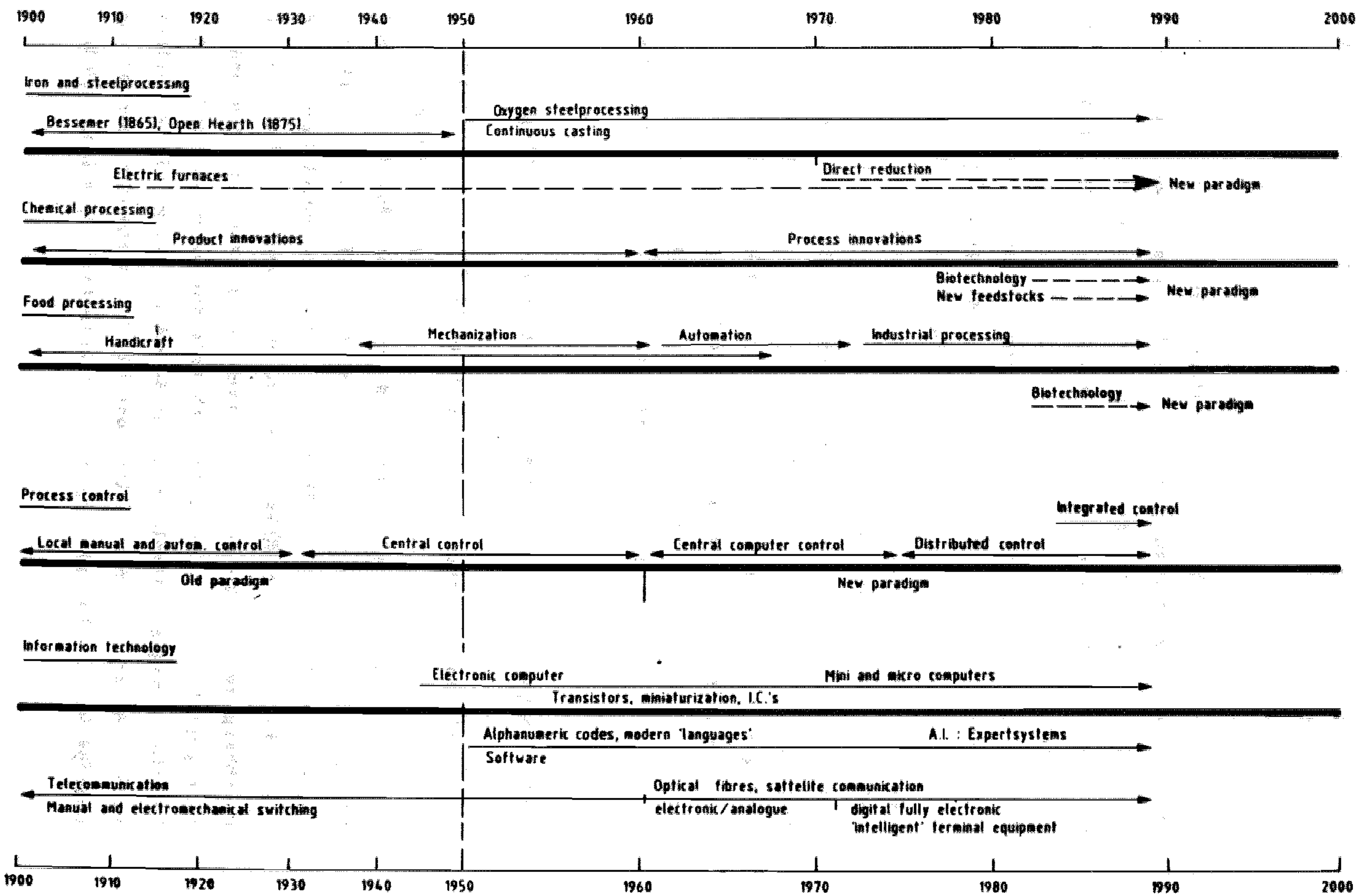
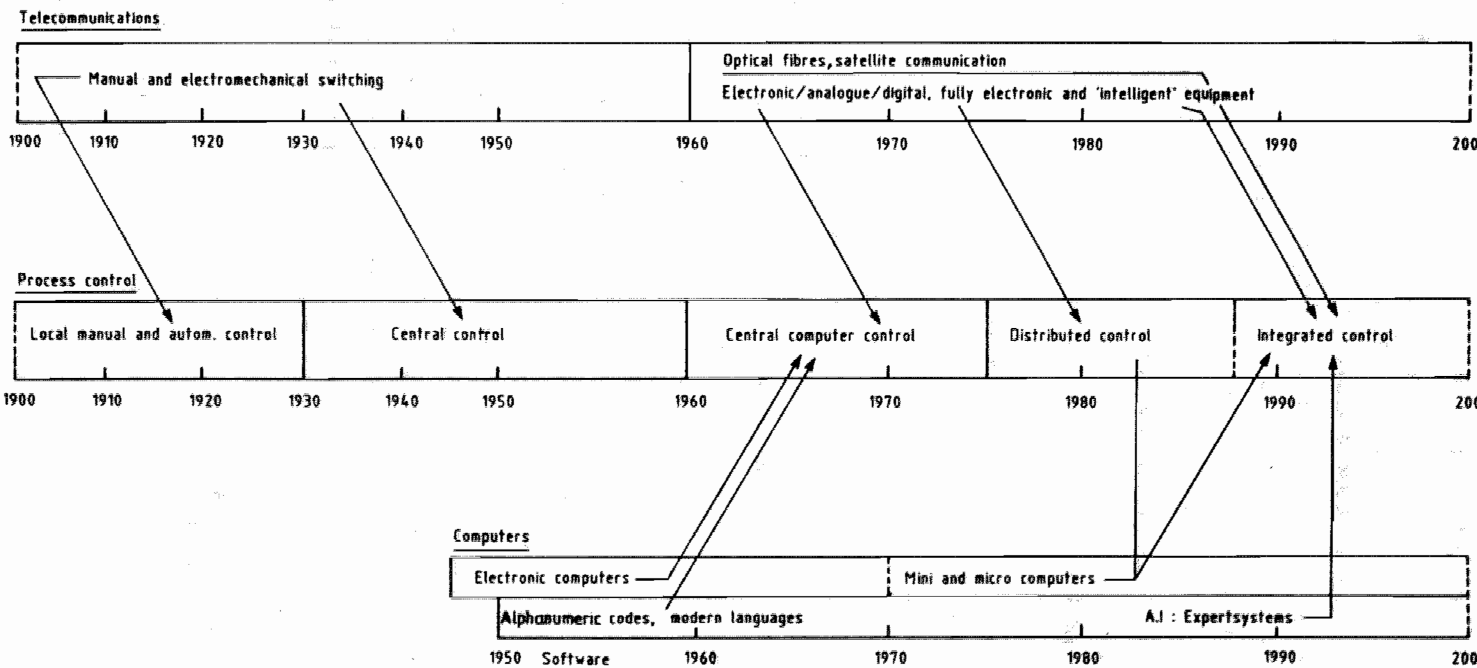


Figure 4.2 : Information technology and process control.



on this surface are attainable, but only at cost in time and resources. They are not available in blue print form"[1]. This meta-production function has some resemblance to Schumpeter's previously discussed attempts to define innovation in terms of production functions. Nelson and Winter paraphrased this concept of meta-production function as " ... a frontier of achievable capabilities, defined in the relevant economic dimensions, limited by physical, biological and other constraints, given a broadly defined way of doing things"[2]. The concept of technological regime, however, is ".... more cognitive, relating to technicians' beliefs about what is feasible or at least worth attempting"[3]. An example of a technological regime, presented by Nelson and Winter, is the development of the DC 3 and the choice of materials, constructions, engines, et cetera involved. The engineers working on the development of this airplane had strong notions on the development of this regime. In that sense Nelson and Winter's description of technological regime comes very close to one of Schumpeter's attempt to define production functions as given technological possibilities within the horizon of producers.

The concept of technological regime is also comparable to the concept of technological guideposts introduced by Sahal. In his terminology a technological guidepost is a basic design which remains "..... unchanged in its essential aspects over extended periods of time"[4]. A technological guidepost or basic design can be seen as a more concrete model for further development with clear 'puzzle-solutions' as in Kuhn's 'examplars' of scientific development[5]. In the literature the relation between 'regime' and 'paradigm' is interpreted differently by some authors. To avoid confusion I will interpret technological regimes as basic designs. In my opinion, the interpretation of a regime in terms of basic

1) N. Rosenberg, Inside the black box: technology and economics, 1982, p. 17.
2) R.R. Nelson and S.G. Winter, In search of useful theory of innovation, in: Research Policy, Vol. 6, 1977, p. 57.
3) ibidem.
4) D. Sahal, 1981, p. 33.
5) See T.S. Kuhn, 1974 (1962), p. 178 and idem , 1977, p. 298, and G. Gutting, 1984.

basic designs can lead towards a more concrete understanding of this concept. Compared to a technological paradigm a basic design can be seen as a material 'precipitate' from one or more paradigms. In the history of technological development there are numerous examples of basic designs apart from the already mentioned DC 3. The famous EDVAC, electronic computer, the first micro-processor, the blast furnace in iron and steel processing are all examples of basic designs.

In a sense the choice of a basic design is given by the level of generality one is to choose. In the case of process control basic designs can be understood as the configuration of the system of control. In the modern paradigm of process control there are two basic designs:

- central computer control with its configuration of a mainframe computer 'linked' to controllers, instruments and sensors;
- distributed control with a variety of micro-computers which act as controllers; and
- a more extended version of the latter in integrated control in which distributed control is integrated into an overall system of complete production control ranging from processes to management information and company strategies in a wider context.

For a more concrete understanding of technological development and the position of different companies which supply systems and/or distinct elements of systems the description of complete systems will not suffice. A further understanding of technological development might have to incorporate major components or products. Then a basic design or technological regime should be further disaggregated into <u>key-elements</u>. A key-element can be defined as an essential component of a basic design. The choice of essential components is based upon technical information.

In the study of process control it is possible to distinguish key-elements at different levels of control. From the lowest level of control upwards the following key-elements are to be mentioned: sensors, controllers, programmable controllers, complete process control systems and production control systems, emphasizing software and system configuration.

Sensors are devices which provide representation of condition variables such as pressure, temperature, chemical concentration, flow, level, weight, et cetera. Sensors are closest to industrial processes giving the initial input of information to control systems. As there are so may different types of sensors it is difficult to relate technological development to a few trends. In a very crude generalization it could be stated that the introduction and integration of microelectronics in so-called 'smart sensors' is a major topic in sensor technology.

Controllers are information processing mechanisms which receive data from sensors and which control the actual process, if necessary new values for control variables are calculated and this new information is sent to one or more mechanisms controlling input variables, e.g. shutters, valves and electromotors. Hardwired controllers were developed before World War II. The first generation was a pneumatic version, later generations became electronic controllers. At present hardwired controllers are considered as an obsolete technology for most applications, usually applied in older installations, or in pilot-plants and start-up situations. A modern version of the hardwired controller has become programmable, it is the so-called dedicated controller based upon digital programming techniques.

Programmable controllers and programmable logic controllers are electronic controllers which receive their input from sensors. PLC's are frequently applied in security systems, in start-up and shut-down stages and in batch processing. Although the first PLC's were quite different from computers in terms of programming, dataprocessing, and storage of information, later sophisticated generations resemble process computers in many functions (see also table 4.1).

With process control systems one reaches the higher hierarchical levels of process control. Although hardware is still important with respect to the performance of mainframe-, mini- and micro-computers, systems architecture and software aspects have become more relevant for understanding technological development in process control. With modern process control systems it is possible to control processes from the actual processing upto the co-ordination of different stages of production.

Production control systems with integrated control couple process control with management information systems. Information on processing can be connected to other sources of information such as stock control, order processing, logistics, planning, security control, quality control, maintenance, equipment monitoring, external information, communication with other plants, et cetera. Production control systems with integrated control is the most advanced stage of control, but few companies apply such systems completely.

Technological trajectories and generations in key-elements of process control

So far most attention has been paid to the possibility of analyzing technological development in terms of paradigms, basic designs and key-elements. In other words analyses at different levels of abstraction and generality. In some of the contributions mentioned in the previous sections technological development is analyzed in terms of trajectories. Dosi introduced the concept of technological trajectory which resembles the concept of natural trajectory as put forward by Nelson and Winter. The latter illustrated their thoughts referring to Rosenberg's concept of technological imperatives. According to Rosenberg technological imperatives guide the evolution of certain technologies, but Nelson and Winter lay more emphasis than Rosenberg on the 'straighter' path followed by natural trajectories[1]. Nelson and Winter do not pay much attention to the question of changes in natural trajectories. They more or less assume that:

a) there is a tendency for returns to fall if the prevailing trajectory is followed; and
b) occasionally knowledge is created which improves the structure of knowledge on technologies which had been ignored hitherto.

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1) Like Nelson and Winter Rosenberg stresses the cumulative and self-generating aspects of technology which make its development proceed in particular directions, see N. Rosenberg, 1976, pp. 110, 111.

Then if this knowledge or these new technologies turns out to be effective, a significant shift in the nature of R&D is to be expected. This change might involve not only new knowledge but also different people and different firms. This new trajectory would be developed until the new areas of research become well explored as well[1].

Dosi's concept of technological trajectories is very close to Nelson and Winter's concept of natural trajectories. Technological trajectories are defined by Dosi as patterns "... of 'normal' problem solving activity (i.e. of 'progress') on the ground of a technological paradigm"[2]. From a purely terminological point of view I prefer this term technological to natural because the latter might imply a somewhat deterministic connotation. In Dosi's perception technological trajectories develop within a technological paradigm up to the boundaries of this particular paradigm. These boundaries or limits of technological trajectories are, in theory, defined in last instance by physical laws[3].

In theorizing about technological development in terms of trajectories one touches upon the, already briefly memorized, issue of the possible deterministic character of such a notion if the social context of technological development is neglected[4]. Then, technological trajectories follow a given path from which future results are determined by a narrow set of technical data. In my perception of technological trajectories there are both deterministic and voluntaristic elements in technological change. First of all, technological paradigms are made up of a broad set of search

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1) The passage to which I refer did not occur in the text in Research Policy. It is not clear whether Nelson and Winter themselves do interpret changes in technologies as explained in the above as a shift of trajectories. The context of this part of their text, however, suggest my interpretation. See R.R. Nelson and S.G. Winter, An evolutionary theory of economic change, 1982, p. 262.
2) G. Dosi, 1982, p. 152.
3) See G. Dosi, Technological paradigms and technological trajectories, in: C. Freeman (ed.), Long waves in the world economy, 1983, p. 96.
4) See e.g. R.A. Walker, Technological determination and determinism: industrial growth and location, in: M. Castells (ed.), 1985, p. 236 and H. van den Belt and A. Rip, 1987.

procedures which are well accepted by a technological community. Such searching will result in basic designs which set the technological standards for a considerable period of time. The diffusion of such regimes is mediated by social acceptance. In capitalist economies companies, markets and social relations play a considerable role in this acceptance as they act as a selection environment[1]. Depending on the character of a technology and its socio-economic environment different social groups play different roles in the further development of paradigms and basic designs. E.g. nuclear energy is to be seen as a particular technological paradigm which is influenced by a wider context of political and social groups and not just producers and procurers of nuclear plants. For other fields of technology, such as process control, the selection environment is usually restricted to suppliers and companies which invest in the application of the technology.
If a particular field of technology is characterized by an 'immature' paradigm it can be expected that several versions of basic designs are to be found. In case of technological maturity or the dominance of one or a few suppliers it is to be expected that only one or a small number of basic designs will feature. If one particular basic design has become well accepted and dominant there will be technological improvements given the possibilities of that design and technological trajectories follow a deterministic path. However this does not imply that all technological development is of a deterministic character as the improvements of a basic design take place in an environment in which complex interrelations between changes in paradigms and economic selection set the wider context for technological development. In other words, as e.g. also pointed out by Piore and Sabel, technological development is characterized by both diversification or patterns of 'branching' and longer periods of uniformity[2]. A basic design might be accepted for a period of time but it can be made redundant by new technological options and/or failing acceptance by demand. To give an example from process control technology:

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1) See G. Dosi, 1982, p. 155, R.R. Nelson and S.G. Winter, 1977, p. 63, and N. Clark and C. Juma, 1987, p. 40.
2) See M.J. Piore and C.F. Sabel, The second industrial divide - possibilities for prosperity, 1984, p. 39.

In the early sixties computer control was introduced to process control. A large mainframe computer 'guided' processes from a centralized position. This basic design of central computer control developed from so-called off-line computer control to direct digital control. Several technological trajectories have marked this 'perfection' of this basic design. Once the computer was introduced its role became more and more crucial. At first it was applied in an off-line mode in which the operator still functioned as a link between the actual controllers and the computer which was engaged in data collection and calculating of set-points, et cetera. At the next stage, the on-line mode, there is a direct link between controllers and the computer, but computer 'response' goes via the operator. In the in-line mode there is direct communication between controllers and the mainframe computer, the operator is still active in supervising process control. At the final stage of this trajectory all controller-functions have been taken over by the central computer.

Once the computer was introduced as a central regulatory device the development towards in-line control and the change from analogue to digitalized systems became almost determined by the existing possibilities. However, this basic design of central control did not become well accepted and in the mid-seventies it was replaced by distributed control in which there is a multiple set of micro-computers. There are two reasons why central computer control was eventually replaced. First, user-companies were reluctant to accept the development towards direct control. Most companies did not regard the system as very safe because all control functions were regulated by one computer. In case of failure the costs of system breakdown would be enormous. An alternative could be found in extensive back-up facilities but this turned the system into a very expensive, complex, and therefore not a very popular control system.

The second reason for the change to another basic design is found in new technological options. Developments in information technology, the introduction of micro-computers and 'intelligent' controllers enabled the introduction of another system in which computer control could be performed at a decentralized level. This new system was less complex and less vulnerable than the previous basic design and it became the new basic design within a few years time.

For further empirical research it will be necessary to operationalize technological trajectory in such a way that its cumulative and progressive character becomes clear. Sometimes it will be possible to 'measure' a technological trajectory with a particular characteristic. E.g. miniaturization of micro-electronic chips with the number of components per chip or the reliability of chips with the relative rate of failure per gate. For products for which quantitative information is less feasible a trajectory can be interpreted as a succession of generations of a basic design or a key-element. Such a succession of generations is found in the trajectory from older (obsolete) generations, to average practice, best practice, technological frontier and/or scientific frontier. The older (obsolete) generation of a basic design (or key-element) can still be in use but it will only be supplied for replacement purposes. The average practice generation is the ordinary standard and usually modal application and a best practice generation represents the most advanced level of technology which is applied commercially. The technological frontier refers to applied research and in particular development of the near-future generation. The scientific frontier will be found at the most advanced level of basic research which is not directly aimed at nearby future results. The gap between technological and scientific frontier will probably be most unclear in so-called science-based industries, where both technological and scientific knowledge are to a large extent regenerated within the industry itself. It will be evident that the description of generations is an ex-post generalization and subsequent basic designs will each show several generations for which the time-horizon will vary.
The generations or technological trajectories for each key-element in process control are shown in table 4.1.

Table 4.1 : Generations of key-elements in process control.

	Older (obsolete)	Average practice	Best practice	Technological frontier
Sensors:				
e.g. pressure	Pneumatic, electrical cap. measurement	Electrical cap., strain gauges	Piezo-electr. effect, some micro-electronics	Smart sensors (silicon technology)
e.g. temperature	Thermocouple, non-integrated electronics	Later version of thermocouple and platinum resistor	Integrated (micro-) electronics	Accommodation to extreme environments
Hardwired (logic) controllers:	Pneumatic	Simple solid state electronics	Solid state electronics	Dedicated controller
Programmable (logic) controllers:	Upto 100 program steps, upto a few hundred I/O's, no dataprocessing, specific programming languages	Upto 1000 program steps, increased capacities for storage and I/O's, restricted dataprocessing standardized programming languages	Over 1000 program steps, some thousand and more intelligent I/O's, dataprocessing, user-friendly programming	Megabyte storage capacity, communication, 'higher' programming languages
Process control systems:	Centralized control	Distributed control, analogous signals	Distributed control, digital	Software for adaptive control, simulation and optimalization
Production control systems:	-	-	Advanced production control and M.I.S.	-

Measurement of technological trajectories

A theoretical framework which applies rather abstract concepts such as technological paradigms, trajectories and basic designs is extremely useful for 'painting with a rough brush', but it is less attractive for incorporating it into a more standardized method of economic analysis at a lower level of aggregation. The only way to improve the usefulness of such a framework is to find more operational definitions and constructs for some of these concepts in order to measure technological development. A stimulating contribution to this field of innovation theory, has been made by Metcalfe and Saviotti[1]. They provide a construct for analyzing and measuring technological change in a detailed description. This approach resembles Knight's contribution of functional and structural measurement of technology. Knight proposed an analysis of the evolution of technology based on functional and structural descriptions of a technological system, or a basic design or key-element in the present terminology. Structural descriptions are restricted to key information related to basic operations, omitting unimportant features. Functional descriptions are obtained by describing a vector of performance capabilities[2].
Saviotti and Metcalfe perceive technological development in terms of changes in technical and service characteristics of products or processes and by a change in the pattern of mapping these characteristics. The relation between both technical and service characteristics is shown in figure 4.3 below.

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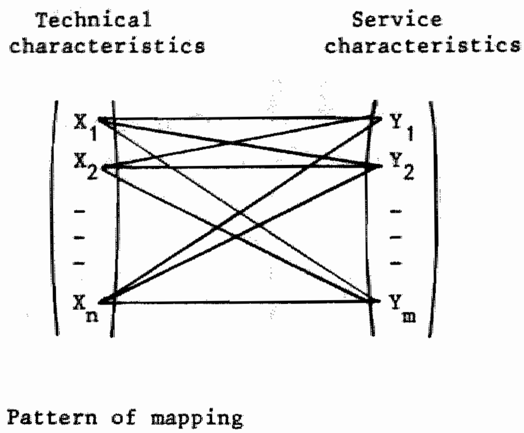
1) See P.P. Saviotti and J.S. Metcalfe, A theoretical approach to the construction of technological output indicators, in: Research Policy, Vol. 13, 1984, see also P.P. Saviotti, P.C. Stubbs, R.W. Coombs and M. Gibbons, An approach to the construction of indexes of technological changes and of technological sophistication, in: Technological Forecasting and Social Change, Vol. 21, 1982, and P.P. Saviotti, An approach to the measurement of technology based on the hedonic price method and related methods, in: Technological Forecasting and Social Change, Vol. 27, no. 2/3, 1985.
2) See K.E. Knight, A functional and structural measurement of technology, in: Technological Forecasting and Social Change, Vol. 27, no. 2/3, 1985, pp. 107-127.

Figure 4.3: Representation of a product as two sets of characteristics, technical and service, and a pattern of mapping.



Source: P.P. Saviotti and J.S. Metcalfe, 1984, p. 142.

Within this framework there are five dimensions of technological change:

a. change in absolute values of X_i;

b. change in the mixture or balance of X_i (changes in weights);

c. change in the pattern of mapping $(X_i) \leftrightarrow (Y_j)$;

d. change in mixture or balance of Y_j;

e. change in absolute values of Y_j.

Elaborating upon this Saviotti and Metcalfe applied both technological regime and technological trajectories. They described a technological regime, or basic design, as "....consisting of a given list of technological characteristics X_i ...."[1]. A technological trajectory is defined by them as the pattern of gradual improvements of X_i.

Apart from technical and service characteristics they distinguish process characteristics as well. Consequently "... any trajectory will have joint implications for the set of service characteristics and the set of process characteristics. If the set of X_i, is changed, we have a change of regime and thus the definition of a

1) P.P. Saviotti and J.S. Metcalfe, 1984, p. 145.

new technological trajectory"[1]. In theory the analysis can be extended to three different situations: a substitution of a regime, the appearance of a new product and partial substitution. Such contributions to the theory of 'technometrics' have been subject to a lively debate in the world of technological forecasting and related fields of interdisciplinary research of technological change. Measuring technological development in terms of characteristics, in particular if combined with the so-called hedonic price method, is not free from some serious questions about its usefulness. Without attempting to discuss all relevant issues in this field I will point at some of the most interesting items of the debate.

Lenz mentions three approaches in measuring technological development. (Lenz refers to a heuristic approach, but I think at this level of abstraction they apply to other approaches as well). These three approaches are:

- the single parameter approach, in which one particular parameter is defined to determine the operational superiority,
- the parameter tree approach which defines a hierarchy of parameters of which the values are traded-off in lower branches but which culminate in one or a few primary measures of performance,
- or, a single value measure as an all encompassing compound measure of performance[2].

The single parameter and single value measure can be chosen if there is consensus about the superiority of the chosen parameter or if there is a clear discriminating value. However, both provide so much more measurement than real understanding of different influences upon technological change. E.g. measuring productivity growth in value indicates technological development, it does not provide us with information about underlying factors.

A parameter tree sort of approach can be the preliminary work in achieving a vector of characteristics if a hierarchy of parameters is applied to deduct a number of primary measures or characteristics.

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1) ibidem.
2) See R.C. Lenz, A heuristic approach to technology measurement, in: Technological Forecasting and Social Change, Vol. 27, no. 2/3, 1985, pp. 249, 250.

In building a set of characteristics a number of constraints have to be considered. Apart from the lack of relevant empirical information, which can be decisive, there are some theoretical shortcomings which have to be discussed first. A major obstacle in building a list of characteristics is found in the heterogeneous character of most products. In theory it is possible to relate a number of heterogeneous products to a basic design. The characteristics of this design can be gathered by using technical data references in combination with consultance of technical experts, and a principal components analysis. Alexander and Mitchell mention three problems related to building a set of characteristics for heterogeneous products.
These methodological problems arise when:

- there is a change in relative importance of characteristics,
- new characteristics are added,
- others are eliminated[1].

Furthermore, in measuring technological development of a particular basic design or key-element one has to take into account the trade-off's between several characteristics. Such considerations lead towards a 'moderate' view on the use of characteristics. Applying characteristics is by no means an objective method; if a considerable input of technological knowledge has been used it is possible to reach a stage of 'convenient' inter-subjectivity. Longitudinal monitoring of basic designs and utilizing the knowledge of a large number of experts can diminish the risks involved in the shortcomings as mentioned by Alexander and Mitchell.

In Hagedoorn et al. an attempt was made to 'measure' technological trajectories in so-called key-elements of process controllers, such as sensors, hardwired controllers, programmable logic controllers, process control systems and production control systems[2]. Technical and service characteristics which were analyzed separately in Metcalfe and Saviotti were joined as service

1) See A.J. Alexander and B.M. Mitchell, Measuring technological change of heterogeneous products, in: Technological Forecasting and Social Change, Vol. 27, no. 2/3, 1985, p. 193.
2) See J. Hagedoorn, P. Kalff and J. Korpel, 1988, pp.114-133.

and technical characteristics appeared to be too interrelated to justify a distinction. The number of characteristics per key-element varied from 5 to 10; for each key-element the actual characteristics were deducted from the technical literature and checked with a large number of experts.

An example of such a 'measurement' is given in table 4.2 for technological trajectories in pressure-sensors.

For each characteristic of all key-elements the changes were 'measured' for three generations and the technological frontier was also indicated where possible. Unfortunately, quantifiable information could only be obtained for some characteristics but then again such quantified measures do not share a common denominator. Therefore, development for each characteristic was given in a quality mark ranging from 1 (lowest quality) to 5 (highest). The markings were obtained by collecting all markings and technical elaborations provided by technical experts. Hence, such a measurement of technological development in terms of technological trajectories is of a fairly 'intersubjective' nature.

In the example in table 4.2 it can be observed that there has been a clear improvement for most characteristics from generation to generation. An important field of future developments can be expected in the improvement of the useful temperature range, a characteristic on which best practice sensors fail to score more than satisfactory due to the present limitation in silicon technology.

Through the analysis of a number of key-elements it is possible to achieve a fairly thorough, albeit qualitative, understanding of many aspects of technological trajectories in a particular field of technology.

Technological development as an evolutionary process

In the above I have made an attempt to re-organize a conceptual framework for understanding technological development. This framework leads from a general level of analysis in terms of paradigms to technological trajectories in terms of generations within a key-element of a basic design. It enables the identification of major heuristics, be it at the level of a paradigm or a key-element. Rules of search, focal points in industrial R&D, incremental

Table 4.2: Quality indications for relevant characteristics of pressure-sensors; I = obsolete or older types; II = average practice; III = best practice.

Characteristic	I	II	III	Remarks
1. Useful temperature-range	4	4	3	Integration of microelectronics limits T-range
2. Electronic standardization	4	4	5	Fully accepted international standards
3. Reproducibility of production technology	1	3	4	'Smart' sensors can be set to fit specifications
4. Accuracy	2	3	4	
5. Long term stability	5 2	- 3	- 4	*) **)
6. Protection against mechanical and electrical interferences	5 -	- 3	- 4	*) **)
7. Response times	1 -	- 3	- 4	*) **)
8. Quality/price ratio	2	3	4	

*) pneumatic types.
**) electrical types.

Source: J. Hagedoorn et al., 1988.

changes and more radical changes in technology can be identified. As the analysis covers both general trends and specific developments, and system development and technological trajectories in key-elements, it accomodates criticism on the shortcomings of an analysis based on isolated subsystems as e.g. Hughes has formulated. The latter has criticized those analyses in which 'technological systems', basic designs in the present analysis, are divided into "... subsystems and calling them systems for purposes of comprehensibility and analysis (which) ... may offer only a partial, or even distorted, analysis of system behavior"[1]. In the foregoing analysis of process control developments in both control systems and key-elements picture technological change of a system and its major components. Then if the analysis proceeds towards industrial economics it will enable a further analysis of diffusion of particular technologies and the industry structure of suppliers of both systems and components. It also supports the explanation of the history of technological development, the interrelatedness of different fields of technology which would otherwise be reduced to 'pale' indicators such as R&D expenditures or number of patents. This does not imply that quantitative indicators are to be seen as useless. Statistics provide very valuable information even if, as in the case of technological development, the sheer number of indicators available is restricted. The interpretation of such statistics, however, will be improved considerably if they are placed against a background of a more than superficial understanding of technology itself. Then, changes in the speed of technological development, new areas of search, 'cross-fertilization' of once separate technologies and succeeding periods of radical and incremental change, which will all be extremely difficult to deduct from statistics, can be interpreted if the theoretical framework of an evolutionary understanding of technological development is applied.

At the level of analysis of concrete key-elements of a basic design it is possible to achieve some in depth understanding of actual technological trajectories for major characteristics of

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1) T.P. Hughes, The evolution of large technological systems, in: W.E. Bijker, T.P. Hughes and T.J. Pinch, 1987, p. 55.

such key-elements. As demonstrated in the next section these insights will turn out to be very useful when the analysis of technological development in an industry is connected with the study of the diffusion of technology.

4.3 DIFFUSION AND TECHNOLOGICAL DEVELOPMENT

In the foregoing section the cumulative character of technological development was stressed in explaining the viability and advantage of concepts such as technological paradigms, basic designs and technological trajectories. These thoughts on technological trajectories and the like stress the gradual development and shifts of best practice technology and technological frontiers. In this section I will relate the diffusion of technology to this evolutionary character of technological development.

Relating diffusion and technological development might seem somewhat peculiar at first sight. After all, diffusion, defined as the progressive distributional change in the spread of an innovation or a technology, is understood to be at a different level of analysis from technological development itself. In particular in neo-classical economics diffusion and innovation have been separated as two distinct issues[1)]. However in reality the process of diffusion of innovations or new technologies is not only characterized by a gradual growth of adoption it also has a cumulative character. In my opinion it is important to see diffusion and technological advance in their interrelatedness. As e.g. explained by David both technological development, in the sense of advancing frontiers, and in particular the diffusion of technology have far-reaching consequences for economic development[2)].

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1) See e.g. C.G. Thirtle and V.W. Ruttan, 1987, pp. 130, 131.

2) See e.g. P. David, Technology diffusion, public policy, and industrial competitiveness, in: R. Landau and N. Rosenberg (ed.), The positive sum strategy, Harnessing technology for economic growth, 1986, p. 376.

In the following I will first pay some attention to the theory of diffusion with emphasis on those contributions which stress the cumulative character of diffusion. This enables me to connect diffusion with technological change in terms of trajectories and generations of key-elements of a basic design. Following this procedure I will be able to demonstrate the viability of such an approach with the analysis and measurement of diffusion of information technology in process control equipment sector.

Stylized patterns of diffusion

Despite many differences in orthodox theories of diffusion there is a 'communis opinio' among many students of diffusion about the pattern of diffusion processes. This pattern of diffusion follows Schumpeter's description of the process of innovation and imitation, the so-called bandwagon effect with a few originators and a slowly growing number of imitators or followers. This pattern of diffusion is generally pictured as a sigmoid (S-shaped) curve. These S-shaped curves can be generated by different models, including logistic function, Gompertz function, the modified exponential function, the cumulative normal distribution function and the cumulative log-normal distribution function, all of which are based on different assumptions of which it is, according to Sahal, "... not possible to discriminate (....) on empirical grounds"[1]. Nabseth and Ray have listed six factors which might influence this sigmoid curve in the opening phase:

1. At a first stage of risk and uncertainty just a few firms will try to be the first to innovate.
2. If a few firms succeed they reduce the risk for others which have not yet adopted the new technique.
3. Information from users has a great influence on the large majority of firms (more than information in the press or from suppliers).

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1) Sahal, 1981, p. 78, see also V. Mahajan and R.S. Peterson, Models for innovation diffusion, 1985, p. 10.

4. Modifications of innovations increase both the potential range of production and the superiority of new methods over the existing ones.
5. ".... there may be a bunching of the new adoptions as part of a cyclical mechanism of Schumpeterian type".
6. The age of the existing technology can be in favour of the new technology.

They also present two factors which can slow down the diffusion process, if:

7. there is a more or less restricted number of areas of application, or
8. the success of new techniques stimulates improvement of the first existing technique[1].

The material basis for this S-curved pattern of diffusion is often found in the growing number of firms or units within firms which gradually learn to adopt new technologies. A large number of theories and models attempt to explain diffusion more specifically[2]. Some models take the concepts of Baysian learning and reduction of uncertainty as central elements, many others are related to Mansfield's theory of both inter- and intra-firm diffusion as an epidemic process.

Although S-shaped curves are in general accepted as a realistic approach to diffusion processes, there is evidence that some empirical findings and theoretical considerations do lead towards a more differentiated approach. In his study of six mature technologies Ray stresses the need for a cautious approach. In his findings "... the figures do not provide much concrete evidence for the exclusive validity of any very regular S-curve but they definitely support the rational expectation of some kind of an S-curve (.....). The slopes are different for each technology, the turning point into growth also differs and therefore the use of an S-curve

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1) See L. Nabseth and G.F. Ray, The diffusion of new industrial processes, 1974, p. 9.
2) For reviews of many of these models, see C.G. Thirtle and V.W. Ruttan, 1987, P. Stoneman, The economic analysis of technological change, 1983, pp. 65-134, and L.A. Brown, Innovation diffusion, 1984.

assumption for various purposes, for example, forecasting, requires caution"[1]. A further criticism of the S-shaped conception of diffusion has been put forward by Gold[2]. Gold's alternative to the S-shaped diffusion curve seems to be fairly compatible with the evolutionary theory of technology outlined in the foregoing section. He criticizes the present method of measuring diffusion because:

- ".... counting the number of plants or firms using the innovations obviously fails to indicate whether these represent only limited developmental applications or pervasive commitments".
- Measuring output of new technology is more effective, but even then it is hard to determine "..... whether any given output represents high or low levels of diffusion of the particular innovation being studied"[3].

If output is considered as an indicator of diffusion it usually involves the assumption that a particular innovation is applicable in all of the production of that industry. This conception of diffusion is in fact a saturation model approach, in which "... it is supposed that a specific innovation is progressively adopted by an unchanging and essentially homogeneous population of potential users"[4].

In a more dynamic approach to diffusion both the population of potential users and the innovation itself will change during the process of diffusion. E.g. in the process control industry the diffusion of information technology has been influenced by the cross-entry of companies from the electronics industry which changed the number of potential users, see chapter 5.2. The changes within the technology itself can be explained as changes within technological trajectories. If a particular innovation, or

1) G.F. Ray, The diffusion of mature technologies, 1984, p. 80.
2) See B. Gold, Technological diffusion in industry: research needs and shortcomings, in: Journal of Industrial Economics, Vol.29, no. 3, 1981, and idem, On the adoption of technological innovations in industry: superficial models and complex decision processes, in: S. MacDonald, D. Md. Lamberton, T.O. Mandeville (ed.), The trouble with technology, 1983.
3) Gold, 1981, p. 249.
4) Gold, 1983, p. 105.

in the present terminology a basic design or a key-element of it, goes through a process of diffusion the parameters can change from generation to generation. If technological trajectories within a product are defined in terms of generations then the process of diffusion is not so much characterized by a single diffusion curve but instead by an envelope of successive curves or different situations regarding diffusion[1].

Such ideas about technological change and generations can be elaborated upon for some hypothetical situations as follows:

Technological development within a particular basic design or a key-element is to be seen as the gradual improvement of a basic design along technological trajectories. Different stages of this improvement are found in subsequent generations which can, in retrospect, be seen as older, average and best practice. The relation between technological development and diffusion is pictured in a stylized diagram in figure 4.4, showing some basic ideas about this matter.

If a fixed population of potential adopters is assumed, the diffusion of three generations, representing technological trajectories, can follow a sigmoid pattern. The particular shape of the diffusion curve is generated by the rate of diffusion of the three subsequent generations. Technology itself is changing in terms of generations while the number of adopters grows over time as the technology is improved. Gradually the diffusion of the older technology is declining but the other two generations more than compensate for this decline.

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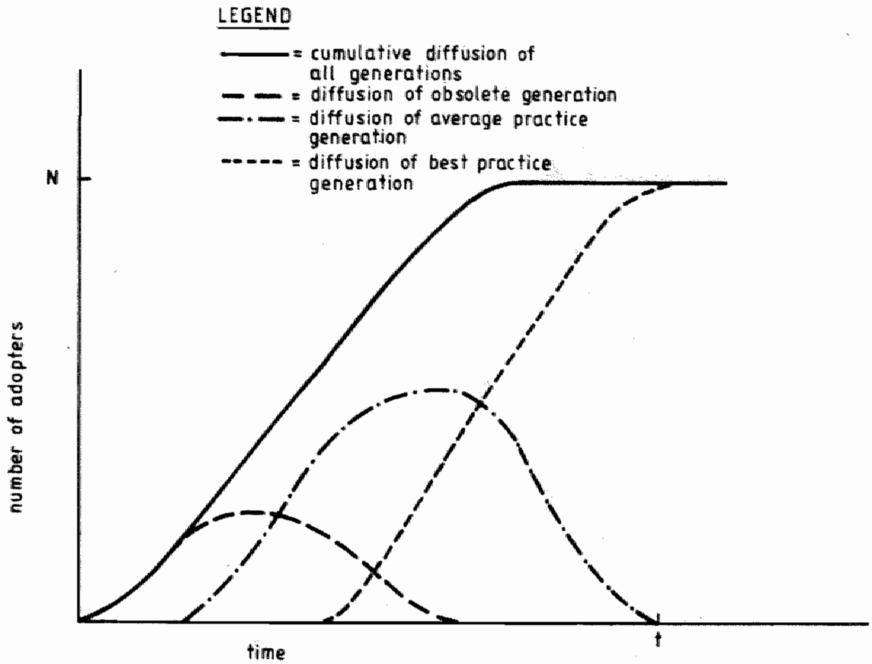
1) See also B. Gold, 1983, pp. 107, 108, J.S. Metcalfe, Impulse and diffusion in the study of technological change, in: Futures, Vol. 13, no. 5, 1981, and L. Soete and R. Turner, Technology diffusion and the rate of technical change, in: The Economic Journal, 94, 1984, R. Coombs, P. Saviotti and V. Walsh, 1987, pp. 124-133, C. Freeman, Diffusion: The spread of new technology to firms, sectors and nations, 1987, and V. Mahajar and R.A. Peterson, 1985.

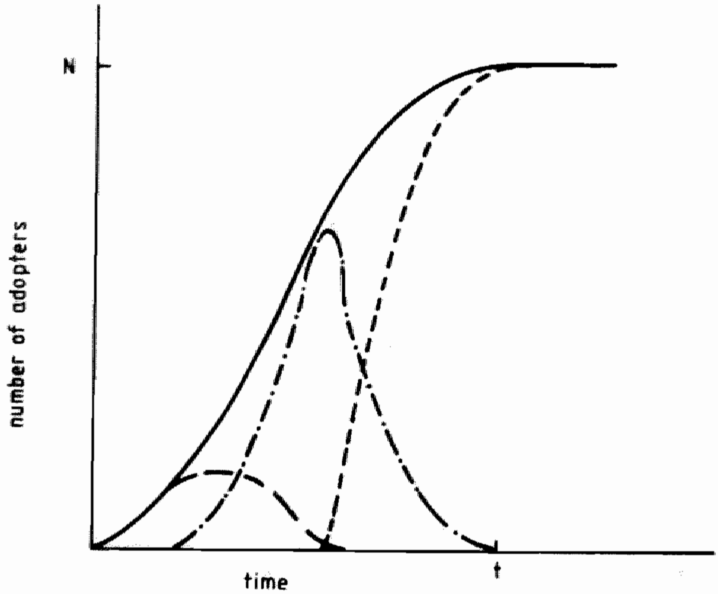
Figure 4.4 : Diffusion of generations of a product within a fixed population of potential adopters.



In figures 4.5.a and b the relation between diffusion of subsequent generations and the overall diffusion is pictured for a situation with rapid diffusion and another with slow diffusion. In case of rapid diffusion it is obvious that the subsequent generations will follow within due time. If diffusion evolves slowly, the overall S-curve is 'flattened' as the gradual diffusion of each generation takes more time than in the other situations pictured in figures 4.4 and 4.5.a.

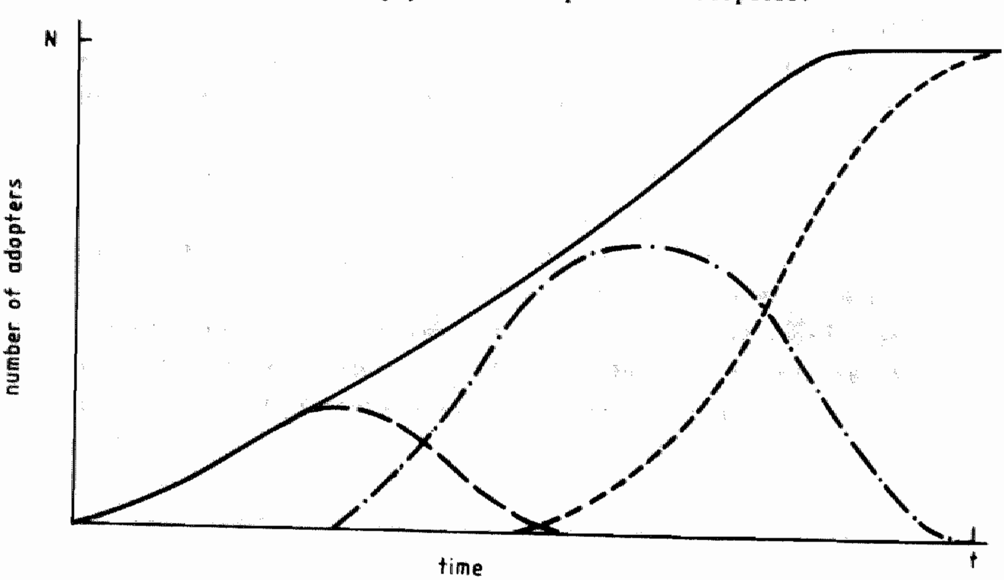
These general ideas about diffusion and generations will be applied in the analysis of diffusion of information technology in generations of key-elements of process control in a following paragraph.

Figure 4.5.a : Rapid diffusion of generations of a product within a fixed population of potential adopters.



Legend: see figure 4.4.

Figure 4.5.b : Slow diffusion of generations of a product within a fixed population of potential adopters.



Legend: see figure 4.4.

Factors influencing diffusion

So far economic theory has not been able to provide a more or less general theory explaining the diffusion of technologies. Some economists even doubt whether it is at all possible to draw up a general theory of diffusion. As Rosegger has stated "... the diffusion of innovations is probably too complex a phenomenon to be explained in general for all types of technology and all kinds of potential adopters, no matter how many factors one takes into account. Therefore, while a general theory about, say, the spread of epidemics may be very useful, we are not likely to gain any great insights from an all-encompassing theory of diffusion in the economic setting".[1]. Instead of a general theory Rosegger opts for a range of different hypotheses for different industries and innovations. Whether Rosegger is right in principle or not, the present state of diffusion-research does suggest that a modest and 'middle-range theory' approach would be more fruitful in the present situation. A review of the relevant literature shows the relevance of this approach in view of the contradicting outcomes of many studies regarding different key-factors of diffusion. Key-factors which are frequently mentioned are:

- Profitability. If new technologies are more profitable than conventional technologies then one might expect a relation between expected profitability of an innovation and the speed of diffusion. So far several studies by Mansfield, Duchesneau and Hakanson show a significant correlation, although others, e.g. Smith and Romeo, did not find a significant result[2].
- Financial resources. Nabseth and Ray list access to capital, together with overall profitability and the attitude of management as the three most important factors influencing diffusion[3]. In most studies it is found that absolute capital requirements have some influence on diffusion.

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1) G. Rosegger, The economics of production and innovation, 1980, p. 246.
2) See J. Kleine, Investitionsverhalten bei Prozessinnovationen, 1983, p. 107 and P. Stoneman, 1983, p. 90-94.
3) See L. Nabseth and G.F. Ray, 1974, p. 20.

- Size, structure and organisation. As Nabseth and Ray stated: ".... large companies may, for a number of economic, technological, or other reasons, behave differently from medium-sized or small firms; the organisation and structure of the industry as well as of the companies (.....) can also have a marked effect on diffusion, and may be particularly important in explaining international differences. High concentration, or a monopoly position, may create conditions which can influence innovation or diffusion either way."[1].

  In general, size of firms is introduced as an explaining variable in empirical studies because, from a theoretical point of view, Mansfield's position is supported where it is argued that large firms are better able of diffusing innovations due to their financial resources, capacity to manage information and to maintain large R&D facilities. However, even here we find rather contradicting results. In a study covering ten processes Nabseth and Ray find "..... no definite evidence that large companies have always been in the forefront of technical progress in the sense of being leaders in innovation and the adoption of new techniques".[2]. In a more recent study Ray concludes that ".... size has less to do with the diffusion of new technologies in the mature phase than was believed some ten or twenty years ago".[3]. Kleine has compared several studies which refer to this relation between size and speed of adoption. Studies by Mansfield, Romeo and Globerman do verify this hypotheses, while in some other studies there is only a partial verification, e.g. for some countries or sectors. In some studies, notably by Baumberger and by Duchesneau, no relationship was found; in a study by Smith a significant positive relation between size and lag of adoption was found[4].

  The same holds for such factors as growth of firms and market structure and competition. Several studies contradict each other and there is no clear evidence supporting relevant hypotheses.

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1) Idem, p. 13.
2) Idem, p. 21
3) G. Ray, 1984, p. 90.
4) See J. Kleine, 1983, pp. 99, 100.

Many other factors such as access to information, R&D activities, technical applicability of an innovation, life-cycle of the relevant sector, qualification of labour and managerial attitudes might be of some relevance as well.

Measuring diffusion of information technology in process control

Measuring the spread of innovations can be done at four levels: intra-firm, intra-sector, inter-industry and the international level. In general only the first three levels of analysis are considered. Usually the rate of diffusion at any of these levels is expressed in terms of capacity, employment or most frequently in terms of output or numbers of firms[1]. Stoneman has presented a useful listing of the above mentioned levels of diffusion[2].

- Intra-firm diffusion is measured as the change over time in the proportion of a firm's output produced on new technology. In case of a firm i in industry j, which produces a total output in time t of X_{ijt}, of which an output with new technology Y_{ijt}, the intra-firm diffusion ratio is Y_{ijt}/X_{ijt} which is assumed to approach the post diffusion ratio $(Y_{ij}/X_{ij})^* \leqslant 1$.
- Intra-sectoral (or inter-firm) diffusion regards the situation in which the output of firms produced on the new technology is compared to the total sector output, after the introduction of the innovation. Then $Y_{jt}/X_{jt} \Longrightarrow (Y_j/X_j)^* \leqslant 1$.
- The least applicable ratio of these three measures is related to inter-industry diffusion which is a mere aggregation of inter-firm diffusion. In establishing this kind of diffusion-ratio one finds oneself confronted with the problem of comparing different sectors of industry. As a consequence of the heterogeneous character of products in a cross-industry comparison it is in practice hard to find a discriminating measure. In case of research into diffusion of process innovations there is a tendency to take stocks of new capital goods as a proxy-measure[3].

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1) See L Nabseth and G.F. Ray, 1974, p. 8.
2) See P. Stoneman, 1983, pp. 67, 68.
3) Idem, p. 68.

In theory the best over-all indicator of diffusion is found in considering both intra and inter-firm diffusion-ratio's.

Although output is probably the most elegant unit for expressing diffusion-ratio's it is not most frequently used as such. E.g. inter-firm diffusion is more often measured in terms of the percentage of companies in a specific industry which apply a particular technique[1]. This more well-known standard for inter-firm diffusion expresses how N_t (= number of firms using a new technology) approaches N^*_t (post diffusion level of N_t) or how N_t as a proportion of the total number of firms approaches N^*_t expressed as a similar proportion[2].

In survey research one is frequently on the mercy of the ability, (institutional) memory and/or willingness of companies to provide information on diffusion. In this study of diffusion of information technology in process control measurement became somewhat more complicated as diffusion is linked to technological development in terms of generations or technological trajectories.

In section 4.2 generations of each key-element of process control were characterized in terms of advancing stages of applied information technology. Hence, later generations are more sophisticated in terms of information technology and the distribution of turnover for each generation of a key-element can be interpreted as an indicator of the diffusion of information technology. In applying this method the importance of gradual improvement during the process of diffusion is stressed. Diffusion of information technology can be demonstrated in terms of an older generation, average practice and best practice technology. The activity of companies at the technological frontier is operationalized as their involvement in R&D for coming generations[3].

The survey of the international process control equipment (p.c.e.) industry included 56 companies (see also Appendix I). In the following the development of diffusion for each key-element is given for two years 1980 and 1985. Compared to e.g. figure 4.4 diffusion

1) See L. Nabseth and G.F. Ray, 1974, p. 8.
2) See P. Stoneman, 1983, p. 68.
3) For a description of generations for each key-element see table 4.1.

is not measured along the time axis but at two points in time. Extension of the period to e.g. 10 years was not feasible due to the lack of institutional memory in companies as far as particular, detailed information is concerned. Detailed information on diffusion from year to year would demand too much effort from participating companies and raise the non-response.

In the survey companies provided only relative distributions and no absolute figures. Compared to the levels of diffusion mentioned above the measurement of diffusion which follows should be regarded as the average intra-sectoral rate of diffusion and the average rate of diffusion for different size-classes. In other words, some extra information is gained in comparison with a measure for the number of companies which apply a technology, but some information is lost in comparison with a straightforward intra-sectoral diffusion ratio.

As far as key-factors mentioned in the literature are concerned it will only be possible to search for a relation between industry structure, in terms of size-categories, and diffusion. With only a few exceptions most companies were reluctant to provide information on other key-factors such as profitability and financial resources. Furthermore, as for other findings of the survey, results have to be interpreted with some care as the information refers only to a limited number of companies.

In the following I will discuss outcomes on diffusion of information technology for each key-element[1]. First I will discuss the outcome for all companies which manufacture a key-element. This will be followed by a comparison of four categories of size[2]:

- small companies with a size upto 500 employees;
- medium sized companies with a size between 500 and 5,000 employees;
- large companies between 5,000 and 50,000 employees; and
- very large companies with over 50,000 employees.

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1) No information on diffusion of information technology in generations of production control systems can be provided. In fact all production control systems and management information systems are sophisticated, best practice, technology.

2) The rationale of this particular division into categories of size is discussed in chapter 5.

Diffusion of information technology in sensors generates a 'smooth' distribution which will not be found for any other key-element, see figure 4.6. In the survey 35 companies manufacture sensors. In the distribution of generations for all companies one observes a decline in the share of the older generation from 24 to 16%.

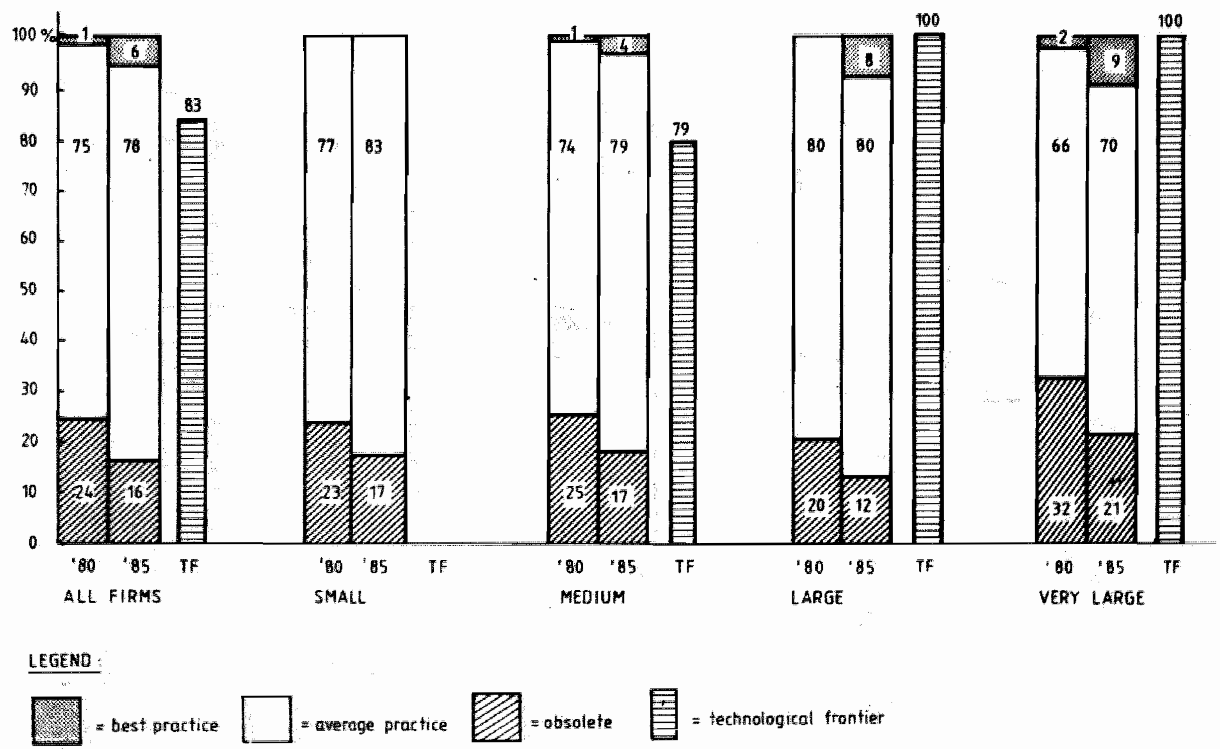
Average practice sensors go from 75 to 78%. The share of best practice sensors has developed from 1% in 1980 to 6% in 1985. In other words, the diffusion of information technology in sensors has been very moderate as far as the introduction of smart sensors is concerned.

However, the diffusion of the most advanced level of information technology increases with the size of companies. Small companies do not manufacture micro-electronic integrated sensors and they apparently are not engaged in relevant research as well. For the other size-categories an, albeit small, increase in the share of smart sensors is visible. All large and very large companies conduct R&D at the technological frontier of sensors. The modest rate of diffusion of best practice sensors reflects the oft mentioned stagnation in application and development of sophisticated sensors.

Diffusion of information technology in hardwired (logic) controllers follows a different path, see figure 4.7. There are 37 manufacturers of this device in the survey. Best practice technology, dedicated controllers, has been almost stable in the first half of the eighties for the population as a whole. There has been a slight increase in the share of best and average practice generations, consequently the share of obsolete generation has gone down to a mere 10%. The pattern of diffusion, however, becomes very different for each size-class.

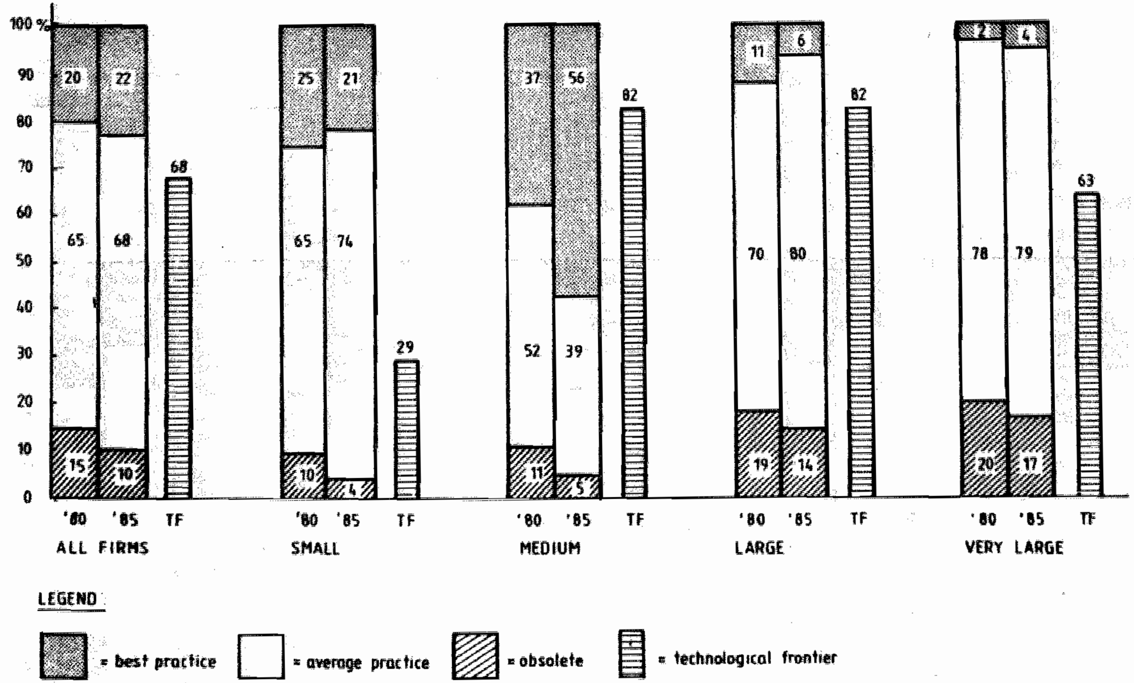
For all size-classes the share of older generation hardwired controllers has declined. For small and medium sized companies it has reached a minimum level of about 5% in 1985. Large and very large companies still manufacture a substantial share of older generation controllers.

Figure 4.6.: Diffusion of information technology in sensors[1].



1) See also Appendix 2.

Figure 4.7: Diffusion of information technology in hardwired (logic) controllers[1].

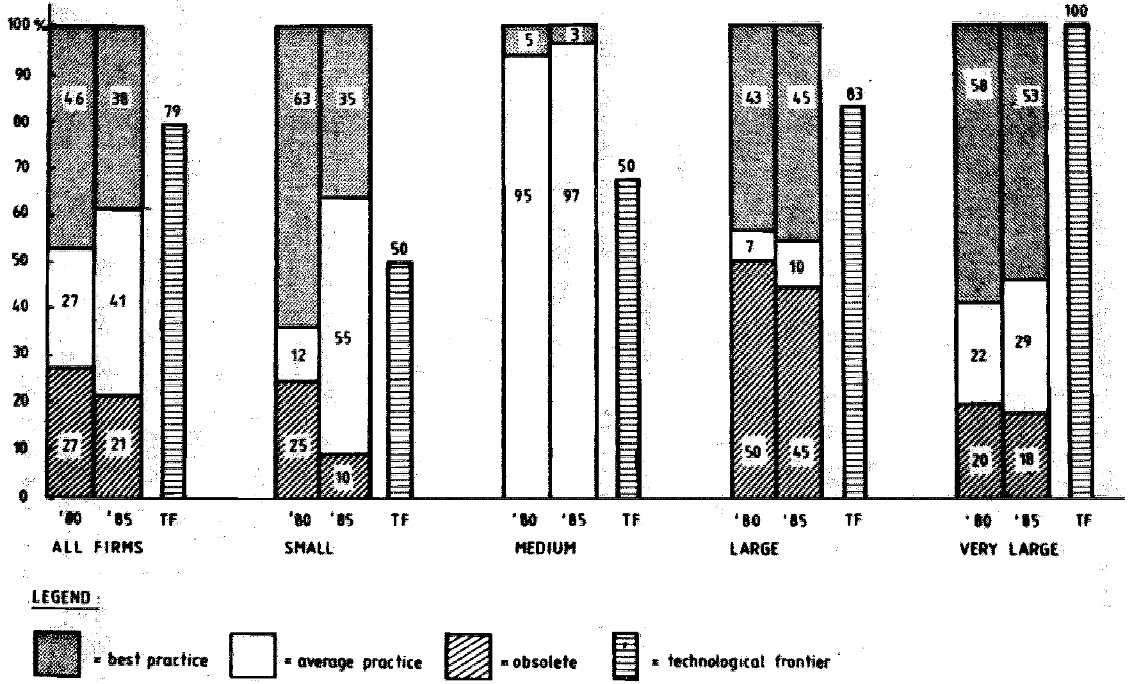


1) See also Appendix 3.

Small companies show a rising share of average practice and a slightly decreasing percentage of best practice technology controllers. Diffusion of information technology in controllers as materialized in 'dedicated controllers' has clearly been most advanced in the group of medium sized companies, where it reaches a share of 56% in 1985.
Large and very large companies apparently concentrate their production of controllers on average practice technology which constitutes about 80% of the turnover for controllers. The share of best practice technology has either declined, as for the large companies, or it remained at an insignificant level as for the very large companies. Research at the technological frontier of dedicated controllers is performed by 68% of all companies, with only few small companies, more than 80% of medium and large companies and over 60% of the very large companies.

Programmable Logic Controllers (PLC's) have become 'stripped computers' which are able to perform many tasks which until 10-15 years could only be dealt with by computers. There are only a small number of producers of these PLC's, in the survey there are only nineteen of them. Most of these manufacturers are large or very large companies.
For all companies a decline of the share of best practice technology and a rise of average practice technology PLC's is clear, which could indicate that demand for the most advanced generation is stagnating, see figure 4.8.
Small companies demonstrate a shift from best practice and older generations to average practice which in 1985 takes a share of 55%. Medium sized companies apparently concentrate virtually all their production at the level of average practice technology.
The group of large and very large manufacturers are more important. Large companies provide most of their PLC's with either best practice or older technology. There has been a slight decrease of the older generation from 50 to 45%, but no significant change in the share of best practice technology.

Figure 4.8: Diffusion of information technology in PLC's[1].

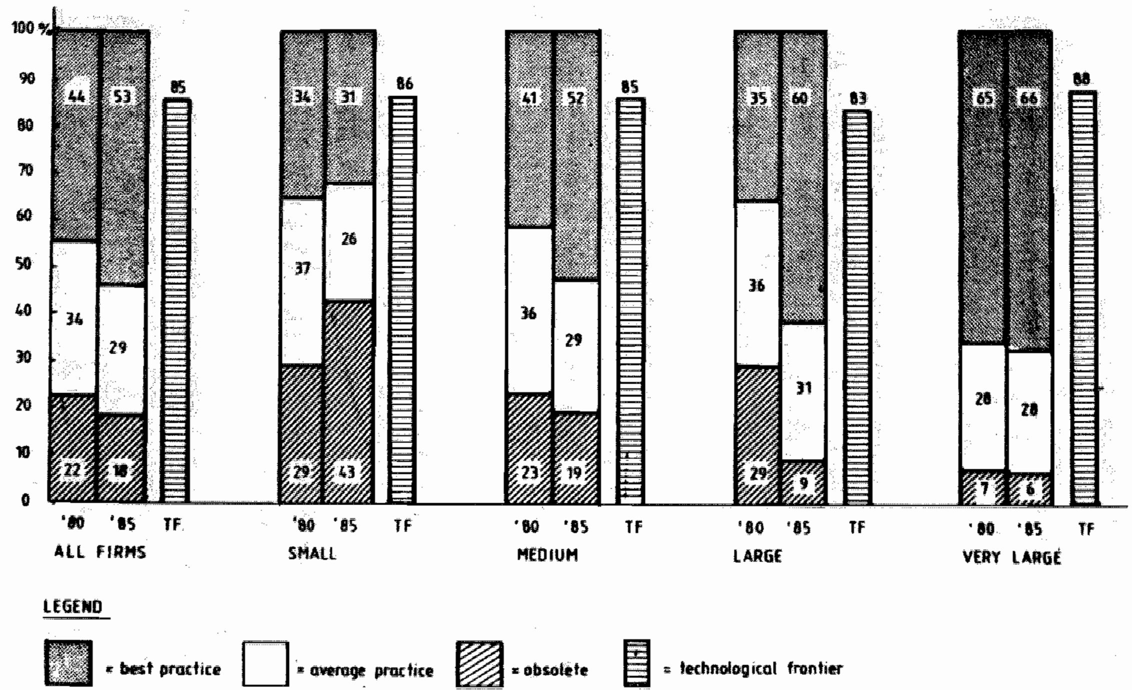


1) See also Appendix 4.

For the very large companies it can be observed that best practice technology is, although with a decreasing share, still well above 50%. The share of older generations is fairly low and the share of average practice has risen to approximately 30%.
Research at the technological frontier of PLC's is a clear function of the size of companies as shown in increasing participation with the increase of size-classes.

For Process Control Systems a growth in the share of best practice systems to over 50% can be observed in figure 4.9. This growth is parallelled by a decline of both average practice and older generations of control systems. Also most companies (about 85%) participate in research at the technological frontier.
There are some striking differences between in particular small companies and the other size categories.
Small companies show a remarkable increase in the share of the older generation of centralized control systems of which the share has gone up to over 40%. The share of best practice, digitalized distributed systems has dropped somewhat to just over 30%, but average practice technology has dropped from 37% to 26%. This could indicate that small companies attempt to find 'new' markets for less sophisticated systems for less developed process industries or processing companies.
For other size categories it is clear that best practice technology has already reached a substantial level of diffusion: over 50% for medium sized, 60% for large and over 65% for very large companies.
For very large companies older generation systems with less developed information technology have dropped considerably to an insignificant level.
Average practice technology for control systems has dropped or stabilized at a level of around 30%.

Figure 4.9.: Diffusion of information technology in Process Control Systems[1].



1) See also Appendix 5.

Diffusion of information technology in the international process control equipment sector

The analysis of diffusion coupled with technological trajectories at this level of detail has a major advantage in the in-depth knowledge of diffusion of a particular technology. However it also creates some problems regarding the interpretation of a more diffuse pattern as created in the above.

- Diffusion of advanced information technology has different levels for each key-element. Diffusion of best practice technology has been very moderate in sensors, it is stagnating for controllers in so-called dedicated controllers, it has even dropped back for PLC's, but has risen considerably for process control systems.

  The diffusion of average practice technology has increased slightly for sensors and controllers but at an already high level of over 75% and over 65% respectively. It has gone up to over 40% for PLC's and it dropped with 5% to 29% for process control systems.

  The share of older generations of each key-element has been diminished to a share between 21 and 10% in 1985.
- For different size-classes some trends can be observed:

  Small companies are hardly engaged in the production of sensors for which they concentrate on average practice technology without research at the technological frontier. They also reach a considerable share of average practice for controllers with a, albeit slightly decreasing, reasonable share of best practice controllers. In PLC's their share of best practice has dropped considerably, but the share of average practice has been expanded substantially. For process control systems there has been a rise of older generations within the group of small companies. So, in no key-element do small companies play an outstanding role in the diffusion of advanced information technology.

  The picture is slightly different for medium sized companies. They concentrate on average practice for sensors. In particular for PLC's, diffusion of best practice information technology has been almost negligible. For hardwired controllers and process control systems the diffusion of information technology (in terms of the share of best practice controllers and digitalized control systems) has been considerable for medium sized companies.

Large and very large companies dominate best practice technology and to a certain extent also the technological frontier of three out of four key-elements. The only key-element in which both large and very large companies do not demonstrate a substantial share of best practice technology is in the older technology of hardwired controllers for which dedicated controllers are an electronic new version. It has to be stressed that diffusion of sophisticated information technology in best practice generations and participation at the technological frontier has been most advanced in the group of the very large companies.

4.4. DYNAMICS OF DIFFUSION AND TECHNOLOGICAL CHANGE

In the above the analysis of technological development has been integrated with an analysis of diffusion. For both issues it was necessary to choose a theoretical and conceptual framework which is quite distinct from traditional economics. With this approach it appears to be possible to analyze both diffusion and technological change. The analysis of technological paradigms and basic designs sets the general background for understanding technological development. Analysing technological change in key-elements, as improvements of characteristics of different generations, provides a clear identification of technological trajectories. Technological trajectories are also apparent in gradual improvements during a process of diffusion. The economic and social implications of technological development is not manifest until this process of diffusion takes place. Both diffusion and technological change influence each other. In capitalist economies companies can be expected to seek only further improvement of technologies if the intra-firm diffusion of existing best practice technology generates returns from which further development can be financed. Within modern companies project-evaluation, decision making and priority setting will, in particular in larger companies, not take place on a week-to-week basis but efforts to improve on best practice technology will be effected by the succes (diffusion) of existing technology. In the analysis of intra-sectoral diffusion the linkage of technological progress to diffusion of best practice technologies reveils the endogenous character of technology. The dynamic aspects of this relation is reflected in the interdependence of both elements. In traditional theories of diffusion the dynamic aspect of this process is defined as the gradual growth in the number of adopters[1]. In the context of this study this is seen as only one feature of the dynamics of technological and industrial development. For a further study of this relationship the understanding of technological development will have to be supplemented with an analysis of industry structures and innovation strategies of companies.

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1) See e.g. C.G. Thirtle and V.W. Ruttan, 1987, p. 78.

5. STRUCTURE AND INNOVATIVE PERFORMANCE OF THE INTERNATIONAL PROCESS CONTROL EQUIPMENT INDUSTRY

5.1 INTRODUCTION

Having analysed major technological developments effecting process control and diffusion of information technology in amongst other things best practice applications of equipment and systems the next step will be to analyse innovation in the process control equipment (p.c.e.) industry. In chapter 3 it was stressed that the relation between size, market structure and innovation is mediated by the technological opportunity and the 'age' of industries. It was also mentioned that this technological opportunity is influenced by the process of creative destruction which causes industries and companies to change. Therefore it will be necessary to first picture this process of industrial and technological development and the companies which play a role in it.

Due to the lack of statistical data it will not be possible to reveal the relation between industrial concentration and innovation. However, based upon the statistical material from the survey it will be possible to pay extensive attention to the role different categories of companies play in generating innovation in this particular industry[1]. In this analysis the relevance of a differentiation of companies not only in terms of size but also in referring to e.g. their 'age' and diversification patterns will be discussed. Innovation will be operationalized with some of the more well known research input indicators such as categories of R&D and some indicators of innovation in terms of new products and best practice technology. In chapter 3 it was proposed to extend the analysis of innovation and size of companies with some attention to be paid to innovation strategies followed by different categories of companies. In this chapter innovation strategies of different categories of companies are analysed. It will be demonstrated that there appears to be no significant relation between

1) See Appendix 1 for details on the survey.

size and innovation strategies, although there are some differences in the distribution of innovation strategies to different categories of size.

A survey of a limited number of companies restricts the possibilities of statistical elaborations upon the material. As argued below the survey-population represents the international p.c.e. industry with in particular the group of large, international companies included almost integrally. In order to be able to perform some simple statistical manipulations with a limited number of respondents it will be necessary to restrict the analysis to size-categories of companies in a substantial share of the following. Also due to the small numbers and variance in the statistics results will have to be interpreted with care.

5.2 STRUCTURE OF THE PROCESS CONTROL EQUIPMENT INDUSTRY

In the following paragraphs attention will be paid to changes in the industrial structure during the past decades when some companies grew to considerable size. This growth and the identification of major companies is set against the background of technological changes analyzed in the previous chapter. Such changes in the industry have been substantial even if Schumpter's creative destruction took place only to a moderate degree.

The categorization of companies in the industry is seen in the context of categories mentioned in the foregoing such as size, age, diversification and specialization.

Industrial development and creative destruction in the p.c.e. industry

The history of control technology and its industrial application in control equipment goes back at least as far as the nineteenth century. The introduction of steam powered machinery created the technical environment for further development of industrial control. It led to a number of inventions and the production of several control devices which gradually enabled the control of machines or processes without so-called direct manual control.

After several decades of experimentation the introduction of electricity as an information transmitting medium enabled the origin of a first stage of modern control technology in the early twentieth century. A gradually growing range of measuring equipment and sensors such as thermocouples, light sensitive cells and many pneumatic and hydraulic control devices were developed and manufactured by electrical and mechanical engineering companies.
In this period the growth of some of these early p.c.e. manufacturers is clearly connected with the role some entrepreneurs/capitalists played in innovating their business. In the leading company Honeywell entrepreneurs such as Albert Butz and in particular Mark Honeywell and Harold Sweatt resemble Schumpeter's conception of the entrepreneur and his role in capitalist society. In many other companies established in the late nineteenth or early twentieth century the role of entrepreneurs is reflected in the names of companies such as Allen-Bradley, Emerson, Fischer & Porter, Brown and Boveri, Hartmann and Braun. And although company records on these men can be mistrusted to a certain extent as they present only one side of the picture it nevertheless becomes clear that entrepreneurs and entrepreneurial capitalists played an important role in the industry during the first half of this century. With the growth of the industry and its companies the role of 'the' entrepreneur has clearly diminished, although small companies have pioneered the development of several new process control products in the post-war period of growth[1].
This growth has been effected by the growth of industries applying control instrumentation. The gradual rise of process industries such as iron and steel and chemicals caused a growth in demand for p.c.e. A number of companies specialized in the production of this equipment and many of them grew with the increase of demand for more advanced control technology. In those days the industry already knew a segmentation in larger companies such as e.g. Honeywell and a group of small and medium sized companies operating in sub-markets.

1) See e.g. D. Shimshoni, The mobile scientist in the American instrument industry, in: Minerva, Vol. 8, no 1, 1970.

The first group of manufacturers produced not only individual pieces of equipment such as sensors and controllers they also supplied the early versions of overall control systems. The growth of these leading companies, listed in table 5.1, resulted from both internal growth (concentration) and centralization through acquisitions and mergers. Company records of these corporations show a continuous process of acquisitions, mergers, joint ventures, foreign direct investments and the building of new plants. The second group of companies produced individual devices which could either fit into a larger system or be applied in more simple single-loop control. Many of these companies were either acquired by larger corporations or, in case they did not vanish, they remained in particular market niches.

As mentioned before the introduction of computer technology in the late fifties and early sixties caused a change of technological paradigm in the p.c.e. industry. Electromechanical instruments were replaced by electronic devices and the gradual introduction of electronic controllers, micro-processors, and mainframe, mini and micro computers actually turned the p.c.e. industry into a sector closely related to the electronics industry. The differentiation of the industry became even more apparent as suppliers of control systems had to be able to integrate information technology into their systems and sub-systems and suppliers of single devices could either offer advanced equipment to be linked to control systems or produce less advanced equipment for the lower end of the market. Many larger companies diversified extensively. For some of them diversification strategies, which began in the sixties, might have gone too far. In recent years a number of companies such as Honeywell, Gould and Combustion Engineering divested major businesses. Honeywell divested its Information Division into a joint venture with Bull and NEC, Gould sold its Medical and Defence Divisions and Combustion Engineering is reshaping its activities to core-businesses.

Table 5.1: List of leading companies in p.c.e.

NAME	COUNTRY	ESTABLISHED IN	NUMBER OF EMPLOYEES IN 1986	SALES '86 IN US$ MLN.	BRANCHES IN ORDER OF IMPORTANCE
Honeywell	USA	1885	78,000	5,378	- Aerospace & defence - Home and building automation & control - Industrial automation and control
Foxboro	USA	1908	7,850	543	- Electronic systems & products - Other electronics
YEW	Japan	1915	12,150	667	- Industrial instruments - Measuring instruments - Information equipment
Fischer & Porter	USA	1937	2,650	177	- (Process-) control equipment
Rockwell (Allen-Bradley)	USA	1928 (1903)	121,000 (14,500)	12,296 (±1,000)	- Aerospace - Electronics - Automative - General industries
Gould	USA	1928	10,600	909	- Electronic systems - Electronic components - Instrument systems
Emerson Electric	USA	1890	60,700	4,953	- Commercial & industrial systems - Consumer products - Government & defence
Brown Boveri (merged with ASEA in 1987)	Switzerland	1891	97,500	5.700	- Power distribution & generation - Industrial equipment - Electronics, measurement & control

Table 5.1: List of leading companies in p.c.e. (cont.).

NAME	COUNTRY	ESTABLISHED IN	NUMBER OF EMPLOYEES IN 1986	SALES '86 IN US$ MLN.	BRANCHES IN ORDER OF IMPORTANCE
Siemens	FRG	1847	363,000	20,000	- Energy & automation - Communications & information systems - Telecommunications - Medical engineering - Others
Toshiba	Japan	1875	120,000	18,738	- Electronic components & industrial electronics - Consumer products - Heavy duty electrical apparatus
Combustion Engineering	USA	1910	24,150	2,551	- Power generation - Process industry & engineering - Public section & environmental
Mannesman (Hartmann & Braun)	FRG	1890 (±1880)	111,100 (6,300)	6,000 (240)	- Machinery & engineering - Electronics - Steel products
Monsanto (Fisher Controls)	USA	1901 (1880)	51,700 (9,000)	6,879 (645)	- (Agro-) Chemicals - Control systems & products

Source: J. Hagedoorn, P. Kalff and J. Korpel, Technological development as an evolutionary process, 1988, with minor changes and updating.

Nowadays most of the p.c.e. manufacturers still offer some of the 'older' equipment for replacement purposes and for applications with less advanced customers. However, no company can be expected to 'survive' in the industry without the ability to integrate relevant sub-fields of information technology into its products. All this has led to an industry which has become more and more science based. E.g. over 90% of the companies studied in the survey, 51 out of a total 56, are engaged in R&D. Only three medium sized and two larger companies reported no formal R&D (see table 5.6).
The change-over to a more science based industry and the transformation into an electronics-related sector has to a large extent been realized within existing p.c.e.-manufacturers and electronics companies. Specialized computer companies and software houses do supply hardware and software for production control and management information systems but their activities are to be seen as general system-architecture or top-level, computer-based, information systems. Companies such as IBM, Digital, etc. are, however, not to be seen as suppliers of process control systems and therefore they do not appear in the list of leading companies in p.c.e. On the other hand some of the more widely diversified p.c.e. manufacturers such as Siemens, Gould, Toshiba and Philips offer computersystems which can also serve within a complete production or process control system. The integration of information technology related activities and the creation of a broad spectrum of control products and systems in large p.c.e. manufacturers did not only take place in the reshaping of in-house capabilities. As shown in table 5.2 many leading p.c.e. companies have been very active in acquiring relevant companies in order to strengthen their technological competence in sophisticated control and information technology.

Table 5.2: Take-overs of information technology and p.c.e. related companies by major p.c.e. manufacturers since 1970.

<u>Gould</u> acquired:
- Biomation
- Hydrosystems
- Modicon
- Denison
- Hoffman Electronics (all '77)
- Deltec ('80 until '84)
- System Engineering Labs ('80)
- Taylor Electronics ('80 until '83)
- SRL Medical
- Gettys Manufacturing
- Technicon's testing division
- De Anza Systems (all '81)
- American Micro Systems ('82)
- Bryons Southern Instruments
- Dexcell (both '83)
- International Cybernetics
- Micro Bond Technologies (both '85)

<u>Emerson Electric</u> acquired:
- Xomox
- Rosemount
- Micro Motion
- Automatic Switch Corp.
- Kiowa Corp.
- Ueshima (all - year unknown)
- Western Digital ('78)
- Smith Kline Beckman ('84)
- Copeland Corp. ('86)
- Hazeltine Corp. ('87)

<u>Rockwell</u> acquired:
- Allen - Bradley
- Robotronics (both '85)
- 3M Corp.'s communications unit
- ECA (both '86)

<u>Combustion Engineering</u> acquired:
- Taylor Instruments ('83)
- Analytical Instr. Division from Allied Corp.
- Jamesburry
- Impell (all '84)
- Sprout - Waldon
- Accu Ray ('86)

<u>Honeywell</u> acquired:
- GE's computer division
- Dienes (both '70)
- SAICOR ('72)
- GE's p.c.e. division ('74)
- Synertek ('78 until '84)
- Incotherm
- Spectronic
- Skinner (all '78)
- Electronics for Medicine
- Space-Kom (both '79)
- Megadyne ('80)
- A.C.S.
- Cometa (both '81)
- Tetra Tech
- ISSC (both '84)

<u>Siemens</u> acquired:
- Dickson ('74)
- Advanced Microdevices
- Litronix (both '77)
- Microware Semiconductors
- Databit (both '79)
- Treshold Technology ('80)
- G.T.E. ('86)

<u>Mannesmann</u> acquired:
- Kienzle (year unknown)
- Hartmann & Braun ('81)
- C. Bauer ('84)

<u>Foxboro</u> acquired:
- I.C.T. ('76)
- Wilks ('77)
- Jordan ('78)
- Octek ('83)
- Systronics ('84)

<u>Brown Boveri</u> acquired:
- George Kent ('75)

<u>Monsanto</u> acquired:
- Fisher Controls ('70)
- Posi-Seal Int. ('85)

Source: Annual reports, company profiles, various articles in specialized journals, L. Soete, Electronics, in L. Soete (ed.) 1985, pp. 22-23.

The change of the p.c.e. sector and the creative destruction accompanying it is not characterized by the general or substantial destruction of the sector of industry itself. However, there has been a moderate effect of creative destruction in the sense that the p.c.e. sector developed from measuring equipment and simple controls into a 'high tech' sector. Leading companies have diversified into electronics and information technology, some electronics companies have diversified or integrated smaller p.c.e. manufacturers. As demonstrated in chapter 4 also many small and medium sized companies have, although not always at the technological frontier, been able to apply more advanced forms of information technology.

It is important to note that side entries and new companies played but a moderate role in the reshaping of the industry after 1980. As shown in table 5.1 most of the leading companies or their p.c.e. subsidiaries have been in the industry for a long period. Many typical p.c.e. manufacturers such as Honeywell, Foxboro, YEW, Allen-Bradley, Hartmann & Braun and Fisher Controls were established in the late nineteenth or early twentieth century. Even the 'youngest' of the leading companies still have a history which goes back to the first decades of this century. The near-absence of very recent (side-)entries is reflected in the 'age' of p.c.e. production in the 56 companies from the survey. As can be read from table 5.3 over 70% of all companies were already manufacturing p.c.e. before 1970. Only four existing companies entered the market after 1979. Three of these are small companies and one entry refers to a large company. The latter is a side entry of a diversified company with a relatively small p.c.e. line of business[1]. However, in the period from 1960 upto 1980, with the emergence and perfection of the new computer-based paradigm in process control many companies have entered the industry. About 40% of the companies in the survey, most of which small or medium sized, entered the p.c.e. market in that particular period.

1) See J. Hagedoorn et al., 1988, p. 166.

Different categories of p.c.e. companies

The relevance of a differentiation of companies has been discussed extensively in chapter 3. This led to a proposed framework of several categories of companies based upon size and some other categories such as new companies, subcontractors, and multinational and multidivisional companies. An impression of the size-distribution in the p.c.e. industry is given in the bottom row in table 5.3. The four size-classes applied in this study have been constructed after information on the actual size of companies in terms of number of employees had been gathered. In many other studies categories of size are frequently introduced beforehand and remain quite arbitrary. The size-classes in this study represent the actual sub-populations and clusters in a frequency distribution. Total employment of each company has been taken as an indicator of size for several reasons. First, overall size reflects the broader capabilities and activities of companies which

Table 5.3: The 'age' of p.c.e. production, number of companies and %.

	Total	Overall size			
		< 500	500- 5,000	5,000- 50,000	50,000+
before 1950	21 37.5%	1 7.1%	8 42.1%	7 50.0%	5 55.5%
1950-1959	9 16.1%	3 21.4%	2 10.6%	1 7.1%	3 33.3%
1960-1969	11 19.7%	5 35.7%	3 15.8%	2 14.2%	1 11.1%
1970-1979	11 19.7%	2 14.3%	6 31.6%	3 21.3%	-
after 1979	4 7.1%	3 21.4%	-	1 7.1%	-
Total	56 100%	14 100%	19 100%	14 100%	9 100%

due to indivisibility cannot always be disaggregated into separate activities. Second, process control is not a distinctly administered industrial activity for all companies in the survey and employment figures for process control are 'rough' estimates for some companies. Third, in Hagedoorn et al, 1988, both indicators of size, overall and p.c.e. employment, have been analysed generating but few differences in outcomes. All in all, overall size appears a sufficient and reliable indicator to distinguish between companies.

In the population of p.c.e. manufacturers there are fourteen small companies, nineteen medium sized companies, fourteen large companies and nine very large companies[1]. For some other differentiations into categories of companies the following remarks are to be made:
As already mentioned in the above new companies do not appear to be a relevant category for this particular industry at the present stage of its development. If one abstracts from the large company which entered the p.c.e. market after 1979 there are only three small firms in the survey which could have started as a new company after 1979.
Also subcontractors, companies which largely depend on intrasectoral trade and their 'jobbing' capacity, are not an important category in the industry. No company in the survey sold more than 75% of its production to other p.c.e. manufacturers. Only two companies depend for 50-75% of their turnover on sales to other p.c.e. producers. One of these companies is small, the other is medium sized but its p.c.e. activities are of minor importance.

Like many other sectors of industry the p.c.e. sector has become internationalized in the past decades. Nowadays many p.c.e. procuring companies are large, world-wide operating, companies in process industries, consequently the market is not restricted to national markets. This international character of the market

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1) The group of small and medium sized companies are in a sense a 'sample' of the total population of such companies, the group of large and very large companies are a close representation of those categories of p.c.e. manufacturers, see Appendix 1.

forced p.c.e. companies to at least internationalize their marketing activities. Most of the companies in the survey are multinational in the strict sense implying that they hold offices in other countries then their country of origin. Only a minority of companies, probably only seven small firms, are not multinational in that strict sense. However, the large and very large companies represent multinational companies in the commonly accepted sense.

Most of the leading companies from table 5.1 operate on a transnational level with a network of world-wide manufacturing sites, assembly factories, local businesses and sales representatives.
Many of these companies are also multidivisional, diversified companies but the multidivisionality and the degree of diversification differs from company to company. Electronics and electrical engineering companies such as Siemens, Philips, the new Brown Boveri-ASEA merger, Toshiba and to a certain extent also companies such as Rockwell, Gould, Emerson Electric and Combustion Engineering are diversified and multidivisional within the broad field of electronics, electrical engineering and defence systems. For most of these companies, in particular for the largest, control systems and instrumentation represent only a small share of their total industrial activities, although such products are frequently integrated in other systems.
Honeywell, once a specialized controls manufacturing company and still one of the leading companies, has developed to a multidivisional company with businesses such as aerospace and defence, control systems and control products (Its information systems division merged with NEC of Japan and Bull of France in 1987). YEW, Foxboro and Fischer & Porter are examples of more specialized companies, although in particular the first two are diversifying into electronics and a wider range of control systems for discrete manufacturing. Many well-known specialized p.c.e. firms have become subsidiaries of larger companies. Hartmann & Braun and Fisher Controls have become backward integrated subsidiaries of Mannesmann and Monsanto, respectively. Allen-Bradley became a subsidiary of Rockwell in 1985. Rosemount, Brooks Instruments and Beckmann have all been integrated into Emerson Electric. Kent is a subsidiary of Brown Boveri and Combustion Engineering owns Taylor Instruments, another well known p.c.e. manufacturer.

Specialization and diversification in the p.c.e. industry can also be seen in table 5.4 wich gives a somewhat different picture than would probably be expected. It is remarkable that small companies are on average almost as little specialized in p.c.e. as the group of very large companies, although the coefficient of variation for very large companies indicates that specialization in p.c.e. varies considerably for the group of very large companies. Small companies have about 30% of their turnover in p.c.e.; metal products, micro-electronics and other electronics are product groups that small companies have diversified into. Very large companies are diversified into p.c.e., other electronic capital goods and a wider array of products. Both medium sized and large companies concentrate on average about 50% of their turnover on p.c.e. which turns both groups into relatively 'specialized'. For medium sized companies other electronic capital goods are important as well, for larger companies metal products take a substantial share of the turnover.

Within p.c.e. there is a differentiation of companies according to specialization in the number of key-elements. As shown in table 5.5 only 10 companies produce all 5 key-elements of p.c.e. Some companies (3) produce p.c.e. but none of the key-elements which can only mean that they produce particular devices and instruments of minor importance to p.c.e. From table 5.5 it becomes clear that larger companies tend to produce more key-elements. Most small companies specialize in a smaller range of key-elements.
If the structure of the p.c.e. industry has to be characterized in a few words the following can be mentioned: the industry and its companies can be divided into four size categories, small, medium sized, large and very large. New companies, recent side-entries and subcontractors do not play an important role. A relatively small number of large and very large multinational and multi-divisional corporations operate within this industry. Many of the well-known specialized companies have been integrated into these companies. Small and very large companies are more widely diversified than the other two classes of companies. However, within p.c.e. production the larger a company the more key-elements it will probably produce.

Table 5.4: Diversification in productgroups as share in turnover, in 1980 and 1985, (cv), N=52, 54 or 56[1].

	Total		Overall Size							
			< 500		500-5,000		5000-50,000		50,000+	
	1980	1985	1980	1985	1980	1985	1980	1985	1980	1985
p.c.e.	42.1 (0.94)	43.3 (0.89)	30.4 (1.06)	33.0 (0.81)	48.6 (0.84)	49.8 (0.81)	53.8 (0.81)	52.9 (0.85)	28.3 (1.40)	30.7 (1.25)
micro-electronics	11.1 (1.84)	10.2 (1.81)	21.1 (1.33)	23.3 (1.18)	10.4 (2.03)	7.6 (1.79)	6.2 (1.68)	2.9 (2.14)	3.1 (2.23)	3.9 (1.85)
other electronics capital goods	15.5 (1.74)	18.3 (1.58)	15.4 (1.71)	15.0 (1.39)	17.4 (1.70)	23.7 (1.48)	5.3 (2.24)	5.8 (2.12)	27.9 (1.34)	32.0 (1.21)
metal products	18.1 (1.72)	15.8 (1.84)	23.6 (1.42)	23.6 (1.41)	15.3 (2.00)	8.5 (2.56)	23.8 (1.54)	23.5 (1.60)	6.3 (2.23)	6.4 (2.33)
other products	11.7 (2.00)	9.2 (2.18)	9.6 (1.52)	4.4 (1.63)	7.8 (3.04)	10.4 (2.46)	7.5 (1.74)	6.8 (2.05)	31.5 (1.22)	19.6 (1.43)

1) Several companies could not provide information on different productgroups for both 1980 and 1985; figures for p.c.e. N=56, for other productgroups 1980 N=54; 1985 N=52.

Table 5.5: Specialization within p.c.e.; combinations of production of sensors, HWC's, PLC's, process control systems and software for production control systems, number of suppliers and %.

Combinations:	Total	Overall Size < 500	500-5,000	5,000-50,000	50,000+
All 5 key-elements	10 17.8%	-	2 10.5%	2 14.3%	6 66.7%
4 key-elements	16 28.6%	3 21.4%	6 31.6%	7 50.0%	-
3 key-elements	10 17.8%	3 21.4%	4 21.1%	2 14.3%	1 11.1%
2 key-elements	9 16.2%	4 28.6%	1 5.3%	2 14.3%	2 22.2%
1 key-element	8 14.3%	3 21.4%	5 26.3%	-	-
0 key-element	3 5.4%	1 7.1%	1 5.3%	1 7.1%	-
Total	56 100%	14 100%	19 100%	14 100%	9 100%

5.3 SIZE AND INNOVATION IN THE P.C.E. INDUSTRY

In chapter 3 the so-called Schumpeter controversy in the literature and research-findings on the relation between firm size and innovation has been discussed. Several hypotheses regarding the subject have been deducted from the literature. In the following I will relate the size of companies as found in the survey of the p.c.e. industry to several indicators of innovation. The distribution of size classes will be related to innovation-inputs, i.e. the distribution of basic and applied research and product development, followed by the analysis of the relation between size and R&D intensity. Innovation-output indicators are applied for the relation between size and the share of new products in company turnover. These output indicators will be briefly compared to the findings on the distribution of best practice generations of p.c.e. as reported more extensively in chapter 4[1].

Size and R&D

The distribution of research inputs is the first indicator for innovation. In table 5.6 the distribution of categories of R&D such as basic, applied and product development is reported. 51 companies, about 90% of the companies, perform R&D which confirms the science-based character and to a certain extent also the general technological opportunity of the industry. Most of the research is devoted to both applied research and product development. Only 13% of the funds for R&D is used for basic research. However some qualifications have to made. For the population as a whole as well as for the sub-categories of size the coefficients of variation point out that there is much scatter in the percentage of basic research. These outcomes also refer only to relative distributions of R&D and not to absolute figures or R&D as a percentage of e.g. sales. In other words, the actual spending of R&D is unknown, which could have changed the picture. Furthermore, companies might have different perceptions of categories of R&D. Keeping in mind such considerations some marked results for different size-classes can be observed.

The group of small companies applies on average only 25% of their funds for product development, while the larger companies distribute over 50% of their funds to product development. From the distribution of funds for basic research one learns that under conditions of quite identical coefficients of variation small companies

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1) One particular indicator of innovation output, frequently mentioned in the literature, refers to the number of patents per firm or the distribution of patenting companies. In the survey of the p.c.e. industry too few companies scattered throughout the population reported to have applied for patents in the past years. Due to these small numbers plus the wide variation in patenting-activity it is impossible to draw any conclusions from the material.

concentrate much more of their R&D funds on basic research. Small p.c.e. manufacturers spend on average about 50% of their R&D funds on applied research, and about 25% on basic research and product development each. Medium-sized and large companies concentrate most of their research on applied research and product development (±90%) and spend relatively few of their funds on basic research. The findings for the group of very large companies come very close to results from other studies on large and very large companies. E.g. in an EIRMA study on R&D expenditures by over 100 large companies similar results were generated: basic research 9% (p.c.e. 11%), applied research 32% (p.c.e. 34%), development 59% (p.c.e. 55%)[1].

Table 5.6: Distribution of categories of research in % of total research in 1985.

	Total	Overall size < 500	500-5,000	5,000-50,000	50,000+
Basic research:					
average %	13	24	12	7	11
cv	1.5	1.2	1.3	1.3	1.1
Applied research:					
average %	43	51	41	42	34
cv	0.6	0.6	0.6	0.8	0.6
Product development:					
average %	44	25	47	51	55
cv	0.7	0.9	0.6	0.6	0.5
Total	100%	100%	100%	100%	100%
Number of companies with R&D	51	14	16	12	9
% of total	91%	100%	84%	86%	100%

1) See EIRMA, How much R&D?, 1983, p. 50.

In tabel 5.7 the research intensity of p.c.e. manufacturers is presented. It is clear that the research intensity is quite identical for three out of four size-classes. The group of small companies appears to be more research intensive than the other classes, but there is substantial variation in research intensity of small companies. In other words, a substantial part of the group of small companies probably belongs to the class of highly research intensive small firms mentioned by Freeman.

Table 5.7: Research intensity (share of number of R&D employees in total number of employees) in 1985.

	Total	Overall Size			
		< 500	500-5,000	5,000-50,000	50,000+
Research intensity	0.09	0.18	0.05	0.06	0.06
c.v.	1.4	1.12	1.04	0.81	0.89

Size and product-related indicators of innovation

Since innovation is generally defined as an invention that has been introduced to the market, innovativeness can be measured by the share of turnover that is generated by new products. In tables 5.8 and 5.9 the share of the 1985 turnover for new products, introduced after 1980, is set against the different size classes. In table 5.8 the category new products is defined as new to the company, in table 5.9 new refers to new to the market.

In table 5.8 it is shown that only one small company stated that new products did not contribute to its turnover. Over 40% of the companies mentioned that 50% or more of their turnover in 1985 resulted from the introduction of new products. The group of small companies and the largest companies have been most innovative in terms of the share of new products in 1985 turnover.

Table 5.8: Share of companies new products in 1985 turnover for p.c.e

	Total	Overall size			
		< 500	500-5,000	5,000-50,000	50,000+
no new products	1 1.8%	1 7.1%	-	-	-
less 10%	11 19.7%	2 14.3%	5 26.3%	3 21.3%	1 11.1%
10-50%	20 35.6%	3 21.4%	9 47.4%	5 35.6%	3 33.3%
50%+	24 42.9%	8 57.1%	5 26.3%	6 42.9%	5 55.5%
Total	56 100%	14 100%	19 100%	14 100%	9 100%

A probably even more suitable indicator is found in the share of 'really new' products, i.e. products introduced since 1980 that were new to the market and not only to the company itself. These figures are shown in table 5.9. It is evident that the share of turnover realized with these really new products is lower than with the products mentioned in the previous table. Eight companies mention that new products have had no share in their 1985 turnover. Only three medium-sized companies claim to have generated at least 50% of their turnover in 1985 with new-to-the-market products.

If a minimum of 10% of the turnover realized with real new products is accepted as a reasonable indicator of the innovativeness of companies, then the groups of small and very large companies are most innovative as:

- Over 60% of the group of small companies reach the minimum level of 10%.
- Over 50%, 5 out of 9, of the group of the very large companies achieve the same minimum.

Table 5.9: Share of companies' new to the market products in 1985 turnover for p.c.e.

	Total	Overall size < 500	500-5,000	5,000-50,000	50,000+
no new products	8 14.3%	2 14.3%	1 5.3%	4 28.6%	1 11.1%
less 10%	23 41.0%	3 21.4%	10 52.6%	7 50.0%	3 33.3%
10-50%	22 39.3%	9 64.3%	5 26.3%	3 21.3%	5 55.5%
50%+	3 5.4%	-	3 15.8%	-	-
Total	56 100%	14 100%	19 100%	14 100%	9 100%

The diffusion of best-practice technologies reported in chapter 4 can also serve as an indicator of innovativeness. It has been reported that small companies play only a minor role in the generation of best-practice technologies. Large and in particular very large companies are most innovative from the perspective of best-practice technologies and technological frontiers in p.c.e. Medium sized companies take a position in between the groups of small and large companies.

In order to achieve a more aggregate indicator of best-practice performance the percentages of turnover for best practice of each key-element supplied by a company can be added and devided by the number of key-elements it produces. Through this simple procedure one is able to have an overall indicator of each company which can be added for different size-classes as shown in table 5.10[1].

1) See Appendix 6 for individual records.

It follows from this table that the group of the very large companies have been most innovative in terms of best practice technology in the key-elements they produce. Small companies are clearly less advanced in terms of diffusion of best practice technology than the other classes. Medium and large companies take an intermediate position.

Table 5.10: Share of best practice technology in all key-elements supplied by p.c.e. manufacturers in 1985.

	Total	Overall size			
		< 500	500- 5,000	5,000- 50,000	50,000+
< 20% best practice	24 42.9%	8 57.1%	8 42.1%	6 42.9%	2 22.2%
20-40% best practice	19 33.9%	4 28.6%	6 31.6%	5 35.6%	4 44.4%
>40% best practice	13 23.2%	2 14.3%	5 26.3%	3 21.3%	3 33.3%
Total	56 100%	14 100%	19 100%	14 100%	9 100%

5.4 INNOVATION STRATEGIES IN THE INDUSTRY

General trends of technological development in process control, in particular the further integration of several aspects of sophisticated information technology, return in the major topics in the innovation and R&D strategies of the leading companies. It will be clear that these companies do not provide detailed information on their R&D activities. However, annual reports, company profiles and interviews with management reveal some of the main topics of research in the industry.

All leading companies mentioned in table 5.1 perform research at the technological or scientific frontier of at least some of the issues mentioned below. The largest companies and those engaged in several sub-disciplines of information technology cover virtually all these topics. Smaller and more specialized companies appear to concentrate on a smaller number of research items. These topics picture a stable set of commitments and broadly defined innovation targets for the nearby future.

The following topics, ranging from direct process measurement to overall production control, are worth mentioning:

- research on the combination of sensors and advanced micro-electronics (smart sensors);
- further digitalization of stand-alone equipment;
- integration of computer and communication technologies with e.g. local area networks and speech recognition systems;
- advanced computer science which does not only include hardware and micro-electronics but also advanced software, artificial intelligence and expertsystems.

For the next step in the analysis of innovation strategies it will be necessary to assess the relevance of a number of innovation strategies, mentioned in chapter 3, in the context of the p.c.e. industry. One strategy, the traditional strategy, can be disregarded before hand as the modern p.c.e. industry has little in common with handicrafts. In a previous section it also became clear that subcontractors do not play a role of any importance in the present population which makes it unnecessary to pay attention to the dependent strategy. An opportunist strategy could be reflected in the degree of specialization into one key-element as shown in table 5.5. However, the degree of diversification into other product groups outside p.c.e., shown in table 5.4, suggests that only very few companies will follow an opportunist strategy as defined in chapter 3.

All this leads to a set of alternative strategies, offensive, defensive or imitative, which can be analysed for the industry structure of the p.c.e. industry. In the following a principal components analysis is applied to identify the relation between classes of size and innovation strategies[1]. To operationalize

1) See e.g. A. v.d. Zwan and J. Verhulp, Grondslagen en technieken van de marktanalyse, 1980 and F.N. Kerlinger, Foundations of behavioral research, 1969 for brief descriptions of factor analyses.

these strategies a number of variables were identified. Most of these variables were also applied in the previous section. In the final principal components analysis five variables have been introduced: research intensity (RDINT), research intensity in p.c.e. as the share of R&D employees for p.c.e. in total number of p.c.e. employees (RDINTPCE), share of new products in turnover (NEW PROD), share of new-to-the-market products in turnover (REALNP), and the average rate of best practice in key-elements produced (BESTPRAC).

In principal components analysis the smallest possible number of linear combinations of components which together explain a maximum degree of (standardized) variance is sought. The proportion of explained variance (communality) is applied as a measure of goodness of fit. Principal components analysis is a technique for datareduction e.g. to measure one scale for a number of indicators (variables) at which all elements take a position. In this study a scale is built for measuring innovation strategies of companies in the p.c.e. industry. The correlation matrix in table 5.11 pictures the relation between the five variables mentioned above. Correlations between these variables are generally low and hardly significant.

Table 5.11: Correlation matrix of innovation indicators.

	RDINT	RDINTPCE	NEW PROD	REAL NP	BESTPRAC	INSTRAT1
RDINT	1.0000	.2301(*)	.2000	.2316(*)	-.0907	.3826**
RDINTPCE	.2301(*)	1.0000	-.1096	-.1107	-.2048	-.2677*
NEW PROD	.2000	-.1096	1.0000	.4156**	.3058*	.8475**
REAL NP	.2316(*)	-.1107	.4156**	1.0000	-.0373	.7269**
BESTPRAC	-.0907	-.2048	.3058*	-.0373	1.0000	.4025**
INSTRAT1	.3826**	-.2677*	.8475**	.7269**	.4025**	1.0000

(N = 56) 2-tailed Signif: (*) - .10 * - .05 ** - .01

As the aim of the present analysis is to find one scale, the principal components analysis is applied for only one component. The weights of regression of the variables on the component, the so-called factor loadings, are given in table 5.12.

Table 5.12: Factor matrix

Variables:	Factor loadings of variables on the component:
RDINT	.38261
RDINTPCE	- .26768
NEW PROD	.84750
REAL NP	.72685
BEST PRAC	.40252

Variance: 1.63

Proportion of explained variance: .33

The coefficient for RDINTPCE is apparently negative because a higher scoring on this indicator is in general related to lower scores on the other indicators, see also table 5.11. It can be concluded that the R&D intensity in p.c.e. does not fit with the other indicators. The relatively low absolute value of the factor loading (.27) indicates that this variable is less important to the scale for innovation strategies.

The position of elements, companies in this study, on the scale for innovation strategies is fixed by so-called factor scores, i.e. scores of elements on a component. By definition factor scores form a normal distribution with an average of zero and a standard deviation of one. Correlations between factor scores (INSTRAT 1) and the five variables on which this scale is based are of course relatively high, see table 5.11. In Appendix 7 the scores of companies on five variables and the original and classified factor scores are presented. The original factor scores have been classified into innovation strategies (INSTRAT 2) as follows:

1: factor scores $< -.50$ = imitative

2: $-.50 \leq$ factor scores $\leq +.50$ = defensive

3: factor scores $> +.50$ = offensive

Finally, these outcomes for innovation strategies can be set against the size of companies as in tables 5.13 and 5.14. From these tables and the tests of independence it is evident that there is no or hardly a significant relation between size of companies and innovation strategies. From table 5.13 it is obvious that a substantial share of small and very large companies follow an offensive strategy, while almost all large and most medium sized companies have a defensive or imitative strategy.

Table 5.13: Innovation strategies versus size of companies, number of companies and %.

Strategies	Total	Overall size < 500	 500–5,000	 5,000–50,000	 50,000+
Imitative	19 33.9%	4 28.6%	8 42.1%	5 35.7%	2 22.2%
Defensive	18 32.1%	2 14.3%	5 26.3%	8 57.1%	3 33.3%
Offensive	19 33.9%	8 56.1%	6 31.6%	1 7.1%	4 44.4%
Total	56 100%	14 100%	19 100%	14 100%	9 100%

Chi-Square : 10.69375
D.F. : 6
Significance : .0983

In table 5.13 innovation strategies are assigned to three groups of companies which divide the total of companies into equal shares. If one assumes that it is more realistic that there are fewer companies with an offensive strategy and a larger number of companies with a defensive strategy the picture might change.
In tabel 5.14 size of companies is set against innovation strategies (see appendix 7, INSTRAT 3) after a re-classification of the original factor scores as follows:
1: factor scores < −.50 = imitative
2: −.50 ≤ factor scores ≤ + 1.00 = defensive
3: factor scores > + 1.00 = offensive
In that case there is clearly no significant relation between size and innovation strategy. Nevertheless, a certain pattern becomes clear. Imitative strategies, with relatively small innovative

efforts, are followed by a comparatively large share of medium sized and large companies. Few small and very large firms appear to follow such a strategy. Defensive strategies, at some distance from radical innovating companies, are in particular pursued by large and very large companies. Offensive strategies can be attributed to a relatively large share of small companies and to some medium sized and very large companies but not to large companies.

On the whole both small and very large companies in the p.c.e. industry follow a more innovative strategy than medium sized and large companies.

Table 5.14: Innovation strategies versus size of companies, number of companies and %.

Strategies	Total	Overall size ≤ 500	 500- 5,000	 5,000- 50,000	 50,000+
Imitative	19 33.9%	4 28.6%	8 42.1%	5 35.7%	2 22.2%
Defensive	26 46.4%	5 35.7%	7 36.8%	9 64.3%	5 55.6%
Offensive	11 19.6%	5 35.7%	4 21.1%	-	2 22.2%
Total	56 100%	14 100%	19 100%	14 100%	9 100%

Chi-Square : 7.35537
D.F. : 6
Significance : .2892

5.5 SOME CONCLUSIONS

The findings of the survey of the international p.c.e. industry regarding the relation between size of companies and innovation do not unambiguously support any of the well-known hypotheses completely. The results vary to some degree depending on the applied indicator of innovation.

Nevertheless it is still possible to arrive at some conclusions for the industry:

- The findings for R&D activities support the general notion that the industry has become science based as nearly all companies perform R&D.
- All small companies perform R&D. Surprisingly, they concentrate, on average, most of their R&D on basic and applied research and far less than other size categories on product development. On average small companies are more research intensive than the other classes. They also reach a substantial share of their turnover with new products. However, they do lag in the diffusion of best practice technology.
- On the other hand the group of the very large, multinational and diversified, companies as a whole appear most innovative. All the very large companies perform R&D, the relative importance of R&D categories is similar to results found in other studies. More than half of these companies have been able to generate a substantial share of their turnover with new products and they clearly lead in the introduction of best practice technologies.
- The other two size-classes take an intermediate position. Most of these companies, but not all of them, perform R&D. Their position regarding innovation changes depending on the indicator. Over 40% of the medium sized companies depend for a substantial share of their turnover on new products, for large companies this goes only for about 20% of this size-class. On average both classes have been less successful with the introduction of best practice technology than the group of very large companies.
- Innovation strategies of the large, multinational, companies reflect major issues of technological development mentioned in the preceding chapter. In the p.c.e. industry companies follow several innovation strategies such as offensive, defensive and imitative. Other strategies are hardly relevant in this particular sector of industry. Size of companies is not decisive for pursuing any of the three strategies mentioned above, but in particular many small and very large companies follow a more innovative strategy, while few companies in these categories depend on an imitative strategy.

- The distribution of innovative performance in this industry, with both small and very large companies standing out as major groups of innovating companies, can be explained by the technological and industrial changes in the past decades. The large-scale introduction of information technology and electronics led to a 'rejuvenation' of the technologically mature instrument industry. World-leading companies in information technology entered the market and the largest instrument companies diversified into electronics. Therefore, the group of very large, diversified, multinational companies with their broad fields of interest in information technology and microelectronics is a major source of innovation in the industry. On the other hand, a number of relatively small companies can benefit from well-known advantages attributed to this category of firms and play a substantial role in generating innovations. In other words, if creative destruction in an industry is characterized as a change from maturity into a new phase of advanced technological rejuvenation, both small, R&D intensive, and very large, diversified, companies pay a disproportionate contribution to technological change in the industry.

6. SOME CONCLUSIONS ON TECHNOLOGICAL AND SECTORAL DEVELOPMENT

In this final chapter I will summarize the main arguments developed and the conclusions which have emerged for the development of the theory of innovation and industrial change.

At the outset of this study two major objectives were formulated. One objective was to assess the contribution to innovation theory made by some heterodox theories of economic and technological development. In particular those theoretical contributions are stressed in which disequilibrium effects of technological and dynamic changes within the economy are of particular relevance to this study. Both Marx and Schumpeter are accepted by many as early contributors to this field who stand out as having paid extensive attention to changes caused by technological development. In order to capture the value of their contributions I felt it necessary to return to the original texts and present my interpretation of both Marx's and Schumpeter's theories on many issues which are still the subject of debate and research in innovation theory and industrial economics. This assessment has been quite critical of certain elements in both theories while others were more appreciated. The review of these theories furthermore enabled me to pay attention to neo-Marxist and neo-Schumpeterian contributions which have taken the original arguments one step further. The review and interpretation of the relevant literature led to a synthesis of different approaches in a framework in which continuity and discontinuity of technological development, asymmetry of companies, the dynamics of technological development in relation to its environment and the importance of company strategies are stressed.

The other major objective of this study was to develop the line of argument not only at the theoretical level but to demonstrate the viability of the approach in an empirical analysis as well.

This empirical analysis has been restricted to one sector of industry which limits the possibility of generalization as is the case in a multi-sector study. However, it also has a large number of advantages to research with an experimental design. The sector studied, the process control equipment (p.c.e.) industry, is clearly at the intersection of several important economic and technological developments. The study of this wider context and interrelations provides the necessary information to the analysis of inter-sectoral patterns of change which would be hidden in an isolated sector study. Also the emphasis on the international setting of sectoral and technological development has given this approach a wider significance. The emphasis on change in the structure of industry found in many evolutionary theories of innovation is fully reflected in the present research. Technological change has led to a relatively new sector which developed from the older measurement industry to an electronics and information technology related sector. There is a lack of official statistics on this sector and empirical material had to be created through survey-research. To study effectively the consequences of technological change for the industry structure will necessarily lead to applied research on other material than official statistics which have a time-lag of several years. As Schumpeter already pointed out a large number of sector studies is restricted to official statistics and as a result the emergence of new industries and changes within branches is neglected. Too often economic studies are too independent on time-series from archaic industrial classifications. The analysis in the previous chapters is a contribution to the understanding of new and 'hidden' sectors of industry which are not identified in official statistics and therefore generally disregarded in industrial economics. The somewhat experimental character of the study is partly shown in the empirical research in the survey of companies, an approach to research, which is generally accepted in many other social sciences, but a little neglected in industrial economics.

Another argument in favour of a sector study relates to the experimental character of the theoretical and conceptual design of this study. The viability of a set of analytical tools and indicators of innovation, different from the familiar ones, which are not based on concepts such as technological trajectories and dynamic diffusion, can be tested tentatively for a group of companies and relevant technologies first. The argument in favour of the need for more in-depth study of technological development itself limits the range of technologies to be considered in a study but it provides information which could not be analyzed otherwise.

Elements of an evolutionary theory of technological change

For the further development of a critical evolutionary theory of industrial development it will be helpful to understand the relationship between technological development and a selection environment as a dialectical relationship in which both elements influence each other. In that sense this dialectical relationship is identical to the forces of production and production relations in Marx's theory. The selection environment in terms of production relations affects not only social relations in a wider perspective but also the setting of different competing companies. Marx's attempt to understand technological development itself and to analyze it as an endogenous factor is still most relevant to modern innovation theory. The shortcomings in his theory in over-emphasizing process innovations and building a crisis theory on a one-sided interpretation of the effects of mechanization cannot prevent us from recognizing the scientific benefits from any serious and in-depth understanding of technological development. Contrary to Marx, Schumpeter paid less attention to technological development itself. In his early writings technology is both endogenous and exogenous. Invention is discussed as an exogenous factor and innovation is partly endogenous in its contribution to the growth of (new) companies in pre-trustified capitalism. In Schumpeter's theory of modern capitalism invention and innovation become endogenous in the innovative role of large, science based, companies. For present attempts to develop a theory of innovation, Schumpeter's definition in either new production functions or new combinations is only of limited value as he took both technical and organizational innovation into his definition. Although technical and organizational aspects of innovation are definitely related it appears more useful to distinguish between them analytically. Another necessary improvement on Schumpeter's theory is to emphasize the role minor technological improvements play once more or less radical innovations have been introduced. This particular feature has been stressed throughout this study in the emphasis on understanding technological development as a process of innovation and diffusion in which technological trajectories play an important role.

An effort has been made to provide analytical tools to understanding technological development as a process of evolutionary and dynamic change. Following Marx, the interaction of science and technology has to be stressed as an important feature of present day capitalism. However, this does not imply that despite interaction both technology and science do not have their own autonomous momentum. Technology can be distinguished from both science and craft as a different realm of technical change. It is more applied and practical than science and more theoretically mediated than craft which is mainly based on trial and error and tradition. In industries which can be characterized as science-based or 'high tech' the interaction of applied scientific research and technology becomes more intensified. In the p.c.e. industry this intensification is found in the R&D intensity and the present research agenda which disclosed advanced research at the technological and scientific frontier of a broad spectrum of sub-disciplines in information technology.
To understand the heuristics in particular fields of technology and industrial sectors it will be necessary to further develop a theoretical and conceptual framework which goes beyond orthodox economic theory. It also has to go beyond the Marxist notion of forces of production which is too abstract. In some recent contributions serious attempts have been made to broaden the scope of economics with an analytical framework including notions such as technological paradigms, basic designs, technological trajectories and technological frontier. These notions are well-suited to impressionistic pictures of general developments without too much care for detail. However, it is possible to 'tighten' an analytical framework with such notions in distinguishing levels of abstraction, providing clear definitions and demonstrating the coherence of it. In the present study the relevance and advantages of such an analytical framework has been demonstrated in more concrete operational constructs and empirical research.

Analyzing technological change as a change from or within a technological paradigm analogous to Kuhn's scientific paradigm is a subject to be developed more extensively within other disciplines such as technology dynamics and sociology of technology. Theoretical developments in these disciplines can be integrated into the economics of technological change. In the present study technological paradigms have been analyzed as a first approximation of the identification of technological opportunities in relevant industries.

The concept of technological paradigms has been used to analyze changes in process technologies and information technology which have become interlocked in process control technology. On the 'demand side' of process control chemical, iron and steel, and food processing, as major fields of process technology, depend to a large extent on further development of advanced process control. For both developments within present dominant paradigms and the emergence of new paradigms in process industries advanced process control is essential. In its turn sophisticated process control is partly dependent on technological input from information technology, and in particular computers, software, microelectronics and (tele-) communications. The introduction of computers led to more advanced p.c.e. and a shift of paradigm from pre to post computer guided control. Technological complexity of present control technology is caused by the interaction of process technologies and information technology.

The interplay of several paradigms is characteristic for the complexity of modern technology. Changes of paradigms effect the opportunities of companies operating within an industry and a field of technology. Changes within technological paradigms, whether caused by companies or other institutions from the technological infrastructure, will influence the competitive (dis)advantages of particular companies. However, changes of paradigms have a further reaching effect because they go beyond existing routines and heuristics. In that case it can be expected that the asymmetry of companies operating in an industry is enlarged and, moreover, new companies and cross-entries familiar with basic heuristics in the new paradigm will change the structure of the industry. Some of the financially better equipped companies will be able to find sophisticated take-over partners or merge with other companies. With the emergence and gradually growing impact of a new paradigm disorder of industry structure is even more apparent than in the case of gradual changes within a technological paradigm.

For further empirical research the notion of basic design is more suited because it can be interpreted as a material 'precipitate' from one or more paradigms. Technological development of basic designs can be measured in the technological performance of its characteristics. In the early stages of a new paradigm there will be a branching pattern of developing basic designs. In the process of maturation of a paradigm there will be more clarity as to the direction of technological change and gradually fewer basic designs will be found. The selection of technological options is mediated by the selection environment in terms of the strategies of competing companies at the supply and demand side. In an oligopolistic structure a relatively small number of basic designs developed by leading companies can be expected to set standards for the industry. In an oligopsonic structure choices made by a few leading companies are decisive to the further development of basic designs. With a change of technological paradigm the existing industry structure becomes more destabilized than in case of a routinized paradigmatic development.

In the process control industry the change of paradigm in the early sixties led to a phase of experimentation with different applications of computer control and programmable controllers. Several forms of computer control were developed until modern distributed and integrated control became the new standards. Meanwhile the structure of both supply and demand had changed. Technological development in major process industries such as iron and steel processing and chemicals led to a more complex industrial processing with a need for more sophisticated control. This demand for advanced control was met by the experiments with computer control in which some large users played a decisive role. The change of paradigm in process control is partly demonstrated with the entry of electronics companies and take-overs of small information technology companies by larger p.c.e. companies. It also led to a differentiation of suppliers into suppliers of complete systems, manufacturers of sophisticated stand-alone equipment and producers of simple devices and 'older' equipment. Although there were a number of competing basic designs the preference for a distributed system was apparent in many large users of process control systems. Technological development in information technology, in particular the introduction of micro-computers, enabled the emergence of this new basic design pioneered by Honeywell and a small number of other companies.

Although the analysis at the level of basic designs has gained in concrete understanding of both more radical and gradual technological changes it will in many instances be necessary to further disaggregate the analysis of concrete technological developments. In particular if complex technological systems are studied in relation to the role different suppliers play, it might be compulsory to analyze the development of so-called key-elements. These key-elements are essential components of a technological system. In this study the system of process control is examined from bottom-up, from sensors to controllers, programmable controllers, process control systems to production control systems, including both hard- and software.

To understand the direction of technological development in basic designs or key-elements, to discover the heuristics and routes of problem solving, it will be necessary to identify a set of characteristics and the gradual improvements along these characteristics. In such a procedure one can select generations of a key-element in order to operationalize the concept of technological trajectories. For each key-element generations are related to older, average practice and best practice technology, as well as to the technological frontier. The complete exercise provides a detailed and overall view of technological development in a complex system. Through the disaggregation of a basic design and the operationalization of technological trajectories it becomes feasible to measure the technological performance of companies at the level of technological sophistication of their supply of components and/or systems. In other words, it is possible to analyze the position of companies vis à vis the range of key-elements in a basic design and the technological trajectories thereof.

In this study it has been stressed several times that technological development is not only a matter of forward moving frontiers of best practice technologies, but also the interaction of best practice technologies with diffusion which give technological development its full economic impact. In the process of diffusion technology affects a wider group of users and suppliers going beyond the effects on the original innovator/adopter. In the relationship between technology and diffusion the dynamic and evolutionary character of both economic and technological development becomes most clear. In the traditional theories of diffusion its pattern is usually depicted as an S-shaped curve. Some criticism has been concentrated on doubts regarding the regularity of the S-curve with different slopes and different points of inflection in concrete patterns of diffusion. More fundamental criticism stems from the lack of dynamics in traditional theories of diffusion. In traditional theory dynamics is only reflected in the gradual growth of the number of adopters of which the maximum of potential adopters is given. In a more dynamic and evolutionary approach two important features are stressed:

- there is a change in the number of potential adopters during the process of diffusion, while there is not a given limit to the potential number of adopters;
- the technology itself changes during the process of diffusion.

Changes in technology can, in retrospect, be related to technological trajectories in terms of the previously mentioned generations. The analysis of the rate of diffusion measured as diffusion of generations provides knowledge about trends in diffusion admitting for dynamic changes within the process of diffusion.
In most studies diffusion is measured at either the intra-firm, intra-sectoral, or inter-sectoral level. The output with a particular technology or the number of companies applying a technology is usually taken to measure the rate of diffusion. In this study the average intra-sectoral rate of diffusion has been applied with a differentiation for several categories of companies. One of the results of this approach is detailed information on the diffusion of information technology, the principal determinant of technological trajectories in process control, at key-element level for the complete system of process and production control.

As the technological frontier is operationalized as the direction of applied research for the near-future generations it is also possible to assess participation of companies at the technological frontier.

Technological change and its selection environment

It has to be stressed that technological development is neither an autonomous nor a deterministic process. There is a dialectical relationship between technological development and its selection environment in which there is mutual influence. For some technologies the selection environment is dominated by other social relations than just companies as e.g. state agencies and capital-labour relations constitute the selection environment. For many technologies the selection environment is formed by companies and consumers within a state regulated context. In capital goods producing sectors, such as the p.c.e. industry, the selection environment consists mainly of producers on the supply and procuring companies on the demand side. However, state regulation, e.g. in setting standards for pollution control, has an effect on the number of control variables and the complexity of control systems. Another useful analytical distinction to be made refers to the ex ante and ex post selection environment which do, however, interact. Ex post selection mechanisms influence economic, and eventually also technological, results and opportunities of companies. Competition between suppliers acts as a selection mechanism, but demand is probably just as important as it sets the limits to growth for a sector. Demand by a differentiated set of buyers can articulate particular technological and economic specifications. In process control there has been a growth of the sector and many of its companies with the increase in investment in control in process industries in the first decades following the second world war. Since the seventies excess capacity in many user-industries has caused a stagnation in the volume of demand for p.c.e. However, the qualitative change in demand for more sophisticated equipment together with a stagnation of aggregate demand has induced strong competition, in particular for more advanced systems and stand-alone equipment.

The ex ante selection environment is determined by the behaviour of companies in their strategies, routines and search procedures for innovation. Behaviour of companies differ because there is an asymmetry in the configuration of companies. This asymmetry was already expressed in the theories by Marx and Schumpeter. Marx built his theory on the uneven development of companies in the process of centralization and concentration which caused and disequilibrium effects in the economic structure. Both Marx and Schumpeter saw the innovation generating process as a powerful mechanism for growth of individual companies which were able to capture incidental extra-profits. They both paid attention to the role of small companies as innovators, although not to the same extent. Schumpeter stressed the role of the entrepreneur as the personification of innovation in so-called pre-trustified capitalism. Marx saw the importance of new companies as innovative, example setting, front runners. There is evidence that Marx and Schumpeter neglected a more subtle differentiation of companies and over-emphasized the dominance of large companies in modern capitalism. Nevertheless, the dynamic elements in their theories are valuable to the understanding of present day capitalism. This holds in particular for Schumpeter's understanding of market power and monopoly as short-run monopoly based on innovation which, due the creative destruction and competition, is far from a structural monopoly.

Some traits of static elements in Marx's and Schumpeter's theories have been accentuated in neo-Marxist theories of monopoly capitalism and Schumpeter-inspired theories such as in Galbraith. There are differences between such heterodox theories of capitalism but grosso modo they picture technological development as being dominated by very large companies. As such there is hardly any role for other categories of companies while the effects of creative destruction are neglected. Contrary to Marx's and Schumpeter's original contribution, monopoly has become size-dependent in many neo-Marxist and Schumpeter inspired theories. In some other neo-Schumpeterian theories the importance of small and new companies as innovators is stressed as in Schumpeter's earlier contributions.

The debate so far has led to a series of hypotheses and explanations of the relationship between size and innovation. An interesting perspective for empirical research is found in the introduction of technological opportunity as an intervening factor explaining inter-sectoral differences. Another way-out of the existing stale-mate is to pay more attention to a differentiation into categories of companies and innovation strategies. In this study I arrived at a categorization of companies such as small and medium sized companies, new companies, subcontractors, large companies and very large multidivisional companies. Also cross-entries can be an important category of firms to understanding changes in the industry structure and technological performance.
In the international p.c.e. industry some categories of companies do not or have ceased to play a relevant role in the industry as innovator. The role subcontractors can be ignored and new companies, often discussed in the debate on innovation, probably played only a germane role with the emergence of the new paradigm in process control three decades ago.
In the analysis of the innovative performance of companies in the p.c.e. industry different categories of companies in terms of size, measured in numbers of employees, were derived from the actual distribution in the international industry. The analysis of size as a relative instead of an absolute category is an important feature of this study. It seems almost trivial to point at the differences in relevant size-categories for different industries and international markets: e.g. the size of a large company in the Dutch furniture industry is almost negligible compared to the size of a medium-sized company in the international chemical industry. Nevertheless, many studies and statements about the relationship between size and innovation neglect the inter-sectoral, international and technological context of this issue.

Indicators of innovative performance

Some of the confusion in the innovation debate is caused by the choice of indicators which can have a strong effect on the assessment of innovative performance of companies. In many economic studies of technological development the subject is studied with some poor indicators of innovation. No attention is paid to technological development itself, which, as a consequence, usually remains a 'black box'. In this study both innovation input indicators such as R&D intensity and the distribution of research categories and output indicators such as the share of new products in company turnover and the diffusion of best practice technologies have been applied. Innovation input is to a large degree determined by commitments in the ex ante selection by companies. Innovation outputs results from both ex ante and ex post selection mechanisms, i.e. the supply of new products and best practice technology will result from deliberate company strategies but the distribution of the outcome of turnover and diffusion is also determined by competition and demand.

The results for different indicators do not generate a clear pattern for size and innovation. Some of the results give some support to the literature in which a U-form distribution is proclaimed. Small companies are most R&D intensive but the degree of variation indicates that there are both 'normal' and 'high tech' small companies. The variation between and within results for different indicators supports the idea that the group of small companies is quite diverse in its innovative performance. On the other end of the spectrum the group of very large companies is most innovative in particular in terms of new products. Medium sized and large companies take an intermediate position. In other words, from the results of this international sector study there is little reason to support theories in which small companies are seen as the major innovative agents in capitalism, in particular because they lag in the diffusion of best practice technologies. But there is also little evidence that innovation and technological development in de p.c.e. industry is totally dominated by 'monopoly capital' or a small number of very large companies. As mentioned in chapter 5 the importance of both small and very large companies, which appear most innovative in this industry, can be explained by the technological revival into an electronics related sector in which both very large diversified companies and a group of small R&D intensive companies are important innovators.

If it is accepted that industries are 'structured' by perturbation, then disorder is generated by different innovation strategies of several categories of companies. There are a number of strategies of which three, notably offensive, defensive and imitative, can in principle be followed by all companies in this particular industry. This might seem to contradict the assumed asymmetry of companies because it cannot be expected that a small company can behave as if it were a very large diversified multinational company covering a large number of markets. Larger companies can follow different strategies for their diversified interests. Small companies are by definition restricted to a small number of (sub-)markets and strategies. However, in one sector it is feasible to relate all companies to their innovative strategy in that particular sector. For large companies it is possible to deduce the main topics in their strategies from publicly available information and interviews with management. In the p.c.e. industry, for instance, it is relatively simple to picture innovation strategies of the leading companies at the technological (or scientific) frontier of applications and development of information technology. For the analysis of the industry as a whole one has to rely on several indicators of innovation in a multivariate analysis. The complexity of the relationship between innovation and size of companies is reflected in the impossibility to relate particular innovation strategies exclusively to classes of size of companies.

So, even for an industry for which the technological opportunity for companies is grosso modo identical, it is difficult to arrive at some generalizations. Given the state-of-the-art in the analysis of technological and industrial development it will, however, not be necessary to find straightforward and unambiguous relations. In my opinion at least a part of the present research agenda should be directed towards developing analytical tools and more in-depth understanding of phenomena associated with economic and technological development. This field of research is well suited for multi- and interdisciplinary research with contributions from social sciences and e.g. engineering. Taken the complexity of disciplines one cannot expect an interdisciplinary and holistic approach with an integrated body of knowledge. But even a moderate attempt to generate knowledge applicable in a more multi-disciplinary approach to the understanding of technological development will have to go beyond accepted routines. It is in this perspective that in this study an attempt has been made to make a modest contribution to be field of technology and economics.

Consequences for innovation policies

Technological development follows a diffuse pattern with many differences as far as industry structures, size of companies, international comparisons, and company behaviour are concerned.
There is little reason to suspect that general theories and laws will bring about new insights within the near future. But while it does not necessarily lead to a pessimistic view of the practical relevance of economic theory and research, it does lead to a modest and middle-range theory oriented approach. If there is no general pattern of technological development then most attention should be paid to analyzing inter-sectoral patterns, differences in company behaviour and differences in technological opportunities. Such a differentiated approach will not render general policy options and measures. Innovation policy can not consist of mainly general policy instruments which have a positive effect on the innovative potential of all companies. There is no panacea, or to quote an American commercial for a fitness centre: "If it came in a bottle, everybody would have it". In other words, stimulating innovation can never be successful by just providing financial support to all companies which claim to perform some innovative activity. Some companies will never be capable of becoming innovative while for many others innovative performance will not depend on financial support. In some countries the opportunities for companies in certain sectors will remain dim for many decades to come. For national states it will only be possible to develop innovation and innovative policies if particular circumstances in a large number of industries is taken into account. In a large number of sectors it will be necessary to investigate the composition of a sector in terms of the national or international character of

the companies, the international trends against which national sector developments will have to be judged, the technological opportunities, the distribution of companies according to relevant categories and the major national and international strategies of leading companies. The character of technological development has to be assessed because it is not only innovation but also diffusion of relevant technologies which is important to understanding the opportunities of a particular industry. In such a differentiated approach policy instruments are derived from the analysis of technological opportunities in a number of industries. Such analyses could benefit from some of the tools developed in this study. Improving technological performance of companies in some industries will rely heavily on the diffusion of modern technologies, for others the costs of R&D or the improvement of the technological infrastructure will be more relevant.

The complexity of modern technology with the interaction of different technological paradigms, the asymmetry of companies and international perspectives, and rapid changes in technological opportunities, can only be an object of useful state intervention and public debate, if the pattern of its development is revealed in extenso.

APPENDIX 1

THE SURVEY OF THE P.C.E. INDUSTRY

The p.c.e industry is not directly related to a class or sub-class of a census of production or a standard trade classification due to the fact that this sector is gradually evolving from both the instruments and electronics industry. In order to study the industry it was necessary to go beyond official statistical material and perform a survey research amongst p.c.e. manufacturers. Also the present conceptual framework for understanding technological developments in terms of basic designs, key-elements, and trajectories, made it necessary to construct appropriate empirical data through survey research.

A provisional list of possible p.c.e. manufacturers was established by compiling information of all companies known through different sources of information such as: expert interviews, manuals and trade directories. The following criteria were introduced to define the survey-population:

- in order to be able to communicate with companies on a large number of subjects within a reasonable time-horizon it was necessary to select only those which have established a place of business in the Netherlands;
- several business units or subsidiaries of one company were taken together as one entry, in other words: in the survey the company is the accounting unit, which may encompass more than one firm;
- since the population should exist of manufacturing companies, companies which serve solely as dealers were neglected; manufacturing, however, may take place in the Netherlands and/or in any other country;
- a minimum annual turnover for p.c.e. of about US$ 400.000 in 1985 was set because the issues to be discussed in the survey dealt with several technological and business aspects of p.c.e. which made a minimum size compulsory.

These four criteria led to a reduction of the list of possible p.c.e. manufacturers to 81 companies. Unfortunately, only 56 companies agreed to participate in our survey research. In that sense this research is effected by the present upheaval in empirical research on innovation-related subjects to which many companies refer as 'survey- or interview mania'.

It is important to note that the population of p.c.e. manufacturers in this study is not a sample as such. Given the limitations mentioned in the four criteria above and given the response of the group of manufacturers this population presents a fair reflection of the international industry structure. It is assumed that the international industry structure is well represented in this survey because:

- 80% of the leading companies mentioned in table 5.1 participated in the survey;
- the market for p.c.e. companies operating in the Netherlands is extremely open, most process industries in the Netherlands are internationally oriented, e.g. most of the leading chemical companies and engineering contractors are found in the Netherlands.

Unless otherwise indicated the information from the survey refers to 1985.

The interviews and first information processing during the survey were carried out by SKIM MC.MA, Rotterdam.

APPENDIX 2

Distribution of value of production of generations of sensors in % and coefficients of variation for 1985 and (1980), and number and % of companies with research at the technological frontier of sensors, N = 35.

	Total	Overall size ≤ 500	500-5000	5000-50000	50000+
Pneumatic:					
average %	16 (24)	17 (23)	17 (25)	12 (20)	21 (32)
cv	1.6 (1.4)	1.7 (1.7)	1.5 (1.4)	1.3 (1.4)	1.9 (1.4)
Electronic:					
average %	78 (75)	83 (77)	79 (74)	80 (80)	70 (66)
cv	0.3 (0.4)	0.3 (0.5)	0.3 (0.5)	0.3 (0.3)	0.5 (0.7)
Smart sensors:					
average %	6 (1)	- (-)	4 (1)	8 (-)	9 (2)
cv	1.7 (3.0)	- (-)	2.3 (3.0)	1.5 (-)	1.3 (2.0)
Total %	100 (100)	100 (100)	100 (100)	100 (100)	100 (100)
Companies with research at technological frontier	29 83%	- -	11 79%	11 100%	7 100%
no research	6 17%	3 100%	3 21%	- -	- -
Total	35 100%	3 100%	14 100%	11 100%	7 100%

APPENDIX 3

Distribution of value of production of generations of hardwired (logic) controllers in % and coefficients of variation for 1985 and (1980), and number and % of companies with research at the technological frontier, N = 37.

	Total	Overall size			
		< 500	500-5000	5000-50000	50000+
Pneumatic:					
average %	10 (15)	4 (10)	5 (11)	14 (19)	17 (20)
cv	2.1 (1.8)	2.8 (2.6)	2.2 (1.6)	1.3 (1.1)	2.4 (2.2)
Electronic:					
average %	68 (65)	74 (65)	39 (52)	80 (70)	79 (78)
cv	0.5 (0.6)	0.5 (0.7)	0.9 (0.6)	0.3 (0.5)	0.5 (0.6)
Smart sensors:					
average %	22 (20)	22 (25)	56 (37)	6 (11)	4 (2)
cv	1.4 (1.8)	1.6 (1.7)	0.6 (1.0)	1.5 (2.7)	2.0 (1.5)
Total %	100 (100)	100 (100)	100 (100)	100 (100)	100 (100)
Companies with research at technological frontier	25 68%	2 29%	9 82%	9 82%	5 63%
no research	12 32%	5 71%	2 18%	2 18%	3 38%
Total	37 100%	7 100%	11 100%	11 100%	8 100%

APPENDIX 4

Distribution of value of production of generations of PLC's in % and coefficients of variation for 1985 and (1980), and number and % of companies with research at the technological frontier, N = 19.

	Total	Overall size ≤ 500	500–5000	5000–50000	50000+
Upto 100 programm steps, no data processing:					
average %	21 (27)	10 (25)	- (-)	45 (50)	18 (20)
cv	1.8 (1.6)	1.4 (1.4)	- (-)	1.2 (1.1)	2.2 (2.2)
Upto 1000 programm steps, restricted data processing:					
average %	41 (27)	55 (12)	97 (95)	10 (7)	29 (22)
cv	0.9 (1.4)	0.1 (1.4)	0.1 (0.1)	1.2 (2.1)	1.1 (1.5)
Over 1000 programm steps and data processing:					
average %	38 (46)	35 (63)	3 (5)	45 (43)	53 (58)
cv	1.0 (1.0)	0.6 (0.8)	2.0 (1.4)	1.2 (1.2)	0.8 (0.8)
Total %	100 (100)	100 (100)	100 (100)	100 (100)	100 (100)
Companies with research at technological frontier	15 79%	2 50%	2 67%	5 83%	6 100%
no research	4 21%	2 50%	1 33%	1 17%	- -
Total	19 100%	4 100%	3 100%	6 100%	6 100%

APPENDIX 5

Distribution of value of production of process control systems in % and coefficients of variation for 1985 and (1980), and number and % of companies with research at the technological frontier, N = 40.

	Total	Overall size			
		≤ 500	500- 5000	5000- 50000	50000+
Centralized:					
average %	18 (22)	43 (29)	19 (23)	9 (29)	6 (7)
cv	1.5 (1.5)	1.6 (1.6)	1.4 (1.3)	1.4 (1.4)	1.3 (1.6)
Distributed, analogous:					
average %	29 (34)	26 (37)	29 (36)	31 (36)	28 (28)
cv	0.9 (1.1)	1.2 (0.9)	1.0 (0.9)	0.7 (0.9)	1.1 (1.1)
Smart sensors:					
average %	53 (44)	31 (34)	52 (41)	60 (35)	66 (65)
cv	0.6 (0.9)	0.8 (1.0)	0.8 (1.0)	0.4 (0.9)	0.5 (0.6)
Total %	100 (100)	100 (100)	100 (100)	100 (100)	100 (100)
Companies with research at technological frontier	34 85%	6 86%	11 85%	10 83%	7 88%
no research	6 15%	1 14%	2 15%	2 18%	1 13%
Total	40 100%	7 100%	13 100%	12 100%	8 100%

APPENDIX 6

INDICATORS OF BEST PRACTICE TECHNOLOGY SUPPLIED BY P.C.E. MANUFACTURERS IN 1985.

SENSORS	HWC	PLC	PCS	PCMIS	NUMB	BESTPRAC
20.00	0.0	0.0	90.00	0.0	4	27.50
0.0	0.0	0.0	0.0	14.29	4	3.57
0.0	0.0	0.0	0.0	0.0	3	0.0
0.0	0.0	0.0	40.00	57.14	2	48.57
0.0	0.0	0.0	0.0	14.29	2	7.14
0.0	0.0	0.0	35.00	0.0	4	8.75
0.0	45.00	0.0	30.00	57.14	4	33.04
0.0	75.00	0.0	0.0	14.29	4	22.32
10.00	0.0	0.0	0.0	0.0	1	10.00
0.0	0.0	0.0	0.0	28.57	3	9.52
0.0	50.00	0.0	100.00	0.0	3	50.00
0.0	0.0	0.0	0.0	14.29	1	14.29
0.0	0.0	0.0	0.0	0.0	2	0.0
0.0	20.00	0.0	20.00	0.0	3	13.33
0.0	0.0	0.0	0.0	0.0	1	0.0
0.0	0.0	0.0	70.00	0.0	1	70.00
10.00	20.00	0.0	70.00	0.0	4	25.00
0.0	0.0	0.0	0.0	0.0	1	0.0
0.0	0.0	0.0	0.0	0.0	0	0.0
0.0	0.0	100.00	0.0	0.0	2	50.00
0.0	10.00	0.0	80.00	85.71	4	43.93
0.0	0.0	0.0	100.00	100.00	2	100.00
0.0	100.00	0.0	20.00	14.29	4	33.57
0.0	0.0	0.0	100.00	14.29	3	38.10
0.0	100.00	0.0	0.0	0.0	1	100.00
0.0	0.0	0.0	0.0	0.0	2	0.0
30.00	0.0	85.00	40.00	14.29	5	33.86
5.00	0.0	0.0	50.00	0.0	3	18.33
10.00	0.0	0.0	25.00	85.71	5	24.14
0.0	0.0	0.0	0.0	0.0	3	0.0
0.0	0.0	0.0	50.00	0.0	2	25.00
0.0	20.00	0.0	0.0	0.0	3	6.67
0.0	0.0	0.0	0.0	0.0	2	0.0
0.0	0.0	0.0	10.00	28.57	4	9.64
0.0	0.0	0.0	100.00	42.86	5	28.57
0.0	0.0	0.0	60.00	14.29	3	24.76
0.0	0.0	0.0	15.00	14.29	3	9.76
0.0	0.0	0.0	0.0	0.0	0	0.0
0.0	70.00	10.00	90.00	100.00	5	54.00
0.0	0.0	40.00	75.00	42.86	5	31.57
15.00	0.0	0.0	34.00	28.57	4	19.39
0.0	0.0	0.0	70.00	85.71	3	51.90
0.0	0.0	0.0	60.00	28.57	4	22.14
10.00	5.00	95.00	100.00	14.29	5	44.86
0.0	0.0	0.0	0.0	28.57	1	28.57
0.0	20.00	0.0	100.00	57.14	4	44.29
0.0	50.00	20.00	25.00	57.14	4	38.04
20.00	0.0	15.00	100.00	14.29	5	29.86
0.0	0.0	0.0	0.0	0.0	0	0.0
0.0	0.0	50.00	50.00	14.29	3	38.10
0.0	0.0	0.0	0.0	0.0	0	0.0
0.0	0.0	0.0	0.0	85.71	3	28.57
40.00	0.0	80.00	30.00	57.14	5	41.43
30.00	90.00	0.0	60.00	28.57	4	52.14
0.0	20.00	80.00	5.00	42.86	5	29.57
0.0	0.0	0.0	0.0	0.0	0	0.0

*) As all production control/management information systems are best practice, this measure for best practice has been modified. In the questionaire companies producing this key-element were asked how many of a total of seven functions were integrated in their system. Best practice technology has been measured by the 'scores' of functions from a total of 100%.

APPENDIX 7

SCORES ON INDICATORS OF INNOVATION AND INNOVATION STRATEGIES FOR P.C.E. COMPANIES

RDINT	RDINTPCE	NEW PROD	REAL NP	BESTPRAC	INSTRAT1	INSTRAT2	INSTRAT3
.06	.06	5	3	27.50	.14186	2	2
.10	.05	2	2	3.57	-1.45075	1	1
.03	.05	3	2	0.0	-1.26966	1	1
.42	.25	6	5	48.57	1.97480	3	3
.50	.75	5	5	7.14	1.08562	3	3
.01	.07	4	4	8.75	-.21345	2	2
.05	.05	5	2	33.04	-.13099	2	2
.11	.40	4	5	22.32	.27492	2	2
.06	.06	4	4	10.00	-.10379	2	2
.07	.27	6	4	9.52	.55222	3	2
.00	1.00	4	1	50.00	-1.19427	1	1
0.0	0.0	6	6	14.29	1.21491	3	3
0.0	1.00	3	2	0.0	-1.78690	1	1
.01	.02	3	2	13.33	-1.13443	1	1
.00	.04	4	2	0.0	-.93795	1	1
.02	.20	4	1	70.00	-.56223	1	1
.02	.63	5	4	25.00	.06672	2	2
.02	.25	6	4	0.0	.34472	2	2
.03	.04	2	2	0.0	-1.62938	1	1
.03	.03	6	3	50.00	.69909	3	2
.01	.07	6	1	43.93	-.04737	2	2
.10	.05	6	3	100.00	1.36277	3	3
.10	.08	6	4	33.57	.95674	3	2
.01	.04	6	4	38.10	.83924	3	2
.08	.10	5	3	100.00	.91963	3	2
.36	.20	6	4	0.0	1.06395	3	3
.01	.05	5	5	33.86	.73683	3	2
.06	.10	4	1	18.33	-.97369	1	1
.02	1.00	3	4	24.14	-.86995	1	1
.03	.05	6	6	0.0	1.08820	3	3
.01	.07	2	2	25.00	-1.40552	1	1
.13	1.00	6	1	6.67	-.65694	1	1
.13	.11	2	2	0.0	-1.45232	1	1
.57	.57	6	4	9.64	1.39827	3	3
.05	.05	5	4	28.57	.45002	2	2
.14	.08	6	1	24.76	-.00074	2	2
.17	.30	5	3	9.76	.04409	2	2
.01	.15	4	3	0.0	-.67349	1	1
0.0	0.0	6	6	54.00	1.63741	3	3
.14	.50	6	4	31.57	.81183	3	2
.16	.17	3	5	19.39	.07991	2	2
.12	.20	6	4	51.90	1.12545	3	3
.03	.03	6	3	22.14	.40972	2	2
.04	.19	6	2	44.86	.27586	2	2
.03	.03	3	3	28.57	-.64045	1	1
.06	.04	6	4	44.29	1.00938	3	3
.09	.03	6	4	38.04	1.00659	3	3
.08	1.00	6	4	29.86	.41611	2	2
.04	1.00	1	1	0.0	-2.74856	1	1
.13	.08	3	2	38.10	-.67723	1	1
.02	.13	6	5	0.0	.72838	3	2
.15	.80	4	3	28.57	-.40372	2	2
.02	.05	6	2	41.43	.27242	2	2
.07	.07	4	2	52.14	-.27136	2	2
0.0	0.0	4	1	29.57	-.92461	1	1
.11	1.00	5	2	0.0	-.82791	1	1

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NEDERLANDSE SAMENVATTING

In deze studie wordt een bijdrage geleverd aan zowel een aantal nieuwe ontwikkelingen in de theorie rond innovatie en industriële ontwikkeling als de concretisering en uitwerking van dergelijke theorievorming in empirisch onderzoek. Wat betreft de eerst genoemde doelstelling wordt aansluiting gezocht bij de recente discussie rond de verdere ontwikkeling van een aantal heterodoxe bijdragen, met name in het deelgebied van innovatie theorie en 'industrial economics'. Theoretische bijdragen die in dat kader in de belangstelling staan zijn te vinden in het werk van onder andere Nelson en Winter, Freeman en Rosenberg. De uitwerking van een theoretisch kader is gebaseerd op heterodoxe theorievorming gedeeltelijk gebaseerd op het werk van 'klassieke' auteurs zoals Marx en Schumpeter, maar ook op het werk vanuit neo-Schumpeteriaanse en neo-Marxistische optiek en onderzoek van een meer multidisciplinair karakter zoals dat gestalte krijgt in bijdragen aan het onderzoek rond de aard en effectiviteit van technologie-meting. In algemene zin kan gesteld worden dat in deze studie een kritische beschouwing van een aantal varianten van evolutionaire theorievorming rond technologie en industriële verandering centraal staat. Daarbij gaat het niet alleen om de theorievorming rond de veranderingen in de industriële structuur onder invloed van technologische ontwikkeling en vice-versa maar er wordt tevens uitvoerig aandacht besteed aan het karakter van technologische verandering zelf waarbij diffusie en innovatie als een organisch geheel worden gezien.

In het empirisch onderzoek dat in dit kader wordt uitgevoerd staan de technologische ontwikkelingen en veranderingen in de industriële structuur in de internationale proces controle sector centraal. Het onderzoek betreft niet zozeer een geïsoleerde sector studie maar veeleer de relatie tussen verschillende velden van technologische ontwikkeling zoals procestechnologieën en informatietechnologie en veranderingen in de industriële structuur in bredere zin. Bovendien stelt dit onderzoek ons in staat aandacht te besteden aan een sector die 'verborgen' is in de officiële economische statistiek.

Zowel Marx als Schumpeter kunnen gezien worden als grondleggers van een aantal theoretische aanzetten voor evolutionaire theorievorming rond technologie en economische verandering. Een belangrijk aspect in het werk van Marx is zijn grote inhoudelijke aandacht voor het effect van technologische ontwikkeling op de maatschappij in het algemeen en veranderingen in de economische structuur in het bijzonder. Deze aandacht kreeg vooral vorm in Marx's analyse van de gevolgen van het proces van mechanisatie in de eerste helft van de 19de eeuw waarmee een eenzijdige en logisch onhoudbare economische krisistheorie werd gefundeerd hetgeen echter onverlet laat dat Marx een ongeëvenaarde diepgang in zijn analyse van de effecten van technologische ontwikkelingen introduceerde. Verspreid door het werk van Marx treft men tevens een grote aandacht voor een differentiatie van ondernemingsvormen en categorieën ondernemingen aan. In de uitwerking van een analytisch kader voor empirisch onderzoek in deze studie is gebruik gemaakt van een vergelijkbare categorisatie van ondernemingen. In de analyse van Marx zelf is echter meer aandacht besteed aan de rol van concentratie en centralisatie bij de vorming van grote ondernemingen die een dominante rol in het economisch proces zouden gaan innemen.

Schumpeter besteedde duidelijk minder aandacht aan de analyse van technologische ontwikkelingen dan Marx. In Schumpeter's economische theorie is innovatie eerst weliswaar een gedeeltelijk endogene factor terwijl technologie in het algemeen toch vooral exogeen blijft. In het latere werk wordt technologie meer endogeen waarbij met name de rol van zogenaamde 'science based' ondernemingen worden benadrukt.

Voor zowel Marx als Schumpeter heeft technologische ontwikkeling een evenwichtsverstorend effect op het proces van economische ontwikkeling.

In beide bijdragen wordt, in tegenstelling tot hetgeen in de literatuur veelal wordt gesteld, het behalen van een technologische voorsprong door innovatieve ondernemingen niet gekoppeld aan lange termijn monopoliewinsten maar eerder aan korte termijn monopolieposities. Monopolie voortkomend uit de succesvolle introductie van nieuwe produkten en produktieprocessen heeft in de regel geen structureel karakter, het is eerder gebaseerd op tijdelijke marktmacht en niet ten principale afhankelijk van de grootte van ondernemingen.

In deze studie wordt veel aandacht besteed aan een noodzakelijk geachte differentiatie van ondernemingen naar grootte en functie. Bij Schumpeter vindt men een basis voor een verdere differentiatie in grote, veelal 'science based', ondernemingen, kleinere ondernemingen waarin de entrepreneur een centrale plaats inneemt en, vooral in zijn latere werk, kleine en middelgrote ondernemingen in een toeleveringsfunctie of opererend in specifieke markt-niches. Onder invloed van het verschijnsel van creatieve destructie waarbij nieuwe sectoren en ondernemingen gaan ontstaan worden zowel nieuw opgerichte ondernemingen als 'cross entry' categorieën die bij een analyse van structuurveranderingen kunnen worden opgenomen in een analytisch kader. In het werk van Marx vindt men tal van verwijzingen naar het belang van centralisatie en concentratie voor het ontstaan van grote ondernemingen terwijl ook het belang van kleinere innovatieve ondernemingen wordt benadrukt. In tegenstelling tot de 'jonge' Schumpeter heeft Marx weinig aandacht voor de entrepreneur als personificatie van innovatie, hetgeen gezien de aard van de ontwikkelingen van moderne technologie terecht is. Het is van belang te benadrukken dat wat betreft de analyse van de rol van grote ondernemingen in de veranderingen van marktstructuren er een grote mate van overeenstemming is tussen het werk van Marx en de latere bijdragen van Schumpeter.

Voortbouwend op het werk van Marx en vooral Schumpeter zijn er de afgelopen decennia tal van bijdragen geleverd aan de theorievorming rond technologische ontwikkeling en aspecten van economische structuurveranderingen, zoals de rol van ondernemingen van verschillende grootte en industriële concentratie.
In neo-Marxistische bijdragen kan men grofweg twee varianten binnen deze theorie onderscheiden. In een variant wordt de lijn van Marx inzake centralisatie en concentratie verder doorgetrokken naar een monopolietheorie waarin het kapitalistische economische

stelsel wordt gedomineerd door zeer grote monopolie-ondernemingen, hetgeen resulteert in een eenvoudige dichotome economische structuur met enerzijds monopolie-ondernemingen en anderzijds een groep van kleine ondernemingen. In een andere variant van de radicale politieke economie wordt veeleer aansluiting gezocht bij de klassieke economische theorie waarin monopolie, zeker in het licht van innovatie, wordt gezien als onafhankelijk van ondernemingsgrootte en eerder verbonden met het behalen van tijdelijke extra-winsten als gevolg van het behalen van een technologische voorsprong.

In deze studie wordt de radicale theorie van het monopolie-kapitalisme zoals onder andere ontwikkeld door Sweezy bekritiseerd. Kenmerkend voor deze neo-Marxistische theorie van het monopolie-kapitalisme is, naast het reeds gememoreerde eenvoudige twee sectoren model met een monopolistische en een niet-monopolistische sector, dat het kapitalisme wordt geanalyseerd als een statisch systeem. Technologische ontwikkeling wordt niet geanalyseerd als een dynamische factor waarbij creatieve destructie tot veranderingen van industriële structuren zal leiden. Concurrentie wordt, ten onrechte, gezien als een centraal element van vroegere fasen van het kapitalisme, Een bijkomend, maar niet onbelangrijk bezwaar, is dat de operationalisatie van het begrip monopolie-kapitaal in meer concrete analyses of aanzetten daartoe nogal slordig wordt gehanteerd.

In sommige neo-Schumpeteriaanse bijdragen zien we een vergelijkbare statische variant van de theorie. Met name bij Galbraith wordt zowel de technologische als de economische ontwikkeling gedomineerd door zeer grote ondernemingen binnen een statische structuur waarin andere groepen ondernemingen en de opkomst van nieuwe sectoren weinig relevantie hebben. Een belangrijke consequentie van dergelijke theorievorming is dat zeer grote ondernemingen en een hoge graad van industriële concentratie geacht worden bevorderlijk te zijn voor de stimulering van technologische ontwikkeling.

In kritiek op dergelijke benaderingen, en gedeeltelijk aansluitend bij het vroegere werk van Schumpeter, wordt in andere theoretische bijdragen meer aandacht gegeven aan de dynamische rol die met name kleine en of nieuwe ondernemingen in het innovatie-proces spelen.

Een midden positie wordt gekozen in theorie-varianten waarin een gunstig effect op innovatieve ontwikkelingen wordt geschetst in een industriële structuur met een juiste 'mix' van kleinere en grote ondernemingen of bijdragen waarin het verband tussen innovatie en industriële concentratie of grootte van ondernemingen in een zogenaamde omgekeerde U-relatie wordt verondersteld. Vanuit theoretisch oogpunt lijken echter varianten waarin aandacht wordt besteed aan het effect van dynamische veranderingen, sectorale verschillen en inter-sectorale effecten van technologische ontwikkelingen te prefereren.
Het empirisch onderzoek naar de zogenaamde 'Schumpeter controversie' heeft geleid tot een inmiddels zeer omvangrijke verzameling studies waarin weinig echte consensus valt te onderkennen. Wel wordt in een toenemend aantal studies gepleit voor het betrekken van inter-sectorale verschillen in technologische mogelijkheden als een van de verklarende variabelen van verschillen in innovativiteit tussen ondernemingen van verschillende grootte en marktstructuren. Voortbouwend op dergelijke aanzetten wordt in deze studie gepleit voor het verbreden van de speelruimte in het onderzoek naar de relatie van ondernemingsgrootte en technologische ontwikkeling. Belangrijke bouwstenen in deze verbreding van de analyse zijn: de verdere operationalisatie van het begrip technologische mogelijkheid, de onderscheiding van een aantal categorieën van ondernemingen en het introduceren van verschillende innovatie-strategieën.

Technologische ontwikkeling dient in de eerste plaats gezien te worden als een evolutionair proces waarin zich zowel revolutionaire als incrementele veranderingen kunnen voordoen. Voor de analyse van technologische mogelijkheden als medebepalend voor verschillen tussen ondernemingen en sectoren dient dit concept eerst verder te worden geconcretiseerd. Aansluiting kan worden gevonden bij onderzoek uit de technologie dynamica en technologie meting, twee velden van onderzoek die vooral door hun multidisciplinaire benadering worden gekenmerkt. Technologische ontwikkeling kan verder worden geanalyseerd als de ontwikkeling en verandering binnen en van technologische paradigmata, enigszins analoog aan de ontwikkeling van Kuhn's wetenschappelijke paradigmata. In een aantal stappen naar een concreter niveau van analyse verschuift het onderzoek naar de ontwikkeling van 'basic designs', naar sleutel-elementen of belangrijke componenten, om uiteindelijk uit te komen bij de analyse van technologische trajecten. Aanzetten voor een dergelijk analytisch kader vindt men in een aantal bijdragen tot een evolutionaire theorievorming over technologische ontwikkeling. Dergelijke concepten worden echter niet altijd even duidelijk gedefinieerd en vooral toegepast in een algemene schildering van technologische ontwikkelingen.

In dit onderzoek wordt het begrippen-apparaat duidelijker omschreven en in de onderlinge samenhang geplaatst. De concrete toepassing wordt gevonden in de analyse van veranderingen en interdependenties in technologische ontwikkelingen in proces technologieën, informatie technologie en proces controle. Voor de analyse van technologische ontwikkelingen in proces controle is een stap verder gegaan in de bestudering van 'basic designs' in de systeemontwikkeling die samenhangen met wisselingen in technologische paradigmata onder invloed van de introductie van informatie technologie, met name computer technologie. Hierbij kan worden aangetoond dat er na een wisseling van paradigma sprake is van een periode met experimenten waarin geleidelijk een dominant 'basic design' naar voren komt. Vervolgens kan een systeem, zoals dat voor proces controle, worden opgedeeld in sleutel-elementen of belangrijke componenten. Het gehele systeem wordt dan onderverdeeld naar niveau van controle van proces meting tot het top-niveau met management informatie systemen. Voor elk sleutelelement kan tenslotte een analyse van technologische trajecten worden gemaakt in termen van technische verbeteringen in een drietal generaties, te weten: verouderd, 'average practice' en 'best practice' en verder de toekomstige veranderingen aan de technologische grens.
Aangezien het economisch effect van technologische ontwikkeling niet alleen tot uitdrukking komt in de verschuiving van technische grenzen maar juist in de diffusie is het van belang om aandacht te

besteden aan diffusie als een zeer belangrijk aspect van technische verandering. In de standaard analyse van diffusie wordt dit proces veelal geanalyseerd als een statisch verschijnsel waarbij artefact noch populatie van potentiële gebruikers gedurende het diffusie proces veranderen. Hier is diffusie geanalyseerd als een dynamisch proces waarbij met name de technologie zelf gedurende het proces aan verandering onderhevig is. In theorie kan ook in zo'n benadering het diffusie proces als de bekende S-curve worden geprojecteerd alleen wordt deze in een dynamische benadering gegenereerd door de diffusie van opeenvolgende generaties. In deze analyse wordt de diffusie van informatie technologie in de internationale proces controle industrie gemeten per sleutel-element. Voor de industriële structuur wordt een onderscheid gemaakt naar een aantal grootte-klassen. Op deze wijze krijgt men een gedetailleerd beeld van het diffusie proces als een dynamisch veranderingsproces in termen van technologische trajecten, de verschillen van diffusie in onderdelen van het systeem en de positie van een aantal groepen bedrijven. Eén van de conclusies van het betreffende empirische onderzoek is dat vooral de zeer grote ondernemingen het meest geavanceerd zijn bij de diffusie van informatie technologie en de participatie aan de technologische grens van proces controle.

Het empirisch onderzoek leidt vervolgens tot een verdere analyse van innovatie en veranderingen in de structuur van de internationale proces controle apparatuur industrie. Deze sector is in de afgelopen decennia gekenmerkt door een gedeeltelijk creatieve destructie die samenhangt met de wisseling van paradigma in proces controle onder invloed van de introductie van informatie technologie. Deze wisseling van paradigma dateert van rond het begin van de jaren zestig, een periode waarin ook een toetreding tot de markt van grote elektronica bedrijven en ondernemingen op het gebied van informatie technologie valt te constateren. De industrie veranderde in een korte tijd tot een 'science based industry' waarin de achterblijvers tot bepaalde, minder ontwikkelde, marktniches werden veroordeeld. De sector is geleidelijk een, aan de elektronica verwante, industrie geworden hetgeen onder andere tot

uitdrukking komt in de aantallen met informatie technologie verbonden bedrijven die door de leidende ondernemingen zijn overgenomen. De verandering van de industriële structuur heeft vooral het karakter van een 'verjonging' van een 'volwassen' meet- en regelindustrie. In die verjonging blijken zowel kleinere R&D intensieve als zeer grote en gediversificeerde ondernemingen een vooraanstaande rol te spelen.
Voor de vraag naar het verband tussen grootte van ondernemingen en innovatie is gebruik gemaakt van een grootte-indeling die nogal afwijkt van standaard indelingen en die gebaseerd is op de frequentieverdeling in een internationale context. Voor het meten van innovatie is gebruik gemaakt van verschillende indicatoren, die betrekking hebben op zowel de R&D-input, de output in nieuwe produkten, als de toepassing van 'best practice' technologie. Tevens is met behulp van principale componenten analyse een verband gezocht tussen alternatieve innovatiestrategieën en grotteklasse waarbij overigens in deze sector geen significant verband is gevonden. Wel is duidelijk dat vooral een belangrijk deel van de kleinere R&D intensieve ondernemingen en de zeer grote multinationale en multi-divisionele ondernemingen tot de meer innovatieve ondernemingen kunnen worden gerekend.

Al met al levert deze studie een bijdrage aan heterodoxe stromingen binnen het economisch onderzoek naar de gevolgen van technologische ontwikkelingen voor de industriële structuur. Uitgaande van de reconstructie van klassieke theorieën en voortbouwend op een reeks van theoretische bijdragen wordt een experimenteel analytisch kader 'getest' waarmee een 'diepte analyse' van technologische ontwikkelingen en industriële structuurveranderingen mogelijk wordt gemaakt. Centraal in deze benadering staan de asymmetrie van ondernemingen, de dynamische veranderingen in technologie en diffusie processen en de wederzijdse beïnvloeding van technologie en haar omgeving.

Curriculum vitae

De auteur van dit proefschrift is op 4 februari 1950 te 's Gravenhage geboren. Na een Mulo-opleiding is hij tot 1972 werkzaam geweest in diverse beroepen. Van 1968 tot 1972 is met goed gevolg het avondcollege Noctua te 's Gravenhage doorlopen, deze opleiding is afgesloten met het diploma Atheneum. Van 1972 tot 1978 heeft de auteur Economische Sociologie en Politieke Economie gestudeerd aan de Rijksuniversiteit Leiden. Het doctoraal diploma is cum laude behaald.
Vanaf 1978 is de auteur wetenschappelijk (hoofd-)onderzoeker geweest bij het Studiecentrum voor Technologie en Beleid TNO. Sinds 1 juli 1988 is hij werkzaam als projectleider bij het Maastricht Economic Research institute on Innovation and Technology (MERIT) van de Rijksuniversiteit Limburg.

Voor de totstandkoming van dit proefschrift dienen, naast de reeds eerder genoemde instanties, collega's bij het Studiecentrum voor Technologie en Beleid TNO te worden genoemd die met de auteur hebben samengewerkt in een aantal onderzoeksprojecten, die gedeeltelijk hebben bijgedragen tot dit proefschrift. In dat verband moeten met name Paul Kalff, Jaap Korpel en Jos Schakenraad worden genoemd. Speciale woorden van dank gaan uit naar Martina van Amersfoort die de moeilijke taak had om van een aantal slordige manuscripten een nette eindversie te produceren, dat laatste is met veel vakvrouwschap gelukt.