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THE DEVELOPMENT AND DIFFUSION OF INDUSTRIAL ROBOTS

Two Volumes

Volume I

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SUMMARY

This thesis describes the history of robots and explains the reasons for the international differences in robot diffusion, and the differences in the diffusion of various robot applications with reference to the UK. As opposed to most of the literature, diffusion is examined with an integrated and interdisciplinary perspective. Robot technology evolves from the interaction of development, supply and manufacture, adoption, and promotion activities. Emphasis is given to the analysis of adoption, at present the most important limiting factor of robot advancement in the UK.

Technical development is inferred from a comparison of surveys on equipment, and from the topics of ten years of symposia papers. This classification of papers is also used to highlight the international and institutional differences in robot development. Analysis of the growth in robot supply, manufacture, and use is made from statistics compiled. A series of interviews with users and potential users serves to illustrate the factors and implications of the adoption of different robot systems in the UK.

Adoption pioneering takes place when several conditions exist: when the technology is compatible with the firm, when its advantages outweigh its disadvantages, and particularly when a climate exists which encourages the managerial involvement and the labour acceptance. The degree of compatibility (technical, methodological, organisational, and economic) and the consequences (profitability, labour impacts, and managerial effects) of different robot systems (transfer, manipulative, processing, and assembly) are determined by various aspects of manufacturing operations (complexity, automation, integration, labour tasks, and working conditions). The climate for adoption pioneering is basically determined by the performance of firms. The firms' policies on capital investment have as decisive a role in determining the profitability of robots as their total labour costs. The performance of the motor car industry and its machine builders explains, more than any other factor, the present state of robot advancement in the UK.

Industrial robots

Development

Innovation

Diffusion

Ricardo Zermeño-González

Submitted for the degree of Doctor of Philosophy, 1980

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CHAPTER 1

INTRODUCTION

1 - INTRODUCTION

Social attitudes towards science and technology changed dramatically in the 1960's. The naive optimism of finding technological solutions to all our problems which was predominant in the decades after World War II, gave way to an equally radical rejection of technology. This swing of the pendulum also stimulated sound criticism of the simplistic view that technology develops in a deterministic fashion controlled only be internal physical variables and isolated from the social and economic environment. Technology assessment (TA), the study of the impact of new technology on society, was encouraged by this change in social attitudes. The concept of TA basically stemmed from a conviction that society exerts a certain degree of control over technological change, and can therefore direct it.

The Technology Policy Unit (TPU) of the University of Aston in Birmingham, was formed in the mid-1970's to conduct research related to technology assessment and to examine the broader social and economic aspects of technological change. This thesis on robot technology is a natural extension of the TPU's previous work. As the Unit's first major research project stated:

> "No doubt, the present state of development of solid state electronics and of computers will lead to more automation. What is much harder to tell is what form this automation will take, and what social repercussions it will have. In the factory, automation may change in quality and machines which may legitimately be called robots may take over many human tasks. Robots can assemble cars, they can weld, operate warehouses spray paint. Remotely controlled robots may mine coal or operate chemical plants. The problems associated with these possibilities are great and most of them are not technical. Will robots create enough wealth to give employment to the many workers they are bound

> to displace? Can people to be engaged in high technology maintenance and control work be given the necessary education and training and will they achieve the social status they require? Will human production-line workers tolerate sharing work with robots, which make no demands, take no breaks, drink no tea and provide no companionship? (Braun and Macdonald 1978, p 192-193).

In this thesis no attempt is made to give definite answers to such important questions. But to lay the foundations on which a comprehensive assessment could be made, a study of the development and diffusion of robots was clearly necessary. Arnstein (1977, p 575) explains this saying:

> "Since TA's are concerned with the future impact and consequences of emerging technologies, the TA team must make assumptions about when the technology will become available, about alternative strategies for introducing the technology, about the length of time involved before it is widely diffused, and about other technological innovations which may become available and replace it or affect its diffusion..... the team needs to forecast not only the impacts and consequences of the technology on society, but also how a future (hence changed) society might impact on the development and diffusion of the nascent technology."

Robot technology was, particularly at the start of the project, an emerging technology of which little about its technical, economical, and social aspects was known. Hence the overall objectives of the thesis became: (1) to study the history of robot development, invention, innovation, and diffusion in western industrialised nations, and (2) to study the factors and implications affecting the adoption of robots in British manufacturing industry. A closer look at the UK situation intended to identify the impact of various robot systems and to highlight the reasons for the international difference in the level of robot advancement. *

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* This and another PhD thesis on robots in the motor car industry focusing on the Metro project at BL (Scarbrough 1981) are the background to further work recently undertaken at the TPU. The aims of this new research project are: (1) an

assessment of the potential use of robots in different industrial sectors, (2) an analysis of the kinds of robot technology that could most profitably be encouraged for a range of given objectives, and (3) an examination of labour requirements and labour relations where robots are introduced into existing manufacturing processes.

CHAPTER 2

THE NATURE OF RESEARCH INTO TECHNOLOGICAL CHANGE AND ROBOTS

2 - THE NATURE OF RESEARCH INTO TECHNOLOGICAL CHANGE AND ROBOTS

2.1 The Process of Technological Change

The importance of technological change in economic and social development has increased enormously since science was first incorporated into production activities. In economics, technological change has been studied at two different levels (Kennedy and Thirlwall 1972, and Nabseth and Ray 1974). One body of research has been concerned with studying the role of technological change in economic growth; the other body of research has focused on the study of the process of technological change itself. Since Schumpeter (1934) made a sharp distinction between the notion of invention and innovation, technological change has commonly been regarded as consisting of three distinctive phases: (1) invention, the production of a new technically feasible idea or prototype, (2) innovation, the introduction of the invention into the market, and (3) diffusion, the continuous adoption of the innovation by the potential users. Later, economists paid attention to organised science in the form of research and development (R&D) as another important source of technological change (Freeman 1977 p 232). Since then R&D has been regarded as another crucial phase in the creation of technology.

2.2 The Diffusion of Innovations

Technological change has its largest impact on society until the benefits and disadvantages of innovation spread across industry. Studies of diffusion of innovations abound, and have been conducted by professionals of numerous disciplines. Rogers and Shoemaker (1971, p 50) identified sociology,

anthropology, education, communication, marketing, and to a lesser extent, economics, as some of the major research traditions (1084 empirical publications were reviewed). These traditions vary in the kinds of innovation studied, the methods of data gathering and analysis, the unit of analysis, and the types of findings. One of the oldest and most active research traditions has been that of rural sociology (Rogers and Shoemaker reported 480 empirical publications). These have studied the spread of novel agricultural ideas in farms and rural communities, using interviews with individual farmers and statistical analysis as their methodology.

Rogers and Shoemaker (1971, p 72) also classified the diffusion literature into eight different types of research analysis (see figure 2.1). The majority of the empirical generalisations reported, dealt with the determinants of individual innovativeness (type 4). This can be associated with the predominance of disciplines having the individual as the main unit of analysis. On the other hand, one of the less common types of diffusion research identified (type 1) were those treating innovations as the unit of analysis. These studies tested the effect of the attributes of innovations, as perceived by the adopters, upon their rate of adoption ("the relative speed with which an innovation is adopted by members of a social system" p 157). The main innovation attributes considered have been:

1. "Relative advantage ... the degree to which an innovation is perceived as being better than the idea it supersedes..

2. "Compatibility ... the degree to which an innovation is perceived as consistent with the existing values, past experiences, and needs of the receivers..

3. "Complexity ... the degree to which an innovation is perceived as relatively difficult to understand and use..

4. "Trialability ... the degree to which an innovation may be experimented with on a limited basis..

5. "Observability ... the degree to which the results of an innovation are visible to others" (Rogers and Shoemaker 1971, p 138-155).

Other types of diffusion research (type 2) consider different determinants of the rate of adoption: the type of decision involved (optional, collective and authority), the communication channel used to promote the innovation (mass media or interpersonal), the nature of the social system (modern or traditional), the extent of change agents' promotion efforts, and some interactions between these variables (e.g. innovation attributes and communication channel use). Furthermore, these variables may be considered as changing over time. Rogers and Shoemaker (1971, p 161) identified the 'diffusion effect', 'interaction effect', 'bandwagon effect', or the mounting influence upon the decision maker "to adopt or reject an innovation, resulting from the increasing rate of knowledge and adoption or rejection of the innovation in the social system". The growth over time in the number of adopters as a result, resembles a logistic or sigmoid function.

2.3 The Diffusion of New Manufacturing Technology

Work on the diffusion of manufacturing innovation has mainly been undertaken by economists. Mansfield (1961) initiated research in this field when he studied twelve innovations in the coal, steel, brewing and railroad industries (research type 1 in figure 2.1). The relative advantage (profitability), the observability (rate of interaction among adopters), and the investment required to install the innovation were found to be significantly related to their rate of

adoption. Later, Mansfield (1968a and 1968b) studied other innovation and social system variables. He identified the equilibrium or ultimate level of use (the potential use) of a new process as dependent upon its economic advantages over the other inputs it replaces, "and on the sensitivity of the demand of the product it produces to any decline in price or increase in quality induced by the innovation" (Mansfield 1968a, p 119). He then described four main factors governing the speed at which the diffusion of an innovation approaches its potential use:

"1. the extent of the economic advantage of the innovation over older methods or products,

2. the extent of the uncertainty associated with using the innovation when it first appears,

3. the extent of the commitment required to try out the innovation, and

4. the rate of reduction of the initial uncertainty regarding the innovation's performance." (Mansfield 1968a, p 119)

Mansfield built a mathematical model to explain differences in the diffusion of innovations. The rate of diffusion in each of the four industries studied was found to be linearly related to the innovation's profitability and investment requirements relative to the adopting firm (i.e. relative to the internal demands on investment and the firm's total assets). Factors such as the life of the equipment displaced and the growth rate of the industry were not found to be significant. The effect of industrial concentration was not clear.

The characteristics of firms pioneering adoption were also studied by Mansfield (1968a and 1968b). The firm's size and the profitability of its investment seemed to be positively related to the speed with which it begins using an innovation. However, no evidence was found of a connection between a firm's

speed of adoption and its growth rate, profit level, liquidity, profit trends, or the age of its management.

Mansfield (1968a, p 122) was well aware of the simplicity and limitation of his model. More recently he and other scholars have complemented his early empirical work on diffusion (Mansfield et al 1977). The mathematical model has been, and is being, extended to include the level of R&D expenditure, market structure and scale of an industry; the length of time that the innovation has been in use in another industry; and the dispersion of the profitability of an innovation among firms. Mansfield's model was used to explain the differences in diffusion of numerically controlled (NC) machine tools in various industries (140 firms in ten industries). NC machine tools spread more rapidly in less concentrated industries and in industries with a high level of R&D expenditure ("... even when the innovation is not directly related to the areas in which the R&D is done .." Mansfield et al 1977, p 143). The characteristics of adopting firms were similar to those identified in earlier studies. The number of people having to approve the adoption decision, a characteristic not studied before, was found to be negatively related to its speed of adoption. The effect of firm size was further studied. This was not significant "for innovations where the costs of introduction are relatively low in comparison to the assets of the firms in the industry" (p 117).

Several empirical studies of diffusion of manufacturing technology have been conducted in the 1970's (for example: Tilton 1971, Golding 1972, Fisher 1973, Nabseth and Ray 1974, Scott 1975, Simon 1975, and Davies 1979). An international study of the diffusion of ten industrial processes in seven

countries highlighted the complexities of the process of adoption, the problems of a rigid methodology, and the limitations of statistical analysis (Nabseth and Ray 1974). Various factors relevant to the spread of information, the earliness of awareness, and the speed of adoption were studied. It was found that the diffusion of information of new techniques such as NC machine tools and special paper making presses was a fairly slow process ("Timelags of about ten years between the first and the last firm are not uncommon" Nabseth 1974, p 300). In these cases, large firms usually get information about new processes earlier than small firms. Although information flow was found to be important, the most common explanatory variables were the innovation's relative advantage or profitability, other economic variables, institutional circumstances, and the attitudes of management. Nabseth (1974, p 303) concluded that profitability was an important factor, but that it was "difficult to say anything about its importance relative to other factors in explaining diffusion of new technology". He emphasised some important problems of profitability measurement. Capital markets are imperfect and firms' opportunity costs differ: "A high internal rate of return for one firm may very well be considered a rather low rate for another" (p 302). Manufacturing innovation is not introduced with perfect foresight, particularly in the pioneering stages where uncertainty is high.

> "One general conclusion seems to be that calculating the profitability of a new process is more difficult than is usually acknowledged in studies on the subject. For some processes, for instance numerically controlled machines and continuous casting, profitability turned out very difficult to calculate ex post, and even more difficult ex ante.... It follows that profitability calculations for new processes are very much linked with

> management attitudes, especially when experience of the technology is scarce and perhaps contradictory." (Nabseth 1974, p 302)

In some cases, proxies for profitability such as wages for very labour-saving innovations were used. The level of diffusion of NC machine tools for example, showed a strong positive correlation with the level of wages in countries and firms (see figure 6.11). Other economic factors considered were the magnitude of investment and the firm's own financial resources. Nabseth and Ray's study concluded that the advantages of large and internationally-based firms vary with the type of technology being adopted. The nature of the work suitable for NC machine tools, small to medium-size batch manufacture of complex products, may be the reason for the more intensive use of NC technology in small firms. The institutional factors identified were also very specific to the technologies studied: the successive nationalisation and denationalisation of the British steel industry played a negative role in the diffusion of oxygen steel and continuous casting in the UK; legal barriers to the use of gibberellic acid in malting in the FRG and Italy inevitably influenced its adoption; the existence of a large aerospace industry in the UK and the US contributed to the relatively rapid diffusion of NC machine tools; the abundance of small firms in the cotton-type weaving industry in the UK and Italy seemed to have resulted in a slower diffusion of shuttleless looms; and the influence of strong industrial and research associations in Sweden favoured the adoption of special presses (Nabseth 1974, p 308-309).

2.4 Limitations of Diffusion Research

Several limitations of the approach to the study of innovation diffusion have been identified in the literature (see for example: Rogers and Shoemaker 1971, Utterback 1974, Warner 1974, Sahal 1977, Hurter and Rubenstein 1978, Sahal 1979, and Uhlmann 1979). Rogers and Shoemaker (1971, p 77) argued that the reliance on recall data from interviewees, since diffusion is a dynamic process of change, imposed serious limitations of accuracy. They also criticised the emphasis on studying relatively inconsequential innovations (e.g. automobile seat-belts or a new food product) and the lack of interest in radical innovations of a restructuring nature (e.g. new organisational forms). Furthermore, the type of innovations that have been studied usually involved decisions from an individual regardless of the decisions of other members of the system (optional innovation-decisions). Diffusion research should pay more attention, they argued, to collective and authority innovation-decisions. Rather than the indivdual, the unit of analysis should be the social structure and the relationships between individuals (relational analysis). Diffusion studies generally work on the assumption that the innovation should be adopted and that its rate of adoption should be speeded up. Rogers and Shoemaker (p 164) identified only a handful of publications dealing with what they called "overadoption" or "the adoption of an innovation by an individual when experts feel s/he should reject".

Rogers and Shoemaker also identified the limitations of their own approach which involved comparing empirical publications for the purpose of making generalisations about the diffusion of innovations (p 91-95). Cross cultural equivalence

is doubtful and thus international comparisons and generalizations are difficult. Categorization of variables as dependent and independent is arbitrary and may correspond more to the interests of the researchers than to "the expected time-order in which the variables occur in the real world" (see figure 2.1). Finally Rogers and Shoemaker (p 93) recognised the theoretical oversimplification of the generalizations.

> "Another shortcoming of our generalizations in the following chapters is the deceit of their neatness and simplicity. Our generalizations deal almost entirely with pairs of concepts, whereas the real nature of diffusion is certainly a cobweb of interrelationships among numerous variables".

Others have stressed the complex nature of diffusion and have called for a more interdisciplinary, multidimensional approach (e.g. Warner 1974, p 433 and Sahal 1977, p 296). Uhlmann (1979, p 18) referring to the seemingly contradictory generalizations of innovation studies, argued that this was the case because the studies were not comparable:

> "Obviously, innovativeness may be a function of size but certainly it is in the same way a function of other criteria of firms.
>
> "Of course, economists have been well aware of the general interdependence of the factors they explore. But they have neglected their scruples and have taken up a position behind the clausula ceteris paribus, assuming that all influencing factors but one be of no influence. But the cetera are not paria. The inescapable condition for applying that stipulation is homogeneity of the items in question. It turned out that this condition is not satisfied. The factors excluded are determining the results."

Several scholars have also warned against the danger of a simplistic division of the process of technological change. Rosenberg (1976) strongly criticized economists for the artificial segregation of invention from innovation, and of invention from diffusion. The consequence of this Schumpetarian

framework, Rosenberg argued, "is the failure to exploit technological factors in furthering our understanding of innovation and diffusion" (p 68). These factors can account for the timing, the rate, the direction, and the consequences of the diffusion of innovations throughout the economy.

In general, Rosenberg emphasized the influence of supply factors affecting the diffusion of technology: "much of the literature ... simply assumes the existence of a profitable invention and then goes on to try to account for the lag in its adoption" (p 73). In reality, "highly significant technological and economic adaptations are typically waiting to be made" (p 194) after the conventional dating of an invention (see also Sahal 1979, p 259, Ray 1974, p 19-20). Rosenberg associated this gradual process of improvement, the learning period, with the development of human skills in using and in making the innovation, and with the invention of complementary technologies which would relax or bypass constraints hampering the diffusion of the innovation. The length of this period will vary according to many factors such as the complexity of the innovation, and its novelty or dependence upon available skills.

> "This process of problem-solving and accommodation is central to a better understanding of the timing of technical change and the rate of diffusion of new inventions. For it is the speed with which performance characteristics are improved, techniques modified to meet the needs of specialised users, and the price of the invention gradually reduced, which determine its acceptability among an increasingly widening circle of potential users" (Rosenberg 1976, p 200)

2.5 An Approach to the Study of Robot Technology

New technology is the result of the interaction of activities that take place simultaneously and adoption is

only one of them. The case of robots is an excellent example supporting Rosenberg's views against an undue separation between the different facets of technological change. The complexity of this process is even more acute in its early stages, the transient period, when the imitation forces have not yet been unleashed as a result of high uncertainty about the benefits of adoption. As robot technology is in its infancy, the problems of its introduction into production cannot be isolated from problems of research, development, invention, innovation, and diffusion. Adoption has to be considered in a wider context of robot advancement. Figure 2.2 serves to illustrate this view. All the activities relevant to technological change interact with each other and the nature of these interactions changes in time as the process becomes more stable. This equilibrium, however, is likely to be disturbed by both radical and incremental improvements in the technology. Robot advancement should be regarded as a continuum rather than a cycle. Perhaps the only sequential characteristic of the process is the shift in the relative importance of research, development, invention, innovation and diffusion as the technology advances. Obviously, at least from an economic standpoint, the importance of diffusion in the end surpasses that of the other activities.

Diffusion studies generally consider innovations as successful, monolithic, and static. Furthermore, they take their potential use as known and unchanging. At the present stage of robot advancement these assumptions are particularly shaky. Here, diffusion research should: (1) deal with innovations as heterogeneous objects with changing characteristics and therefore disaggregate the analysis, (2) focus

more on the identification of clusters of interacting factors and implications relevant to adoption using an interdisciplinary framework rather than on the "empirical" testing of unidimensional hypotheses, and (3) focus on identifying the innovation potential and the variables that control it as the basis for forecasting and assessment. In no other case are these directives of research more appropriate than in the case of complex innovations with wide repercussions in the adopting environment.

Various studies of assessment and forecasting of robot technology have been conducted. These have generally dealt with technical, economic, and social factors affecting the diffusion of robots. In the early years of robot symposia, the first half of the seventies, assessment and forecasting papers were abundant and fairly vague. Later they became less common but more serious since they reported the results of relatively large investigations (e.g. the Humanisation of Life at Work Project in the FRG).

Various reports of limited circulation from consulting agencies have been made since the early days of robots (e.g. Frost and Sullivan 1974, 1975, and 1980; Tassel 1975 from Arthur D. Little; and Ingersoll 1980a and b). These studies have reviewed all the important aspects of robotics with the purpose of informing firms or government agencies about the developments of the market in different countries (they are useful historical documents although often they do not give their sources). Emphasis has therefore been placed on forecasting the size of the market of various robot types and applications. These projections have usually been overoptimistic. Unfortunately, these reports have seldom disclosed the assumptions

on which these forecasts were made. As opposed to the literature on diffusion, consultant reports have dealt with robot innovation in a highly disaggregated manner studying various generations of robots and types of applications (they are referred to, later in this thesis).

Consultant reports and other studies (see for example Yonemoto and Shiino 1977 and Varvello 1980) attempted to identify the importance of various factors to the question of robot adoption. In general, they sent questionnaires to users and potential users asking for an assessment of the relative weight managers gave to technical, economic, and labour problems. These studies have shown the complexity of robot adoption since they identified other factors, besides the profitability of robot investment, as crucial. The labour problems related to bad working conditions, the technical difficulties of robot introduction, and the flexibility demands of manufacturing operations, were regarded as some of the most important determinants of robot adoption.

Some studies of the social implications of robots sponsored by the West German government are particularly relevant to this thesis (SOFI 1978 and Battelle-Institute 1978). According to these reports (Brodner and Schacks 1979, p 124) robot technology evolves from the interaction of two distinctive forces: the firm's drive for productivity and the workers' demand for improved working conditions. These studies identified not only the benefits, but also the risks of robot adoption. The loss of working places can have a harmful impact when associated with a stagnant economy. While robots reduce some strains and stresses they introduce new ones, particularly if not properly introduced. They also eliminate

skilled tasks and cause an imbalance in the distribution of work and qualifications. Their social implications, these studies emphasized, are fundamental to the development and diffusion of industrial robots. They recommended work restructuring, at the same time as robot introduction orientated to using the potential of the workforce. (Other papers concerned with the impact of robots on labour written by trade unionists are: Connole 1970, Bo Jonsson 1973, Cooley 1973, and Friedrichs 1973. Research on the social implications of robots has been conducted by Ciborra and Romano 1977, Liff et al 1977, Hasegawa 1977, and Rosenbrock et al 1980. Hagmann-Petersen 1977 reported the conclusions of a symposium on the socio-economic aspects of industrial robots and programmable logic controllers).

The report by the Battelle-Institute in Frankfurt covered the factors and implications of ten cases of robot introduction (Gizycki 1978). Gizyki was perhaps the first to deal systematically with robot adoption as a heterogeneous process. He was not content with lumping all the diverse robot applications in one class nor was he happy with only describing their most specific aspects. The factors and implications of the adoption of robots which handle workpieces (IRW), Gizyki pointed out, differ from those of robots which handle tools (IRT). He concluded that although no controversy had arisen because of easy transfer and gradual introduction, this may not be the case in the future. In general, the humanisation potential of IRT's is weaker than that of IRW's. IRW's lead to a cooperative relationship whereas IRT's stimulate a polarisation of interests. Thus, Work Councils would more readily accept IRW's unless IRT's were associated with hostile

environments. If the sample of case studies is representative, Gizycki pointed out, the diffusion of IRW's, especially if technical and economic problems are solved, is likely to be more widespread.

Gizycki's attempt to relate factors and implications of adoption to different robot categories was, clearly a step in the right direction. However, he did not go far enough in identifying distinctive robot categories. Consequently, his generalisations do not hold for some robot applications. The fact that some robots handle tools and others workpieces is important, but more fundamental criteria such as those recognised by Bright (1958) and Bell (1972) in classifying levels of automation must be used (these criteria will be described later in the thesis).

The factors and implications of adoption are associated with the levels of automation, integration, and complexity of manufacturing operations before and after the introduction of robots. Considering the level of automation alone, four distinctive robot categories can be recognised: transfer, manipulative, processing, and assembly robots. These are the most aggregated categories which will be used in this thesis.

2.6 General Methodology

A "methodology" which could avoid the main limitations of the literature and achieve the objectives of this thesis had to be to a large extent, ad hoc to the particular circumstances of the research work. Nabseth (1974, p 299) described the problems of finding a common theoretical and methodological approach to study the diffusion of new technology in various

countries.

> "It is obvious from the preceeding chapters that a strictly 'common' approach was not found ... this was less a failure to agree on a standard analysis than a question of differences in the techniques studied and in the empirical material available. Furthermore, it may very well be that such a standardisation would in fact have hidden important explanatory factors in the diffusion of some processes."

Three distinctive topics of analysis can be distinguished in this thesis: (1) the pattern of change in the technical characteristics of robots in the market, and in research and experimental development; (2) the pattern of change in the characteristics of development, supply and manufacture, adoption, and promotion activities in various countries; (3) the technical, labour, managerial, and economic factors affecting the introduction of robots in manufacturing firms in the UK.

Several research tasks were undertaken to provide the information needed. The outcome of each of these research tasks is largely self-contained and is therefore reported in the form of an appendix together with a description of the sources of information and the methodological limitations. Six main sources of information were used: mail enquiries, interviews, visits to conferences and exhibitions, and published and unpublished literature. Information for the first topic was mainly inferred from samples of commercial equipment in different years (appendix 2), and from the focus of research and experimental development papers in nine international symposia on industrial robots (appendix 3). Information for the second topic was gathered in many different ways. Qualitative historical information is presented in the form of chronologies of research and experimental development (appendix 5), invention and innovation

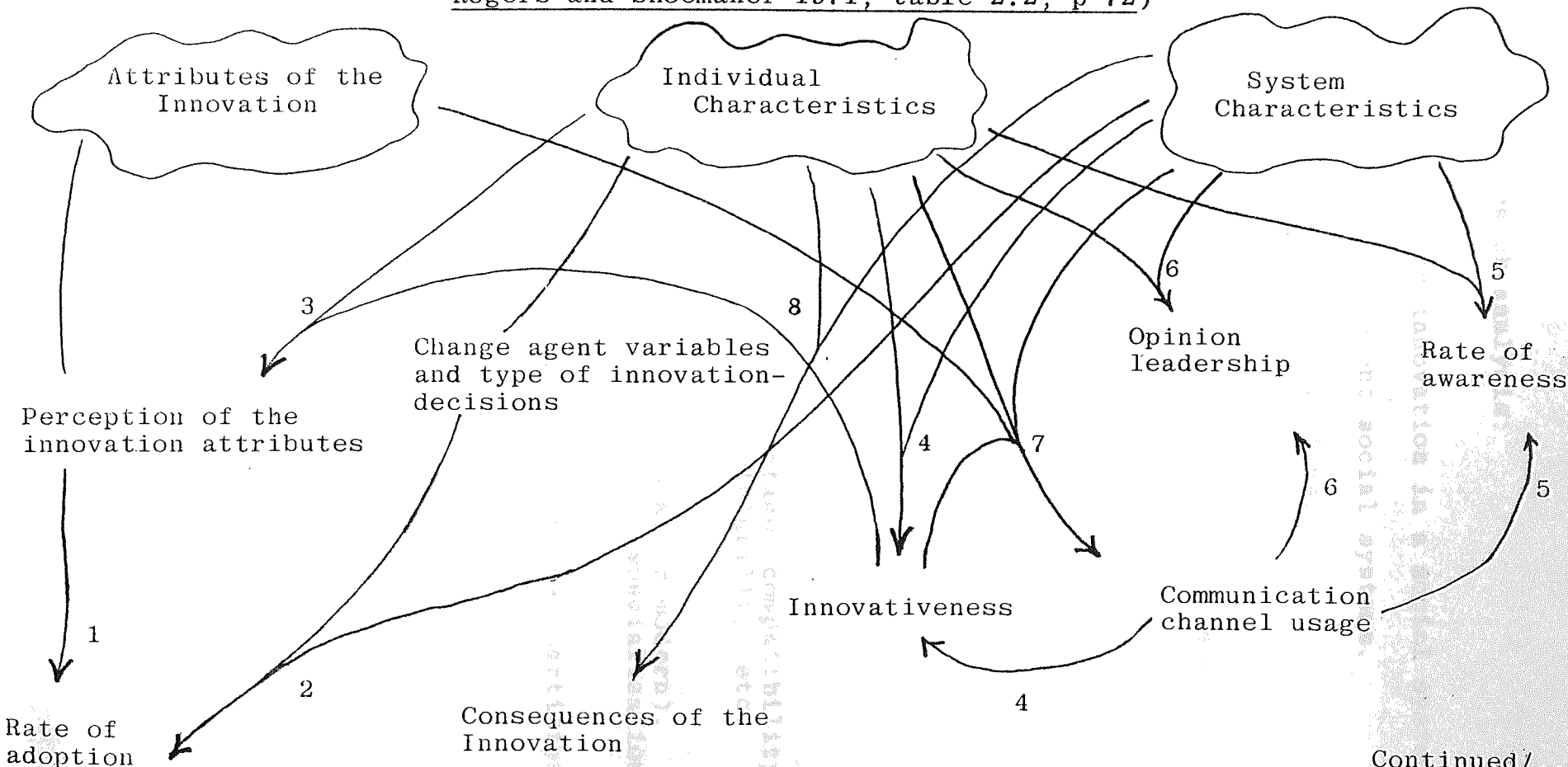
(appendix 4), adoption (part of appendix 7), and promotion (appendix 11). Quantitative indicators of the level and pattern of robot advancement are also reported: international development (appendix 3), international supply and manufacture (appendix 6), international diffusion (appendix 7), international pattern of usage (appendix 8), British pattern of usage (appendix 9), and a sample of UK robot applications (appendix 10). Information for the third topic was obtained from interviews with users and potential users of robots in the UK. The technical, managerial, economic, and labour motives and implications of the adoption of different robot categories, and the general characteristics of user and potential user firms are given in tabulated form in appendix 12.

The most original and most difficult task was that of studying the factors and implications of robot adoption in the UK. When the research was started, comparatively little interest in robots existed in the UK. The response from firms to mail enquiries regarding the initiation of case studies was rather low. Only after a second and more intensive attempt was access gained via interviews to firms' experiences. The restricted access to information, often regarded as confidential, meant that the intended scope of the field work had to be reduced. As a result no comprehensive interviews with workers who experienced the adoption of robots were conducted. This is one of the main limitations of the field work.

Eventually some sixty interviews with users, potential users, suppliers, researchers and other professional people involved with robot technology were conducted. The sample

of interviews was of course, not randomly chosen. It is perhaps more appropriate to say that the sample chose itself! The size of the robot 'community' at the time was smaller than it is today. The only feasible 'methodology' was that of getting as much information from as many sources as possible, preferably by interviews. Only by talking to people in the robot 'community' was it possible to reach a better position from which to build a richer picture of the development and diffusion of this technology.

Figure 2.1 Type of Diffusion Research Analysis (Elaborated from Rogers and Shoemaker 1971, table 2.2, p 72)



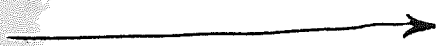
Continued/....

Key notes for figure 2.1

Type of diffusion research analysis:

1. Rate of adoption of an innovation in a social system.
2. Rate of adoption in different social systems.
3. Perceived attributes of innovations.
4. Innovativeness.
5. Earliness of knowing about innovations (rate of awareness)
6. Opinion leadership.
7. Communication channel usage.
8. Consequences of innovation.

 : Major independent variables

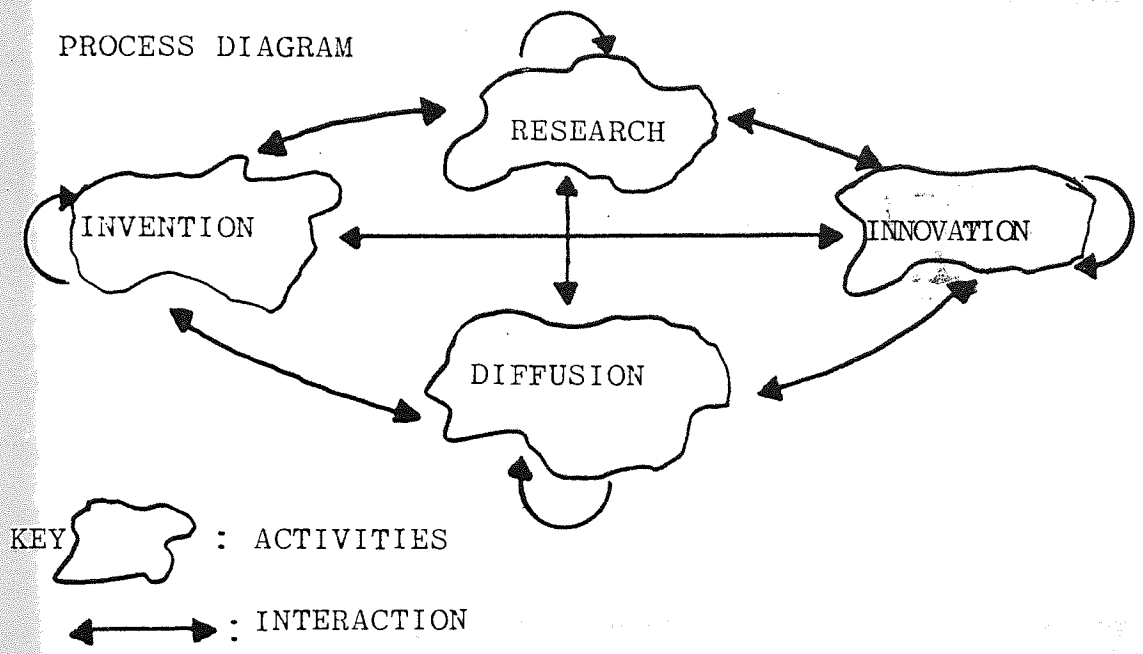
 : Casual relationship investigated

Innovation attributes : relative advantage, compatibility, complexity, trialability, etc.

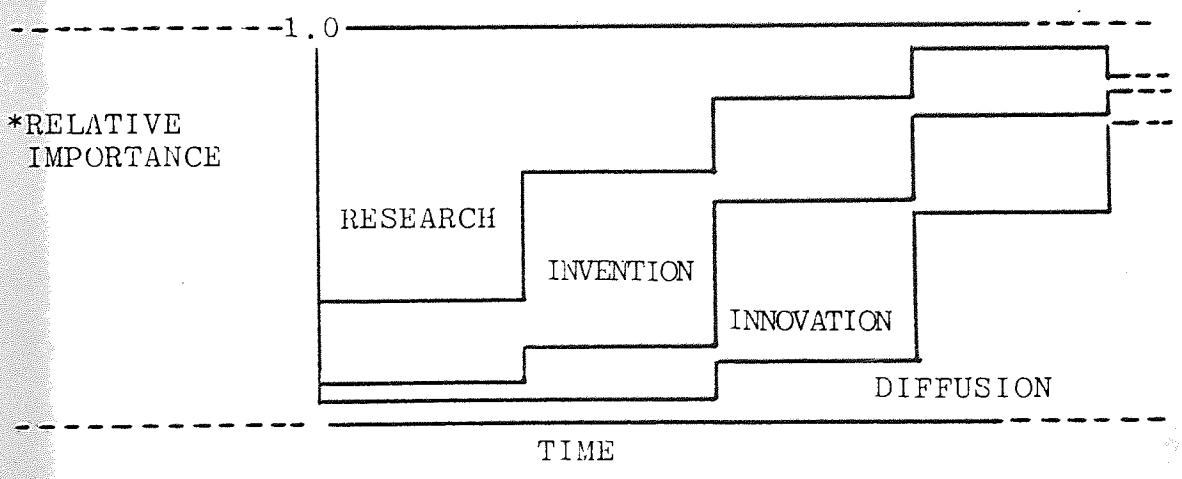
System characteristics : norms (traditional or modern), integration, size, specialization, etc.

Individual characteristics : age, education, status, participation, mobility, dogmatism, etc.

Figure 2.2 - A View of the Dynamics of Technological Change



GRAPH SHOWING POSSIBLE BEHAVIOUR OF THE PROCESS



* MEASURED, FOR EXAMPLE, IN TERMS OF THE RESOURCES INVESTED AT TIME "T" IN EACH OF THE ACTIVITIES RELATIVE TO THE TOTAL.

CHAPTER 3

INTRODUCTION TO ROBOTS

3 - INTRODUCTION TO ROBOTS

3.1 Machine Evolution

The concept of industrial robots, like automation and machinery, is a notion with a wide variety of interpretations and its definition has, for a long time, been a matter of controversy (Warnecke 1973, p348; Weisel and Katoh 1975, p1; Hall 1976, p3; and Engelberger 1976a, pJ4-55). Even now, after nine international symposia on industrial robots, a standard and consensus definition of the term does not exist (Ciborra et al 1976, p21). "The point is that the definition of robots is not easy, because there is a gradient of technology" (Engelberger 1976b, pK23).

The diversity and changing nature of robot devices demands that our efforts should be spent in identifying the fundamental aspects of robot technology and not in finding all-embracing definitions which are, in the end, bound to be limited. These aspects will then be the basis for a classification of robots.

The description of ancient mechanical devices, built mainly to imitate the form and movement of animals and human beings for the purpose of amusement, is often given as an introduction to the subject of industrial robots (Vantzelfde 1974, Heginbotham 1974, Albus and Evans 1976, and Reichardt 1978). However, relevant as they might be to robots, they are even more similar to the continuous stream of toys which are still being invented (Culberton 1963, p11). Machines devised for performing the tasks of animals and human beings at work

virtually from the 18th century onwards are the real ancestors of the industrial robot. Thus, an overview of machine evolution is essential to the understanding of the invention of robots and their development, "..in technological change as in other aspects of human ingenuity, one thing often leads to another - not in a strictly deterministic sense, but in the more modest sense that doing some things successfully creates a capacity for doing other things" (Rosenberg 1976, p30).

Mechanisation progresses alongside other changes in the technology of manufacture either in the materials, the products, the processes or in the organisation of the factory. Each of these elements affects the development of machinery, at one time or another, either as constraints or as agents.*

Although the particular form that these evolutionary changes take can only be described with reference to a specific manufacturing operation, some general lines of development can be identified. This task has been the focus of attention of various writers and the works of Usher (1954), Bright (1958), and Bell (1972), summarised below, are of particular interest.

Usher, concentrating on the machine itself, identified advances in mechanisation as improvement and/or extension of mechanism to new tasks. Refinement of machinery

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* See the concept of technological desequilibrium in Rosenberg (1976, p29).

followed a trend towards the complete and continuous control of motion. This was very often a requisite for using more intense forces to drive the mechanism, and achieved by the building up of mechanical constraints. Control was fundamentally identified as structural precision (1954, p116).

Bright, looking at the factory as a whole supplemented Usher's views by pointing out that the process extends outside the domain of individual machines. Mechanisation extends across all manufacturing activities, "span and penetration of mechanisation", in a drive towards the total integration of the system i.e., the transformation of the factory into a machine-like whole in continuous motion. This makes mechanical precision the overriding characteristic not just of the machines themselves but of the entire production system. In addition to span and penetration, Bright, in a similar manner to that of Usher, identified a third dimension: the level of mechanical accomplishment.* Bright's concept of mechanical perfection demands more than the building up of positional constraints for the control of motion. It also requires chronological, relative, and environmental constraints. This is: time and speed control, harmonious coordination of machines relative to each other and to the system, and capabilities for the adaptation of machine response to environmental disturbances. In this context, control becomes and element on its own, somewhat separated from the structure of the machine.

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* Bright (1958, p41) divided machinery into seventeen levels according to the degree to which machines supplement human muscles, senses, mind and judgement as a more automatic production sequence is achieved.

Finally, Bell, breaking down the analysis further, recognised that mechanical accomplishment advances in different directions. Machines, therefore, differ not only in the extent of mechanisation but also in the form. He identified three basic lines of development according to the type of manufacturing tasks: transformation, transfer and control. The degree of sophistication along each of these lines is not directly comparable. These tasks can be mechanised in different ways by different technical elements whose sophistication, especially concerning those of the control task, may be too ambiguous to rank. Bell (1972, p59) criticised the lack of homogeneity of Bright's classification of the levels of mechanisation saying: "he (Bright) has forced into a single scale a number of very different types of technical development". In addition, Bell claimed that Bright excluded ..."any characteristics concerned with technical differences of the handling functions in production "...and concentrated on the control cycle of the transformation process".

To summarise, Usher, Bright and Bell identified three main aspects of the process of mechanisation. Firstly, mechanisation is a process of refinement of machinery and of extensions to three fundamentally different tasks: transformation, transfer, and control. Secondly, refinement, follows a trend towards the complete and continuous control of motion making the machine progressively independent of direct human intervention. This in turn demands the achievement of mechanical precision and adaptable control. Thirdly, mechanisation spreads to new tasks in an stochastic manner but steadily approaching the total integration of the factory.

3.2 Antecedents to the Invention of Robots

The robot machine does not emerge from one clearly recognisable line of evolution. It may be regarded as a more complex and adaptive version of previous mechanisms, as a new breed of machines pioneering the mechanisation of difficult tasks, or simply as a transfer machine for the integration of automated operations. However, different trends and developments in machine design are the unmistakable context for the robot invention.

In the early stages of the industrial revolution, when a machine was more an artificially powered mechanism guiding the human hand than a performer of repetitive cycles, machine designers built general-purpose machine tools for use in a wide variety of workshops. Later the growth of industries having common manufacturing processes, especially those in the US, led to an exceptional degree of specialization in the machine-producing sector (Rosenberg 1976, p17) and single-purpose machinery became increasingly popular. Braverman explains this phenomenon saying:

> "As machinery underwent its first phase of progress towards increase in control, this took the form of fixed arrangement adapting the machine to a particular product or operation... Such machines can be used for no other purpose, and they come into existence when the continuous volume of production can repay the cost of elaborate equipment". (Braverman 1974, p191)

Further changes in the philosophy of manufacturing (e.g., the assembly line) and the standardisation of products encouraged greatly the introduction of highly mechanised special purpose machines and transfer lines in high volume industries, such as the motor-car industry. The factory as a result was transformed into an extremely

inflexible system. Important changes in manufacturing science and technology now offer a different panorama.

Precision and control, thanks to breakthroughs in technology are no longer tied to mechanical constraints. The separation of control from the structure of the machine, and the increasing role of control systems as efficient processors of high level information may be the most fundamental of these breakthroughs. Of these developments, the well known and outstanding achievements in digital electronic control have greatly reversed the trend and made mechanisation a more flexible option "..the ability to guide the machine from an external source of control in many cases restores the universality of the machine. It can now regain its adaptability to many purposes without loss of control, since that control is no longer dependent upon its specialized internal construction" (Braverman 1974, p190).

The improvements in versatility and capacity for handling information recently boosted by microelectronics are with no doubt the main agents of modern mechanisation. As a result, the number of tasks likely to be performed by machines and the feasibility of integrating large manufacturing areas have increased radically.

Numerical control (NC) of machine tools is a definite step towards more flexible automation, gaining some of the versatility lost through the use of conventional automation (Seligman 1966, p5). The batch production sector of manufacturing industry consequently, has become the target for the spread of highly mechanised systems. In the words of Bell (1972, p79): "The most recently developed systems

have broken the close connection between automation and scale of production".

In addition these developments in control made possible the extension of automation to tasks whose complexity overpowered mechanisation. Contouring intricate shapes and manipulative tasks were, for instance, the sole domain of humans. The necessity for mechanising such complex tasks in hostile environments (e.g., nuclear, space and ocean) led to the development of other technology relevant to the industrial robot - remote manipulation.

> "...teleoperator technology had its beginnings...in the late 1940's and early 1950's, when it became necessary to control remotely located manipulators in hazardous environments of nuclear laboratories. With few exceptions, their work was done under the aegis of the AEC" (Johnsen and Corliss 1967).

The evolution of telechiric devices from simple mechanical extensions manually driven, to complex antropomorphic arms with electrohydraulic actuation and sensory feedback (Mosher 1964, p88) can be regarded as leading to robots. Yet again the advances in control technology made increasingly feasible the shift of human attention from direct to supervisory control until it became feasible, for simple and repetitive industrial tasks, to design manipulators for autonomous operation.

Beside NC machine tools and telechiric devices, the obvious ancestors of industrial robots are the diverse pick-and-place mechanisms used for loading and unloading stations and machines, and especially tailored to each application. These devices are particularly close to the invention of robots by George Devol in 1954 (Warnecke 1973, p347), which was at first aimed at loading and unloading

machine tools. Their evolution, from fixed-sequence and cam control to multipositional mechanisms with external digital command, can be regarded as directly leading to robots.

Finally, these developments were largely made feasible by the availability of people competent in the technologies needed to build robots. Engelberger (1976c, p486) identified the expertise developed during World War II on servo theory, mechanical engineering, and hydraulics in the aerospace industry as an essential base for the creation of the robot industry.

3.3 The Aims of the Invention of Robots

Originally, most manufacturing machinery emerged from inside the factory as tailor-made equipment. The growth of the market, however, encouraged the progressive formation of the machine-producing sector of industry, first as a supplier of custom-made devices and second as a manufacturer of standardised products.

Automatic assembly and transfer lines, due to the diversity of applications, were (and still are) to a very large extent tailor-made and special purpose.* Efforts to rationalise production of these devices had to be confined to modular design achieved by the standardisation

---

* Tailor made and special-purpose automation (hard automation) can, simply, be classified into low-cost transfer mechanisms (pick-and-place devices) and single-task assembly machines (highly-integrated rotary or linear assembly systems).

of the main blocks of machine components - a compromise between full standardisation and special design.

Further efforts to economise in the making of transfer mechanisms and to popularise them must be identified closely with the invention of robots. The only way to embrace the continuous trend towards cheap machinery in the manufacture of a larger variety of goods, was perhaps to shift to design versatile, from single-purpose automation. Built-in machine redundancy would make a unified design applicable to many different situations and reproducible in large batches. This in turn would bring down the cost of the machine, making such technical redundancy a cheaper option.

The invention of robots owes as much to the shift to more versatile machines stimulated by technical developments, as to the drive to produce standardised, off-the-shelf automation. However, these two fundamental characteristics of robot technology must not be regarded as absolute clear-cut concepts. They consist of a combination of different aspects, and may be regarded more as trends than strictly determined notions. Furthermore, versatility and standardisation are intimately connected rather than independent of each other.*

A simplified diagram can represent the goals of the invention of robots (see figure 3.1). The exent of robot achievent is seen as having two dimensions. On the

---

* Modular design, for example, is an approach to achieve a certain degree of standardisation in manufacture and at the same time, some versatility or applicability to different situations.

one hand, the degree of standardisation with two artificial extremes (tailor-made and off-the-shelf equipment); on the other hand, the degree of versatility, also, with two utopian extremes (single-purpose and universal machines). The upper right hand corner of figure 3.1 is the goal of the robot builders. These two dimensions refer to the entire robot system, hardware and software alike, and not only to the robot itself. In this context the achievement of both total universality and full standardisation can, for practical purposes, be considered as unattainable.

The advantages of robotic automation may be summarised as the ability to automate highly dynamic processes (small batch production and highly unstable product design) and the ease and speed of introduction of automation (Engelberger 1966, 1970, 1972 and 1979; and Sutherland 1970).

A comparison of the advantages of different approaches to automation is shown in table 3.1. Some of the benefits of using robots can be identified as a result of either their versatility or their degree of standardisation, or both. The advantages achieved by versatility and standardisation, are advantages exclusive to the robot approach. Consequently, the inherent benefits of hard automation are those listed in the lower left-hand corner of table 3.1.

Figure 3.1 - The Scope of Robot Development

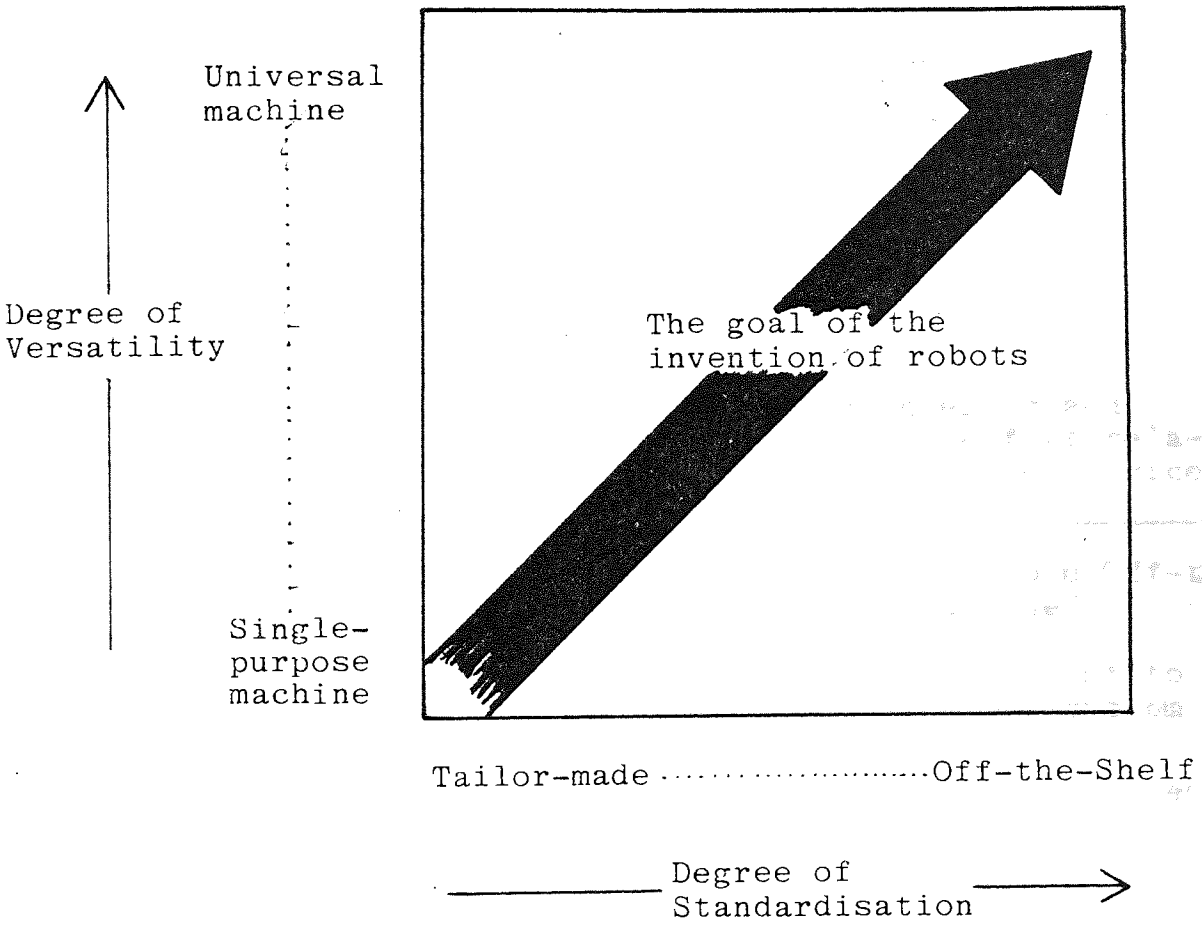

TABLE 3.1 - Advantages of Robots as Compared to other Approaches to Automation*

Degree of Versatility ↑	Degree of Standardisation →
"Tailor-Made Robot" . Complex manipulative and contouring tasks can be automated. . Task (cyle) can be modified . Compatible with exiting equipment . Fast set-up time . Less dislocation of labour (rate of introduction approximates rate of attrition)	**"Robot"** . Automation becomes feasible in odd applications . Machines can be used to automate different products and different tasks . Learning experience (operation, maintenance, management) is enhanced . Stocks of tools and spares are simplified and less expensive . Automation becomes cheaper as design and development costs are spread . Each machine incorporates very high engineering and design effort relative to their price
"Single-purpose Tailor-made Machine" . Perfect fit of design might mean a cheaper machine (especially cost of materials) . Less sophisticated . Efficiency and effectiveness of operation is increased (high accuracy, high volume, high reliability)	**"Single-purpose Off-the-Shelf Machine"** . Effort and cost to develop the system is decreased . Fast economic assessment of introducing automation . Better time and cost prediction . Quick delivery time . General ease of introduction (installation/debugging) in terms of time and money)

* These four approaches are, here, regarded as "utopian". In reality the borderlines are not clear cut.

CHAPTER 4

THE INDUSTRIAL ROBOT

4 - THE INDUSTRIAL ROBOT

4.1 Robot Versatility

The extent of standardisation of robot systems depends heavily on the success of the process of diffusion to be examined later. On the other hand, the degree of versatility is crucial to the understanding of the technology itself, and further attention will therefore be given to it in this section.

The search for versatility and consequently redundancy of design features, makes the robot machines a fairly direct replacement of humans for certain tasks. Often this is misunderstood as the goal of robot design. The fact that robots are a more direct replacement of humans to do certain tasks does not mean that the aim is to imitate humans. Only by consequence of the design approach do robots do tasks in a manner that resembles humans. Special-purpose mechanisms do not perform tasks like humans because more efficient solutions to a problem can be found at the expense of versatility. Versatility can also be equated to several other human characterisitcs such as dexterity, ability, adaptability, and flexibility. These concepts must be understood here, in the context of machinery. Thus, a systematic definition of robot versatility is given below (for another treatment of the requirements of versatility see Heginbotham 1976, p126).

The more applicable a robot is to differnt situations, the more versatile it is. Versatility can be divided into structural versatility, command versatility (programm-ability) and adaptability.

Structural versatility is further classified into positional and manipulative versatility. Positional versatility is the ability to move the end point of the robot mechancial structure through different points in space. Manipulative versatility is the ability to actuate a tool or a gripper located at the end of the structure in a variety of ways allowing for changes in the form and weight of workpieces or tools.

In order to utilise these structural capabilities fully and achieve total robot versatility, it is necessary to have complementary command versatility (programmability). This means:

1. The ability to actuate the robot structure in an optimal fashion (e.g. adequate acceleration/ deceleration and positioning),
2. The ability to follow a particular sequence of events
3. The ability to memorise different sets of sequences, and
4. The ability to communicate with the outside world to modify the sequence of events*.

Most important for achieving high versatility, is the notion of adaptability: the ability to sense changes in the environment and to modify behaviour according to a set of goals or, in its most sophisticated form, the

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* Abraham et al (1977c, p2) defines programmability as "the ability of a manipulator to adjust its path and motions and auxiliary operations to accommodate for variability in parts being handled, how a part is presented to it and what it does with a part once it has been acquired".

ability to adapt to unforeseen situations according to heuristic rules (first forms of robot intelligence). Adaptability should be seen as adjustment of programmed behaviour in the context of manufacturing uncertainties, such as position and orientation of parts, changing dimensions of workpieces and workplace, incidents in the operation, malfunction of the system, and potential accidents (Abraham et al 1977c, p2-3 and Skoog 1979, p729).

The high versatility of today's industrial robot technology is manifest in the diversity of existing applications. These numerous and varied applications can be divided according to the robot task, or for that matter, the human task they replace, into four main categories.

1. Transfer tasks, those where the robot grips a workpiece and changes its position
2. Manipulative tasks, those where a workpiece is handled by the robot guiding it while a machine performs work on it
3. Processing tasks, those where the robot handles a special tool which does work on an object
4. Assembly tasks, those where the robot uses gripping and other special tools with the purpose of mating and joining several components.

Other subclasses and examples of these applications can be seen in table 4.1.

When performing all these operations, robots interact with other devices and equipment. They never work alone. Thus, versatility must be the feature of the whole manufacturing operation or robot system. This implies that peripheral equipment and process machinery should have complementary

programmability and adaptability.

Generally, it can be said that the need for flexible peripheral equipment decreases with increasing robot versatility; so that a highly dextrous robot would need less peripheral equipment and could cope with more rigid equipment. Nevertheless, there would always be a requirement for versatility in the peripheral technology if an automated manufacturing operation is to achieve the benefits of the robot approach.

4.2 Anatomy of an Industrial Robot System*

Robot Elements

Different hardware and software elements can be identified in a robot system: manipulator(s), driving system, peripheral equipment, control system and software system.

The manipulator is a mechanical structure comprising several linkages and joints capable of movements in various axes. This can be further divided into arm or main structure, wrist, and end effectors (grippers or other special tools).

The driving system transforms energy from an external source into mechanical energy for the purpose of moving the manipulator and this consists of a power unit and transmission elements.

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* For a pictorial description see Appendix 1

The peripheral equipment feeds, orientates, and/or fixes the different workpieces to be transformed by the system. It can be divided into feeding equipment and fixtures.

The control system coordinates the whole, actuating the system in a desired manner and storing and trading information with the environment. Control systems consist basically of three elements: (1) input elements and output elements, (2) the processor unit, and (3) the memory.

1. Input and output elements can be divided into servo and non-servo. Input servo elements (eg sensory systems) form part of control loops which monitor the state of variables such as position, orientation, speed, acceleration, force etc. and compare this information to preset goals. Output servo elements then correct discrepancies by actuating the necessary mechanisms. Non-servo input and output elements put the robot in communication with humans and with the rest of the technical environment i.e. other control systems and process machinery.
2. The processor or central unit may be divided into the operating system and the sequencer. The coordination of all the control elements and the operation of a prescribed sequence of events are their respective functions.
3. Memories are the means of storing the different kinds of information needed for running the system.

The software system translates the information from the environment into system commands and the internal information into a form readily understandable to humans. In general the software system is the set of procedures needed by the control system for actuation and the coordination of all hardware elements. Abraham et al (1977c, p3) classify a type of software into sensor processing programmes and executive level software.

> "The sensor processing programs read sensor data, interpret it and pass the interpreted results to the executive level software. This latter set of programs determines what control action to take based on the interpreted results and initiates the appropriate commands to adapt the manipulative task as required".

Other procedures, such as setting, monitoring, testing, fault finding, and maintenance even though they may not be performed by the robot system, are part of the software.

Robot Components

The function of the above robot elements can be performed by a host of particular devices or components. Consequently, the design of robots is of a highly diversified nature.

The manipulator can take various forms according to the type of (1) robot arms, (2) wrists, and (3) end effectors.

1. Robot arms may consist of one, two, three or more structural members; each of them having either a translational or rotational movement. The different combinations of number and type of axes are large, and result in numerous structural configurations and shapes of the working space

of a robot. In the case of three axes, for example, the configurations can be classified, according to the coordinate system into four categories: rectangular, cylindrical, polar, and jointed spherical or prosthetic (see figure A1.3 in Appendix 1).

2. Robot wrists may also consist of one, two or more mechanisms. Usually they have two or three axes of movement and their configurations may be classified into six groups according to the different combinations of roll and bend axes (see Stackhouse 1979).
3. End effectors can be either grippers or other special tools. They are to a very large extent special-purpose and tailor made for each application, hence the variety of devices is large. Grippers are classified according to the number of fingers (two, three, four or five) and according to the kind of mechanisms used to move the fingers. Tools can be for processing work such as surface coating, joining, metal working and others (see table 4.1), or for material handling such as suction pads, magnetic tips, inflatable fingers etc.

Drive systems are basically of three kinds: hydraulic, pneumatic, and electrical. Some robots, however, have a mixture of these (e.g. pneumatically actuated gripper and hydraulic manipulator). The means of transmitting the energy transformed by the power unit can be either by direct linkage between actuators and structural members

or by indirect linkage through gears, chains or ball screws (Tanner 1977, P1).

Peripheral equipment varies widely according to the application. These can be conveyors of all kinds, carts, magazines, vibratory and non-vibratory bowl feeders, feeding tracks, orientating devices, indexing tables, escapements, pallets, special jigs and fixtures and simply bins.

The control systems as a whole could be classified according to their technology as pneumatic, hydraulic, electrical or electronic. However, they are very often a mixture of two or more of these technologies. According to the type of positional control they are servo and non-servo systems (Tanner 1977, p3). In non-servo systems mechancial stops and limit switches serve as positioning devices, whereas in servo systems, continuous measuring and feedback control of position takes place. Other components of control sytems are:

1. Input devices can be either analogue or digital. Examples of these are, potentiometers, encoders, resolvers, tachometers, and all kind of transducers and sensors (tactile, force and visual sensors).
2. Output devices can be of very different kinds, namely, control valves, amplifiers and comparators.
3. The sequencing function of a control system can be performed by an extensive range of equipment such as relay systems, pneumatic logic

units, diode matrix boards, microprocessors and minicomputers.

4. Memory functions similarly, may be carried out by electronic counters, patch boards, diode matrices, potentiometers, magnetic tapes, magnetic discs, or solid state memories (RAM's).
5. In the case of computer control, operating systems are either special purpose electronic circuitry (hard wired), stored in core memory, or programmed in read only memories (ROM's) (Tanner 1977, p2) (For a hierarchy of sequential controllers see table A1.4 in Appendix 1).

One of the most important aspects of software are the control algorithms and the method of programming. Robots are usually classified according to the control algorithm into point-to-point (PTP) and continuous path (CP) equipment. PTP systems control the robot by "recording the operation path in the form of the coordinates of finite positions" (Yonemoto 1975, p23). Continuous path systems control the robot by "recording the operation path in a continuous format" (Yonemoto 1975, p23). However, other types have recently been identified. Hohn (1976, 1978) defined another category: computed path (Comp.Path). This is a type of CP control with added capabilities such as acceleration, and velocity control along the path and other software features made possible by the use of computers (for example: teaching mode in natural coordinates, straight line path motion, data-storage in non-robot coordinates, and tracking of a moving object).

Programming methods may be classified as direct, indirect, or hybrid (Spur et al 1977, p253 and table 4). Direct methods, in turn, are classified as teach-in and manual data input methods. Teach-in can be performed by acoustical, optical, and mechanical sequence. Mechanical sequence, however, is the most commonly used at present, and is of two types: PTP and CP. Teach-in for PTP systems is performed by an operator moving the manipulator with the use of a joy-stick, keyboard, or other types of teaching pendants through each desired position, recording each one of them onto the memory. In the CP systems, teach-in is performed by actually leading the manipulator itself or a dummy along the desired path. Manual data input can be either through wiring and connecting or through setting mechanical storages (they are used in the least sophisticated robots). Finally, indirect methods are either manual programming (coding) or automatic programming. They make use of problem orientated high level languages.

Supervision, monitoring, operation, testing, fault-finding, setting, and maintenance procedures are other important software elements but they vary widely according to the robot make. They can simply be classified into manual, when consisting of checklists in handbooks, or semiautomatic, when devices and special circuitry are supplied which automatically perform part of these functions.

LIBRARY

4.3 The Characteristics of Industrial Robots

There are numerous characteristics which may be used to specify an industrial robot for the purpose of comparison and evaluation. These are either of a qualitative nature or difficult to define and measure. Furthermore, there is some confusion in terminology since no international standards exist; only a few attempts have been made to produce national standards, many of which are still in progress (Yonemoto 1975, Sheridan 1975, Hasegawa et al 1977, Evans et al 1977 and Ozaki et al 1977). Nevertheless, some characteristics can be identified and utilised as criteria for classification of robot equipment.

Five categories of characterisitics are identified (versatility, performance, reliability, complexity and other specifications). Those relating to the versatility of the system are the ones of most interest here. However, the other characterisitics are also important in pointing out the differences between one robot and another, and between robots and other machinery.

Versatility Characteristics

The versatility of a robot is largely the product of the type of components in the system. However, some differences of degree between systems can be highlighted by quantitative indicators of the positional, manipulative, and command versatility and of the adaptability of a robot (see table 4.2).

Positional versatility increases with the number of axes of movement in the arm and wrist or the degrees of freedom in the manipulator. Three degrees of freedom in the arm and three in the wrist are theoretically sufficient to position and orientate an object in space. For some tasks, fewer than six degrees of freedom might be needed (for example if symmetry exists - Lindbom 1972, p141), whereas for others more might be necessary to make the robot mobile.

The kind of configuration and mechanical structure also influences the exent of positional dexterity. For example, prosthetic arms have greater flexibility because they "can reach in a large spatial volume for its size. Such a machine with all rotational axes also has a greater amount of reach flexibility" (Corwin 1975, p456).

Also indicative of the extent of positional dexterity is the volume of the working or operating space. This characteristic varies widely - 0.1 to 10 cubic metres - and can be regarded as more closely dependent on the kind of application.

The ability to cope with different workpieces and tool functions or manipulative versatility, is largely affected by the properties of the end effector. In the case of grippers, for example, increases in the number of fingers augment the possibilities of grasping a larger variety of objects. According to Muldau (Lundstroem et al 1977, p77) grippers with four fingers can handle 99% of the parts that five finger grippers do; grippers with

three fingers, 90%; and grippers with two fingers, 40%. However, the design of the gripper itself can achieve great levels of versatility with as few as three fingers. Other means of solving the problem of workpiece variety exist, such as the facsimile gripper (fast and cheap manufacture of special-purpose grippers), the interchangeable gripper and/or tool, and the provision of more than one gripper/tool in a robot. To achieve manipulative dexterity it is important that robots should be able to move objects of different weights. The range of the load capacity and the maximum pay-load are indicators of this type of versatility. However, these characteristics are closely application-dependent. The size of a robot (working space and pay-load) is not strictly a generic indicator of versatility. A micro robot might be, for example, as versatile, or more so, than a giant one.

In addition to the above structural factors, other aspects are essential to achieve robot versatility. command versatility depends on properties such as memory capacity, the number of programmes it is possible to store, the number of setting points in each axis, and the number of input/output channels available for communication with the external world. In the case of the control systems, even more than for the mechanical components, their qualitative differences such as compatibility and exchangeability of control information, programmability and flexibility of the memory are very important.

Adaptability, the highest form of versatility, depends in the same manner on differences of kind rather than of degree between control systems. On the one hand, it may

be pointed out that adaptability depends on the complexity of the servo system i.e. how much sensory information they receive from their environment. The more variables are sensed and controlled, the more adaptable a robot becomes. On the other hand, adaptability also depends on the sophistication of the control loops and strategies for processing the environmental information into a machine reaction (Nevins and Whitney 1975, p387).

Performance Characterisitics.

These refer to the effectiveness with which the robot achieves its operational goals. Basically they are the speed and accuracy of reaching a programmed position. The speed depends on both the ability of the system to accelerate and decelerate the end effector and on its slewing speed. Accuracy depends on playback accuracy and repeatibility; the precision with which the system achieves a taught position and its continuous faithful repetition. Speed and accuracy are not independent of each other, and both are affected by factors such as the load being handled the resolution of the servo elements, the length of reach, the environmental conditions, the stiffness of the structure, and the kind of configuration.

Reliability Characteristics.

These are basically the lifetime of the system, its mean time between failures (MTBF), and the mean time to repair (MTTR). These depend also on many other factors and are difficult to estimate.

Complexity Characteristics

These are those relevant to the ease with which humans interact with the machine. Hence they are crucial for adoption and may be identified as ease of supervision, maintenance, setting and programming.

Other Specifications

Important specifications are safety, power requirements, weight and dimensions of the robot, floor space required, possibilities of mounting and tolerance to different environmental conditions.

Conclusions

Classification of robots, having such an extensive set of characteristics for comparison, is a difficult task and is subject to the criteria selected. Versatility, being the fundamental drive of robotics is chosen here as the main yardstick for robot classification.

A preliminary selection of criteria for robot classification is given in table 4.2 This is a summary of the main versatility characteristics and the set of alternative values or forms they can take (where appropriate, the degree of versatility increases from left to right). A feasible set of alternative values for each characteristic, therefore, defines a particular class of robots (i.e. two robot models described by the same set of alternatives in table 4.2 have similar versatility).

The study of the actual process of development in the next chapter will be the basis for finding the most

important robot characteristic.

TABLE 4.1 - Classification of Applications According to Robot Tasks

(1) TRANSFER

SIMPLE	COMPLEX	LOADING/UNLAODING
From fixed position to fixed position	From conveyor to conveyor Palletising and depalletising Packaging	Casting equipment Pressure diecasting equipment Injection moulding equipment Metalworking machines Cold/hot pressing systems Heat treatment equipment Glass cutting machines Soldering machines Brazing machines

(2) MANIPULATIVE

Forging
Fettling
Investment casting

(3) PROCESSING

METALWORKING	JOINING	SURFACE TREATMENT	INSPECTION	OTHERS
Flame cutting Grinding Pneumatic chipping	Spot welding Arc welding Stud welding	Paint spraying Enamel spraying Glassfibre and resins spraying Sprinkling enamel powder Ceramic ware finishing Water jet cleaning Applying sealing compounds Metallizing	Dimensional checks	Glass gathering Marking

(4) ASSEMBLY

Automobile alternators
Electric motors
Electric typewriters subassemblies

TABLE 4.2 - The Versatility Characteristics of an Industrial Robot

Degree of Versatility →

Aspects of Robot Versatility:		Characteristics:	Alternatives:				
Adaptability		Control Complexity	PTP	CP	Comp. Path	Sensory	Intelligence
Command Versatility		Programming Method	Manual input	teach-in Pendants	teach-in hand	Manual Progr.	Automatic Progr.
		Input-output Channels	< 8	9-40	> 40		
		Number of Different Cycles	Fixed	Variable (limited)	Unlimited		
		Memory Size (steps)	< 50	50-200	> 200		
		Positioning Control	Fixed stops	Adjustable stops	servo (limited)	servo (unlimited)	
Structural Versatility	Positional Versatility	Degrees of freedom (Arm + Wrist)	⩽ 3	4	5	⩾ 6	
		Configuration	Cartesian	Cylindrical	Polar	Prosthetic	
		Volume of Working Space (M^3)	< 0.1	0.1-1.0	1.0-10.0	⩾ 10.0	
	Manipulative Versatility	Load Capacity (Kg)	< 1	1-5	5-15	15-50	⩾ 50
		Versatility of End Effectors	TOOL		GRIPPER		

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CHAPTER 5

THE EVOLUTION OF INDUSTRIAL ROBOTS

5 - THE EVOLUTION OF INDUSTRIAL ROBOTS

5.1 Changes in the Characteristics of Commercial Robots

Commercial robot types have changed considerably in the last eighteen years (see table 5.1). During this period many types of robots have arrived and left the market place. At present, a large variety of devices in continuous technical change still exists. However, there is evidence to show that robot design is gaining stability (see Appendix 2 for an analysis of the pattern of change in the characteristics of commercial robot types).

The most dynamic element in the development of robots has been the control system. Mechanical structures and driving systems have attracted less development work, and changes have not been as dramatic. A large selection of mechanical structures and actuators is likely to continue being offered since each of these have certain advantages and disadvantages, and are suitable for different operations. For example, hydraulic actuators have a better torque capability and, like pneumatic systems, allow for fast movements. Electrical motors are slow, and have low torque capacity, but can achieve much better accuracy of position. The advantages (versatility, reliability and size) of solid state programmable systems are superior to any other alternatives to perform the control function and are becoming the predominant choice.

Some changes in the structural versatility of industrial robots have occurred.

1. Positional versatility has increased, since the proportion of robots having more than five degrees of freedom grew by fifteen percent. Early universal robots in fact, had only five degrees of freedom and were not modified until the late 1960's. Nowadays, all high technology robots have at least five axes. More importantly, better mechanical designs have been produced. This is the case of the Scheinman arm and the Cincinnati Milacron robot. They represent a trend towards prosthetic structures having superior reach and flexibility (Corwin 1975, p456).

2. A certain polarisation in the availability of positional versatility is taking place since the proportion of simple manipulators ($\leqslant$3 dof) has remained constant, and medium versatility systems have become less abundant. This gap is bridged by the existence of some robots with modular design (Versatran, Electrolux, and Mitsubishi are some examples).

3. Manipulative versatility has also improved since more gripper/tools have been designed and tested, and some standard 'universal' versions have been introduced into the market (For example, Fujitsu Fanuc three-finger gripper).

4. In the early days, a bias towards large load capacity was noticed by Warnecke et al (1974, p107). Recently, the introduction of several small and medium sized robots has widened the choice

of systems. Puma, developed by Unimation and GM, has set a trend towards small robots for assembly, This has already been followed by Hitachi, and Hall Automation have plans for a similar system.

Characteristics related to command versatility showed the most significant changes. The main trends inferred from the information in Appedix 2 are:

1. Although a medium memory size continued to be of importance, larger memory systems are an obvious trend.

2. Variable, but limited, sequence controllers are very rapidly becoming displaced, whereas fixed sequence decreased only by a small proportion.

3. Complex controls and feedback of position are becoming more popular.

These trends are the result of the diffusion of programmable electronic controllers. This is particularly noticeable in the sophisticated side of the market, but simple systems are moving in the same direction*.

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* Suppliers of simple pick-and-place robots and special purpose automation indicated the advantages of microprocessor control (e.g. shorter lead time to develop and better monitoring and diagnostic capabilities) and its likely future adoption. Some of them are already offering the choice between microprocessor or other traditional controllers.

The main feature of new high technology robots is the use of computer based control and powerful software (good examples are the Asea, Cincinnati Milacron and Puma systems). This improves dramatically the programmability and adaptability of robots. The first such improvement was the ability to select different programmes randomly (RPS) according to information from the environment (e.g. change in the type of workpiece). Further development achieved abililities such as interpolation, tracking of moving objects, control of velocity and teaching in external coordinates. In general, software advances point towards a better communication between robots and humans, and between robots and the rest of the manufacturing system (more input-output channels and use of high level information). The spread of the teach-in method of programming (either by pendant or hand), its combination with editing (manual programming), and the provision of monitoring and diagnostics routines, are good examples of advanced software.

Performance and other characteristics have also changed since the early days of robots as a result of improvements in the design of mechanical structures, driving systems and control units. This is particularly true of accuracy (see figure A2.4) and reliability (see figure 9.1) and to a lesser extent of speed. Simultaneously companies have refined their procedures and services for supervision, safety, maintenance and setting, in an effort to decrease the complexity of the systems and improve performance.

A summary of the main technical achievements of the robot industry is given in table 5.1. For an extended coverage of invention and innovation in robotics see Appendix 4.

5.2 The Development of Commercial Robots

The direction of robot development has, particularly in the early days, been a matter of controversy. Warnecke et al (1974) in a study of the characteristics of robots in the market, came to the conclusion that a gap existed between required and available characteristics. He, in agreement with other similar reports (For example: Hasegawa 1973, Herrmann 1975, and Pruvot 1975), also stressed the need for 'modular' as opposed to 'universal' systems, arguing that modularity was a more efficient and effective alternative to make robots applicable to a wide variety of workplaces. Warnecke argued that modularity would result in less sophisticated robots and improve the probabilities of adoption.

This type of study was strongly criticised by Engelberger (1976a) who pointed out the limitations of the data base which it used (little and non-standardised information, mainly concerned with early prototypes), and the lack of consideration of the most important aspects of robots (i.e. their dynamic characteristics). Moreover, he uncompromisingly stressed that increasing sophistication

"will continue to be deemed THE direction for robotic development" (pJ4-56) wherever technically and economically feasible.

From the actual pattern of development of robots examined in this chapter, it would seem that sophistication has indeed been the predominant direction. However, modular systems have also been produced successfully. In general, actual robot development has proved the old universal versus modular robot controversy to be artificial. Universality and modularity are in reality fairly limited, and have performance disadvantages. Trends, such as the design of robots for particular applications, have become more important (see table 5.2).

Several fundamental categories of robots can be identified (see table 5.3). These categories have changed along the path of robotic development. Some have become more common whereas others are nowadays rare.

The frequency of models having a certain combination of memory systems, positioning control, and degrees of freedom is shown in table 5.3. This illustrates which categories of commercial equipment are most common. Twelve categories of robots are theoretically possible, eight of these had a significant share of the models marketed before 1972, but only four can be seen to have a significant proportion by 1977.

Thus, robot development has resulted in four major categories:

I: Pick-and-Place Devices (PPD): fixed sequence non-servo manipulators with low positional versatility ($\lesssim$ 4 dof).

II: Simple Robots (SR): variable but limited sequence non-servo manipulators with low positional versatility ($\lesssim$ 4 dof).

III: Medium Technology Robots (MTR): fully programmable servo controlled manipulators with low positional versatility ($\lesssim$ 4 dof).

IV: High Technology Robots (HTR): fully programmable servo controlled manipulators with high positional versatility ($\gtrsim$ 5 dof).

Pick-and-place devices, according to table 5.3, were by far the most popular before 1972, but then suffered a relative decline. Some of these devices had more than four degrees of freedom, but this type seems to have disappeared from the market. Pick-and-place devices have PTP control, and are mostly pneumatically actuated. They can achieve high levels of accuracy ($\lesssim \pm 0.5$mm) and speed (> 1000mm/sec) since positioning is done with fixed mechanical stops (they have a certain degree of adjustment of position). Programming is simply a matter of mechanically setting the stops.

Simple robots have maintained their share, but become consolidated in the low rather than the high positional versatility range. Although they make use of mechanical stops, they have a great deal of versatility, since several

positions per axis can be chosen. Similarly to PPD's, simple robots have PTP control, and are pneumatically actuated with high levels of accuracy and speed. Programming, however, becomes complex as versatility increases. In the case of simple robots, this is a matter of arranging pegs on boards according to the desired sequence in which the different axes will be actuated, and of adjusting the various mechanical stops. Some indication is already present (see table 5.3) that SR's will adopt programmable electronic controllers, mainly for the purpose of improving the communication between the system and its environment (e.g. faster set up, and monitoring and diagnosis capabilities). This confirms evidence presented in the previous section, and is also true of PPD's and special-purpose automation.

Medium technology robots are servo controlled and mark a qualitative step in robot evolution,,i.e. the step from mechanical constraint to information based, external control described in Chapter 3*. MTR's were common as variable but limited sequence devices with varying degrees of freedom before 1972. Since then, they have become established in the low positional versatility range and rapidly adopted programmable electronic controllers. An insignificant proportion still exists having variable but limited sequence and high positional versatility. These are likely to disappear from the market. Since position

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* A different version of MTR's is one making use of electrical stepping motors. Although they are non-servo, they achieve position control by other than mechancial means, and have virtually an unlimited number of positions per axis. Their performance has been disappointing.

is controlled by information, their accuracy and speed are less than that achieved by devices with mechanical stops. On the other hand, programming (teach-in) becomes easier and the communication between the robot and its environment is greatly enhanced.

High technology robots became the most common in 1977, registering the largest growth rate (29%). Ability to undertake complex contouring manipulation has always required the high command versatility of electronic controllers. MTR's and HTR's are mostly hydraulically or electrically actuated and have extended software capabilities (CP and computed path control for example). In summary they have added structural versatility that make full use of the high versatility of computer based controllers.

The ability of MTR's and HTR's to link the movements of the manipulator to all kinds of information from the environment opens many possibilities for technical development. Different development directions other than sensory perception exist, PPD's and SR's also have a large potential for evolution (e.g. software).

From an analysis of the pattern of invention and innovation in commercial robots, it becomes clear that the development of robots designed for specific applications is the most definite trend. The chronology in Appendix 4 confirms this view. A recent advert of Unimation clearly describes this established trend:

> "From the low cost 1000 series for simple transfer jobs to the sophisticated PUMA for assembly, there is a UNIMATE robot precisely suited for your application. As the founder of the industry and leader in the application of robotic technology, UNIMATION INC.

> knows that the one robot can't fill every job. That's why we make a full line. And that's why you don't have to settle for more or less robot than you need".
>
> (Unimation Inc., 1979, p108)

Five periods of commercial development can be distinguished according to the type of robot introduced (see table 5.2). General purpose ('universal') and modular robots played an important role in the early days, and continue to be successfully marketed at present. However, the introduction in increasing numbers of specialist robots is the most important feature. Success in adapting general purpose robots to particular applications, during one period, triggered off the introduction of specialist robots during another. The key applications were successively: diecasting/injection moundling, spot-welding, coating, arc welding and assembly.

Several people, diverging from the universal v.s. modular robot controversy, have pointed out since the early 1970's that the direction of robot development was that of the creation of families of specialist systems*. This does not imply a reversal to special-purpose design. It is simply, a realistic notion of what a robot should evolve to be: a versatile machine best applicable to a certain type of applications.

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* These actually include Engelberger (1976 a) and Warnecke et al (1974). However, the idea was particularly stressed by Ghali (1972, p6), Rooks and Tobias (1974, p372), Hagio and Ohta, (1974,p429), Hall (1976,p3) Schraft (1977, p50), Whitehall (1977, p28), Manufacturing Engineering (1978, p69), Rooks and Brock (1979, p744) and Zermeño-González et al (1979a, p143).

Rooks and Tobias (1974, p372) clearly explain the reasons for this pattern of development:

> "The simple pick-and-place unit was developed principally from applications in automatic assembly and the loading/unloading of linked machine tools, including presses. Generally these were large volume processes so that the units only needed to be programmed for a limited number of operations. In contrast the poly-operational robot was developed in a pioneering fashion to replace humans in a variety of tasks and not for any particular application. Up to now this lack of dedication has been necessary. The market was not large enough to allow the development of robots for particular tasks but now this is changing. Robots dedicated to particular areas are now beginning to appear, e.g. paint spraying packaging, assembly and welding. In view of this trend it is pertinent to look at the general fields of application now open to robots in relation to the design of present day robots."

Thus a process of specialisation, similar to that of early machine tools (see Chapter 3), has occurred as a result of the influence of other than purely internal technical factors. This brings us back to the fundamental idea that the advantage of robots is not only the degree of versatility, but also the extent of standardisation of the system. A less versatile but off-the-shelf machine adapted to a particular area of applications with a large market will always be a better choice than a general purpose robot. It has all the advantages of the general pupose robot, is simpler and less expensive, and is likely to achieve better performance and reliability.

5.3 Industrial Robots in Research and Experimental Development (see Table 5.4)

Many of the technical achievements reviewed in the above sections emerged from the continuous adaptation of robots to production processes.. Also various improvements have resulted from the work of academic, industrial, governmental, and other research institues. These institutions have especially been concerned with the testing of prototypes and subsystems needed for the development of advanced robots (i.e. sensory controlled and intelligent robots).

Different aspects of robot technology were the focus of research long before the invention of industrial robots (e.g. control, mechanisms, and artificial intelligence). It was not until the second half of the 1960's that robot technology started to emerge as a defined field of research. In 1970 the first symposium dedicated to industrial robots was held in the US. Soon afterwards, in 1972, the symposium took an international character which has increased rapidly ever since. The International Symposia on Industrial Robots (ISIR) are held annually in Europe, Japan or USA. Robotics can, nowadays, be considered as an established field of research.

The directions of research and development work are an indication of likely trends in commercial equipment. Changes in the focus of research are therefore very important, and are inferred from an extensive analysis of ten years of ISIR papers described in Appendix 3, and from a review of the main R & D projects around the world presented in Appendix 5.

Basic and applied research on artificial intelligence, control, and mechanisms relevant to robotics has been reported at the various symposia, but emphasis has always been put on experimental development work. According to the analysis of ISIR papers, the growth of experimental development can be divided into four distinctive periods: up to 1971, from 1972 to 1974, from 1975 to 1977, and from 1978 onwards*.

First Period (up to 1971)

This is a period characterised by little experimental development, mainly concentrated in Japan. During this period, experimental development evolved from two kinds of research: artificial intelligence and remote manipulation.

In the 1960's, research on pattern recognition and computer control of manipulators had little or no cross-fertilisation, and robots were being used only as testbeds of machine perception techniques (this was particularly true of British and American rather than of Japanese research). Later, the emphasis changed under pressure from the financial sponsors of this research (Frost and Sullivan 1974, p223 and 225). Efforts were then concentrated on improving the systems with a view to a more immediate application "to allow limited computers to control sensors and actuators in specific industrial contexts" (Frost and Sullivan 1974, p226).

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* ISIR papers represent the state of research some time before their publication (eighteen months according to Brock 1980). All the dates in Appendix 3 were therefore, backdated two years (the period of two years was selected for simplifying purposes, and as a conservative figure).

Advanced teleoperator technology made use of computers and sensory feedback to perform manipulative tasks. Experienced laboratories thus, had a sound basis for the application of this technology to manufacturing operations in the form of robots (Mosher 1964, p92).

Projects on artificial intelligence and telechiric devices were indeed frequently reported in the symposia during this early period of robotic development. The best examples of robots in artificial intelligence research were: (1) the robot vehicle "Shakey" developed by the Artificial Intelligence Centre of the Stan ford Research Institute, and (2) the robot "Freddy" developed by the Machine Intelligence Department of the University of Edinburgh for assembly tasks. In the area of teleoperators various projects linked to the nuclear and space industry in Europe, Japan and USA were reported during the first ISIR period. The multimoded remote manipulator system developed by the Charles Stark Draper Laboratory and the MIT Artificial Intelligence Laboratory, was actually tested in assembly operations and had vision and tactile sensory capabilities.

At the end of the first period, research projects on robot systems with sensory feedback were well underway, particularly in Japan. The first important advanced robots emerging from Japanese laboratories were: the 'HI-T-HAND EXPERT-1' a tactile controlled robot for packaging solid blocks, and the 'HIVIP Mk 1' a robot with vision for assembly operations, both developed by the Central Research Laboratory of Hitachi (see also Mitsubishi Electric Corporation and Electrotechnical Laboratory for early vision systems in Appendix 5).

Some outstanding work outside Japan already existed at the end of this period. The first programmable assembly machine with visual feedback was developed in the UK by the University of Nottingham.

Second Period (1972-1974)

Dramatic increases in experimental development, led almost entirely by Japan and USA, are characteristic of the second period.

Experimental development in the United States proliferated rapidly. Various exploratory projects were initiated to prepare the way for intensive research on advanced robot assembly, in laboratories such as, the Artificial Intelligence Lab. of Stanford University, the Stanford Research Institute, the Charles Stark Draper Lab., the Artificial Intelligence Lab of MIT, the Thomas J. Watson Research Centre of IBM, and the Westinghouse Research and Development Centre. Sensory controlled prototypes (tact, force and vision) were also under test, performing simple packaging and assembly operations in several US laboratories during the first half of this period (see GTE laboratories, GM Research, University of Rhode Island, and MIT Artificial Intelligence Laboratory).

In Japan, development continued to be intensive and new prototypes of advanced robots emerged - some of them were second versions of earlier systems. The most impressive achievement was the 'HI-T-HAND EXPERT 2' developed by the Central Research Laboratory of Hitachi, a tactile controlled robot capable of performing extremely precise insert operations at speeds close to that of human beings (for example, the insertion of pistons in cylinders with a clearance of

only 20 microns). This company also showed its lead in vision systems. A second version of the HIVIP, the HITACHI hand-eye system*, was developed. This adopted a new approach to the problem of vision. By limiting the workpieces to be identified and manipulated, and by controlling the environment (i.e. reducing visual noise) they came closer to a practical use of vision systems. In fact, several production trials of tactile and vision systems were conducted.

During this period, various other Japanese laboratories continued development work on advanced robot prototypes. For example, the Mitsubishi Electric Corporation had a computer controlled hand-eye system being tested for assembly of electric motor brushes into their housing; the Electrotechnical laboratory had laser tracking and TV systems for robot control, and a manipulator with torque control ability developed in collaboration with the Mitsubishi Electric Corporation; and Kawasaki Heavy Industries, the Japanese licensee of Unimation, was testing a computer controlled industrial robot with visual recognition of position and orientation of flat parts under high contrast conditions.

The R & D scene in Europe remained static. The University of Nottingham and Edinburgh continued to be the only institutions involved in experimental development of advanced robot prototypes, although others were engaged in different aspects of robotics: Olivetti (Italy) was conducting research on robots for assembly tasks; Berlin

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* Hand-eye or eye-in-hand or mobile visual systems are those which have the visual sensor located in the robot gripper.

Technical University had a flexible manufacturing cell* under test in collaboration with SIEMENS (FRG); the IPA (Institut fuer Produktionstechnik und Automatisierung) of Stuttgart University continued conducting research on work-place and robot characteristics (FRG); and the Swedish Institute of Production Engineering Research (IVF) had an intensive programme entirely focused on applications research.

Third Period (1975-1977)

Experimental development on robots diffused widely in Europe, USA and Japan, and became fully established during this period. Vision projects, in particular, were undertaken in many countries. Tactile and force sensory systems, although less common, were also actively developed, and new directions for force control evolved (75% of the papers on vision, and 63% of the papers on all kinds of sensory systems were delivered after the 1976 ISIR. Thus indicating a surge in sensor research after 1974).

Some multisensory controlled prototypes with two arms were produced and tested successfully in assembly applications. Effort seemed, in general, to be rather more orientated towards short-term practical problems. Sensory systems were increasingly conceived for tight industrial contexts. They became relatively simpler and less expensive (e.g. solid state arrays replaced TV cameras in vision systems).

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* It should be noted that in 1974 Kawasaki pioneered commercial flexible manufacturing systems in collaboration with Fujitsu Fanuc (See Appendix 4).

Research into applications also became relevant in areas such as flexible manufacturing systems and adaptable programmable assembly systems; development of programmable peripheral equipment was undertaken for the first time.

A further sign of a trend towards the development of integrated robot systems was the increasing importance of software and control systems, in particular programming languages for assembly, and computer based control.

In Japan, the Central Research Laboratory of Hitachi, the Electrotechnical Laboratory and the Mechanical Engineering Laboratory produced multisensory systems with two arms for assembly operations. The Hitachi system was, again, an impressive prototype with vision and tactile sensing successfully tested in the assembly of vacuum cleaners. Other Japanese developments were orientated to simpler sensory systems, such as the distance sensor of Nagoya University and the piezoelectric tactile sensor for micromanipulators of the Tokyo Institute of Technology.

In the USA, the exploratory investigations on advanced robot assembly, and the work on vision systems started in the second period, yielded excellent results.

The work of the Charles Start Draper Laboratory (CSDL) on the analysis of forces in assembly processes resulted in the design of the remote centre compliance wrist (RCC), a means of accommodating position and alignment errors in the mating of parts in assembly processes. This device was successfully tested on a high speed robot system for the assembly of automobile alternators.

Wrist force sensors developed by SRI International and the CSDL also seemed to have potential for commercial exploitation (Abraham et al 1977c, p6). SRI International demonstrated with success, the use of force feedback for riveting applications.

Several industrial projects on assembly systems reached the prototype stage and underwent production trials. The Westinghouse Electric Corporation, under its APAS project, tested a pilot production line consisting of seven robots, and different kinds of peripheral equipment in the assembly of five different electric motors with seventeen parts each. General Motors developed the robot PUMA in collaboration with Unimation, and installed assembly systems for the inspection of printed circuit boards. Unimation had another assembly project at an advanced stage: the Unimate 6000 robot with two arms developed jointly with Ford Motor Co., and tested in the assembly of C-6 governors.

Mobile and static visual systems were under investigation in various USA laboratories. The most important and closest to commercial exploitation, were the eye-in-hand robot of SRI International, the complex vision system of the University of Rhode Island, and the CONSIGHT vision-based robot guidance system of GM Research (GM described CONSIGHT as "probably the first practical approach in the US to picking up orientated parts from moving conveyor belts - Financial Times 1979).

Development of software for programming and manipulator path control with sensory feedback was conducted in the GTE Laboratories, SRI International, Stan ford University

Artificial Intelligence Laboratory and by Cincinnati Milacron.

During this period experimental development increased dramatically in the Federal Republic of Germany (FRG). Furthermore it took on an organised and fully integrated character. In general all projects were highly orientated towards specific applications, and towards the development of integrated robot systems. Flexible manufacturing systems and adaptable programming assembly systems were under test in Berlin Technical University, Zahnradfabrik Friedrichshafen and IPA of Stuttgart University. They were also engaged in work to develop computer-based control systems, programming languages, and programmable peripheral equipment. Projects to develop sensory systems were also undertaken in the IITB (Institut fuer Informationsverarbeitung in Technik und Biologie), IPA, Berlin Technical University, and in Karlsruhe University. Tactile sensors, in particular were used for metal cutting operations.

Experimental development on robots spread to other European countries. Vision systems research was being conducted in the UK, France, Finland and Switzerland. The most advanced project on vision, with a large potential for commercial exploitation, was that of the Swiss firm Brown Boveri ("The system will not be available from Brown Boveri's Heilderberg, West Germany, Plant until the end of the year - Wood 1979). Flexible manufacturing systems were tested in Sweden and Norway. Computer-based control systems and programming software were under development in Italy and the UK.

Fourth Period (1978-1980)

This period is characterised by a further increase in European activity particularly in Italy.

Projects on vision systems of a relatively simple nature spread widely. More prototypes, beside the CONSIGHT and Brown Boveri ones, came closer to commercial introduction: the Kawasaki and Unimation vision systems. Complex vision prototypes, although less common, were also fairly advanced in the University of Rhode Island and in SRI International (work is being undertaken to reduce the response time of the systems). Other systems such as tactile and force sensors and the remote centre compliance wrist continued being improved and were tested in different applications (see Tokyo Institute of Technology, Jet Propulsion Laboratory and IPA of Stuttgart University).

Voice recognition for partial programming of assembly tasks was introduced by SRI International and similar work is being conducted at the Tokyo Institute of Technology. Other projects to enhance communication between robot and humans by improved software took place in Cincinnati Milacron and Milan Polytechnic.

Some of the new and outstanding application systems were: the APAS prototype with compliance and vision developed by IPA of Stuttgart University and those of the USA electronic companies, IBM and Texas Instruments.

More projects for the development of flexible peripheral equipment and end effectors were undertaken. This represented a continued effort to create integrated robot hardware.

5.4 The Future of Industrial Robots

The development of robots has frequently been classified into different generations. Driscoll in 1972 identified three advanced generations of minirobots of increasing sensory perception and adaptability (in contrast to the large capacity machines). Later on, Frost and Sullivan (1974), and Heginbotham (1976) extended Driscoll's categories, identifying intermediate stages of robot development. The following are, broadly, the characteristics of such generations:

1. Generation 1.0. These robots have extremely limited interaction with the environment, and are fundamentally controlled by pre-memorised information. Sensory information is used, in the most sophisticated versions, for the selection of routines, but normally communication between the robot and the environment is reduced to synchronisation of robots and peripheral equipment. Present-day commercial robots belong to this generation of memory controlled open-loop machines (this categorisation excludes PPD's and SR's). Their servo mechanism is limited to internal position and path variables, and their versatility consists largely of programmability (command versatility).

2. Generation 1.5. These machines are a first approach to the introduction of sensory control (the first vestiges of adaptability). They still operate following pre-programmed routines but have dynamic overrides of the working cycle based on sensory information (i.e. force, torque, simple vision or touch). During the interruptions of memory-controlled behaviour they become actuated by sensory-motor routines (i.e. prescribed interactive robot procedures). They make use of simple rather than complex pattern recognition and their adaptability is limited. "Their success has resulted from applications involving a minimum of sensory interactions by intelligent identification of industrial needs, not by the unintelligent use of machine intelligence" (Heginbotham 1976, p128). This intermediate class of robots is either the result of the adaptation of generation 1.0 machines by the addition of sensors and computer hardware and software, or newly developed prototypes (some examples are the Hitachi HI-T-HAND EXPERT-1 and HIVIP Mk 1).

3. Generation 2.0. These are highly interactive robots with eye-hand coordination capability (i.e. sensory control of manipulation on a real-time basis, with limited pre-programming of position path). These machines are still being developed in laboratories but are close to achieving commercial application. Their ability to recognise

patterns, position and orientation is limited to certain contexts (limited number of objects to be recognised and handled and need for certain rearrangement of the environment). For example, they would be used to pick-up a moving part from a conveyor, to remove a jammed part, to pick-up a dropped part or tool, to clear away scrap, to retrieve objects and to position objects precisely under conditions of visual noise (Driscoll 1972, p199) (e.g. Hitachi HAND-EYE SYSTEM, Nottingham SIRCH robot and Mitsubishi eye-in-hand robot).

4. Generation 2.5/3.0. These are fully interactive and 'intelligent' robots. They would be similar to present day testbeds for artificial intelligence research (e.g. MIT, Edinburgh University, SRI International and Standford University). The development goal is to produce perceptual motor skills and practical (production-orientated) problem-solving capabilities, thus putting machine intelligence in a limited context. Advanced robots, according to Frost and Sullivan (1974, p222), would have the capability to plan the system according to production goals and according to information about the manufacturing process.

This classification of robots has often been used to describe the state-of-the-art and to forecast the future of robot technical and market development. Early attempts to forecast, generally underestimated the problems along the path of producing economically feasible prototypes of advanced robot generations. For example, Frost and Sullivan (1974) predicted generation 2.0, 2.5 and 3.0 to be commercially available by 1977, 1980 and 1983 respectively. Nevertheless, the descriptions of the future generations given in these reports correspond closely to what has happened in practice since their publication. They emphasised the need for limited perception and intelligence rather than for universal human-like adaptability.

Engelberger (1972, 1974a and 1979) has also frequently described the future attributes of robots (see Table 5.5). He did not expect advanced generations to be commercially available in the 1970's. Referring to the highest echelons of robots, Engelberger clearly pointed out in 1972: "The route from the black and white world of the laboratory to the dirty, grey and brown world of the factory is one fraught with pitfalls. The development of a sentient robot may even turn out to be a romantic exercise" (p214). In the field of sensors too, he has stressed the need to focus on simple approaches (rudimentary vision and tactile sensing). "Ordinarily, those involved in character recognition are interested in identifying objects but that is not the problem in the industrial robot area. It is only necessary to know where everything is and not what it is. One would never expect to see a Chevrolet come down one of Ford's assembly

lines!" (Engelberger 1979, p116).

From the analysis presented in the above sections of this Chapter, it has become clear that a pragmatic approach to robot development has predominated. Both experimental development and innovation in industrial robot technology seem to have undergone a similar transformation: they have, as the diffusion of robots gathered momentum, become focused on producing versatile but specialised technology (context dependent versatility). Consequently, a diversification of systems has taken place so that each of these are best tailored to particular groups of applications.

Recent studies of the state-of-the-art and the future perspective of the technology have, thus, put emphasis on an analysis of robot applications (see Yonemoto and Shiino 1977, and Evans et al 1978). An excellent exercise in Delphi forecasting which brought together thirty-one researchers, manufacturers and users was organised by the Robot Institute of America (RIA) and the National Bureau of Standards (NBS) in 1977. They studied the development priorities of eight different types of robot systems and produced a scenario similar to that of Table 5.5. This emphasised the need for and the likelihood of, simple sensory systems becoming commercially available. The following are some of the main conclusions which can be drawn from this study (Evans et al 1978)* .

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* Conclusions relevant to different applications will be discussed later in the thesis.

1. Simple sensors, especially touch, offer the most immediate economic benefit for a user (63% priority, as opposed to 22% priority for complex sensing).

2. Simple sensors, especially simple vision, have the first priority in research into sensors to provide the highest long term benefit (simple vision has 34% priority).

3. Existing imprecision should be easily accommodated by simple vision. This is also true of moving line applications.

4. The most important performance characteristics are, in decreasing order of importance to all applications: high positional accuracy, high slewing speeds, fast short moves, sensor directed control, fast programming and off-line programming (see Table 8.3).

5. Simple sensors will reach commercial availability before 1980, and complex sensors before 1983 (1980-1985). (Now in 1980, I can only say that some commercial simple vision systems are about to be introduced).

6. A shift was foreseen in the middle and late 1980's away from simple and medium technology robots ("the simple bang-bang, and point-to-point servo control systems", p1) to the more sophisticated computer control that would perform coordinate transformation and sensory feedback control.

7. Off-ine programming and higher level languages will become commercially available before 1982 and automatic programming before 1986.

An assessment of the present state of robot technology performed by Abraham et al (1977c) positively concluded that "A technology base exists upon which it appears possible to develop adaptive, programmable assembly systems". They pointed out some weaknesses, and identified directives for research and development which are, indeed, relevant to all kinds of robot systems:

1. Little work has been performed on programmable parts presentation and fixturing equipment.

2. "No demonstrated software system exists which provides executive level control or supervison, to handle style changeover, or to handle sensor-based adaptive control of the manipulator path" (p13).

From the review of robotic research and development it would seem that the trends to fill these gaps (integration of hardware and software into a robot system) have already started (e.g. the work of SRI International on software for sensory control). A focus on specific robot applications is also a sign of the concentration of effort in developing other elements of the systems and the technology for their integration.

Finally, Hewit (1979, p13-14) made "a number of specific proposals for immediate attention". He stressed fundamental problems, some of which are not commonly identified:

1. Improvement of speed by either faster computational methods, or different control algorithms to avoid kinematic problems.

2. Need for a stronger base in mechanical design and better design of actuators ("Many USA workers feel that in the past a disproportionate amount of resources has gone to AI - due to military potential", p14).

3. More attention to flexible manipulators (potential for lower costs).

4. Standardisation of computer software.

5. Development of control theory of robot dynamics.

These directives are important in that they relate to robot performance and thus, to the competitiveness of robots over other technical alternatives.

TABLE 5.1 - Summary of Technical Improvements to Commercial Robots

Structural Versatility

1. Workspace command with six infinitely controllable articulations between the robot base and a hand extremity
2. Mobile robots on floor tracks or gantry structures.
3. Ceiling mountable robots.
4. Weight handling capacity up to 150 kilogrammes.
5. Modular construction of different extents.
6. Flexible wrists (almost infinite combination of motions, compact wrist).
7. Mountable counterweights for increased load capacity and accuracy.
8. Versatile grippers (multifinger grippers and facsimile grippers).
9. Double handed robots.
10. Multiarm robots.
11. Remote centre compliance wrist mechanisms.
12. Prosthetic compact structures.

Command Versatility

1. Local and library memory of any size required (punched tape, magnetic tape, floppy disc and semiconductor memories).
2. Random programme selection by external simuli.
3. Intermix point to point and path following control.
4. Compatible computer interface.
5. Computer control (teaching in natural coordinates, straight line path motion, control of velocity and acceleration along the path, data storage in non-robot coordinates and tracking of moving objects or synchronisation with conveyors).
6. Feedback information sampling rate change - varying accuracy and memory capacity.
7. Fast "hands on" instinctive programming or teach-in (in its various forms: pendant, manual and dummy teach-in).
8. Monitoring routines (display of the robot's position, automatic diagnostics).
9. Simple sensory systems (e.g. pneumatic, electrical, magnetic on/off devices, optoelectronic and T.V. vision, weld tracking systems).

Performance and Other Characteristics

1. Positioning repeatability to 0.3mm
2. High reliability (at least 400 hour MTBF see figure 9.1).
3. Safety procedures and devices.

Sources: Engelberger (1972, 1974b, 1979) and Winship (1979) complemented by Hohn (1978), Potter (1977) Kirsh (1976), Dawson (1977) and Laerdal (1976).

TABLE 5.2 - Synopsis of Events in Invention and Innovation of Robot Technology

1st Period (before 1968)

1. First generation of HTR's (Unimate and Versatran) is introduced into the market as multipurpose machines (Drum/matrix programmable controllers with limited memory and five degrees of freedom manipulator). These were first introduced into diecasting.

2nd Period (1968-1972)

1. Continuous path HTR's are introduced into the market as coating devices (e.g. Trallfa).

2. Simple robots emerge as competitors of HTR's in certain applications (e.g. Prab, Aida, Electrolux, VFW-Fokker, Kaufeldt).

3. First trials on arc welding (e.g. Hawker Siddeley Dynamics Engineering Versaweld in the UK, Westinghouse, in the US, Kawasaki in Japan).

4. PPD's are still the most abundant in the market.

5. Second generation of HTR's is introduced (unlimited memory and six degrees of freedom).

3rd Period (1973-1975)

1. Continuous path HTR's are introduced into the market as arc welding devices (e.g. Trallfa and Kawasaki Unimate).

2. More HTR's for coating are introduced (e.g. Retab and Ramp).

3. Assembly becomes the target of commercial development.

4. First trials on commercial flexible manufacturing systems (e.g. Kawasaki Unimate and Fujitsu Fanuc).

5. Modular construction gets adherents (e.g. Versatran, Electrolux, Autoplace).

6. Prosthetic configuration and minicomputer control with increased software capabilities, such as random programme selection, moving line synchronisation, and external coordinates teach-in method, starts to spread (e.g. Cincinnati Milacron).

Continued/....

TABLE 5.2 (Continued)

4th Period (1976-1977)

1. A wave of introduction of specialist HTR's for spot welding and arc welding occur (e.g. Kuka, Sciacky, Renault, Volkswagen, SAF + Languepin, Retab, ASEA/ESAB, BOC /Hal, and Comau).

2. Simple vision (optosense) system for SR's is introduced by Autoplace in the USA.

3. Commercial flexible manufacturing systems with robots spread (ASEA and Cincinnati Milacron).

4. New PPD's are introduced for diecasting and injection moulding applications.

5. HTR's become the most abundant, with MTR's following.

6. Floppy disc memory starts to replace cassettes.

5th Period (1978-1980)

1. Teach-in programming is widely used. Teach-in plus editing starts to become popular.

2. A new trend of minirobots for assembly operations is started by PUMA (Electrically actuated and computer controlled).

3. Advanced assembly undergoes factory trials.

4. Simple vision systems for HTR's comes near to commercial introduction (Brown Boveri and General Motors systems).

5. Solid state memories are adopted in robot control systems (e.g. Ramp and Boc/hal).

6. Policies for diversification (the marketing of robot families) becomes fully established.

7. Problem-oriented language and other software capabilities become the feature of innovation.

TABLE 5.3 – Pattern of Change in the Categories of Industrial Robot Types – Proportion of Existing Models (%)

(a) Before 1972 (Estimated from a sample of 140 robots reported in Lundstroem et al 1972)

		Memory System				
		Fixed Sequence	Variable Sequence (limited)	Electronic		
Degrees of Freedom	≤4	45	18	0	Non-Servo	Positional Control
	≥5	5	5	1		
	≤4	0	7	6	Servo	
	≥5	0	8	6		

Continued/....

TABLE 5.3 (Continued)

(b) Between 1972 and 1977 (Estimated from a sample of 75 robots reported in Abraham et al 1977c)

		Memory System				
		Fixed Sequence	Variable Sequence (limited)	Electronic		
Degrees of Freedom	≤4	20	25	5	Non-Servo	Positional Control
	≥5	0	0	0		
	≤4	0	0	12	Servo	
	≥5	0	3	35		

TABLE 5.4- Synopsis of Events in Robotics Research and Experimental Development

1st Period (Up to 1971)

1. Little or no direct experimental development on industrial robot technology exists.
2. Projects on robot technology start to emerge from research on artificial intelligence and remote control manipulation.
3. Pioneering work on advanced robot prototypes is conducted mainly in Japan, and to a lesser extent in Britain.

2nd Period (1972-1974)

1. Dramatic increase in experimental development led almost entirely by Japan and USA.
2. Experimental development proliferates rapidly in the USA (Numerous exploratory projects on adaptable programmable assembly systems and on sensory control start in academic, industrial, government and other institutes).
3. Second versions of advanced robot prototypes emerged in Japan and first robot integrated flexible manufacturing systems are tried.
4. R & D scene in Europe remains static, with Britain continuing pioneering work on assembly with visual feedback.

3rd Period (1975-1977)

1. Research and development spreads widely and slowly becomes more orientated toward integrated application systems.
2. Vision systems spread most and new directions of force control emerge. The remote centre compliance is invented.
3. Multisensory robots are tested for assembly operations in Japan.
4. Sensory perception is increasingly conceived in an industrial context.
5. Development of adaptable programmable assembly systems (APAS) and of flexible manufacturing systems (FMS) continues.
6. Development of integrative hardware and software becomes relevant e.g. projects on programmable peripheral equipment and programming languages.

Continued/....

TABLE 5.4 (Continued)

4th Period (1978-1980)

1. Simple vision feedback systems continue to spread, particulary in Europe and reach the point of commercial exploitation.

2. Some tactile and force sensors continue to be under test, and the remote centre compliance wrist is tried in industrial applications.

3. Development of peripheral equipment, grippers and integrative software increases.

4.. Communication with robot systems gathers importance since various programming languages are under development and new features such as voice recognition become important.

TABLE 5.5 - The Future Technical Attributes of Commercial Robots

Robot qualities sought and to be commercially attained before 1984 according to Engelberger (1974a p162 and 1979, p116).

1. Rudimentary vision
   (a) Orientation data
   (b) Recognition data

2. Tactile sensing
   (a) Orientation data
   (b) Physical interaction data
   (c) Recognition data

3. Computer interpretation of visual and tactile data

4. Multiple appendage hand-hand coordination

5. Computer directed appendage trajectories

6. Mobility

7. Minimized spatial intrusion

8. Energy conserving musculature

9. General purpose hands

10. Man-robot voice communication

11. Inherent safety (Asimov's Laws of Robotics)

CHAPTER 6

INTERNATIONAL DIFFERENCES IN THE ADVANCEMENT OF ROBOT TECHNOLOGY

6 - INTERNATIONAL DIFFERENCES IN THE ADVANCEMENT OF ROBOT TECHNOLOGY

6.1 Development (see Table 5.4)

The measurement of the output of research and experimental development presents serious difficulties. These were examined in a report by UNESCO in 1970:

> "...the output of all stages of R & D activity is a flow of information and the final output of the whole system is 'innovations' - new products, processes and systems. This information is conveyed in various forms and through various media, with varying degrees of secrecy or freedom... Some parts of the information flow are captured in well-established accessible forms. The best-known examples are published scientific papers and patents... it must be conceded that if we are able to measure that part of the information flow which is embodied in scientific papers and in patents, then we would in principle be able to measure at least part of the output of R & D activity ... It is argued that the results of empirical work already justify the use of scientific papers and patents for some output measurement purposes, despite the severe difficulties and limitations involved (UNESCO 1970, p333-336)

In the case of robot technology, one such well-established and accessible form in which information from development activity is contained, are the proceedings of the various international symposia on industrial robots. The international and institutional characteristics of the development of robots in various countries can therefore be inferred from their contributions to these symposia. Despite the various limitations (see appendix 3), this indicator provided useful information (patent statistics were less accessible and hence, not used).

Development activities were divided into those concerned with the improvement of the technology (research, experimental development and innovation) and those focused

on the study of its application to industry. Differences in the emphasis given to these types of development were remarkable. Robot development increased dramatically at the beginning of the 1970's. Its rate of growth has augmented steadily and now averages forty-one per cent per annum (the compound rate of growth of the cumulative number of papers delivered at the ISIR, see figure 6.1). Development was largely concentrated in the USA, Japan and FRG up to 1977. In the fourth period (1978-80) their combined contribution declined relative to the rest of the world. Other European and the Comecon countries joined efforts in the advancement of robots (see figure A3.8 and A6.2).

American industry played a pioneering role in the organisation of the international symposia on industrial robots. The transfer of technology from the USA to Japan and Western Europe preceded awareness from most universities and other laboratories (the Electrotechnical Laboratory in Japan is one exception). The first two symposia were dominated by US industry, and the third by her West German counterpart. These three symposia therefore focused on the study and promotion of robot applications. In the fourth symposium, Japan started to change the focus towards research and experimental development. Nowadays, the symposia have become a place for reporting experimental work thanks to the growth in research and experimental development adctivity in various countries(ISIR papers have become more representative of R & D activity).

Various leaps in the level of development activity can be observed in figure 6.2: Japan (1972, 1975), USA (1973, 1977), FRG (1971, 1976), UK (1974), and Italy (1978). These also correspond to the dates when countries hosted the symposia (except for 1971 when Switzerland was the host). According to the magnitude and kind of host country contributions the following leaps are considered more representative of development activity, especially of research and experimental development: Japan (1972, 1975), USA (1973, 1977), and FRG (1976)*.

Japanese activity did not become apparent until the international symposium was held in Japan. Her contributions suddenly surpassed those of the FRG in the fourth symposium. This was representative of the level of activity in government, industry, and universities initiated at the end of the sixties. Japan led particulary in research, experimental development, and innovation overtaking the USA in 1972 (see figure 6.4). The USA in an effort to catch up with Japan, quickly intensified experimental work in universities and in industrial and other laboratories in 1973. The dramatic increase in robot development in the FRG in 1976, especially in experimental development, must also be seen as an intensive response to the activities of the USA and Japan. West German efforts increased fast and joint research programmes were undertaken by universities, industry, and government.

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* The kind of Italy's contribution to the 10th ISIR was not known at the time of writing. The leap in the number of papers is smaller than the rest, except for the UK.

The UK was a pioneer and a leader in experimental development in Europe up to 1976. This was the result of work entirely conducted in universities. Academics and other researchers organised the first and second international conferences on industrial robot technology in 1973 and 1974 and later joined efforts with the organisers of ISIR symposia. British industry, in contrast, contributed little towards development work in robotics. No contributions to the study and promotion of applications are noted in figure 6.3.

Italy followed the UK closely, and finally overtook her at the end of the seventies. Italy's contribution appears finely balanced, since it came from all kinds of institutions. This was not so in the case of Sweden, where most of the work was carried out by industry. Little experimental development was undertaken, especially when compared to the level of activity in the study and promotion of the application of robots.

6.2 Supply and Manufacture (see Table 6.1)

A vast number of firms have introduced their own robot prototypes into the market since the first signs of business potential appeared at the beginning of the seventies. Various kinds of licensing and distribution agreements have also played a major role in robot supply and manufacture, particularly in Europe.

The growth in the number of robot models and firms, and in the capacity of supply can be broadly divided into three periods: (1) before 1968, (2) from 1968 to 1974, and (3) from 1975 to 1980 (see figure 6.5). These are

respectively a period of very low activity, rapid take-off and relative decline in the number of firms and models. Supply capacity has grown steadily (see figure 6.6).

First Period (before 1968)

Commercial ventures around the world stemmed mainly from the pioneering firms Unimation (Unimate robot) and American Machinery and Foundry (AMF) (Versatran robot) in the USA. As early as 1965, three years after the initiation of commercial operations, the Unimate licence was bought by GKN in the UK. Later, Hawker Siddeley Dynamics Engineering (HSDE), also a British company, followed suit, transferring the Versatran technology.

The first attempts to build up a manufacturing capability with native technology outside the USA were made in Scandinavia and Japan (Trallfa and Nissan). These were signs of a strength in robot supply and manufacture that continued to grow in later periods.

The circumstances in which robot invention and innovation took place and the characteristics of the robot firms are of a varied nature and often radically different.

Mr. Joe Engelberger founded Unimation in association with the Unimate inventor Mr. George Devol, in 1962. Development work started in 1958 once Engelberger was able to raise twelve million dollars (Engelberger 1976c, p487). The initial operation was small. The first five prototypes and an additional batch of seventy five robots were "manufactured by hand" (Cakebread 1978). Soon afterwards the business needed a large injection of cash and

Unimation was taken over by two large companies: Condec and Pullman. The former, a company involved in the manufacture of control equipment, provided eighty percent of the capital; the latter, a general engineering corporation, provided the remaining twenty percent.

American Machinery and Foundry (AMF) started development work shortly after Unimation and introduced the Versatran system into the USA market in 1963. In an effort to diversify its business, which included teleoperators, AMF formed the Automatic Division. After the introduction of Versatran, this firm continued to invest in development work and later invented continuous path control (CP).

Acknowledgement for pioneering work on CP control must also be given to a small company outside the USA. Trallfa Nils Underhaug, manufacturer of wheelbarrows in Norway, started a robot project in 1963. Mr. Ole Moulag decided to build a machine for the automation of an extremely obnoxious task: the paint spraying of wheelbarrows (due to the concave shape of wheelbarrows, spray is blown back towards the operator). He set out to reproduce the movements of waist, shoulder, elbow and wrist, and built a continuous path robot. Trallfa manufactured their robot for in-house use only. It was not until 1969 that they introduced the robot sprayer into the market.

Another firm motivated by the potential use of robots inside their own plants was a large automobile company in Japan: The Nissan Corporation. The first machines (1967) were of the PPD and SR types, especially designed for simple transfer in operations such as pressing and diecasting

(Gonsalves and Kurlat 1977, p8).

The American licensees in the UK were both large companies pursuing diversification policies. Hawker Siddeley Dynamics Engineering had suffered from a slow down in demand caused by a decline in missile production, and was looking for new markets. Being in the aerospace sector, HSDE had a suitable infrastructure for making high technology: skills and experience in hydraulics, mechanics, electronics and control, and manufacturing capacity for high precision components. Being in general engineering GKN had a wealth of shop floor experience in many of the types of manufacturing operations where robots are used. To provide the necessary technical expertise and to manage the Unimate project, GKN bought a small firm of five people (Industrial Control Systems) whose director was Mr. Roger Cakebread. Both GKN and HSDE made licence agreements which covered manufacture, freedom to modify design, and further development of the technology. GKN and HSDE set out to supply the European as well as the British market.

In the FRG, VFW-Fokker introduced an SR (the transfer-automat). Soon afterwards this firm realised that the West German market was undeveloped and sold the licence to Japan.

Second Period (1968-1974)

A sudden take-off in the number of firms and models occurred in this period. Japan showed an impressive rate of growth, greater than Europe and the USA. Scandinavia achieved a relatively large manufacturing capacity, whereas in the UK, FRG, and Italy supply grew slowly. A very large number of the commercial ventures of the period were

unsuccessful and did not pass the prototype stage. Engelberger (1976c, p48) wrote: "Worldwide there have been close to two hundred product developments that, on average, have attracted $200,000 each in financial support, half of these are already abandoned". Only fifteen out of thirty-five firms in the USA, and thirty out of more than one hundred in Japan, Tassel (1975) stated, had already sold substantial numbers of robots. In Europe, for example, various firms suddenly decided not to introduce excellent prototypes due to the lack of finance for development work and of market demand.

Many of the new ventures were PPD's and SR's. Prab and Autoplace in the USA, Aida in Japan, Kaufeldt and Electrolux in Sweden, VFW Fokker in th FRG, B&R Taylor in the UK, and Norda and MAS in Italy, were the most important examples.

The main Japanese arrivals were all large firms involved in electrical machinery, machine tools, motor cars, and electronics (e.g. Kawasaki Heavy Industries, Fujikoshi, Yaskawa Electric, Fujitsu Fanuc, Hitachi, Mitsubishi, and Toshiba). They produced indigenous technology and were also eager to transfer foreign makes such as Unimate, Trallfa and Electrolux.

In the USA, Sundstrand Corporation and Robotics were important arrivals. The former was a large manufacturer of conventional and NC machine tools. The latter was a small firm entirely orientated to the robot business and founded by Mr. Ralph Mosher, an expert on teleoperator technology and former employee of the Advanced Technology Laboratories of General Electric Research. Other prototypes were developed

by General Motors and IBM for in-house use only and were discontinued later.

The Scandinavian entries were all Swedish. The Industrial Systems Division of a large manufacturer of domestic appliances (Electrolux) decided to design their own robot. After searching the market, Electrolux realised there was no machine to satisfy their requirements and produced a simple robot for in-house use. Soon afterwards other Swedish firms such as Volvo, Esab and Atlas Copco showed interest in buying the Electrolux robots. The robot was introduced into the market in 1971 and was quickly transferred to many other countries. Later Electrolux became the marketing agent for Unimation in Scandinavia.

Another large Swedish firm entered the business with one of the most sophisticated robots of the time. Like the rest of Scandinavian firms Asea, a manufacturer of electrical machinery, originally developed the robot for in-house use only.

Italy appeared late, but from the beginning it produced important indigenous technology. SIV developed the first robot specialised in spot welding (Deltix 6) in 1969. The large maker of office equipment Olivetti created a sophisticated machine for assembly operations. They first installed Sigma robots in their own plants in 1973, and later formed a division to market them in 1976. Other companies in Italy were already conducting development studies: Coman Industriale (1971), Basfer (1973), Camel (1971), Norda (1970), and Speroni (1974) (see Varvello 1980, p24).

In the UK, the situation did not develop as expected. B&R Taylor, a builder of special machinery and teleoperators, developed a simple robot in 1968. Six prototypes were produced and tested in machine-loading applications. The market did not develop fast enough, and the firm left the robot business. The enthusiastic arrival of HSDE and GKN in the first period met with similar disappointment. GKN dropped the Unimate license in 1969, and HSDE withdrew the Versatran robot from the market in 1974. Unimate continued to be supplied to the British and European market through a new subsidary of Unimation. All the GKN personnel involved in robot supply were employed by the new agency under the direction of Mr. Roger Cakebread.

New entries into the UK market were the British United Shoe Machinery (BUSM) and Hall Automation. BUSM bought the licence of an MTR, which used stepping motors for actuation and positioning control, from their parent company in the USA. Hall Automation developed the first British HTR, the robot Ramp for spraying. This firm was started by the former director of the Automatic Handling Division of HSDE and a leader in its involvement in the robot business, Mr. Douglas Hall. From HSDE Hall moved to the Pye Group, a large firm involved in electronics, and initiated robot development. Ramp was jointly developed with a maker and a supplier of spraying equipment: Binks Bullows. This was a move to complement the technical expertise of the Pye Group with the marketing skills and experience of Binks Bullows. Soon afterwards Hall left the Pye Group and formed his own firm. He bought the design of Ramp, obtained a lease from the Pye Group and continued the venture with Binks Bullows.

Fundamental for the establishment of Hall Automation (HA) was the transfer of personnel from HSDE and the Pye Group. Eighty per cent of HA employees (twenty-one people by 1978) worked in the Automatic Handling Division of HSDE where they acquired crucial skills and experience.

In this period the Versatran licence was bought in the FRG by FVW Fokker which also re-introduced the Transfer-automat into the market. Agencies supplying the internationally successful makes (Unimate, Trallfa, Electrolux and Aida) were operating in West Germany by 1974.

Third Period (1975-1980)

Some evidence that growth in the number of firms and models started to decline after 1974 exists. This, rather than an indication of market saturation, must be seen as a sign that the industry was leaving its infancy. The manufacturing capacity of individual firms grew substantially and the leader maker, Unimation, became profitable for the first time after fifteen years of painstaking development work and commercial losses (its R&D budget was approximately $1.8 million per year). Despite the relative decline in new entries, commercial activity was high. New ventures, take overs and other commercial agreements were frequent. New ventures stemmed particularly from the involvement of the major motor car companies in spot welding applications. A wave of new PPD's was led by manufacturers of diecasting and injection moulding machines. Large electronics firms were planning to introduce small robots for assembly operations. Various large groups achieved a quick entry into the business by taking over firms with experience in supply

and manufacture of robots. Marketing agreements between robot manufacturers and firms with experience in particular markets became common. Other agreements such as for distribution continued to be made.

The most important American entry was Cincinnati Milacron, a large machine tool manufacturer with stakes in the NC range of the market. Cincinnati Milacron (CM) introduced a minicomputer controlled robot in 1975. By the end of this period, agencies in various European countries were established, and plans for massive involvement in the business existed (Brock 1980 and Allan 1980). CM exemplifies the type of firms which will enter the market in the future: multinationals with long experience and a gargantuan infrastructure for developing, making, marketing and servicing high technology. The cost of entry to the robot industry has radically increased with the accumulation of experience and the growth of capacity of individual firms. Plant manufacturing capacities are still far from achieving the minimum levels at which economies of scale start to become significant. According to Hall (1978) and Cakebread (1978) these minimum levels lie at the 1000/2000 robots per year when most of the components are bought from outside contractors (see figure 6.6). Despite this, successful firms have significantly increased reliability (see figure 9.1) and reduced costs, and have started to rationalise robot manufacture. Any new comer must invest larger sums of money than in the past, and must have the resources to compete against established firms.

Prab bought the Versatran licence from AMF and planned its re-introduction into the American as well as the European market. Unimation took over Vicarm and carried out projects

in collaboration with motor car companies (Ford and GM) with the purpose of stepping up their involvement in the assembly area. Several electroncis firms in the USA were planning the introduction of robots for assembly (e.g. Texas Instruments, International Business Machines and Digital Equipment Corporation. See Bylinsky 1979, p90 and Marsh 1980a, p641).

The number or Japanese firms continued to grow. Cooperation between motor car companies and robot manufacturers was commonand resulted in more specialised robots for spot welding (Toshiba and Kawasaki in collaboration with other Japanese automobile firms developed a multiarm robot for spot welding). New entries, for example, Motoda, Komatsu, Tokiko, Shin Meiwa, Daini Chikiko and Kobe Steel, were concentrating on the spraying and welding applications.

A clear example of the halt in the number of firms, compared to the rest of Europe, was Scandinavia. Some new commercial agreements were made: Asea and Esab, and Retab and Hiab-Foco agreed to market arc welding systems. Recently Atlas Copco took over Retab and bought the Coat-a-Matic Licence.

The FRG, Italy, France and Britain experienced a large increase in supply activities.

In West Germany, Volkswagen developed a family of advanced material handling and welding robots for in-house use. Later they started commercial operations to supply these robots to the market. A manufacturer of machinery for the motor car industry, Kuka, also developed and started to market welding robots. Other new ventures were Zahnradfabrik, Reis, Siemens and Durr. The first two firms introduced

simple robots for transfer in metal cutting and diecasting operations. Siemens bought the licence to manufacture Fujitsu Fanuc robots in Europe. Durr started marketing the Hitachi robots from Japan, in particular, the new small process robot for assembly.

Various Italian companies initiated operations. Comau Industriale, a consortium of machine tool manufacturers subsidiary to Fiat, introduced robots for materials handling and spot welding, and developed the robot gate system. Other entries were: Elfin, Olmat, AISA, SLS, MAS, UTITA, Jobs and Digital Electronics Automation (DEA) all of them making Italian robots.

First attempts to give France a manufacturing capability were made in the middle of this period. In 1977 Sciaky, a maker of welding machines supplying the motor car industry, started development work and later bought the licence for a modular spot welding unit from Mitsubishi Heavy Industries. Two other French firms involved with welding machinery, SAF and Languepin, started to market the Robolang system for spot and arc welding. Renault, the state-owned automobile manufacturer, responded to the moves of major motor car firms developing a family of advanced robots for handling, welding and spraying, and also a vision system. Another French entry was the robot for water jet cutting by Bertin & Co. and Exico.

From 1975 to 1978 commercial ventures in the UK were almost entirely reduced to distribution agreements. Agencies for Autoplace, Retab, Star Seiki, Asea, Kuka, MAS, Aida and Prab were established. Hall Automation, at the time still

the only British manufacturer of servo controlled robots, developed an arc welding system in collaboration with the British Oxygen Company (BOC, a maker of welding machinery, bought thirty percent of the shares of Hall Automation). Another British company, Mouldmation, produced a PPD for the injection moulding market.

The situation in the UK did not change significantly until the beginning of 1979. Various agencies were established for distribution of Fujitsu Fanuc - Siemens robots (Hydro Machine Tools), Cincinnati Milacron, Olivetti, and Nordson. New licences were bought, and several British robots were introduced. Unimation made an agreement with WIRS (Wolverhampton) for the marketing of arc welding systems. This confirmed previous trends to adopt this kind of business strategy. GKN returned to the robot business with two machines: a minirobot for palletising, and an arc welding system. The former was jointly developed by GKN Technical Centre and Surrey University; the latter was introduced by GKN Lincoln Electric after buying the licence to manufacture from Yaskawa Electric in Japan (Lincman robot). A manufacturer of machine tools and part of the Davy Corporation, Head Wrightson Machine Co., introduced another arc welding system: the French robot Robolang. S. Russell & Sons a firm belonging to the Elliott Group, bought the licences for the manufacture of two robots of Japanese origin: Press Hand and Husky. BOC and Hall sold the shares of Hall Automation to the large electrical manufacturing group with stakes in the electronics sector, GEC. This was a clear move by GEC to enter the robot business quickly. Plans were being made to support development in assembly robots

and sensory systems to be tried first in-house. Hall's previous robots, Ramp and BOC Hal continued to be supplied by Binks Bullows and BOC.

More British ventures were disclosed in early 1980. Newtool of Fakenham, a subsidiary of the giant engineering firm B. Elliott, introduced the Simbot robot. British Robotic Systems (BRS) was jointly founded by the software house Systems Programming (SPL) and Remek Microelectronics. BRS announced their plans to develop integrated robotic assembly systems. Ingersoll Engineers, one of the largest production engineering servicing groups, was contemplating the production of turnkey robot systems. A new type of arc welding robot (fixed welding gun) was being developed by the British Federal Welder and Machine of Dudley.

Most important of all commercial ventures were those supported by the British government. These were efforts to build up local manufacturing capability by purchasing foreign licences which caused discontent from British makers (Stothard 1980 and Mills 1980). Unimation announced plans to manufacture the Puma robot in the UK with financial encouragment from the DoI and the NRDC (£660,000). The Fairey Group, a state-owned company, made a deal with six Italian firms to market and manufacture their robot welders, diecasters, and paint sprayers (some of these firms were DEA, Jobs and Robox).

6.3 Adoption (see Table 6.2)

Data compiled from a multitude of sources showed significant differences in the extent and kind of robot usage around the world (see appendices 7 and 8). The global robot population has grown seventy three percent per annum since their introduction in 1962 (the compound rate of growth of the cumulative number of robots sold, excluding PPD's. See figure 6.7). By 1979, it was estimated at a level of 11600 robots world-wide, heavily concentrated in the USA, Japan and Western Europe. According to the growth in sales, robot diffusion can be divided into three periods;

1. A period of eight years up to 1969 when commercial activities were at a pioneering stage and robot demand grew little.
2. A period of rising sales up to 1975.
3. A period that began with a slump in 1976 but ended with a record of three thousand robots sold in 1979. Throughout these three periods, the distribution of robots to applications and to industrial sectors have changed substantially. The successful adoption of particular applications by particular industries has sustained the robot business shaping development, supply and manufacturing activities.

First Period (1962-1969)

After a survey of two hundred workplaces the dimensional and capacity characteristics of the basic Unimate design were tailored to the loading and unloading of metal cutting machine tools. However, the first five prototypes failed to be taken by metal cutting shops and diecasting became the first application. The first diecasting systems were

installed by the American motor car industry in their captive shops. This was the first sign of a strong link between the robot industry and the automobile manufacturers (see tables A7.5 to A7.7). At the end of the period, one of the largest single users was Doehler-Jarvis Division, of National Lead in the USA. Nine robots were used for unloading aluminium diecasting machines largely producing components for the motor car industry (Frost and Sullivan 1974, p30, and Vantzelfde 1974, p 43).

By 1969 only two hundred and fifty robots had been sold in the USA (an average of 31 robots per year since their introduction). It is difficult to understand why by 1965 the Unimate licence had been bought in the UK and other firms were entering the business. The fact is that great expectations of market development did not materialise. In Britain, for example, one of the directors of GKN estimated a thousand Unimate to be installed in the course of a few months! At the end of the period the group had installed four robots inside their plants and had sold about fifteen to outside concerns. In general, market studies grossly underestimated the problems of adoption and forecast a swift expansion of robot demand. Arthur D. Little Inc. estimated five thousand robots by 1972 in the US alone, about seven times more than the actual population (see Frost and Sullivan 1974, p26 and Driscoll 1974a and b). It was not a surprise that many companies abandoned the money-losing robot business at the end of the sixties.

International differences in the extent of robot use were already significant. Tassel (1975) put the USA in the lead

(250) followed by Western Europe (150) and Japan (50). Sweden had already installed fifty of the European robots (Fletcher 1979, p222). These estimates are likely to have ignored robots developed for in-house use only which in the early days were a large proportion of the total population. Sweden and Japan were in those days particularly orientated towards in-house development and use of PPD's and SR's. Yonemoto and Shiino (1977, p171) for example, reported five hundred and ten robots in use in Japan by 1969. Ninety three percent of these were PPD's.
In the Fuji City Factory of the Nissan Corporation alone, there were one thousand three hundred units by the end of 1967, mostly small and simple robots used in the manufacture of transmission and steering parts for Datsun cars and trucks (Gonsalves and Kurlat 1977, p8).

Second Period (1970-1975)

A significant rise in 1970 was followed by a period of stagnant sales up to 1973. In 1974, the situation started to change rapidly and in 1975 sales peaked to a record level (1700 robots per annum), not surpassed until 1979. Sales increases were mainly led by the motor car industry. In 1970 General Motors installed the first multiple robot line for spot welding of motor car body panels at their Fisher Body Division in Lordstown, Ohio. This single order for twenty-nine robots is a landmark in the history of robots and of the pioneering firm Unimation. Later it became the glamour area for robotics. Ford and Chrysler in the USA, Nissan and Toyota in Japan, and Mercedes-Benz, Volvo and Fiat in Europe followed GM closely, By 1973

Kawasaki Heavy Industries had a record order for one hundred robots, and in 1974 robots were for the first time, capable of working on a continuously moving motor car assembly line. Second to spot welding were the spraying applications pioneered in Scandinavia. At the end of the period, Trallfa for example, had sold about two hundred and sixty robots (see table A8.5). Twenty percent of them were in Sweden and ninety five percent in Western Europe. In general, Western Europe clearly lagged behind USA and Japan. However, at the end of this period, there were signs of increasing European activity (see figure 6.8). Italy suppassed the FRG in the level of robot usage and came close to Sweden. Smaller increases took place in the FRG, UK, and France (see figure 6.9).

The distribution of robots (excluding PPD's) to applications changed significantly. A substantial increase (about 8%) in the share of processing applications resulted from the success of spot welding and spraying robots. This shift was most remarkable in Europe where both of these applications spread fast, and accounted for nearly forty one percent of the total number of robots by 1974. The proportion of transfer applications changed only slightly and continued to be in the majority. Injection moulding and pressing in Europe and Japan and diecasting in the USA were the most common transfer systems. Robots were spread thinly in a wide range of other uses. Manipulative and assembly robots were still premature. Forging, the only manipulative application adopted in this period, actually reduced its share. Assembly showed some signs of becoming more common particularly in Japan and USA. When PPD's are included,

a totally different picture emerges (see the case of Japan in appendix 8). Transfer applications become by far the most common, with simple component transfer in the lead.

The pattern of robot use in the UK by 1974 was similar to that of Europe in the first period (see appendix 9). Transfer robots predominated with a very large proportion of the population (64%). Of these applications, loading/unloading of glass working machinery (cutting, forming and heat and chemical treatment) and of presses were the most common. Processing robots were second and had a significant share (29%). Spraying was the most successful of all systems (25%). In sharp contrast to Europe, spot welding robots were relatively rare (2%). Manipulative and assembly robots were almost non-existent.

The largest single users of robots in the UK were the domestic appliances, sanitary ware and glass processing industries. The first and second, made use of robots for paint and enamel spraying of cooker parts, tumble driers and bath tubs. The last, played an important pioneering role in the application of transfer robots for glass handling in the early days. This application suffered from the reliability problems of a premature technology, aggravated by this industry's difficult working conditions. The motor car industry tested various systems, but played a meagre role when compared to the strong leadership of the motor car companies in the rest of Europe, the USA, and Japan. less than four percent of the UK robots were installed in automobile plants, at the time when about forty percent of the world's robot population were used by car makers. No multiple robot applications and a low average number of robots

per firm existed in the UK at the end of the period.

Third Period (1976-1979)

Despite a widespread check in the growth of robot sales in 1976, this period must be regarded as one of definite take-off. Particularly in Japan and the USA, sales grew steadily in the last three years of the period. In Europe, the gap between Sweden, and the FRG and Italy seemed to be narrowing at first. In the end Swedish sales rose fast and the gap widened considerably. The FRG was the only country to experience large growth rates in 1976, and surpassed Italy to become the second largest user of robots in Europe by 1977 (her robot population grew 58% between 1976 and 1977). The UK and France continued to lag behind each with a total robot population of less than two hundred. In 1979 the UK seemed to be heading at last for steeper growth rates as her robot population grew 36% between 1978 and 1979.

Large orders for spot welding robots from the motor car industry continued to play an important role. Fiat placed consecutive orders at the beginning of this period, and installed a new body assembly system in 1977. This was the Robogate, a system for body shell assembly and welding that can simultaneously deal with two models and many variants and consequently adapt to sudden changes in market demand. Fiat placed one of the largest orders of the time, a hundred Unimate robots for its Robogate systems in Rivalta and Cassino.

Other types of multiple robot installations failed to be adopted widely. To the surprise of robot suppliers, robot spraying lines were not in widespread use in the automobile

industry. As in the case of spot welding, suppliers of spraying robots went a long way to satisfy the special demands of the motor car industry. Today, colour coats are largely applied by hand on motor car body panels (A new Fiat plant in Sicily is one of the few exceptions). Spraying of underbody sealings and rust preventive compounds became a growth area for robot use in motor car manufacture.

The overall distribution of robots to applications in Western Europe changed only slightly (the distributions for the USA and Japan were, unfortunately, not available). The share of transfer robots continued to decrease, particularly in injection moulding and metal cutting. Only loading and unloading of presses retained its share. Of the manipulative applications forging continued to decline while grinding and investment casting emerged. Joining became the most widely used processing application, thanks to the steady success of spot welding and to the increasing popularity of arc welding systems. Other new processing applications such as fettling and flame cutting appeared. For the first time, spraying applications had shares below twenty percent, and assembly applications had shares above one percent of European robots. Models like Asea, Cincinnati Milacron, Olivetti Sigma and Unimate Puma played an important role in the new areas.

Differences in the use of robots inside Western Europe were significant in 1978 (see table A8.4). Transfer robots had a very large proportion in the UK and the FRG in contrast to Italy. Here, processing applications showed an unusual concentration due to the extensive use of spot welding robots by Fiat. Manipulative robots and processing robots for

metal cutting enjoyed a relatively wider success in Sweden and FRG than in other countries, thanks to the activities of the Swedish company Asea (see table A8.5). Olivetti in Italy played a similarly pioneering role in assembly applications.

The distribution of robot applications in the UK followed the same trends as those of Western Europe. The proportion of transfer applications decreased substantially while manipulative, processing and assembly robots gained popularity. Glass handling showed the largest decline in the share of UK robots, followed by loading and unloading of presses and of injection moulding machines. Joining was a remarkable growth area. Thanks to the first multiple robot installation at BL, spot welding became the largest single application in 1978 (the date when the order was placed. The system was not commissioned until 1980). Arc welding robots also increased their share of the British applications particularly during 1979 when they reached a ten percent level. Since the number of arc welding robots per company was low, this was the single most important sign of growth in the UK market (i.e. many of the new user firms adopted arc welding systems). Surface treatment and enamel spraying in particular, declined in their relative importance. New spraying applications such as fibreglass, underbody sealing and rust preventive spraying emerged.

In this period, the overall distribution of robots in industry in the UK became more like that of other countries, The motor car industry became the largest user (still with smaller shares than its counterparts abroad). Conversely,

the glass, domestic appliances and sanitary ware industries reduced their involvement in robot adoption. This resulted in the decline of glass handling and spraying applications described above. A steady decrease in the share of the plastic industry, and the arrival of the electronics industry as a user of assembly robots were also noticeable.

The distribution of user companies in industry complements the above information. It shows a more dramatic fall in the contribution of the domestic appliances and sanitary ware industry, and a less prominent position for the car industry. The plastics and metal goods industries became more important. These differences are the result of the varying concentration of robots in companies (a large proportion of the UK robots were used by one firm - BL). The average number of robots per firm has been, and still is, pretty low in the UK (information about other countries was not available). Only two percent of the user firms have ten or more robots and seventy three percent have only one. One per cent of the user firms placed at least four subsequent orders and thirteen per cent placed at least two. This low level of intrafirm diffusion shows that the recent take-off in British use derives from the adoption of new systems in new industries and new firms. Robot adoption was still largely an experimental activity.

6.4 Promotion (see Appendix 11)

Direct governmental support has played a very important role in the growth of development, supply, manufacture, and adoption of robot technology. Governmental promotion has

taken various forms, such as financial assistance for private and state R & D programmes, demonstration facilities, and application of new systems; dissemination of national and foreign information and know-how; and coordination of the various activities relevant to the diffusion of this technology.

Other important agents for the promotion of robotics have been the various robot associations established around the world under the initiative of government ministries, professional institutes or simply of groups of enthusiasts. Some of these associations have coordinated entire promotion programmes, planning the allocation of resources and administering the government financial help, as well as organising meetings and other events for information exchange, and encouraging the standardisation of terminology and of certain technical characteristics.

Awareness of the need for organised promotion and massive investment arose in Japan earlier than in the USA and Western Europe. In 1968, the Japan Electronics Industry Development Association (JEIDA) had a technical committee looking into robots. By 1971 the Ministry for International Trade and Industry (MITI) established the first robot association, the Japan Industrial Robot Association (JIRA), and launched a huge programme for the development of artificial intelligence (see Appendix 11). MITI has continued to fund research in its own laboratories, in industry and to a lesser degree, in universities. Research in universities has been largely sponsored by the Ministry of Education (Its total annual budget runs to £0.71M excluding staff and salaries and indirect expenses in 50 universities and 15

research institutes with 300 people active in robotics research). In 1973, MITI started an ambitious project to produce a fully automated machine shop for batch production which approached its second phase in 1978 (Project MUM: Methodology for Unmanned Manufacture). JIRA has been a major agent of promotion, organising the most complete set of activities of any robot association around the world (symposia and exhibitions; interest free loan schemes; technological forecasting and assessment studies; projects for the standardisation of terms, procedures, and quality and performance specifications; international technical exchanges; and projects for the improvement of manufacturing costs, maintainability, and safety of robot equipment). It receives sixty per cent of its funds from the government (MITI) and the rest from corporate members and proceeds from betting in horse, dog and boat races (its membership is composed of 39 robot manufacturers, 43 supporting members and 296 personal members). In 1978 government funding to JIRA amounted to about £1.1M (£0.15M in 1973, £0.19M in 1974, £0.23M in 1975, £0.15M in 1976, £0.19M in 1977, and £0.19M in 1978. See JIRA 1978 and Pugh et al 1979). Recently, MITI announced plans to promote the establishment of a system for leasing high priced industrial robots to small robot enterprises. The plan calls for robot manufacturers, insurance companies and other financial institutions to establish a leasing firm throughjoint investment and loans extended by the Japan Development Bank. Laws for the promotion of the machine building industry and more recently, for the promotion of the robot industry have established preferential tax and other financial privileges encouraging manufacture and use of robots even further.

The Japanese government has intensely promoted development, supply and manufacture and adoption of robots to maintain in the long term as strong a competitive position as Japan enjoys nowadays.

> "Freed from the burden of large scale military spending by a mutual security treaty with the United States, Japan has been able to build up a technological arsenal that effectively combats international pressures. Not only does she ship small consumer goods produced by advanced automation to the Western world but she expects to ship advanced automation itself - industrial robots, numerically controlled machines and whole factories - to the developing nations". (Gonsalves and Kurlat 1977, p2).

Various American leaders in universities and industry pointed with dismay at the Japanese developments and urged the government to react. Dr. Lawrence Goldmuntz (Office of Science and Technology) addressing the participants of the 2nd ISIR in 1972, explained the various market defects and other issues of national R & D policy "that provide the rationale for federal intervention". He described the governments attempts to focus technology on national needs - a strategic approach to technology (Goldmuntz 1972, p89-91).

> "This is the purpose of the technology stimulation programmes proposed in the Administration's F.Y. '73 budget request for the National Science Foundation and the National Bureau of Standards... It is significant that the President, for the first time, has sent a message to the Congress on March 16, 1972 outlining the importance of technical innovation... In that message it is pointed out that the Federal support for R&D is only one mechanism to stimulate technology. There are barriers to innovation in excessive regulation and inadequate incentives. We must to the extent possible, reduce these barriers. We must attempt to determine the side impacts of new technology. We must develop a new partnership between the Federal Government, private enterprise, State and local governments and our universities and research centres in a coordinated, cooperative effort to serve the national interest".

By 1973 the National Science Foundation (NSF) and the National Bureau of Standards (NBS) had started to fund research

directly relevant to robots. The main programmes focused on advanced assembly and were jointly financed by government, industry and universities. Later, the Robot Institute of America (RIA) was founded under the sponsorship of the Society of Manufacturing Engineers (SME). RIA has concentrated its efforts on activities related to the dissemination of information. In contrast to the majority of robot associations, RIA is a trade association governed and controlled by manufacturers, although it includes users and researches (In 1979 its members were 12 manufacturers and distributors, 25 corporate users, 2 research members, 5 accessory suppliers, 1 consultant and 456 individuals). In comparison to Japan the USA has conducted a less intensive direct governmental programme for the advance of robot technology. Promotion has been focused on research and experimental development and on the transfer of the outcome of R&D to industry. However, the role of the NSF must not be underestimated. It has produced excellent results in the area of assembly by careful coordination of development work in industry and universities (at least 22% of the US ISIR papers were financed by the NSF and NBS. See appendix 3).

State related activites of a less direct nature have a large impact on robot technology in the USA. The space, nuclear, and defence industries have contributed to the advancement of robotics. In the 1960's, research in advance remote manipulation was being sponsored by NASA and the AEC Space Nuclear System Office in laboratories which later became involved in advanced automation (see appendix 5). Hewit (1979, p8-10) clearly describes the importance of space programmes.

> "A major proportion of R&D in robotics in the USA is concerned with the space shuttle. The manipulation system housed in this craft is to be used to perform tasks such as the assembly of solar energy collectors and sealed laboratories and their maintenance... "The total cost of a single manipulator arm is a staggering $65M (compared incidentally with a national funding for other robotic research of $3M per annum)".

The US air force (USAF) has recently launched a large programme for the development of computer integrated manufacturing systems (ICAM programme, £42M). The use of robots in fabrication and assembly of aircraft bodies was highlighted as one of the important areas. Companies such as General Dynamics, McDonnell Douglas and Lockheed are being involved in the development of robot drilling, rivetting and other fastening operations.

Soon after a major study (BMFT 1973) identified the FRG as clearly lagging behind Japan, USA, and Sweden, the West German government dramatically increased the promotion of robot technology. In 1974, two public programmes relevant to the development and application of industrial robots got underway: the programme for the "Humanisation of Life at Work" (HLW) and that of "Manufacturing Technologies" (MT) (Brodner and Schacks 1979, p121). The HLW programme* was jointly organised by the Ministry of Labour and the Ministry for Research and Technology (BMFT) inspired by the goal of more humane work design set by the Factory Constitution Act of 1972 (Betriebsverfassengsgesetz). It comprised four main areas: work design and plant organisation, design of

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* In 1974 the HLW programme was seven percent of the total budget for development of "Key Technologies" (£40M). The largest programmes were those of electronic instruments (46%) and optics (24%) (Gerstenfeld 1977, p16).

workplaces, development of humane work technologies, and dissemination and implementation of knowledge of work-orientated sciences (Warnecke and Schraft 1977 and Scholz 1977). The MT programme concentrated on the development of industrial robots and their systems (A total of £13M were assigned to this programme from 1974 to 1977). A working group with the collaboration of industry, universities, and other research institutes was especially organised for the development and diffusion of handling devices and peripheral equipment (the members of the ARGE HHS scheme were Robert Bosch GmbH, ITP Pietzsch GmbH, IITB,IPA, MAN, Pfaff and Volkswagen AG. Some of the projects are described in appendix 5).

For many years most of the public support for robot technology in the UK came from the Science Research Council (SRC) in the form of grants for experimental development in universities. At least 30% of the British ISIR papers were sponsored by the British government. The only non-academic work sponsored by the government was that of the National Engineering Laboratory financed by the Mechanical Engineering and Machine Tools Requirements Board of the Department of Industry. Pioneering work on industrial artificial intelligence and advanced automation conducted in the early seventies seems to have suffered a setback as a result of the Lighthill report to the SRC (Michie 1979, p4). This report questioned the usefulness of research on pure artificial intelligence ("The general purpose robot is a mirage'. Lighthill 1974, pVII). Although it included strong support for industrially orientated R & D, Driscoll (1974c, pG24) described the report as clearly regressive

("despite the justification of throwing a lance at the AI dragon") since it would tend to harm industrial AI. Recently Peltu (1979, p179) said "it led to drastic cuts in British AI during a crucial period in its development".

As a result of the little interest that British industry showed in the 6th ISIR and 3rd CIRT held in Nottingham in 1976, a group of academic and industrial enthusiasts initiated talks on the formation of a robot association. In 1977, the Mechanical Engineering and Machine Tool Requirements Board (MEMTRB) gave signs that the government was beginning to consider the promotion of flexible automation. At the instigation of the same group of enthusiasts, the MEMTRB established the Automated Small-Batch Production (ASP) Committee to study the feasibility of flexible manufacturing systems. In the same year, the British Robot Association was formed and later it received a pump priming grant from the DoI (£15,000).

The BRA organised the first two state-of-the-art review meetings in 1978 and 1979. This time British industry responded more enthusiastically showing a renewed interest in the technology (see figure 6.10). In 1979, the situation started to change dramatically. The DoI announced plans for the development of a prototype flexible manufacturing system based on the recommendations of the ASP committee, and established a research programme entirely devoted to robotics in the NEL. Soon afterwards a report to the SRC (Roberts report) identified robotics as a priority area and proposed a plan for the integration of research. This stimulated further increase in the funding of development

work in universities. The Production Engineering Research Association (PERA) stepped in to promote robot adoption by launching a persuasion campaign consisting of advisory services and demonstration facilities. Further reports to the government (the ACARD report to the cabinet and the Ingersoll report to the DoI) confirmed the low status of robotics in the UK and recommended large public support. The ACARD report suggested grants in the region of £15M to stimulate UK companies to use robots and match the expected West German population in five years (Advisory Council for Applied Research and Development, 1979, p43).

The Swedish, Italian and French governments have not been involved in programmes on the scale of Japan, USA and FRG. However, robot associations and small promotion schemes exist in these countries. In 1972, a committee for industrial robots had already been established in the Department of Production Engineering of the Sveriges Mekanfoerbund in Sweden. This committee focused on publicity, information exchange and planning and coordination of research projects. The Italian Robot Association (SIRI) was founded later, in 1975 and, like the BRA, focused on the organisation of activities such as seminars, exhibitions and study tours. Some funding for robot manufacture has come from the Italian government in the form of low interest rate loans under the law of industrialisation of applied research e.g. the Sigma project of Olivetti (Salmon 1977). France has recently formed her robot association, and supports research and experimental development and application of robots from public funds. Other countries such as Belgium, Bulgaria,

Czechoslovakia, Denmark, Poland and Switzerland have promotion activities coordinated by various kinds of institutions.

6.5 Preliminary Identification of Explanatory Factors

International differences in development, supply and adoption of industrial robots can largely be explained by the extent of indirect and direct government intervention (the only exceptions are Sweden and Italy). The effect of massive governmental programmes is particularly evident in research and experimental development. All important leaps in the level of R&D activity (see figure 6.4) are closely related to the dates when government programmes were launched:

	Dates	
	First Large Promotion Programme	First Leap in R&D Activity
Japan	1971 (£5/annum)	1972
USA	1973 (£1.3/annum)	1973
FRG	1974 (£3.3/annum)	1976

In the FRG, more than anywhere else, government incentives were designed to narrow the gap between her and Japan and the USA. These efforts had a great impact: by 1976 the FRG surpassed the UK in the level of research and experimental development, and Italy in the level of adoption (see figures 6.4 and 6.9).

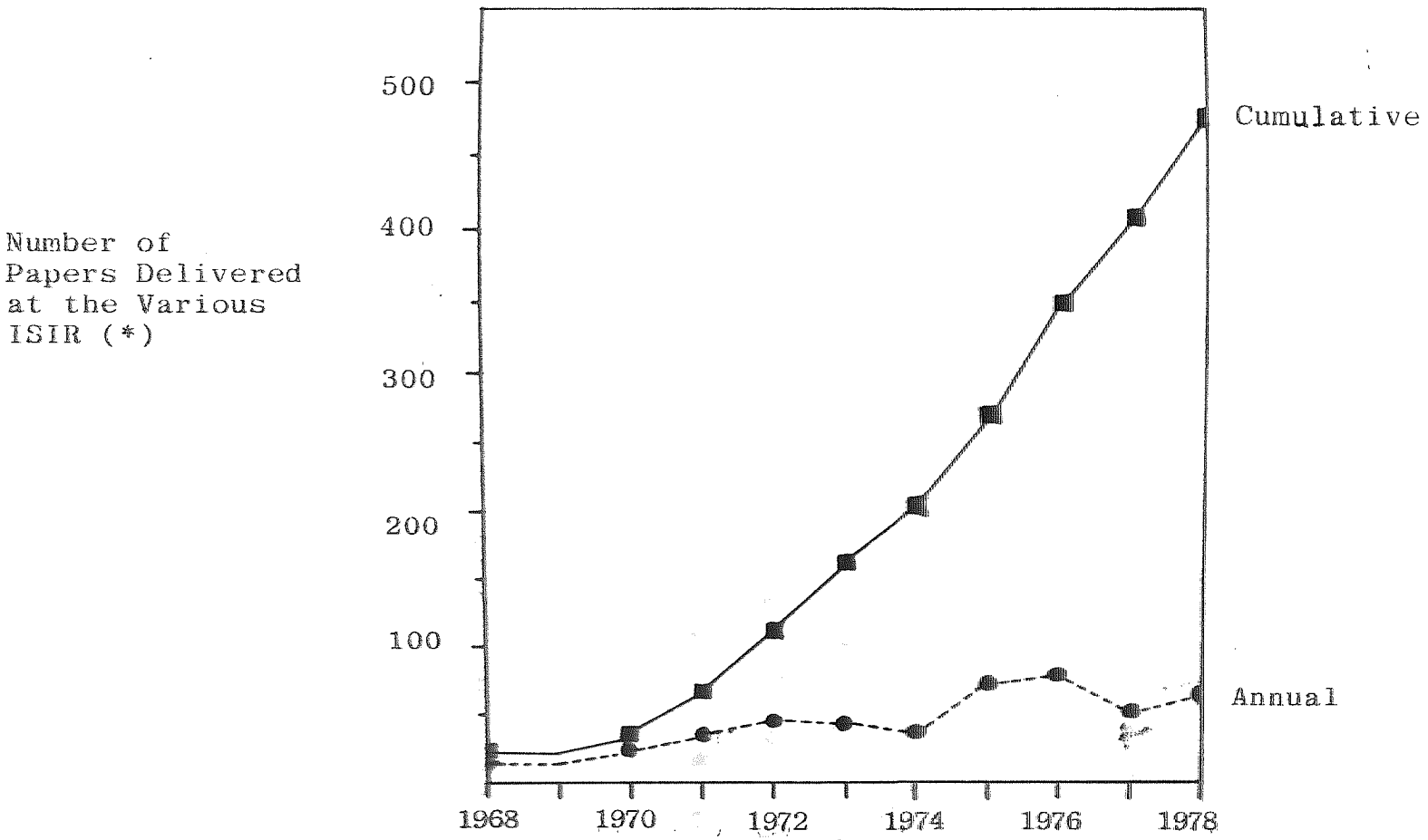
Proper international comparisons must allow for the differences in the potential use of robots in each country. The analysis of adoption in the UK, described in the follow-

ing chapters, is intended to identify the main factors determining the potential use of robots in manufacturing industry. This will be the basis for further work on the estimation of the potential use of different robot applications to be undertaken by the TPU. For a preliminary international comparison, a good indicator of the robot potential use in a country is the size of its manufacturing industry as measured by the number of employees. Thus, the international level of diffusion can be measured by the number of robots per thousand employees in manufacturing industries (see table 6.3). Warnecke and Schraft (1977) have studied the potential use of robots in the FRG. About 420,000 working places were regarded as possible applications for robots (55 robots per thousand employees in manufacturing industry). From a sample analysis it was concluded that automation by robots without sensors was technically and economically feasible in only 5,000 - 10,000 working places (0.66 - 1.32 robots per thousand employees in manufacturing industry). On this basis, and in comparison with other manufacturing innovations like NC machine tools, it is clear that the diffusion of robots has been disappointing everywhere, except Sweden. (According to Frost and Sullivan, 1980, p. 5, saturation levels may be reached in Sweden before 1990).

Since robots are intended to replace human labour, it should be expected that labour costs determine the level of robot diffusion. However, this factor alone will not provide an explanation. In contrast to other labour-saving innovations such as NC machine tools, international differences in the level of robot diffusion cannot be largely explained by the differences in the total hourly labour costs between

countries (see figure 6.11); neither can they be explained by other equivalent variables of the profitability of robot investment such as unit labour costs, gross hourly wages in the motor industry, and labour cost growth rates. Many other factors have been given as complementary explanations for the differences in the level of robot advancement. A list of possible stimuli and barriers has been compiled from the various interviews conducted, particularly those with suppliers, and from various other sources (see table 6.4). The analysis of robot adoption in the UK will serve as a reference for discussion of the relative importance of these factors in explaining robot diffusion on the whole, and the diffusion of different robot categories.

Figure 6.1 – Growth in the Development Activities in Industrial Robots Worldwide (Estimated from the Contributions to International Symposia)



* ISIR papers represent activity started two years before the symposia are held

Figure 6.2 – International Development Activity in Industrial Robots (Estimated from the Contributions to International Symposia)

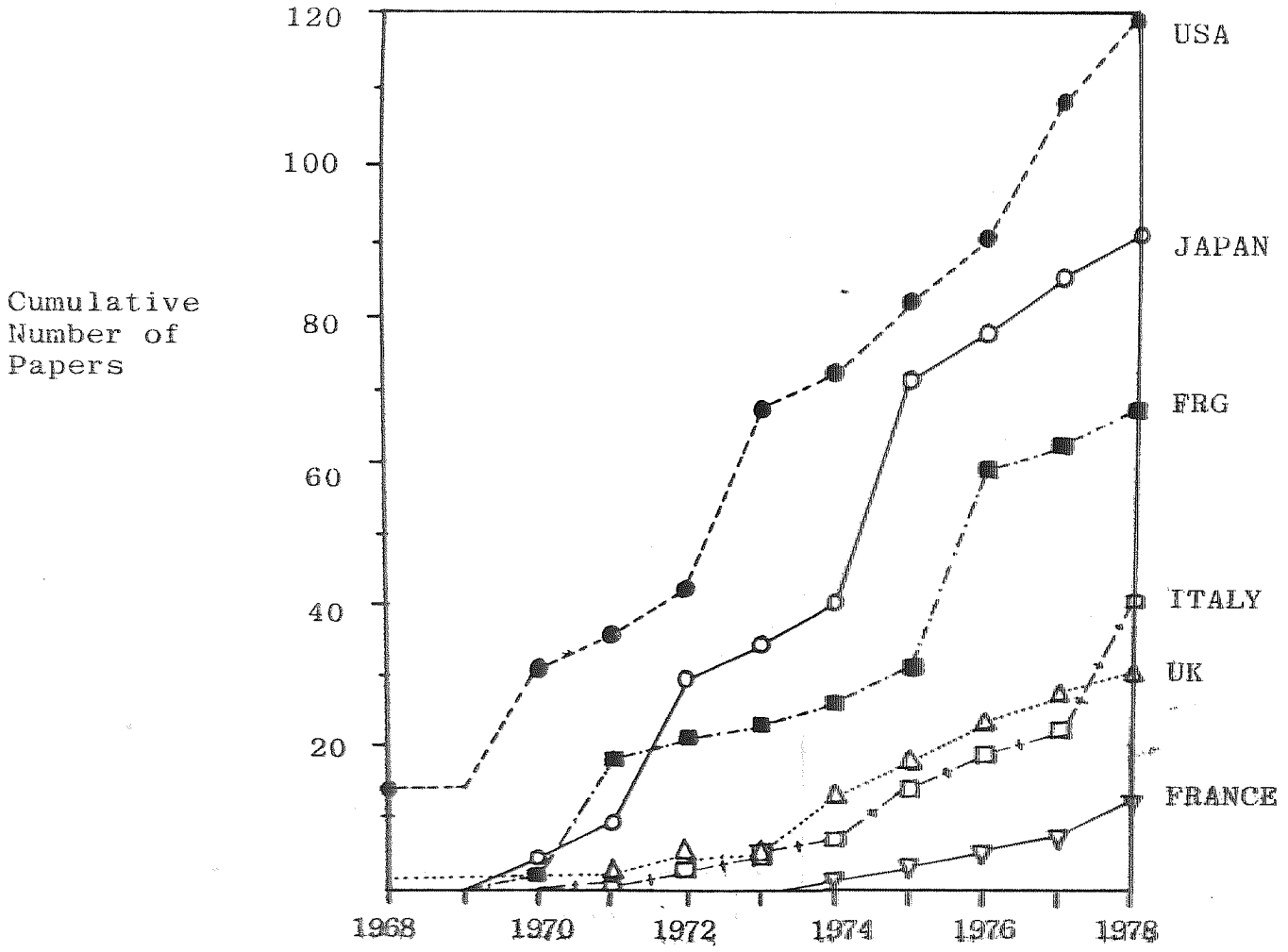


Figure 6.3 – International Activity in the Study and Promotion of the Application of Robot Technology (Estimated from the Contributions to Papers on Applications of the International Symposia)

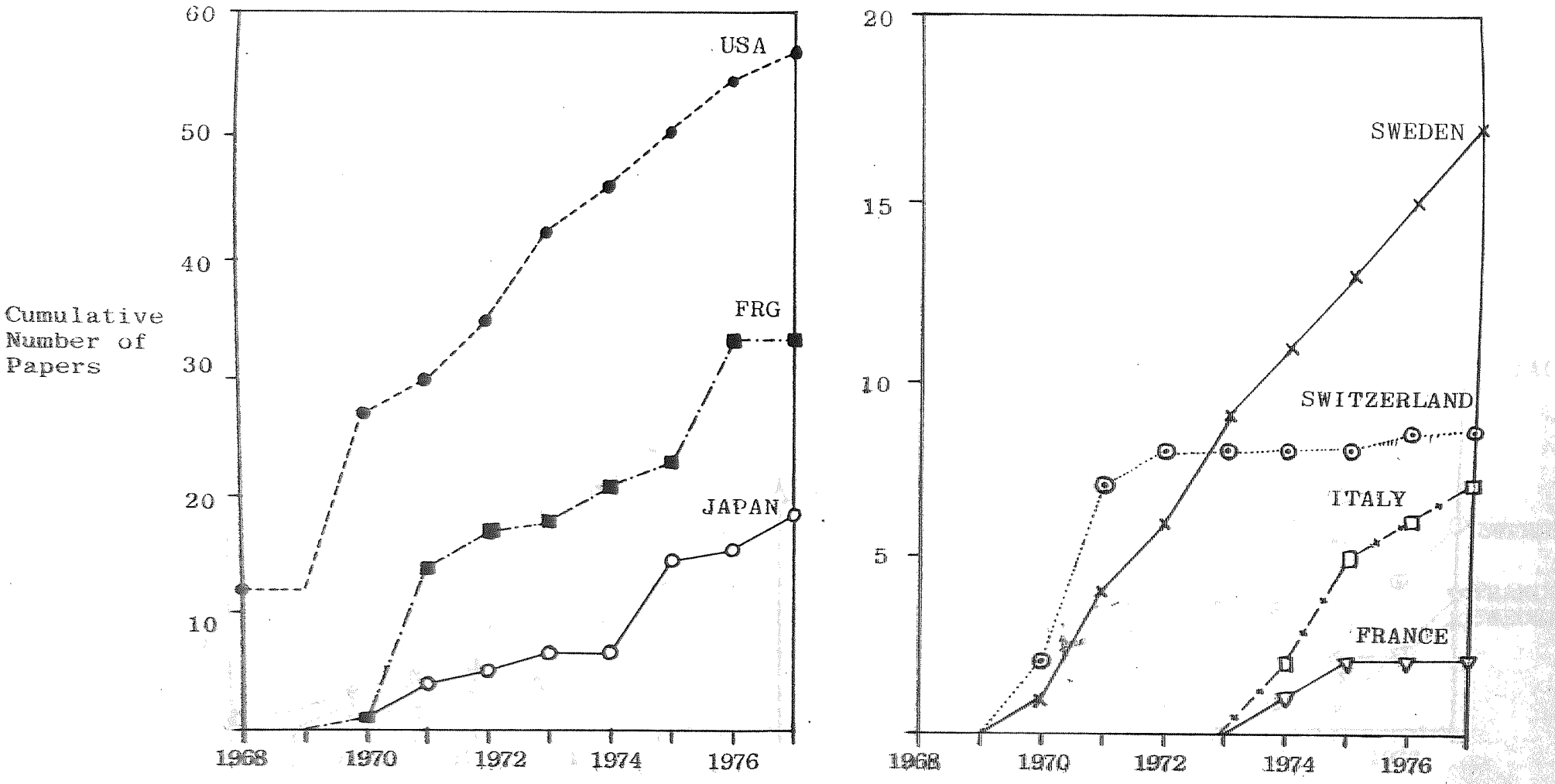


Figure 6.4 – International Activity in the Improvement of Robot Technology (Estimated from the Contributions to Papers on Research, Experimental Development and Innovation at the International Symposia)

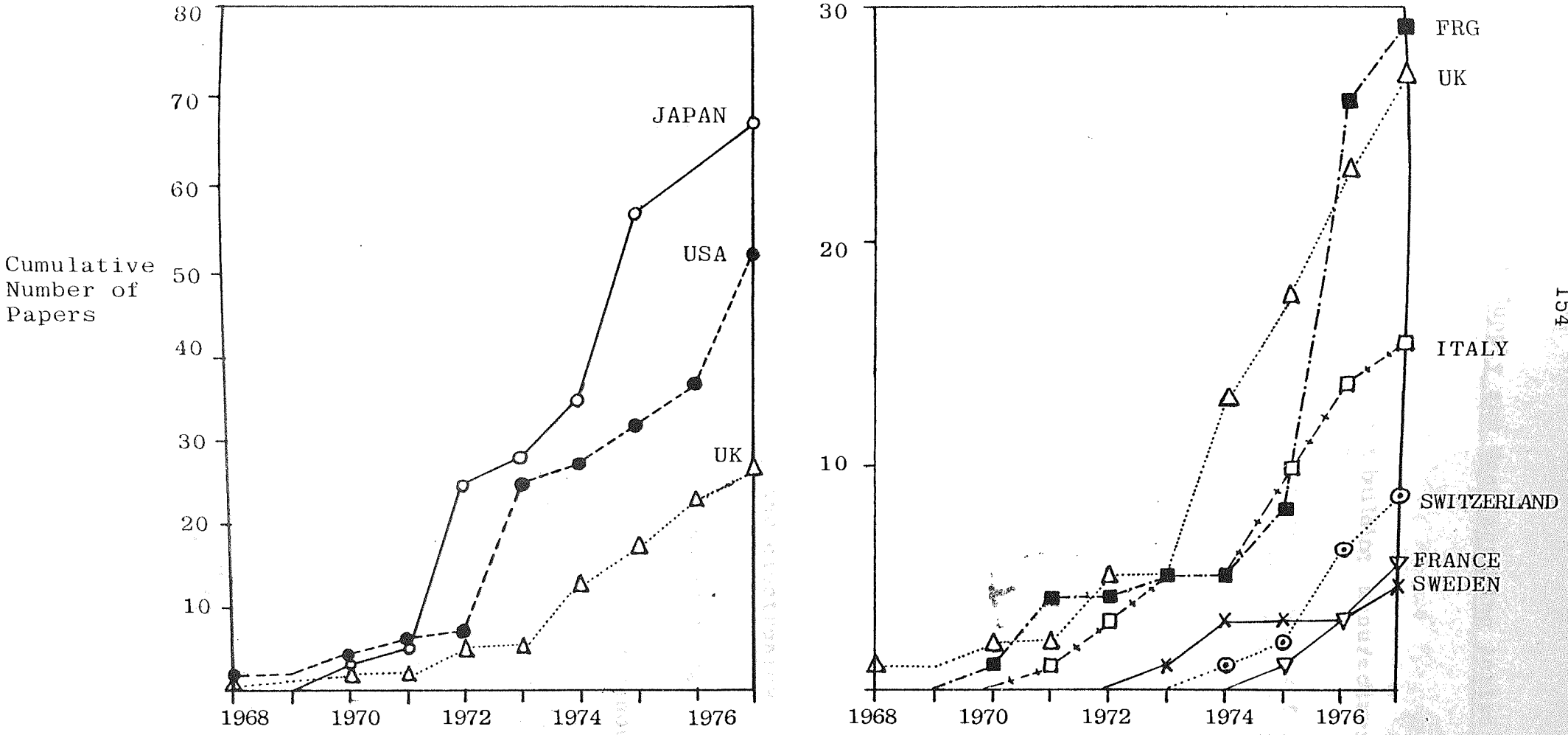


TABLE 6.1 - Synopsis of Supply and Manufacturing Activities

First Period (before 1968)

1. USA, Scandinavia and Japan start building manufacturing capability with native technology.

2. UK transfers American technology buying licences for manufacture, design change and future development of Unimate and Versatran.

3. Three different types of robot ventures can be identified:

   a. New and small firms having robots as the sole interest (Unimation)

   b. Manufacture for In-house use (Trallfa, Nissan)

   c. Large firms with diversification policies (AMF, HSDE, and GKN).

Second Period (1968-1974)

1. Dramatic increase in the number of firms marketing robots in Japan both with foreign and native technology (Main arrivals are mostly from large manufacturing groups in the motor car, machinery and electronics industry).

2. USA and Sweden continue increasing manufacturing activity.

3. Italy starts building own capability using indigenous technology.

4. UK pioneers abandon the robot business but new firms arrive. The first british HTR is developed by Hall Automation.

5. The FRG transfers American technology.

6. Large manufacturing groups with diversification policies or interested in-house use predominate.

Third Period (1975-1980)

1. Relative decline in the number of firms and models and significant growth in robot manufacturing capacity are signs that the industry is leaving its infancy.

2. Cooperation between motor car industry and robot manufacturers for systems development in Japan and USA.

3. European motor car firms and motor car equipment suppliers develop and introduce their own families of advanced robots (Volkswagen, Fiat and Renault).

Continued/....

TABLE 6.1 (Continued)

4. Take overs and link-ups for marketing become frequent.

5. Manufacturers of diecasting and injection moulding machines introduce PPD's.

6. Large Electronics firms contemplate involvement in ventures in robotic assembly.

7. The FRG, Italy, France, and the UK experience growth in supply activities.

Figure 6.5 - Approximate Growth in the Number of Firms and Models Worldwide (See Appendix 6)

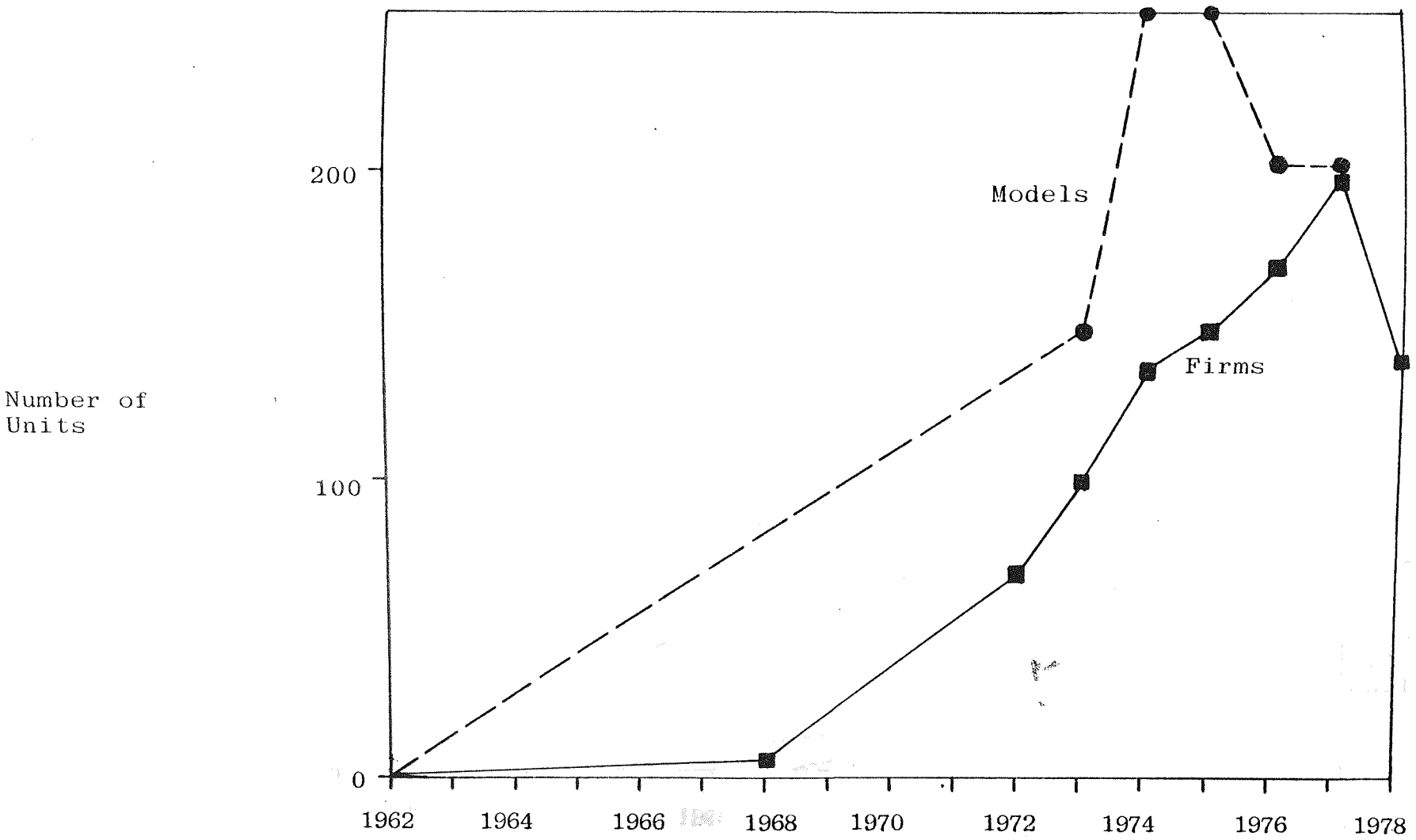


Figure 6.6 - Approximate Growth in the Nominal Manufacturing Capacity of Various Robot Firms (see Appendix 6)

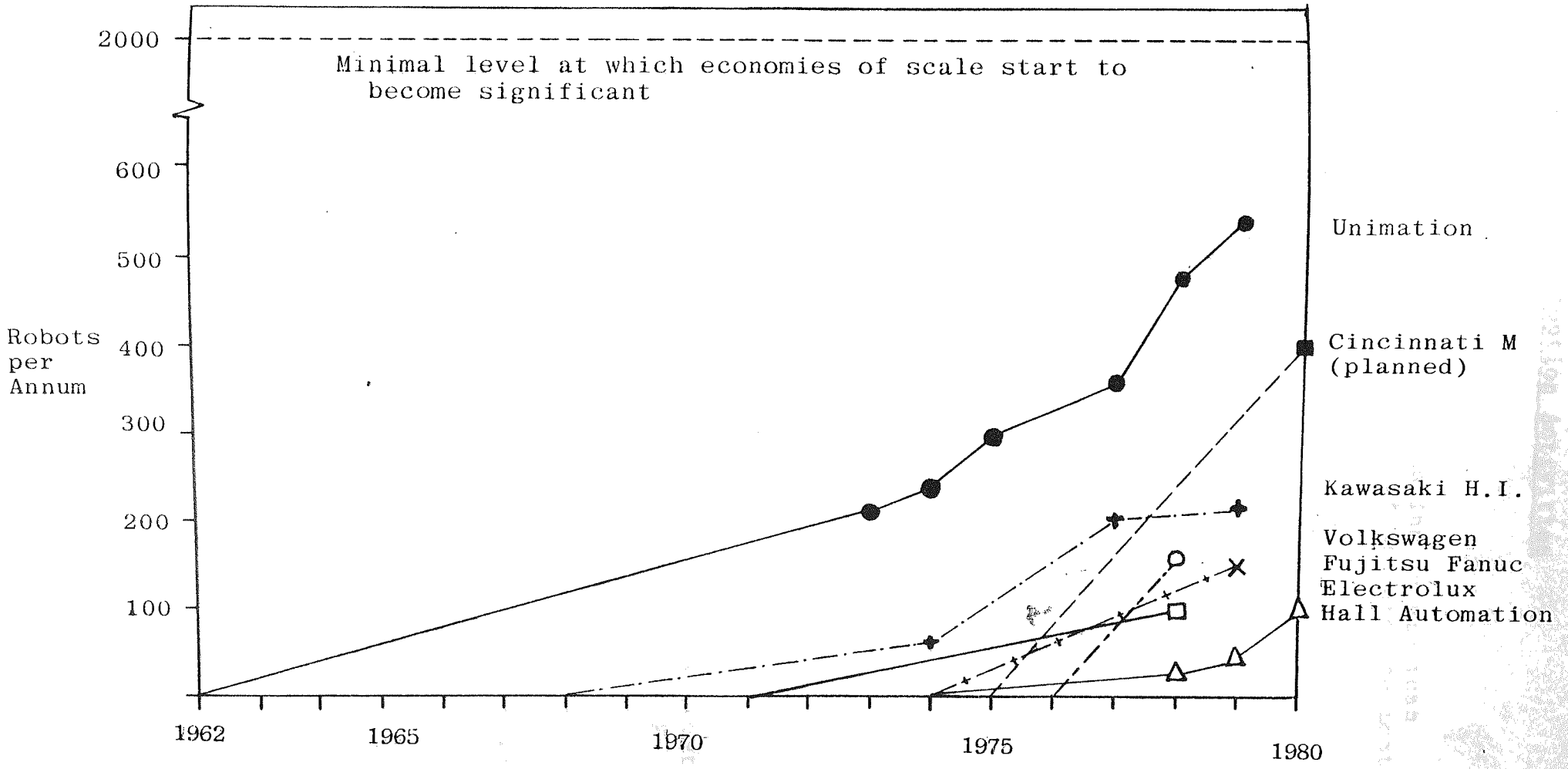


TABLE 6.2 - Synopsis of Adoption Activities

First Period (before 1969)

1. Robots are first applied to diecasting by American automobile firms. Transfer applications are the most popular of the period.

2. Great expectations of market development do not materialise and many companies abandon the business.

3. USA, Japan and Scandinavia lead in robot use.

Second Period (1970-1975)

1. A significant rise in 1970 is followed by a period of stagnant sales up to 1973. In 1975 record sales are attained (1700).

2. Sales growth rates are largely influenced by the multi-robot orders for spot welding from the motor car industry pioneered by GM in 1970. Spraying robots also spread particularly in Western Europe. This success caused an increase in the proportion of processing robots.

3. Western Europe laggs behind USA and Japan. Italy surpasses the FRG and comes closer to Sweden.

Third Period (1976-1979)

1. The main user countries experience steady sales growth in the last three years of this period particularly Japan, USA and Sweden. The FRG surpasses Italy to become the second largest user of robots in Europe. Adoption starts to grow faster in France and the UK.

2. Orders for multirobot installations for spot welding continue from the motor car firms. Demand for multi-robot spraying lines in car manufacture does not materialise.

3. The share of transfer robots continue to decrease. Joining becomes the most widely used processing robot application thanks to the continuing success of spot-welding and the increasing acceptance of arc welding. Fibreglass, underbody sealing and rust preventive spraying become growth areas for spraying robots. Manipulative (grinding and investment casting), new processing (fettling and flamecutting) and assembly robots emerge.

Figure 6.7 - The Global Diffusion of Industrial Robots (Excluding PPD's. Averages from Table A7.4)

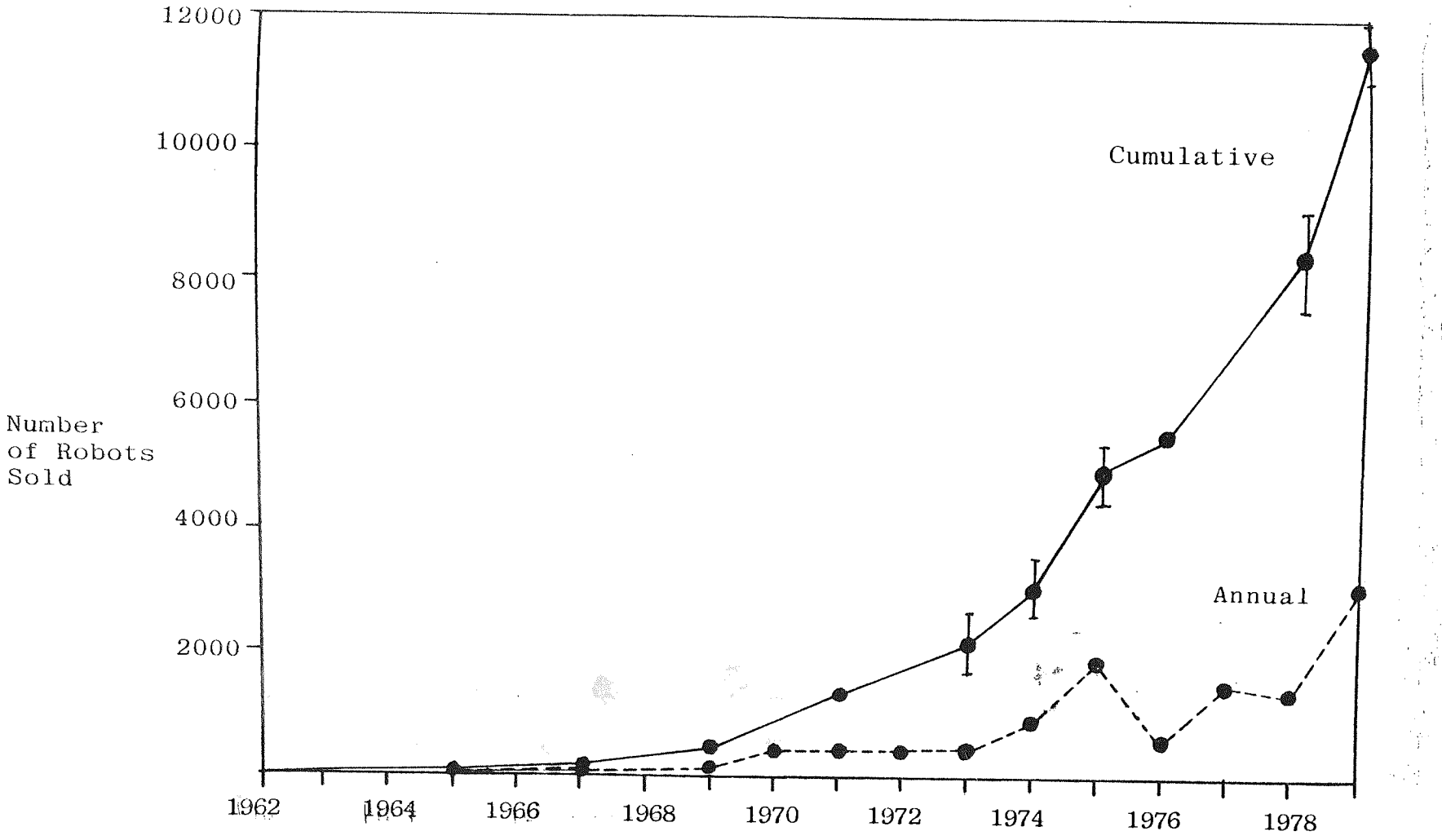


Figure 6.8 – The International Diffusion of Industrial Robots (Excluding PPD's. Averages from Table A7.4)

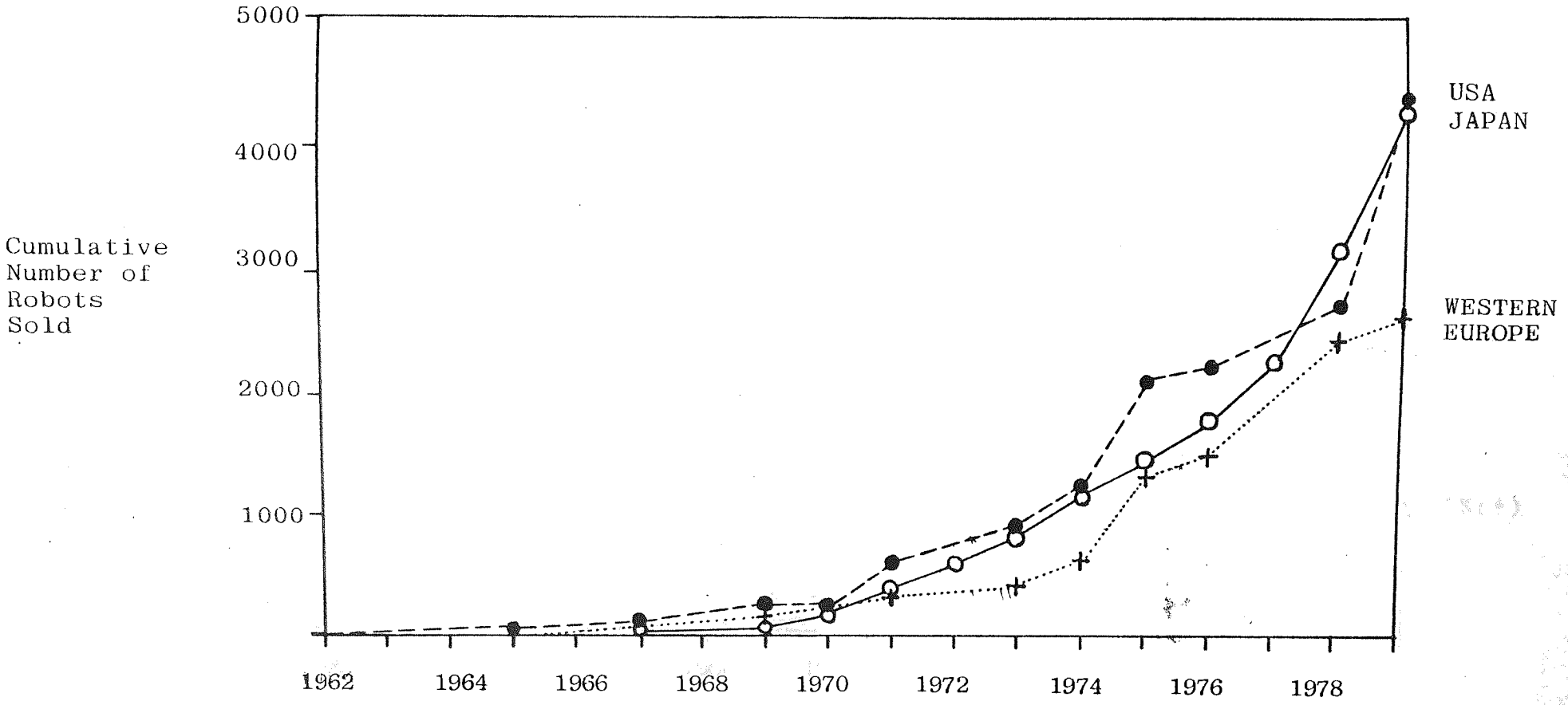
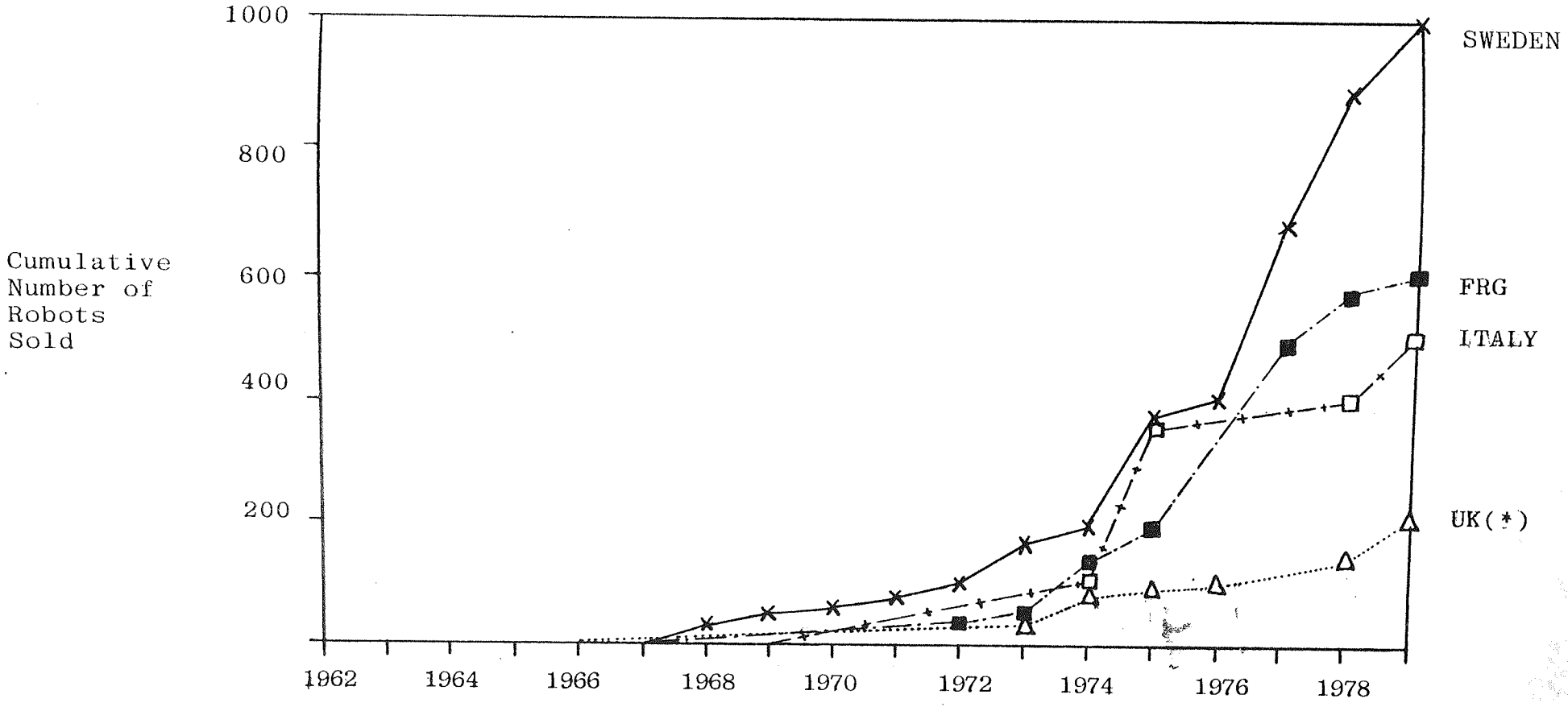


Figure 6.9 - The Diffusion of Robots in Western Europe (Excluding PPD's. Averages from Table A7.4)



*France is not shown for the purpose of clarity. The situation there, was similar to the UK, despite its late start.

Figure 6.10 - British Institutional Participation to UK Robot Conferences

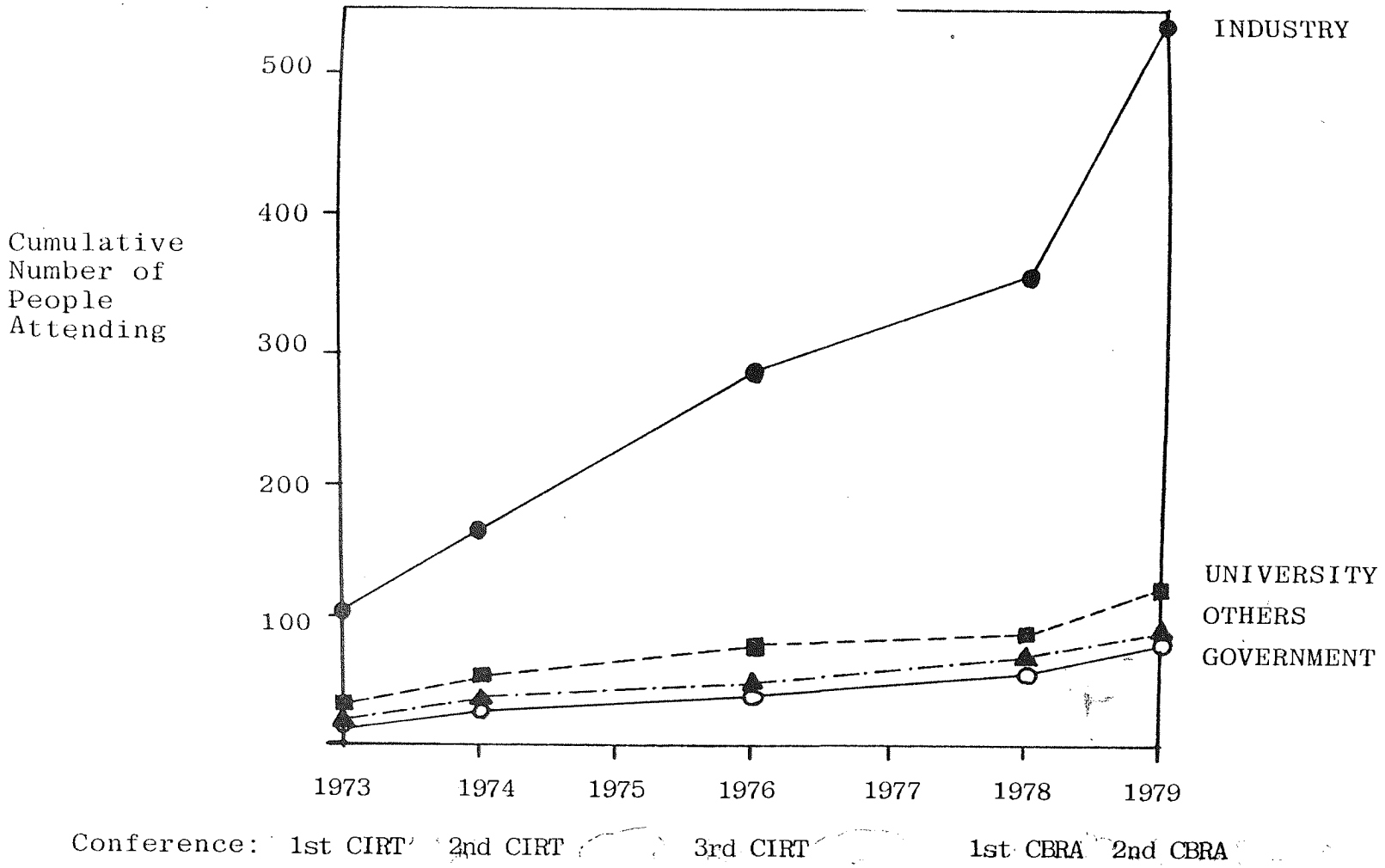


TABLE 6.3 - The Level of Diffusion of Industrial Robots in Various Countries

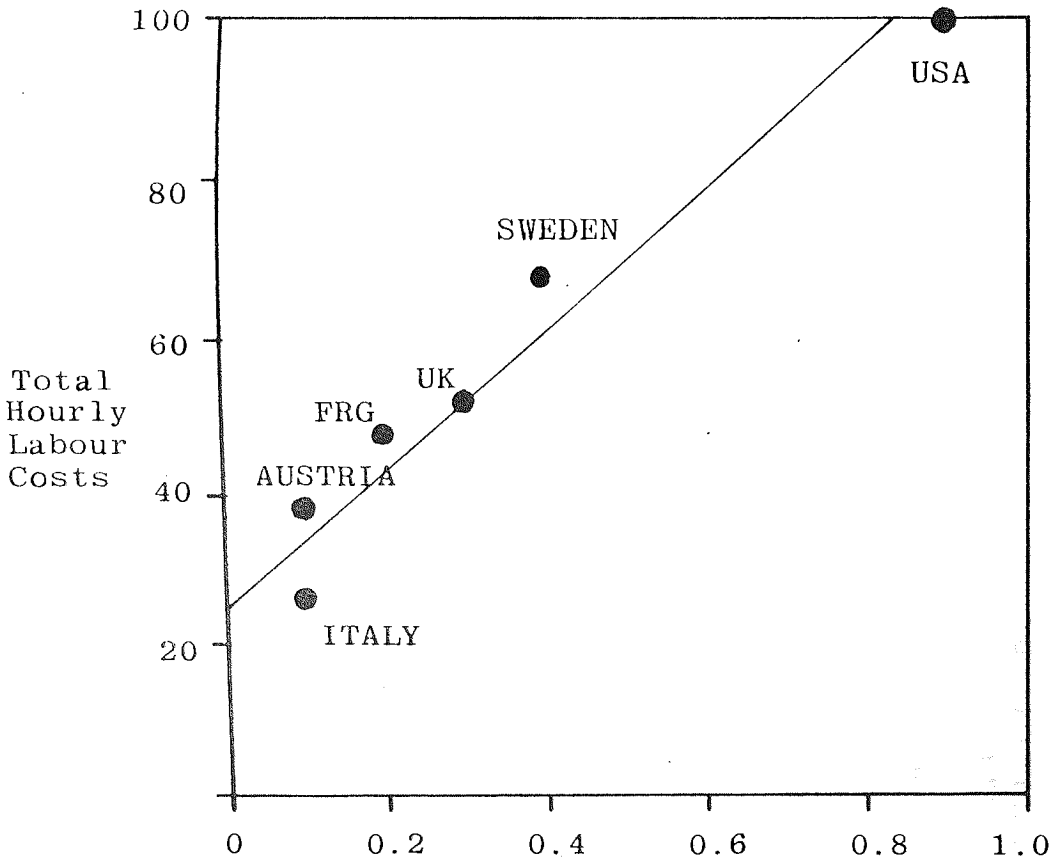
Number of Robots per Thousand Employees in Manufacturing Industry

	Range (A)	Average
Sweden	0.98 - 1.00	0.99
Japan	0.33 - 0.44	0.38
USA	0.18 - 0.24	0.21
Italy	0.09 - 0.11	0.10
FRG	0.07	0.07
France	0.03	0.03
UK	0.03	0.03

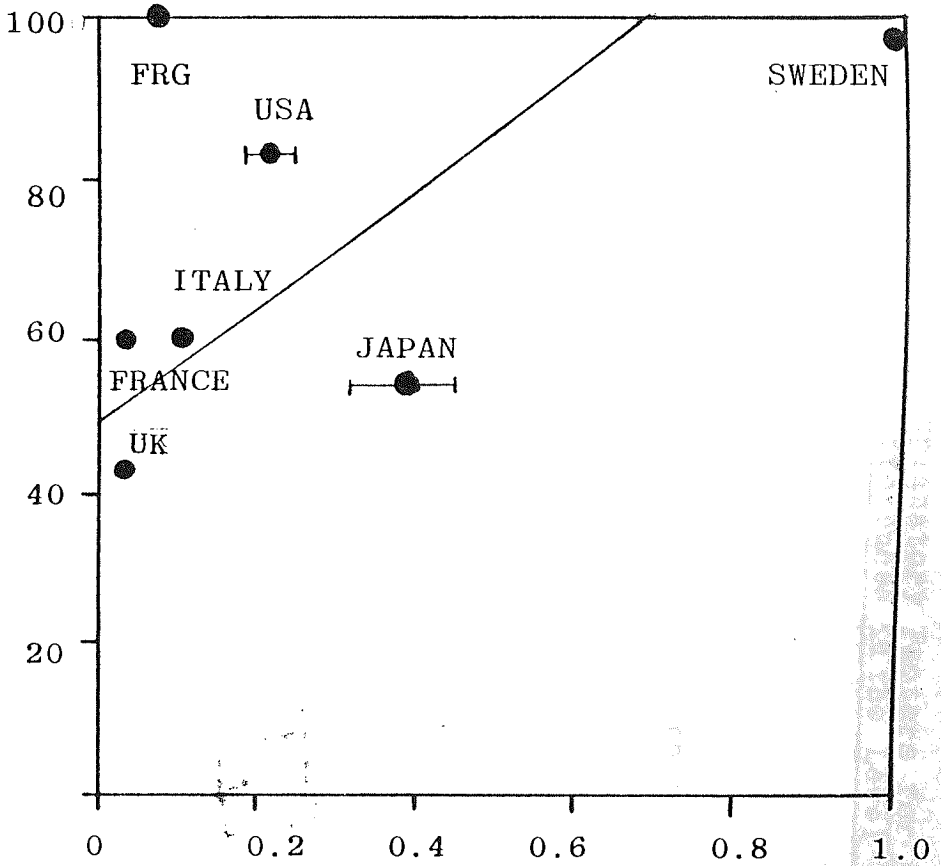
Notes:

A. Estimated from the range of number of robots reported in table A7.4, and the range of number of employees in manufacturing industry reported in tables 2a and 3 of ILO (1979).

Figure 6.11 – The Relation Between Labour Costs and the Level of Diffusion of NC Machine Tools and Robots in Manufacturing Industry (about 18 years after their introduction into the market)



Number of NC machines per 1000 employees in manufacturing industry by 1969 (from Gebhardt and Hatzold 1974, p40)



Number of industrial robots per 1000 employees in manufacturing industry by 1979 (from table 6.3 and data in the Economist 1978, p91)

TABLE 6.4 - Some Possible Explanatory Factors for the International Differences in the Level of Robot Diffusion

Sweden

* High labour costs, high labour cost growth rates, and high unit labour costs.
* High export dependence and exposure to international competition.
* Stringent health and safety legislation and intensive implementation.
* Laws on workers protection and codetermination at work.
* Limited immigration, some labour shortages and high absenteeism.
* Strong industrial and research associations.
* Good record of industrial relations.

Japan

* High labour cost growth rates.
* Massive direct government support and coordination of Industry, universities and research institutes.
* No immigration and predicted acute labour shortages.
* High stability of employment inside firms.
* Strong robot association, freer exchange of information among suppliers and users, and broader marketing efforts.
* Good record of industrial relations.

USA

* High labour costs and low labour cost growth rates.
* Direct and indirect government support (large defence and space programmes).
* Large domestic markets favouring higher volume production and larger number of shifts.
* Stringent health and safety legislation and intensive implementation.
* Poor record of industrial relations.

Continued....

TABLE 6.4 (Continued)

Italy

* High unit labour costs.
* Growing machine tool, motor car, and domestic appliance industries (Fiat policies for pioneering innovation).
* Poor record of industrial relations.

FRG

* High labour costs and low labour cost growth rates.
* Intensive and direct government support.
* Growing machine tool industry.
* Legislation on workers protection and codetermination at work.
* Large immigrant workforce.
* Good record of industrial relations.

France

* Low labour cost growth rates.
* Large immigrant workforce.

UK

* Low labour costs and low labour cost growth rates.
* Declining motor car, machine tool and domestic appliance industries.
* Some immigrant workforce.
* Poor record of industrial relations in some sectors (e.g. Mining and Quarrying, Construction, and Engineering)

Main source: Interviews with robot suppliers and published literature (e.g. Frost and Sullivan 1974, Tassel 1975, Gonsalves and Kurlat 1977, Swords-Isherwoods and Senker 1978, and Coventry Machine Tool Workers Committee 1979)

CHAPTER 7

GENERAL MODEL OF ROBOT ADVANCEMENT

7 - GENERAL MODEL OF ROBOT ADVANCEMENT

7.1 The Structure of the Model

Robot technology advances by the interaction of four basic activities: development, supply and manufacture, adoption and promotion (see figure 7.1). These basic activities do not progress in isolation. They are continuously being affected by other activities taking place in the institutions concerned with robots, and by the activities of other groups of society (financial institutions, consumer groups, government bodies, educational institutes, trade unions, other firms and research organisations, etc.). The particular form of this environment depends on the way in which society is organised within a particular country and between countries. However, the level at which these activities interact, and the nature of their interactions, can be identified in a more abstract manner as being:

Levels

1. The firm
2. The corporation
3. The regional economy
4. The national economy
5. The international economy

Nature of the factors

1. Labour
2. Managerial
3. Economic
4. Technical

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* Part of this chapter was published as a working paper (Zermeño-González, 1979)

As time passes, the importance of the basic activities and of the factors that act upon them, varies. Three distinctive periods of robot advancement can be identified:

Time periods

1. Transient
2. Take-off
3. Saturation

Levels, nature of the factors, and time are the dimensions of a model representing the development and diffusion of robot technology. This conceptual framework will be the basis to explain the differences in the level of advancement between robot systems, and between countries.

Robot technology has already entered the take-off period in some nations and for certain applications, but in general it is at an early stage of its evolution.

The conceptual framework will therefore be especially relevant to the transient period. At this stage, the level of development activity in both research institutions and robot firms is relatively high, and the level of diffusion is relatively low. In the transient period, once equipment has been developed well enough for its introduction into the market, adoption is the limiting factor. A systematic analysis of adoption will identify those factors, inside and outside the firm, which at present control the advancement of robots.

Adoption is commonly regarded in the literature (Rogers and Shoemaker 1971, p25; Bohlen et al 1961, table 1) as a series of iterative functions such as knowledge,

persuasion, decision, communication and action. The checklist used for discussion with users of robot technology in the UK is a conceptualisation of the adoption process similar to that of the literature, and consists broadly of five functions (an extended version of the checklist is shown in Appendix 12):

1. Generation of the idea. Awareness about the innovation and of problems to be solved by its introduction (Motivation stages)
2. Spreading of the idea. Popularisation of the idea of introducing the technology inside the firm
3. Evaluation of the idea. Study of the advantages and disadvantages of adopting industrial robots
4. Application of the idea. The process of acquiring, installing and commissioning the equipment
5. Assessment. Review of the results achieved once the technology is in normal operation, and study of the future perspective of the technology inside the firm.

In reality, these functions can not be easily identified as they happen simultaneously. This problem and the limitations imposed by the methodology (reliance on personal recall information) make the identification of factors on such an extensive and detailed manner very difficult. The model of adoption which I have therefore chosen is a simplified version of the above and consists of three functions:

1. Motivation and evaluation (the antecedents to robot adoption)
2. Application (the introduction of robot technology

into the firm)

3. Assessment (the overall evaluation of the results of the adoption experience).

The uncertainty of robot adoption is high when robots are being introduced for the first time (experimental adoption), especially if adoption takes place in the transient period (adoption pioneering). Once the use of the technology inside a firm reaches a certain level, the acquisition of more robots is less risky and adoption becomes more rapid. During the take-off period, adoption is increasingly a response to a trend (imitation), and finally at the saturation period, adoption finally becomes, to a large extent, simply routine (expansion or replacement).

Experimental adoption and, more importantly, adoption pioneering are the result of a complex interplay of factors. These can also be seen as acting at different levels: the operation, the manufacturing system, and the firm as a whole (see figure 7.2).

1. The operation: the level at which the robot would interact with humans and machines in effecting a change in the properties of an object or workpiece, and therefore increasing its value. This level is commonly identified in the technical literature as "Robot applications" (see table 4.1).
2. The manufacturing system: the level at which a set of products marketed by the firm, is manufactured from external inputs (e.g. raw materials an energy). This consists of a set of linked operations generally classified as storage,

distribution, manufacturing, assembly, finishing, inspection and packaging.

3. The firm: the level at which the organisation and management of one or more manufacturing systems take place. This is the highest level of aggregation within the adopting unit considered here.

Controversy exists over the motives behind the automation of an operation, and over the impact that this has on different parties and aspects of the firm. All the factors involved can be divided into four:

1. Labour factors: those directly relevant to the individual and groups of individuals engaged principally in physical tasks in close interaction with materials, machinery and energy. Direct labour functions are those relevant to an operation and indirect labour functions are those common to more than one operation (fitting, setting, programming and maintenance).
2. Managerial factors: those relevant to the indivual and group of individuals engaged in the coordination of work between operations and manufacturing systems, and in general in the control of the firm for the achievment of its goals. Managerial tasks involve mainly the processing of information which then results in decisions about the different aspects of the business (programming, supervision, monitoring, control, designing, planning, negotiating etc).

3. Economic factors: those relevant to the performance (profit making, for example) of operations, manufacturing systems and the firm as a whole (this category embraces all the others as contributing to the material prosperity of the firm).
4. Technical factors: those relevant to the physical world of the machines and the objects manufactured and expressed in physical units (physical factors).

7.2 Analysis of Robot Adoption

The model presented here is simply a classification of all the factors affecting the introduction of robots in manufacturing firms (see table 7.1). This classification is an attempt to embrace all the factors found to be relevant to adoption through the series of interviews with users, potential users, suppliers and manufacturers (see Appendix 12). It is a systematic description of the categories of variables important to the evaluation of robot technology, and of factors inherent to the firm, which make the success of adoption more, or less, likely. Some of these variables are, of course, also relevant to the introduction of automation and, indeed, to the introduction of any labour-saving technical change, or any innovation with wide implications for the adopting unit. Such a general classification is necessary to comprise all the diverse situations where the question of introducing robots is posed. Robots, like machine tools, are a technology "convergent" to a wide spectrum of industries, and to a

wide spectrum of operations within those industries*. Therefore, the factors and motives important to each case are of a varied nature.

Economic Factors (see table 7.2 and figure 7.3)

The marginal improvements in the performance of an operation and the magnitude of the investment needed for the introduction of a robot system are the main variables affecting the economic feasibility of robot usage. The type of improvements to an operation can either be an increase in output, a reduction in manufacturing costs, or a combination of both. Robots usually achieve higher output in two ways: first by increasing the utilisation of machinery**, and second by increasing the quality of output and reducing rejection levels. A reduction in manufacturing costs is the result of improved materials and energy efficiency due to better consistency and continuity of operation, and/or the result of labour savings. On the other hand, higher capital and space (land) intensity tend to increase the manufacturing cost and the net result will depend on the relative price of the resources and products involved.

The magnitude of the investment required changes radically from case to case, and with the particular design of an application. Nevertheless, it can be said that increases in the level of automation and integration of a system are only

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* Rosenberg (1976, p16) identifies the phenomenon of "technological convergence" (a technology common to many industries) as a fundamental factor in the development and diffusion of machine tools

** The differences in cycle time between a robot operation and a manual operation are in the majority of cases insignificant

achieved by disproportionate increases in the magnitude of investment. Managers in industry regard total automation, even when technically feasible, as an expensive luxury. They prefer to "optimise" the marginal benefits of the investment by designing hybrid (man-machine) system.

The high capital investment needed for the design, building, and debugging of a tailor-made automatic machine demands large improvements in productivity and reduction in manufacturing costs if it is to be justifiable. This has always meant that only those situations where a continuous production or a very high annual volume exist were amenable to automation (mass production). Other sectors of industry where operations handle a mix of products* were not so, as the time needed to change over a purpose built equipment to handle different products, even when possible, is excessively long.

The advent of flexible automation was especially motivated by the need to automate the batch manufacturing sector of industry. Robot systems are intended to cope with a rapid change-over to different products therefore allowing for smaller batches or shorter production runs, and for changes in the product design (a result of design instability or short product life cycle). On the other hand, the standard character of the technology make robots less capital intensive and hence reduces the need for high volumes of production.

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* In some cases the volume of any individual product is not enough to justify the total allocation of one machine. In others, either the demand for the product is unstable or inventories too expensive to make large batches economically feasible.

A useful indicator of the economic feasibility of robots and their alternatives is the unit manufacturing cost. The sensitivity of the unit manufacturing cost to increases in scale varies according to the type of operation. Robot technology becomes the best alternative at the medium volumes, whereas human labour and special purpose automation are cost-effective at the low and high volume ends of the scale respectively (see figure 7.4). These feasibility domains however, change as a consequence of changes in the relative costs of labour and machinery, and their dynamic behaviour is essential for estimating the future potential for robots. In addition to these factors, others such as the capital intensity of the operation and the value added of the products have a significant role in encouraging automation by making the improvements in productivity valuable. Products and processes with these characteristics become the first to be automated.

The general economic characteristics of the firm (size, vertical and horizontal integration, type of ownership, technological level, availability of resources etc.) have been the focus for explaining the speed of response of different firms to new technology. Robots are no exception; being a capital intensive, sophisticated new technology means that firms in the high technology area are likely to be the pioneers. The technology has certainly been most readily accepted by large and successful automobile firms with enough capital for risk projects and in general, with a high rate of investment.

Managerial Factors (see table 7.3 and figure 7.5)

At the present stage of development of the technology the role that the individual plays in the introduction of robots is, indeed, difficult to exaggerate. In the early stages of diffusion when uncertainty is high, adoption is often the mere result of individual commitment. Commitment which translates into courage and effort to move the organisational machinery towards the investment of resources even at the cost of interdepartmental conflict and loss of personal status. In the same way that innovation is generated under the leadership of product champions, diffusion is initiated by "adoption pioneers". This is especially true of innovations where uncertainty exists not only about the innovation performance but also, about the response of a large number of elements in the system to its introduction. The quantity and quality, and other individual characteristics of the managerial resources in an enterprise is therefore a basic controlling mechanism of the speed of response of the firm to robot innovation.

Managers take the decision to engage in the introduction of robots in a context of limited time and resources, and of countless ideas to improve the technical performance of operations. The investment of managerial effort therefore depends also on the perception of priorities for action and risk ratherthan purely on the relative advantage of robots against their alternatives. Fears of labour unrest, of technical difficulties and of interdepartmental politics can relegate the robot project to the lowest places in the list of priorities for managerial action. Its negative connotations of technical sophistication and unemployment have

undoubtedly a large influence on the attitudes of managers towards robot technology.

The development of automation can be regarded as the progressive partition of tasks and the reduction of the extent of control that direct labour has over operations (Braverman 1974). The breaking down of tasks however, has limitations both of a social and of an economic kind, and the creation of proper jobs is therefore an obligation of managers when introducing robots. Design and implementation of robot systems can be done in a variety of ways having different demands on capital and on magerial effort, and different implications on the labour tasks, The participation of the different actors affected by the adoption of the system is a way of making use of such freedom of choice and of finding a compromise between conflicting interests. This however, complicates even further the task of management and is rarely what happens in reality.

The burden that the automation of an operation puts on a manager varies according to the type of system to be introduced but is generally heavy. The managerial effort needed to introduce and maintain robots is a function of the characteristics of the robot and the peripheral equipment, and of the implications that the automation of the system has for other operations. The adaptability of present day robots is still insufficient for the full accomplishment of the goals of the robot approach. Even for the most sophisticated robots available in the market, the degree of special development of peripheral equipment needed is high. Pioneers soon realised that the adoption of robots did not only

consist of buying a robot and plugging it in, but of developing an entire system. Furthermore, in many instances the reliability of the system depends critically on the quality of the components handled and expensive modifications in other operations are necessary. Inspection suddenly becomes crucial, where large variance in specifications was unimportant thanks to the versatility of human labour, and a total review of materials and product design which extends to suppliers and customers is needed. Increased mechanisation in the end demands better management. Integration of production, maintenance, machine building, marketing and sales along the product life-cycle is required. This has implications for the way in which management is formally organised, and also for the way in which departments interact in real life.

Robot technology is very demanding because for many applications, it is a further step in the mechanisation of manufacturing systems (carries the integration of the system to a higher level) and serves as the link between operations constituting what is called an automatic manufacturing cell. If robots are to be used on a large scale, traditional processes have to undergo radical changes. This is usually possible when new plants are built and the freedom for fundamental changes in the design of the whole manufacturing system is large enough.

In the light of these difficulties no manager would ever introduce the technology unless a large incentive exists. After a system has been properly implemented the managerial task might become easier as output becomes more predictable and controllable, labour problems less numerous, quality

more consistent, and in general productivity increased.

In order that the possible benefits of introducing robots should be a sufficient driving force for the managers' efforts, a climate favourable for innovation must exist inside the firm. This climate can be identified as the company policies on product and process innovation and capital investment. It is not surprising that the concentration of robots in firms and the concentration of robots in certain industrial sectors is high. Pioneering firms have clearly defined policies for becoming technical leaders either for prestige reasons, competitive advantage, or long term strategies for the development of the technical, managerial and labour capabilities. These policies on the other hand, are the result of the interaction of individual factors such as managerial attitudes and qualifications, and other general characteristics of the firm.

Labour Factors (see table 7.4 and figure 7.6)

The displacement of human labour from unhealthy, dangerous and generally obnoxious tasks can be traced far back to the industrial revolution. Nevertheless, many jobs with harmful implications for the individual still remain and have been created in the process of development of different technologies, and these are a big incentive for automation. One of the main antecedents of robots, in fact, is the development of telechiric devices by the nuclear industry for the purpose of performing jobs in environments where the utilisation of humans, in the present day, is unthinkable. The nature of the jobs in manufacturing industry is therefore of singular importance for explaining the diffusion of

robots. Physically strenuous, paced, monotonous, dangerous and boring tasks in bad working environments not only result in individual harm but are the recipe for dissatisfaction and industrial relations problems. These tasks favour negative individual and group attitudes to work which result in frequent breaks in production, high labour turnover, absenteeism, and all kinds of industrial conflict. If the situation permits, an increase in the material remuneration of these jobs (which normally is difficult to carry out because of wage differentials) is the only way by which recruitment of labour is possible. However, there comes the time when the only alternative is either automation or a different process altogether.

The prospect of unemployment has always been, especially in low growth periods, an important source of reaction against technical change. The way in which robots affect labour requirements depends on the situation and on the extent of their introduction. Generally it could be said that robots have a lower displacement ratio than special purpose automation. In fact, robots are very often slower than humans and their main advantage is the ability for continuous and consistent work.

Present day policies, agreements and regulations make redundancy as a result of technical change a rare event. This is more the case when labour mobility and labour demands inside the firm make the transfer of workers a possibility. In some instances, transfer is however complicated by occupational regulations, expensive re-training, or political problems rooted in the organisation of trade unions. Thus,

either the introduction of robots is delayed until natural wastage allows or it results in workers redundancy. The particular outcome depends on the bargaining power of labour and management, and their particular interests.

Flexibility in the organisation of work is a demand of technology such as robots which requires a mixture of traditional and new skills. The existence of demarcation difficulties make the running of complex machinery difficult and innefficient, and serves as a deterrent to automation.

Collective participation in the innovation decision process has been identified as a brake for speedy adoption (Rogers and Shoemaker 1971, p37). However as manpower planning is, in modern times, also a responsibility of labour representatives; early notice, consultations and negotiations concerning technical change are necessary for the prolonged acceptance of robots inside a firm. Labour involvement is a requisite that most robot suppliers are beginning to ask of managers wanting to introduce robots.

Finally, the availability of the right mix of skills and experience is a precondition for the wide use of robot systems. Despite efforts by manufacturers to simplify programming, setting, fault finding and repairing, and to educate and provide support services a shortage of skills in electronics inside a firm, for example, is a great barrier to the adoption of robot technology.

Technical Factors (see table 7.5 and figure 7.7)

Physical factors have hardly been identified as explanatory variables of the diffusion of manufacturing technology in the social science literature. The potential for robots is however, primarily controlled by the physical characteristics of products, and the nature of processes. Furthermore, many other factors apparently independent of the physical world are indirectly related to these variables. The kind of material, the dimensions, the consistency of the properties, and the intrinsic value of the workpiece are closely connected to the technical, economic, and social feasibility of automation. The kind of material of a workpiece narrows down the range of feasible manufacturing processes; its dimensional characteristics specify the nature of the human task and the design of machinery; and finally, its value governs the economic feasibility of automating the operation. In addition, the physical nature of the process determines the working conditions, the need for continuity and consistency of operation, and the design of the manufacturing system. The complexity of the process being performed and the degree to which this complexity is understood (the state-of-the-art) are also fundamental requisities for automation. Unless an acceptable level of control of the process involved can be achieved, automation is not possible. All significant variables and their interactions must be known; and means of measuring, control and actuation must exist.

It has been noted that robot technology is a further step in the automation and integration of operations and manufacturing systems. This "integrative" role means that the demand for robots is sensitive to a host of variables inherent

in the rest of the system. In short, the compatibility of the technology and the technical developments that might take place in the products, the machines and the organisation of the systems where robots are to operate, affect the feasibility of their adoption. Technical compatibility in particular, is concerned with the level of automation of machinery and of peripheral equipment, and the possiblities of interlinking all the equipment with the robot. This is therefore a direct result of the characteristics of the existing machinery and its age and versatility are of particular importance for decisions on the use of robots.

The design of the operation and manufacturing system becomes a crucial factor as a consequence of robot integration. Integration, if design is not proper, can increase greatly the implications of a break-down and affect the feasibility of a system. Recent innovations in the design of production systems, especially those pursuing flexibility and integration as the means to respond to the dynamic environment of discrete manufacture, have to be adopted if the diffusion of flexible automation is to be widespread. In the automobile industry for example, robots are related to the development of systems such as the Robogate. Other advances such as computer aided manufacture, integrated manufacturing systems, flexible manufacture, and small batch automation are closely linked to robot technology.

Finally, as different types of robots compete for the same applications, the technical characteristics of robots themselves are crucial in stimulating or discouraging demand for them.

7.3 Synthesis

The above description gives an insight into the nature of the process of adoption. Industrial robots are introduced into manufacturing firms only when numerous conditions exist. Rather than by single factors, adoption pioneering is motivated by the interplay of different forces.

A further categorisation of the factors listed in the classification of table 7.1 can be helpful for finding the main clusters of interacting factors that control adoption pioneering. Figure 7.8 represents the decision to adopt as affected by individual and group characteristics, consequences and foreseen problems, robot characteristics, and the inherent characteristics of the operation, the manufacturing system, and the firm.

Seven clusters of factors affect the decision to adopt robots (see figure 7.9 and 7.10).

The consequences and problems of adoption can be divided into three major clusters:

1. Economic Profitability (EP)
2. Labour Impacts (LI), and
3. Managerial Effects (ME)

Each one of these is the result of the interplay of advantages and disadvantages of adoption, relative to the existing alternatives. These clusters are indicators of the possible net result that the introduction of robots will bring to those concerned with adoption (managers and workers) and to the firm as a whole.

The existing technical, methodological, and organisational systems, and the economic characteristics of the firm can be more or less compatible with robot technology and with their alternatives. Thus, another important cluster of factors can be identified as:

4. Systems Compatibility (SC)

This cluster is a condition for adoption and its consequences. The likelihood and the results of the introduction of robots varies according to how well the characteristics of robots match the existing environment.

The degree of compatibility of the firm with, and the consequences of robot adoption are to a very large extent, matters of judgement (particularly during the transient period). The characteristics of individuals and groups, their perception of the situation, and the priorities they attach to the likely consequences are therefore substantive to the adoption decision. Two additional clusters can be identified which are relevant to the interaction between individuals:

5. Labour Acceptance (LA)

6. Managerial Involvement (MI)

The reaction of individuals to the question of adoption is very much the result of the formal and informal policies and the possibilities that the firm has for engaging in the introduction of capital intensive and sophisticated technology. These kind of variables are contained in a seventh cluster:

7. Climate for Adoption Pioneering (CAP)

This cluster portrays the environment that the individuals have created inside the firm. With no resources and encouragement, labour acceptance and managerial involvement, even when the other conditions exist, are unlikely to be prompt. Adoption in these situations is relegated to the time when the forces of imitation, if diffusion succeeds, break the inertia of the system.

Each of the clusters represents internal and external interactions within and between the categories of the classification. The possible number of external and internal interactions is extremely large since the factors are many and their relationships very often are of a two way nature. Here I have therefore attempted to describe (see figure 7.10) only those interactions considered most important.* The principal factors of adoption can be recognised by locating those variables connecting clusters and those connecting clusters with the external environment of the firm.

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* The following are important criterion for the design of the model shown in figure 7.10:

1. The relationship between factors is confined to cause and effect type.

2. Only direct interactions are shown within clusters (law of transitivity). However, some important exceptions were made (e.g. nature of the task)

3. Relations between factors of different clusters are not shown. Only clusters as a whole can affect single factors from a different cluster.

4. Interaction between factors can be positive or negative with respect to the question of robot adoption. In many cases the kind of interaction depends on the particular situation.

5. Interactions are negative or positive to the question of robot adoption in four fashions: motives and barriers to adoption and benefits and disadvantages of adoption. These of course, must be seen as relative to the parties involved in adoption (Labour and management); one's motive to adopt may be the other's disadvantage of adoption, and so on.

Figure 7.1 - The Structure of a Model of Robot Advancement

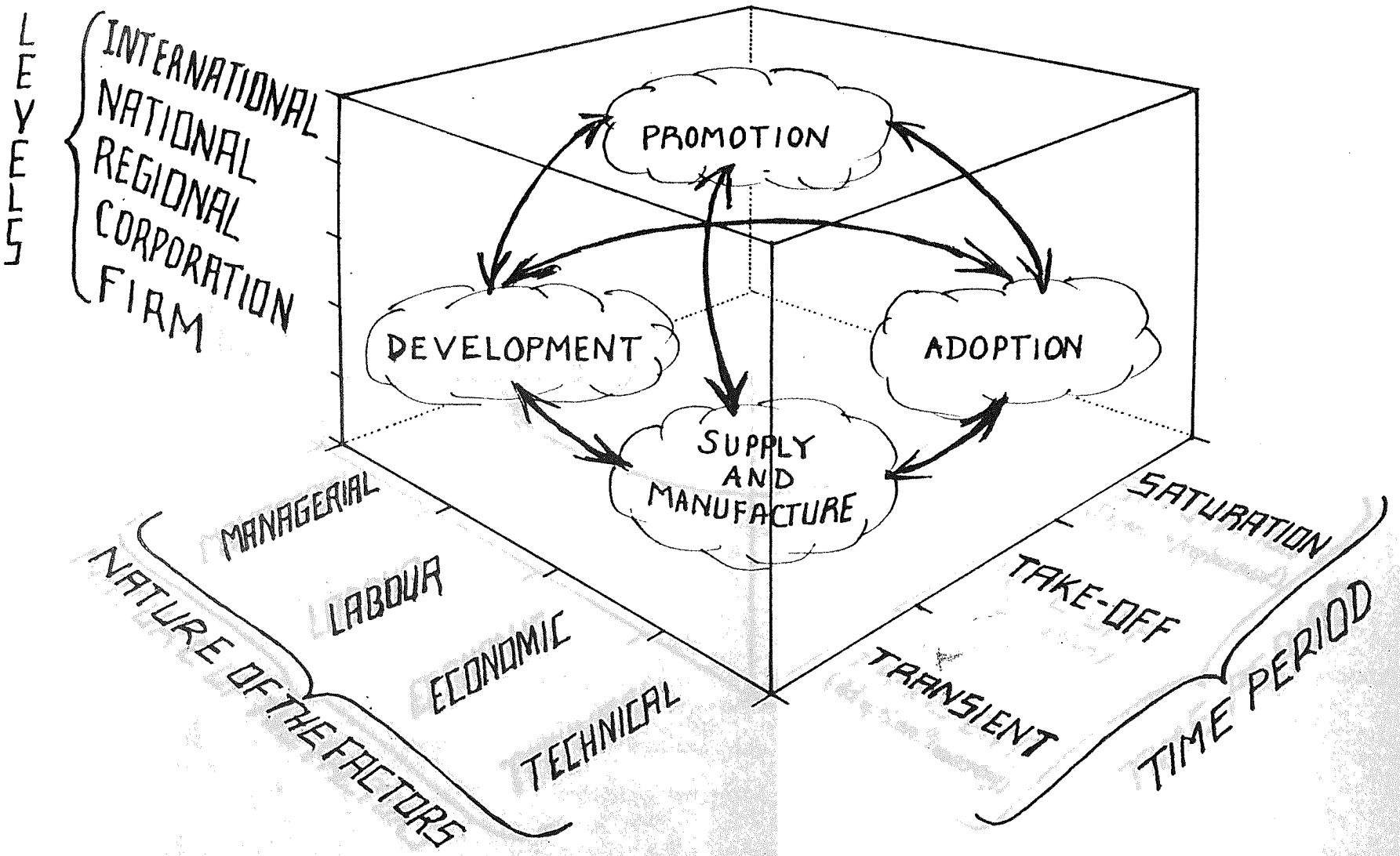


Figure 7.2 - The Structure of a Model of Robot Adoption

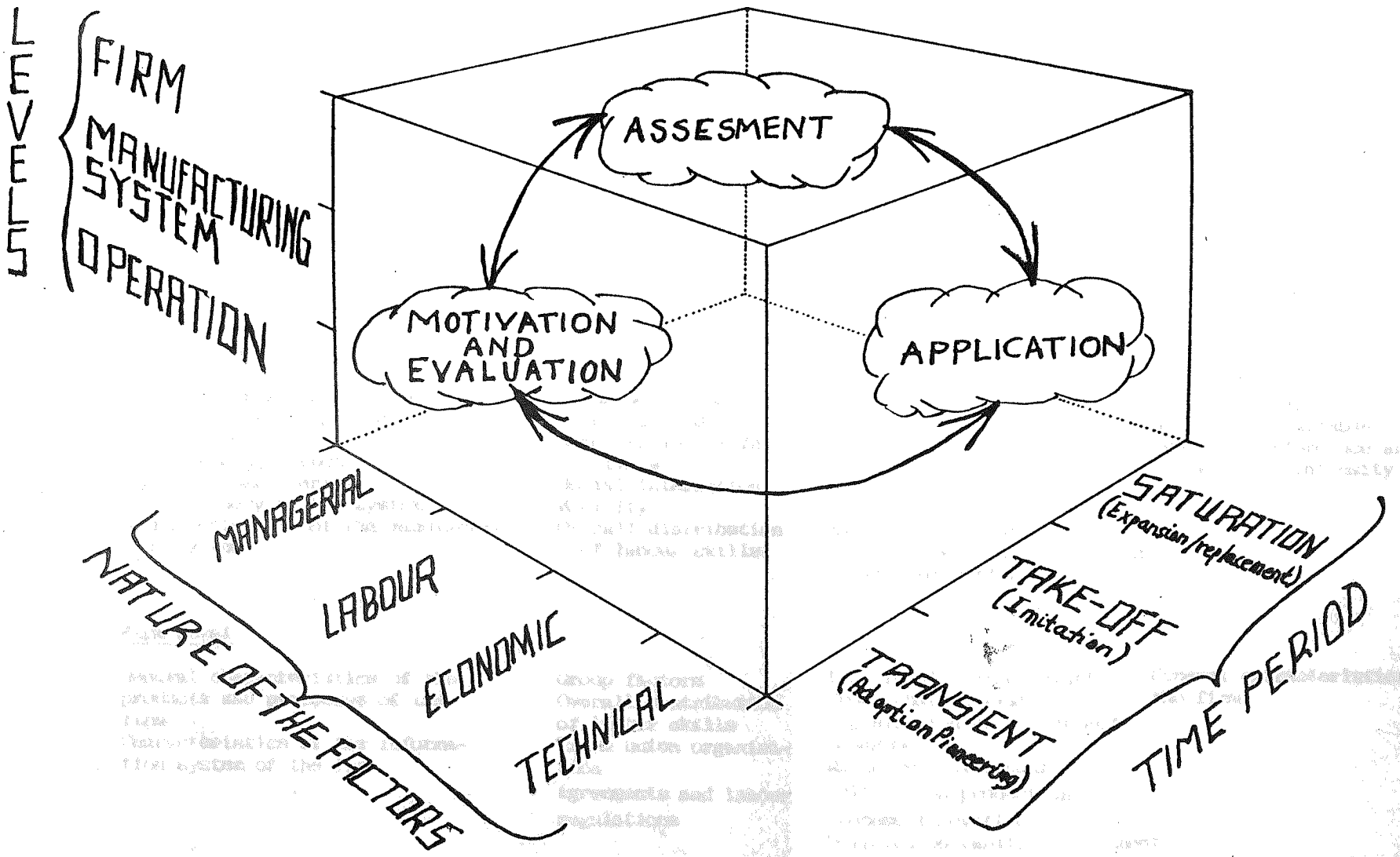


TABLE 7.1 - Categories of Factors Affecting the Introduction of Robot Technology in Manufacturing Firms

Technical	Labour	Managerial	Economic
Operation or Unit Level			
Physical characteristics of the workpieces processed Physical nature of the operation Physical characterisitics of the machinery	Individual wellbeing Nature of the task Individual attitudes Job remuneration Job mobility Labour requirements Group factors	Design of the workpieces Design of the operation Organisation of labour Production scheduling Allocation of labour Supervision, monitoring and control of performance	Product variables Production variables Performance and resourses intensity
Manufacturing System Level			
Physical characterisitics of raw materials and products Physical characteristics of the manufacturing system Physical characteristics of the machinery in the system Characterisitics of the manufacturing system	Group wellbeing Group attitudes Remuneration differentials Social interaction Mobility Overall distribution of labour skills	Design of raw materials, and products Design of manufacturing system Organisation of labour Production planning Allocation of labour Supervision, monitoring, and control of performance	Product variables Production variables Systems performance and resources intensity
Firm Level			
General characteristics of the products and processes of the firm Characteristics of the information system of the firm	Group factors Overall distribution of labour skills Trade union organisation Agreements and labour regulations	Individual characteristics Group characteristics Organisation of labour and management Management of labour Policies on product and process innovation Policies on capital investment	General characteristics of the firm

TABLE 7.2 - Economic Factors Affecting the Introduction of Robot Technology in Manufacturing Firms

Operation, Manufacturing System and Firm Level

Product variables of the operation and the manufacturing system

- Number of products processed
- Product life cycle
- Design stability
- Volume
- Price

Production variables of the operation and the manufacturing system

- Capacity
- Utilisation of capacity
- Consumption of materials, energy and space
- Rejection levels

Performance of the operation and the manufacturing system (value added, payback period, return on the investment and unit manufacturing cost)

Value of Output

Manufacturing costs

- Labour
- Energy
- Materials
- Land
- Capital

Magnitude of the Investment

Indirect Costs

Continued/....

TABLE 7.2 (Continued)

General characteristics of the firm

Size
Vertical and horizontal integration
Type of ownership
Performance (magnitude and rate of growth)
Availability of resources (capital, labour, materials, energy and land)
Technological level (R & D intensity, sophistication of product and process)
Market share (industrial concentration)
Exposure to international competition

Figure 7.3 - Interaction Between Economic Factors

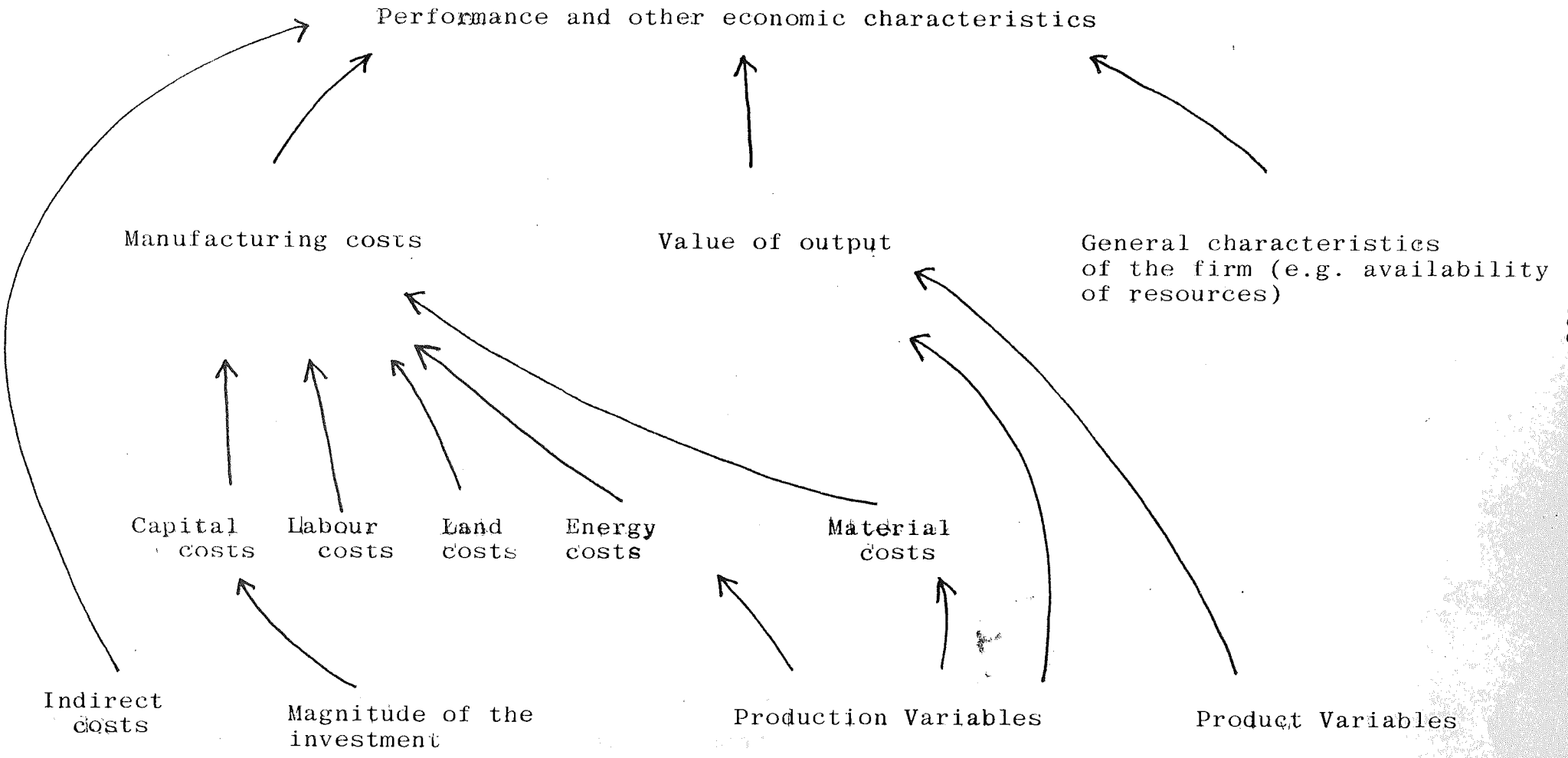


Figure 7.4 - The Cost Efficiency of Different Approaches to Automation (see for example Engelberger 1979, p118 and Nevins and Whitney 1980, p38)

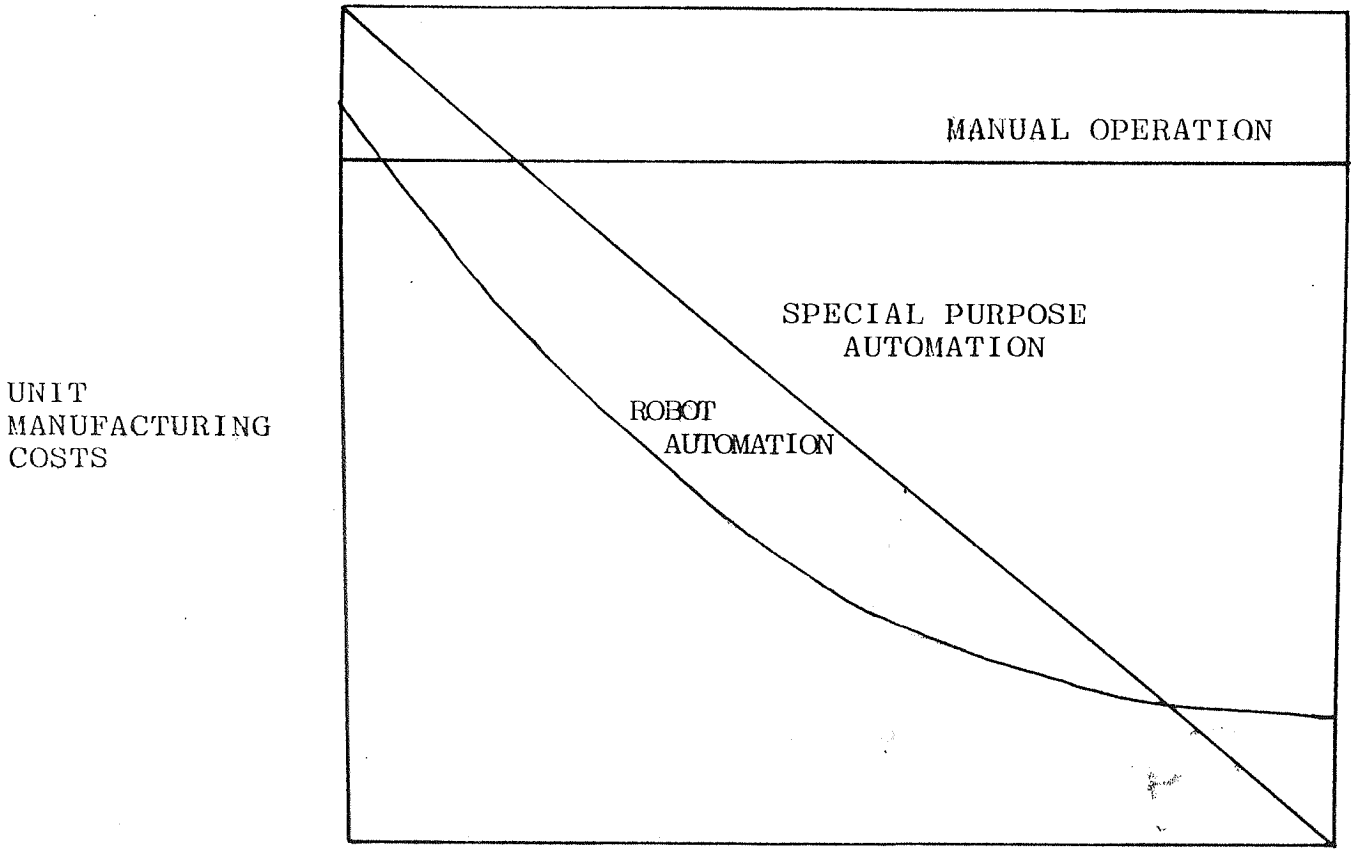


TABLE 7.3 - Managerial Factors Affecting the Introduction of Robot Technology in Manufacturing Firms

Operation, Manufacturing System and Firm Level

Individual factors

- Individual wellbeing
- Individual attitudes
  - Attitudes to work
  - Attitudes to change
  - Perception of priorities
  - Participation
- Individual qualifications and other characteristics
- Job Remuneration

Group factors

- Group wellbeing
- Group attitudes and social interaction (informal and formal relations between managers and workers)
- Overall distribution of individual qualifications and other characteristics

Design management (workpieces, operations, products, and manufacturing systems)

- Selection of design criterion
- Selection of operations and manufacturing systems
- Integration of design functions (production, maintenance, machine, building marketing and sales)

Organisation of labour and management

- Definition of tasks
- Definition of jobs
- Definition of grades of skills and qualifications
- Organisational structure

Continued/....

TABLE 7.3 (Continued)

Production scheduling and planning

- Assignment of workpieces to operations
- Products and workpiece batch sizes and production runs
- Working schedule

Supervision, monitoring and control of performance

- Quality of inputs and outputs
- Inventories
- Material inputs and outputs
- Labour productivity
- Machine performance

Managment of labour

- Allocation of labour to operations
- Recruitment
- Training
- Manpower policies

Policies on product and process innovation

- Search for technical leadership and new products
- Degree of secrecy
- Priorities for technical change
- Reliance on in-house development capabilites

Policies on capital investment

- Procedures for justification of capital investment
- Priorities for capital investment

Figure 7.5 - Interaction Between Managerial Factors

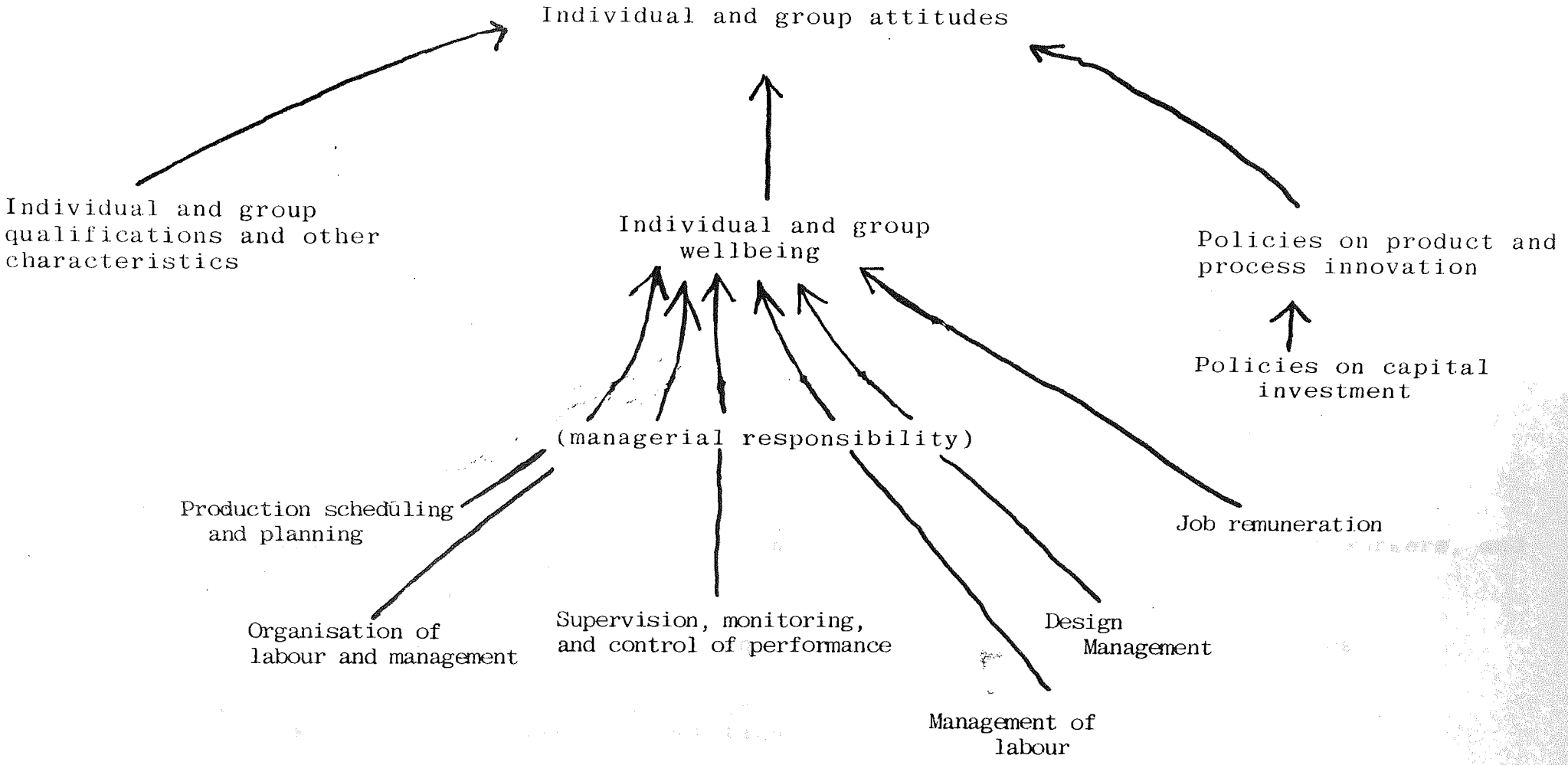


TABLE 7.4 – Labour Factors Affecting the Introduction of Robot Technology in Manufacturing Firms

Operation, Manufacturing System and Firm Level

Individual factors
- *Individual wellbeing (health, safety, standard of living and quality of life)*
- Nature of the task
  - Physical characteristics (strength, speed, precision, frequency)
  - Mental characteristics (responsibility, concentration, tension, monotony)
  - Sensorial characteristics (vision, ear, touch, voice)
- Working conditions
- Individual attitudes
  - Attitudes to work (work effort, breaks on production, absenteeism, turnover)
  - Attitudes to change
  - Perception of priorities
  - Participation (informal and formal workers' organisation)
- Individual skills, qualifications and other characteristics
- Job remuneration
  - Wages
  - Job satisfaction
  - Recognition
  - Social contact
- Job mobility

Group factors
- Group wellbeing
- Group attitudes and social interaction (informal and formal relations between workers, and between workers and managers)
- Remuneration differential
- Mobility
- Overall distribution of labour skills, qualifications and other characteristics

Labour requirements
- Direct labour (ratio worker-to-operation; skills)
- Indirect labour (ratio worker-to-operation; skills)

Trade union organisation

Agreements and labour regulations

Trade union policies on technical change

Figure 7.6 - Interaction Between Labour Factors

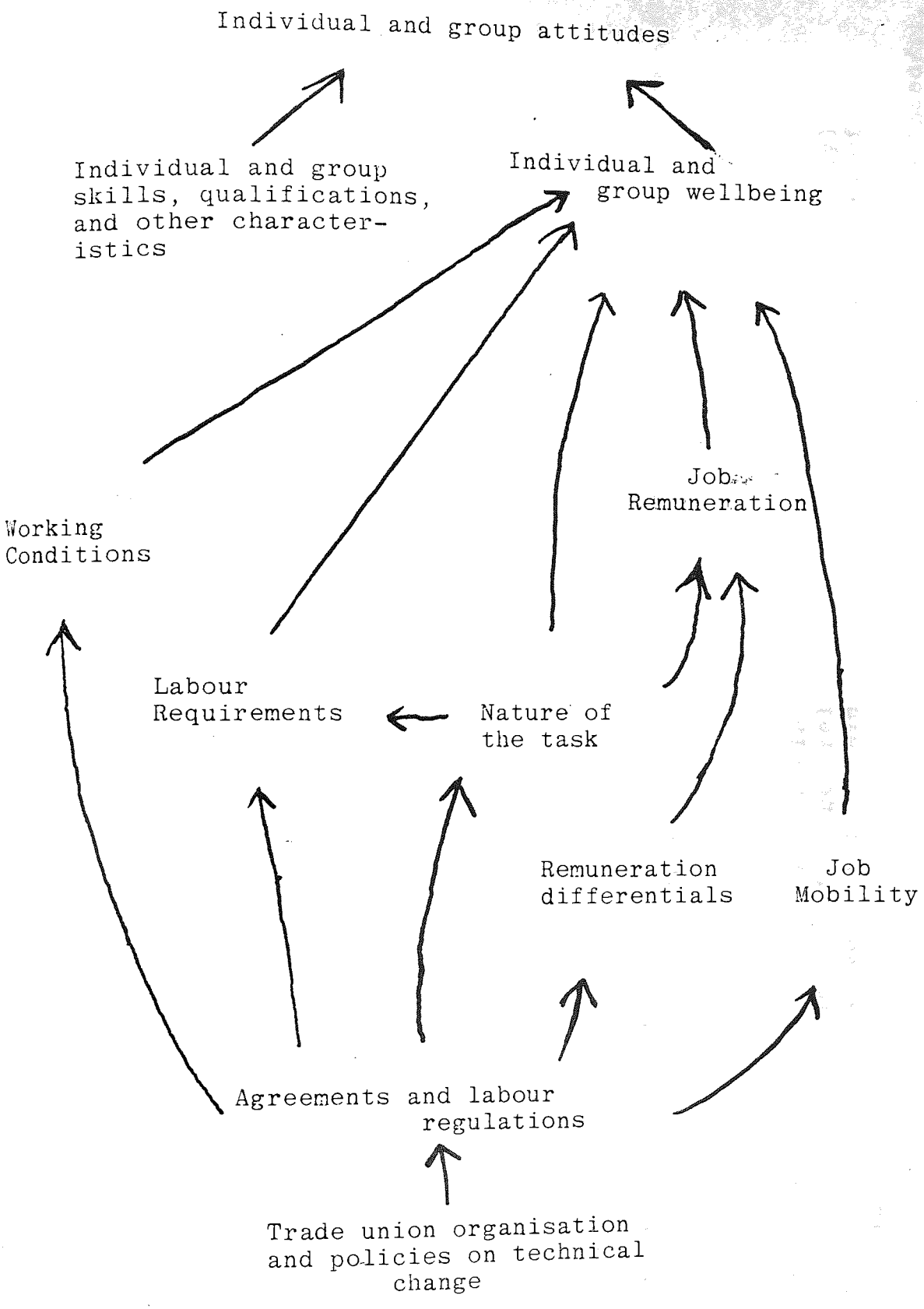


TABLE 7.5 - Technical Factors Affecting the Introduction of Robot Technology in Manufacturing Firms

Nature of the operation

- Transformation process and other tasks (order increasing, thermal, mechanical, chemical, combinations)
- Complexity
- State-of-the-art
- Conditions generated
  - Chemical (fumes, vapours, dust, grease)
  - Physical (noise, humidity, cold, vibration, luminosity, space)

Physical characteristics of materials (raw materials, workpieces and products)

- Properties of the material (state, density, composition, strength, life)
- Dimensional characteristics (geometry, size, precision, surface finish)
- Consistency of characteristics
- Intrinsic value

Nature of the manufacturing system

- Combination of operations
- Interconnection between operations
- Interconnection with the firm

Characteristics of machinery

- Technical specifications (capacity, cycle time, power, accuracy)
- Performance specifications (life, age, reliability, efficiency, serviceability)
- General characteristics (versatility, level of automation, complexity, level of standardisation)

Continued/....

TABLE 7.5 - (Continued)

Characteristics of the manufacturing system

- Overall characteristics of machinery
- Layout-space demands
- Degree of integration and automation
- Flexibility and implications of breakdown

Characteristics of the information system (between operations, manufacturing systems and the firm)

- Speed of response
- Accuracy
- Versatility
- Degree of integration

Robot system characteristics

- Degree of versatility (manipulative, positional and command versatility, and adaptability)
- Degree of standardisation (manipulator, driving system, peripheral equipment, control and software)
- Performance (speed, accuracy)
- Reliability (MTTR, MTBF, Life)
- Complexity (ease of supervision, maintenance, setting and programming)
- Other (safety, floor space required, weight, power requirements, dimensions, environmental conditions, possibilities of mounting)

Figure 7.7 - Interaction Between Technical Factors

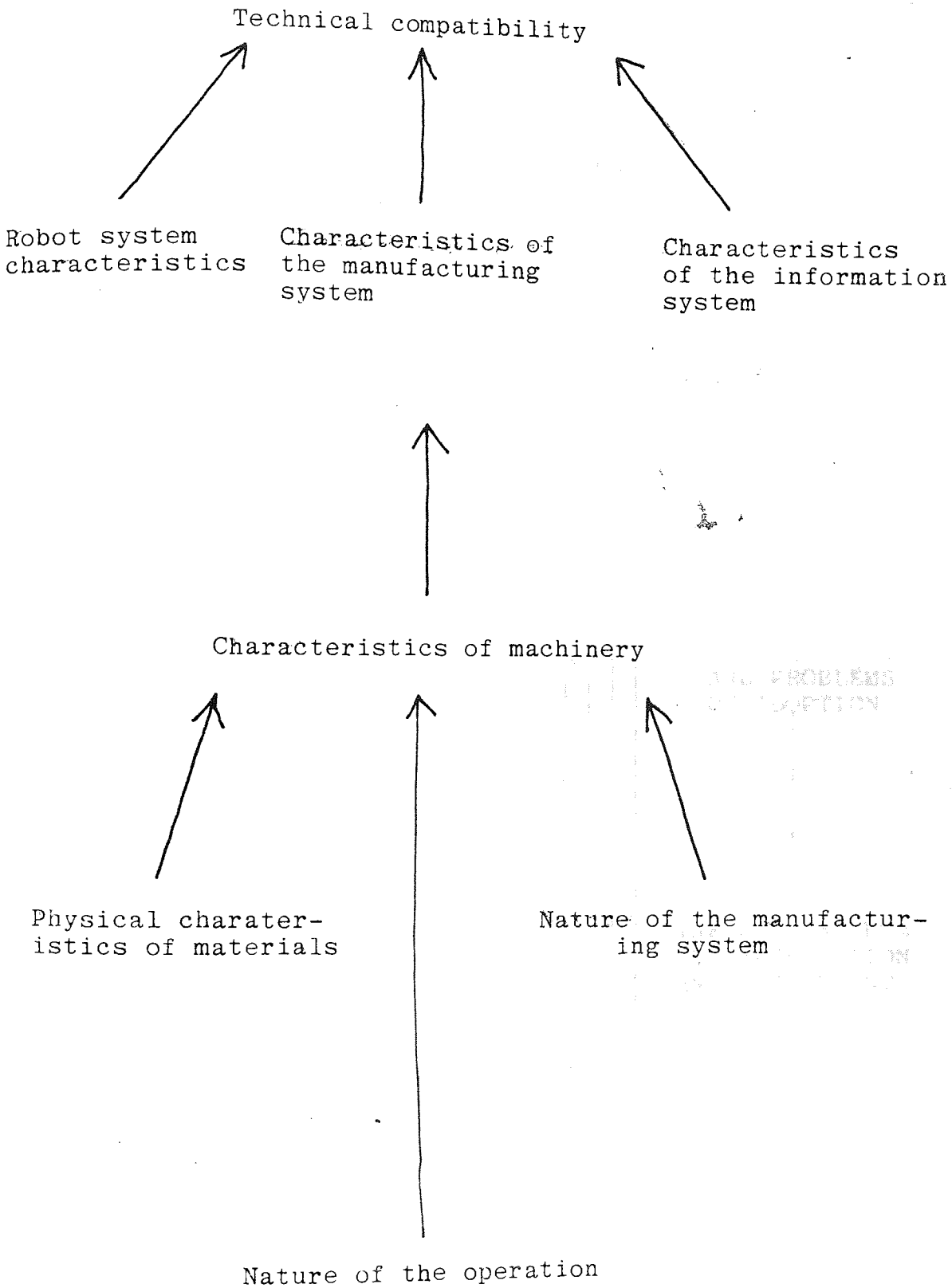


Figure 7.8 - Type of Factors Affecting the Introduction of Robot Technology in Manufacturing Firms

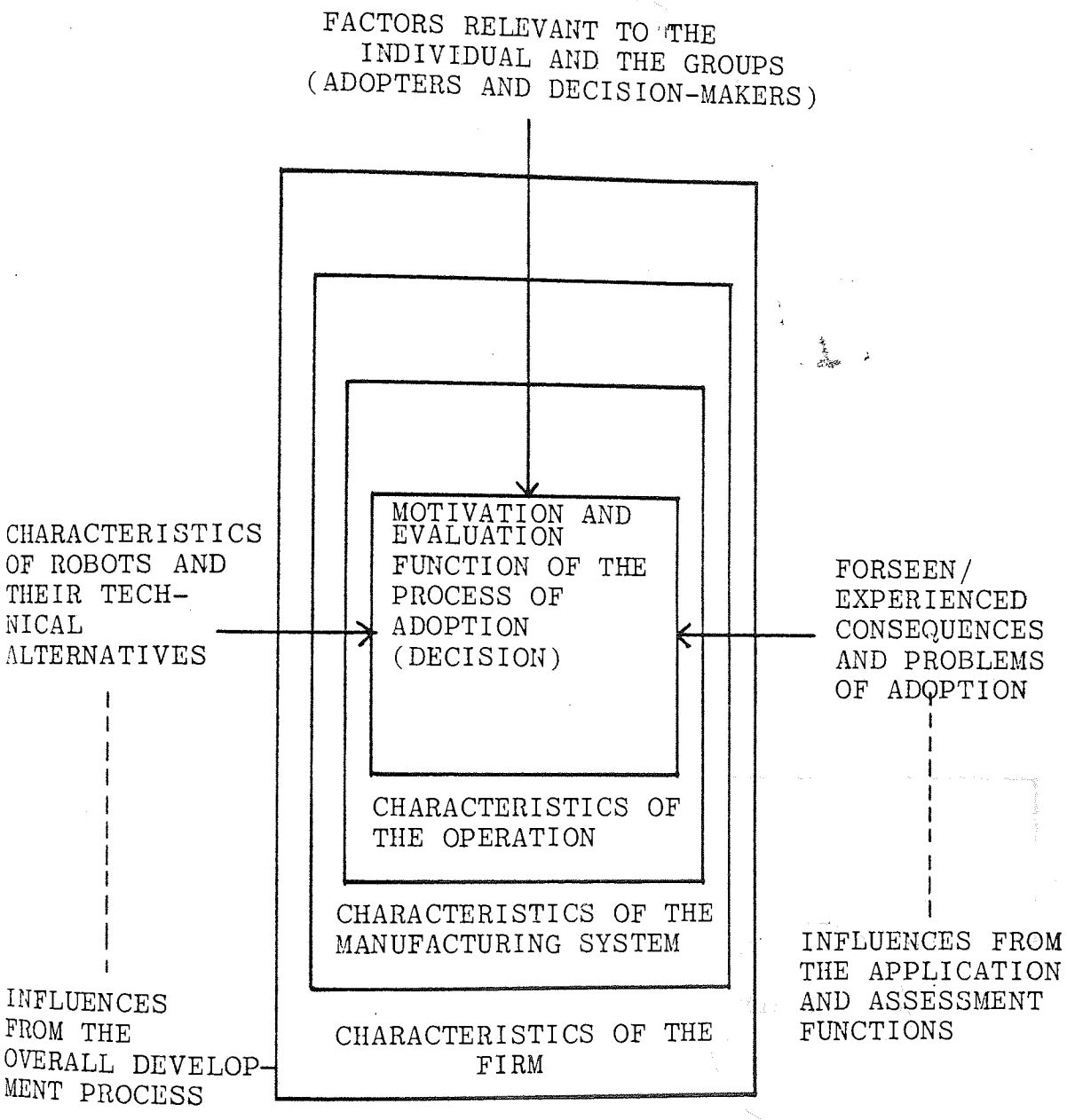


Figure 7.9 - Main Clusters of Interacting Factors Controlling Adoption Pioneering

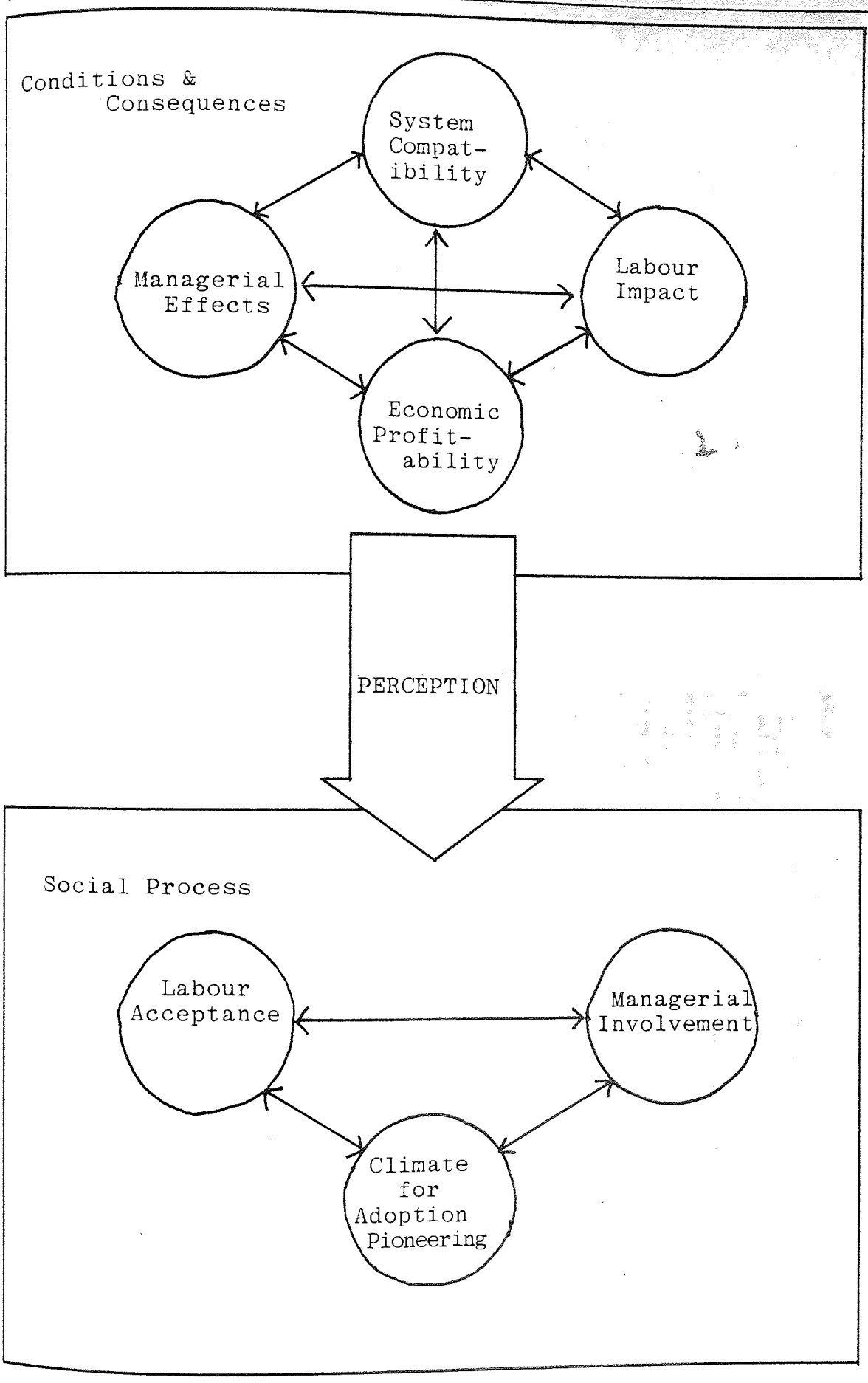
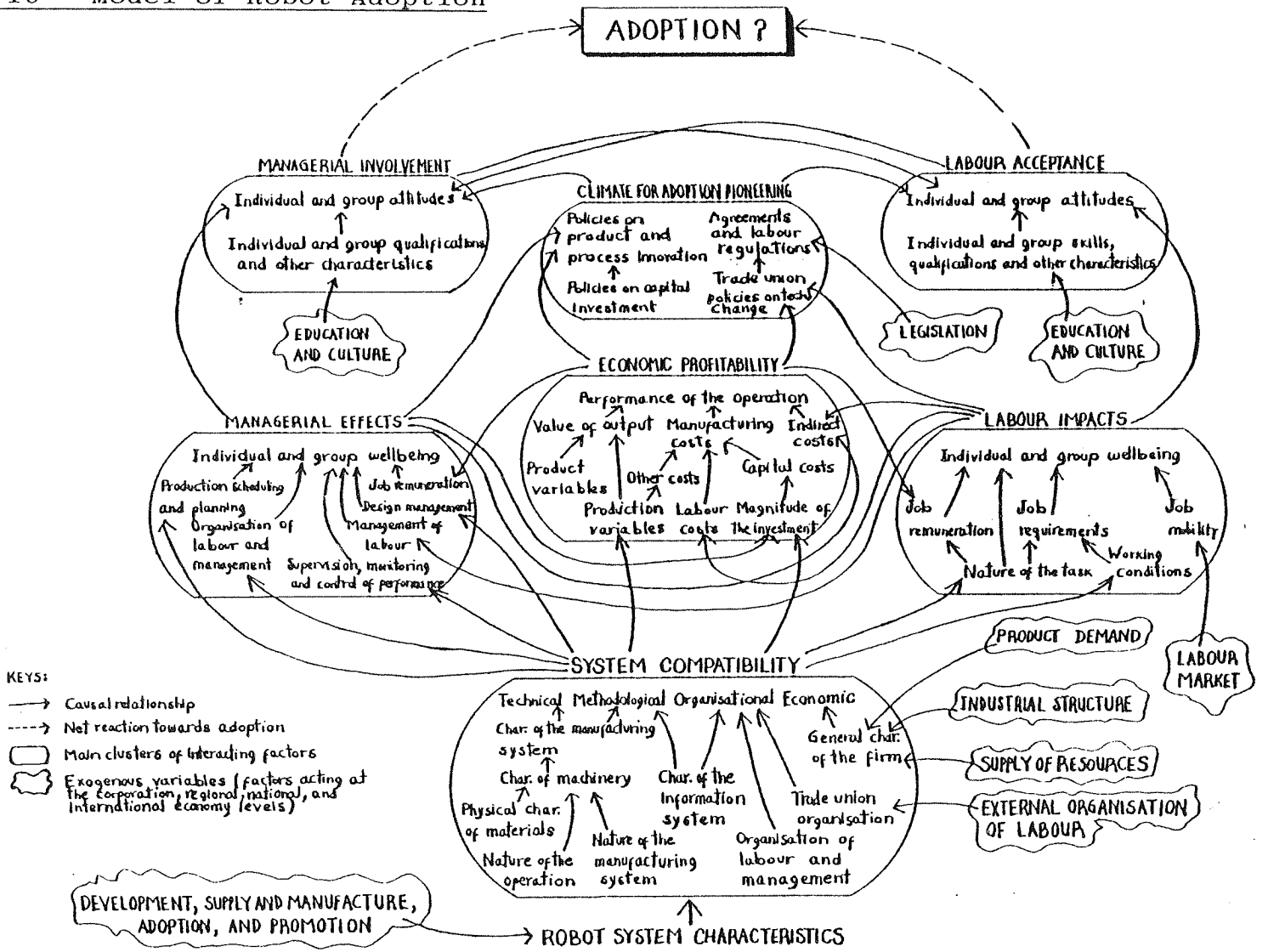


Figure 7.10 - Model of Robot Adoption



CHAPTER 8

THE COMPATIBILITY OF ROBOTS AND MANUFACTURING SYSTEMS

8 - THE COMPATIBILITY OF ROBOTS AND MANUFACTURING SYSTEMS

8.1 The Nature of Different Manufacturing Operations

The use of industrial robots is concentrated in the manufacturing of goods with a geometrically defined shape or piece goods. These manufacturing processes can be divided into different basic operations according to their nature, or according to the characteristics of the materials processed (see table 8.1). Robots can be used to automate the handling of materials (transfer and manipulative robots) or the transformation process (processing and assembly robots) in virtually all types of manufacturing operations (see table 8.2). These various categories of robot systems have radically different requirements and probabilities of adoption. Their technical, methodological, organisational and economic compatibility with the existing manufacturing environment determines the potential use of robots. Only structural changes in both robot technology and manufacturing systems can modify such a potential.

Packaging, storage and distribution operations basically consist of transfer of workpieces. Their complexity varies according to the number of different workpieces handled and the number of positions in the transfer, but this is generally low. If workpieces have to be picked up from, or placed in a moving conveyor, systems become much more complicated. The rest of the manufacturing operations involve physico-chemical processes and are more technically demanding. Automation requires the precise control of the variables which affect

the transformation process and the mechanisation of handling and various other auxiliary tasks. In component manufacture, operations consist of the transformation of a workpiece, whereas in assembly, operations involve various processes on various components and can be regarded as being more complex. Furthermore, assembly being at the end of the manufacturing system, is affected by the quality of previous operations. Test and inspection operations are a combination of varied and specialised procedures. Their complexity may be compared to that of assembly systems.

Component manufacture consists of the shaping and finishing of materials. Shaping can be done by forming and/or material removal. Finishing can be done by various methods, deposited surface finishing and heat treatment being the most relevant to robots. The geometry of the material inputs to these operations becomes more complicated as the component undergoes shaping operations. Since material removal commonly follows forming, it may be regarded as a more complex operation.

Forming operations make use of accurately machined dies. These can be classified according to the state of the material fed into the die as forming from liquid input or forming from solid input. Forming from liquid input consists of the injection of molten material and its solidification into the die under controlled temperatures, speeds, and pressures (e.g. pressure diecasting and injection moulding). Robots usually perform transfer tasks in these operations which are basically the unloading of the moulding or casting. In some rare cases, manipulative and assembly tasks are demanded from the robot (e.g. gathering of molten glass from

a furnace and loading into a press die, and loading of inserts into diecasting or injection moulding machines). Forming from solid input consists of the forced flow (or deformation) of the material into a die by compression or impact under controlled speeds and pressures, and in some instances, temperatures (e.g. hot and cold forging, hot forging of sintered metals, and compression moulding). Here robots are commonly used for transfer tasks only. These include loading of solid inputs, as well as unloading of the formed parts and are therefore, more complicated than the robot tasks in liquid forming. In some cases, such as open die forging, robots perform manipulative tasks at the same time as the forging process is going on. These are extremely difficult and rare applications. Automation is more common where the breakdown of multi-blow to single-blow forging operations can be achieved. Automatic handling in forming operations requires the mechanisation of auxiliary tasks such as cleaning, inspection and lubrication of dies. The development of release agents and other additives for the prevention of sticking, which could be sprayed automatically onto the die by fixed or mobile nozzle systems was necessary (water-based rather than oil-based additives had to be invented).

Material removal operations make use of cutting or other tools to shape components held by fixtures accurately. Metal-cutting operations such as turning, grinding, boring, reaming, tapping, milling, drilling and honing are the most common. Control of the cutting process involves variables like tool and workpiece speeds and displacements, tool wear, and overheat. Industrial robots perform a great variety

of tasks in these types of manufacturing operations. Loading and unloading of machine tools are the most commonly known. More complex robot tasks are the manipulation of components while a tool performs material removal operations (e.g. fettling and deburring) and the performance of the transformation process while the robot handles the cutting tool (e.g. grinding, drilling, routing). Automation of the handling function in material removal operations must be extended to auxiliary tasks such as clamping and unclamping of components, tool change, supply of cooling agents, and swarf removal. One of the reasons for the failure to use the first Unimate robots to load and unload machine tools was in fact, the lack of automatic swarf removal mechanisms (Cakebread 1978).

Deposited surface finishing operations like dipping, sprinkling and spraying consists of the application and drying of coatings on the surface of components or assemblies held by fixtures. Strict control of the characteristics of the coating substance (e.g. viscosity and specific gravity), the thickness of the layer deposited, and the speed of drying are necessary. Robots commonly perform the transformation function in surface finishing operations (e.g. paint and enamel spraying, and metallisation) with the use of special tools. Dipping and stuccoing of wax patterns for investment casting, a special case, are done by the robot manipulating the workpiece. Auxiliary tasks which have to be mechanised or avoided in spraying are for example, the cleaning and change of nozzles.

Heat and other treatments also consist of the controlled exposure of components or assemblies to special physico-chemical conditions which transform the composition of their surface. Robots have mainly been used for the automation of the transfer tasks in these operations (e.g. loading of annealing lehrs in glass manufacture).

Assembly tasks can be divided into parts presentation (feeding, orientation and positioning), gross and fine (mating) transfer, and joining. Assembly can also be classified according to the type of joining processes and the size of parts into fabrication and others. Fabrication is entirely concerned with the joining of rather heavy workpieces by welding processes. Other assembly operations are a complex combination of various tasks generally suitable when assembling small to medium size parts.

Fabrication operations are divided into pressure and fusion welding. Spot and arc welding are the most relevant to robot technology. Spot welding consists of the melting and solification of metal in one point of the interface between two workpieces. Control of position and of the electrical current which generates the heat is necessary. Robots have been used to handle the workpieces while special machines perform the welding (pedestal welding). However, the most common spot welding applications are those where the robot handles the spot welding gun. Periodical cleaning of the tip of the gun is an auxiliary task. Arc welding consists of the fusion of metal along the gap between two workpieces. This welding process is technically more demanding than spot welding. Process control involves from eight to nine variables and their interaction (e.g. wire feed

speed, electrical current, voltage, gap between electrode and weld, and travelling path and speed). The difficulties of introducing automatic methods in arc welding are great and little has been accomplished. There are some automatic and semi-automatic arc welding machines for the simplest jobs (e.g. linear, circular and other symmetrical welds). Robots are used in the automation of more complex arc welding (e.g. tridimensional intricate welds). Generally, handling tasks such as fixturing of parts remain manual.

Automation of assembly of small to medium size parts involve complex and varied mating and joining tasks. Mating tasks are for example, simple peg-hole insertion, insertion with push and twist, multiple peg hole insertion, insertion of peg and retainer, stacking, press fitting, locating pin removal, springing, flipping and supporting. Typical joining tasks are sheet metal crimping, welding, soldering, screwing, riveting, brazing, bending, mechanical pinning, bonding, stitching and wiring (Nevins and Whitney 1980, p30; IPRODE Working Party on Automated Assembly 1979, p12-14; and Bell 1972, p53). Robots perform gross and fine (mating) transfer and joining tasks in assembly systems. At present robots must work in a highly structured environment. Parts presentation tasks must be performed by accurate feeding and fixturing mechanisms for each one of the parts being assembled (the more ordered the parts are the less equipment needed). Sensory controlled robots would need less peripheral equipment if, for example, the ability to pick up parts randomly heaped in a bin were commercially feasible.

8.2 Technical Compatibility

The characteristics of the machinery and of the materials processed determine the technical feasibility of robot use in all the manufacturing operations described.

Simple transfer tasks in packaging, storage and distribution operations do not require robot versatility so pick-and-place devices suffice. Complex transfer requires at least a large memory capacity. Generally, peripheral equipment is used when transfer has to be synchronized to moving conveyors. Other alternatives involve sophisticated control and sensory systems and are not commonly found. High speed is needed since most of these applications take place at the end of continuous processes (in batch production packaging is far from being automated). A servo controlled robot was unsuccessfully tried for glass bottle packaging by one of the firms visited. Packaging was done at the end of a line where output from several bottle moulding machines was combined. Packaging was either into pallets or cardboxes according to customer demands. Palletisation had already been automated by a special purpose machine. Packaging into cardboxes could have been done by special purpose machines, but no space was available. Instead a Versatran robot was tried, but proved to be too slow. The use of more than one robot was not feasible and the operation continued to be done manually. A successful application of robots in this group in the UK was described by Rogers (1979); the palletisation of sacks of chemicals. In this case, special purpose palletisers were not appropriate since slow and medium speed lines were involved (200-600 sacks per hour). Particular problems emerged because the items were floppy and a special gripper had to

be developed. The structural and command versatility of the robot (an Asea) made the operation successful. Other packaging applications discussed were at the planning stage. Packaging of small pistons for hydraulic systems (3/4 inch diameter and 1 inch length). These can be easily damaged and quality would be upgraded if properly automated. Demands for speed are high and therefore a special purpose design may be chosen.

The loading and unloading of machinery in forming and material removal operations have rather low requirements for positional versatility. (In general, all transfer applications involving only one machine have low positional versatility requirements). The number of different positions and sequences is small. This is particularly true of forming by liquid, where loading is not carried out by robots, and machine configuration is relatively uniform. The large influx of new PPD's for diecasting and injection moulding confirms this point. Unloading of machines is a problem basically solved with present technology, with the exception of parts in metal cutting that produce long, tangling stringers of waste metal (Evans et al 1978, p11). Manipulative versatility (the versatility of grippers) is much more important in these transfer operations (diecasting is one exception since the sprue of the casting serves as a standard gripping surface). Complexity of product geometry is thus a major deterrent to robot automation. The most critical gripping problems are in material removal operations. Here, inputs are likely to have more intricate shapes as opposed to forming operations (e.g. bar billets or metal sheets). Rotational parts, especially bars, are the simplest

to feed and load, and are also the most common (67% of a sample of three thousand workpieces were rotational. Konstantinov 1975). Rotational parts with deviations and non-rotational parts (prismatic components for example) present the largest problems of gripping and clamping. From a commercial standpoint these problems are still not solved. A 'universal' gripper does not exist (Barash 1976, pH4-32 and Heginbotham 1978, p153). Solutions such as interchangeable grippers, the use of standard pallets (this is only a partial solution since pallets must be manually loaded in another area), the use of facsimile grippers and/ or the simplification of product geometry may be more effective.

Other problems are related to complex product geometry. In forming operations, automation is only feasible when die design can be simplified greatly. Once this is done, die spraying and inspection are less difficult, defects in the forming process are less frequent, unloading is easier (sticking is less likely), and die life is longer. Changes in the design of components may therefore have to be carried out if robots are to be used in injection moulding, diecasting, forging and metal working.

The performance requirements of transfer in forming and material removal operations are also fairly similar (see table 8.3). High positional accuracy, and fast and short moves are not critical to these applications. High speed movements in long distances are of primary importance, although less so in the loading and unloading of machine tools. The cycle time of forming and material removal machines largely determines the feasibility of different

approaches to automation (product weight and dimensions and the capacity of machinery are important parameters of the cycle time). In liquid forming, for example, small components are produced very fast for human operation, unloading is achieved by ejection and free-fall. Large products, on the other hand, are difficult to take off the die, have long cycles, and make automation uneconomical. Here, manual operation with mechanical aids is necessary. Once the component reaches a certain size, free-fall becomes less attractive since it might result in damage to the surface of the product. Then, take off devices become feasible (around 1-8 products per minute). PPD's are suitable for the small-to-medium range and SR's, MTR's, and HTR's are suitable for the medium-to-large range (see table 8.4).

Two of the firms visited had successfully introduced several robots into diecasting and injection moulding (both were contractors). The diecasting firm used: automatic ejection and free-fall for all small zinc alloy castings; PPD's for automatic ladling of aluminium and for automatic take off of simple products; and versatile robots for large and complex castings (e.g. 14kgs). They had installed seven Unimate robots which, in addition to take off, show the casting to electro-optic sensors (a safety procedure necessary for complex castings). The moulding firm used PPD's only. They had installed five Star Seiki and Mouldmate PPD's to unload screw injection machines where quality requirements make automatic ejection and free-fall unfeasible. Here the ability to mount PPD's on the machine was essential since space was very restricted. They could use versatile robots for moulding of products which have metal inserts,

but these systems eare too technically complex to be attractive to management. Other firms visited were interested in increasing their use of robots. These have installed an insignificant number of PPD's in their captive diecasting and moulding shops (firms producing domestic appliances). Versatile robots have, in general, limited potential use in these companies and no serious plans existed for their introduction.

Forging operations presented many technical problems, particularly in the early days of robots. One of the earliest applications of robots in the UK was in hot pressing of high duty alloys. Initially, a Versatran robot was used to load and unload a small and complex pressing. The pressing was continually getting stuck on the upperdie and proved an unsuccessful operation. Later, the robot was moved to a simpler job. Soon it was realised that a PPD would suffice here, and the robot was laid off. Other problems, such as low speed, unreliability and low accuracy contributed to the failure of robots in this firm. Accuracy was poor, partly because of high vibration in the workplace. The user had to install mechanical stops on the press to improve the accuracy of picking up the pressings. In a different case automation of hot pressing proved less difficult. A manufacturer of small brass fittings tried an MTR (BUSM robot), three SR's (Area 4 robots) and two special purpose automatic presses (AMYSA: only appropriate for small, symmetrical and hollow parts) in a new hot pressing shop. The speed and reliability of the MTR was disappointing (6 components per minute or 50% slower than manual operation and a utilisation level of 50%). Later it was replaced by an SR. The fastest automatic

system was the use of two SR's one for loading and one for unloading (20 components per minute). Successful applications of servo-controlled robots (Unimate) in hot forging operations have recently been reported in the UK (Ross and Gilson 1979). These involve hammer forging of cylinder necks in large (25-50kg) steel tubes and cycle times in the region of fifty components per hour (0.83 components per minute).

Loading and unloading of metal cutting machine tools by servo controlled robots were not observed in the factory visits. Very few of these applications exist in the UK (3.5% by 1979). In one visit, sixteen PPD's (Montech) were seen working on special purpose machining stations. These machines perform secondary operations such as drilling and tapping on very small and symmetrical components (screws and nuts). Primary (turning) operations are fully automated by the use of single and multibar feeding mechanisms and free-fall unloading.

Manipulative and processing tasks in forming and material removal operations demand high robot versatility and performance. Very complex three dimensional contours must be followed in each cycle, thus high positional versatility is needed (>4 dof). Grippers and other special tools must function while the operation is taking place. Servo control of position and path, large memory capacity, and adaptable control are needed. These requirements are particularly high in material removal operations where both cutting tools and workpieces change dimensions throughout the process (e.g. fettling, deburring and grinding). These applications are very rare, although Sweden is making speedy progress.

Asea, the large Swedish manufacturer, is the most experienced supplier of robots for these applications (see Table A8.5). They have recently introduced new sensing features in their control system which are needed in these robot tasks (e.g. speed control and contour tracking for deburring and grinding). High accuracy (e.g. $\pm$ 0.2mm) and high speed are also required. Speed must be controlled according to the requirements of the process, but must be high when the system is performing handling tasks. A wide range of speeds and speed programability are needed (for technical requirements see Weichbrodt 1977 for deburring applications and table 8.3 for drilling, routing and fastening in the aerospace industry).

Robots are likely to be demanded for manipulative and processing tasks in secondary material removal operations. In the foundry industry for example, robots are used for the fettling of castings. Simple and small weight castings can be automatically fettled by special purpose machines (e.g. less than 5kgs). Very heavy and complex castings are best fettled using remote controlled machines. For parts heavier than five kilogrammes and shapes of medium complexity, robot automation is appropriate. Potential for robots varies also with the amount of material to be removed (a determinant of the cycle time); at least five cubic centimeters for fettling is required. Thirty-two percent of a sample of twenty-six castings examined by Rooks (1978) were rotational, had more than five cubic centimeters, and were heavier than five kilogrammes.

Processing robots in deposited surface finishing were the applications most frequently discussed in the interviews. The majority of these were paint and enamel spraying of parts in the domestic appliances and sanitary ware industries. In total contrast to the rest of the component manufacture operations, robot surface finishing is appropriate where the component has very complex geometry. Proper coating of these products can be achieved by manipulation of the spraying gun along intricate shapes in three dimensions. Thus, structural and command versatility are essential requirements (5-6 axes). A high degree of adaptability to parts mixed in a conveyor, changes in conveyor speed, and colour to be sprayed may also be needed. These technical capabilities together with flexible wrists for reaching difficult places and fire-safe electric systems have already been developed by the robot suppliers. Present day robots satisfy the performance requirements for these applications. Parts must be precisely fixed ($\pm$ 2mm) if robot accuracy is to be utilised. Speed is however more important than accuracy. Speed of spraying is largely constrained by the type of spraying gun and the speed of the robot. Robots achieve similar speeds to that of humans, and in some cases they are faster (theoretically robot speed can be increased one and a half times the speed at which the robot is taught).

Automation of spraying can be achieved by various methods. When parts are simple (rotational, flat and semi-box workpieces) PPD's and special purpose machinery of limited positional versatility are appropriate (single, multiple and conveyorised spindle machines; traverse machines with or without shape sensing control; overheads conveyors

with fixed or vertically reciprocating guns; and spinning discs. Dixon 1971). These mechanical devices in combination with process technologies such as conventional, airless, hot paint, electrostatic, turbine and powder spraying achieve very high speeds. When parts are complex, manipulative spraying by hand or robot is appropriate, but other technical alternatives exist. Very high voltage electrostatic (150kv) and turbine (60,000 rpm) guns have very good coverage even for highly intricate shapes (these guns are not compatible with robots for safety reasons).

Suppliers of spraying equipment offer robots for production line spraying of very complex workpieces or for touch-up as an ancillary to other automated processes in very high speed lines (Lupa 1978). Seventy to eighty percent of the external surface area of motor cars is sprayed by vertical and horizontal reciprocators. The rest is done by manual spraying and could be done by robots ie, lower grill and head light area, wheel wells, window openings, cuts in between the horizontal and vertical surface, lower deck areas, engine compartments, door facings, trunk compartments and final dress up (Mosher 1971, p1). No significant numbers of robots for spraying are used in the British motor car industry. All the installations visited were production lines where robots worked alone or in collaboration with workers to spray cooker parts, bath tubs, tumble drier drums, wooden gas fire cabinets and plastic moulds. In only one case, flat and semi-box cooker parts, an interviewee thought other devices would have done the job more efficiently. The rest were fairly difficult parts and justified the use of robots. Enclosed surfaces such as

drums and cabinets pose difficulties for electrostatic spraying (the Faraday effect) and require the flexible wrist recently developed by the robot makers. Consistency in the characteristics of the material to be sprayed is another important factor. The texture of wooden cabinets for example, varies and so does the way of spraying that is required. In this case, a user had to opt for overspraying; this and the need for standard nozzles, increased the paint consumption.

Robots in fabrication operations, spot and arc welding, require a high degree of versatility and performance (see table 8.3). Spot welding demands PTP control, a large number of positions in a three dimensional space, the capability to operate while the workpieces move on a conveyor, fast short moves, and to a lesser extent, high positional accuracy. Arc welding is even more technically complex since the weld is continuous along the gap between two parts. It requires CP control, structural and command versatility to move the welding gun along intricate shapes in three dimensions (5-6 axes), sensory directed control to cope with variations in the gap between parts and to test the quality of the weld, high stability, and high positional accuracy (better than $\pm$ 0.5mm). Robot suppliers have gone a long way to satisfy the requirements of spot welding in the motor car industry (e.g. the ability to spot weld while cars are moving by Cincinnati Milacron). Simple sensors (pneumatic, contact, and magnetic field sensing) have been developed to improve the accuracy of welding, but the requirements in arc welding have not yet been fully satisfied.

Spot welding machinery is either general purpose, consisting of few welding tools, or dedicated, consisting of an arrangement of many welding tools for large, complicated and high speed jobs (e.g. multiwelders in the motor car industry). In conventional general purpose machinery, parts must be manipulated around the fixed welding tool either by hand or by an automatic mechanism (e.g. pedestal welding of car parts or domestic appliances sub-assemblies). Robots manipulate the welding tool and are therefore appropriate for large and complicated parts without being dedicated to one particular shape. They are slower and must be installed in large numbers if high speeds are necessary (e.g. 33 welds per minute per robot). In the motor car industry robots commonly work in re-spot welding after multiwelders have framed the body panels.

Arc welding can be classified into three main variants: (1) manual metal arc welding (MMA), (2) consumable wire electrode methods (3) tungsten inert gas (TIG) and (4) submerged arc welding (Hunter 1977, p1 and Nordsjo 1979, p7). The second variant can further be divided according to the shielding gas used as: metal inert gas (MIG) and metal active gas (MAG). These and the third variant are commonly called semi-automatic processes, since the wire is automatically fed to the welding torch which is guided by hand. Wholly mechanised submerged arc welding is common. Full automation of the other processes is only found where simple, symmetrical, and one-plane paths are followed (e.g. seam and circumferential pipe welds). Machinery for arc welding of complex three-dimensional paths exist, but these are dedicated to one particular shape (e.g. cam controlled

machines). Different approaches to design of automatic arc welding machinery can be taken: torch manipulation, parts manipulation, or both. Robots manipulate the torch, but often the parts must be automatically moved for increased accessability. Automatic arc welding is plagued with problems basically related to inconsistent dimensions of the gap between parts. This stems from low precision in component manufacture, incorrect assembly and tacking of parts, low accuracy of jigs and fixtures, and warping of the parts due to heat generated in the welding process. Although the manufacturing precision of thin plates such as pressings is higher, the above problems are generally more acute for thin and complex parts. The problems of guidance in the semi-automatic arc welding processes are less severe, hence these have the greatest potential for automation. TIG processes are the easiest to automate, but have low deposition rates. MIG and MAG processes are more difficult, but a greater amount of weld metal can be deposited in an uninterrupted run (Hunter 1977, p2). Robot automation is feasible when sub-assemblies have: many irregular and interspaced welds; accurately manufactured components ($\pm$ 0.5mm, $\pm$ 1.0mm) which can be assembled together in a fixture; weights between five and sixty kilogrammes; and production runs between one thousand and sixty thousand. For larger production runs, robots must compete with special purpose machines having numerous welding heads and hence, higher welding speeds (Largerlof 1979). Some interviews focused on arc welding applications (a separate special study of the BL multi robot spot welding line was undertaken at the TPU by H. Scarbrough). Projects for the installation of robots in arc welding were discussed with two firms.

The first case involved the welding of medium size sub-assemblies for excavators and other earth moving equipment (20 minutes robot cycle time). They had plans to improve the accuracy of their components (otherwise unacceptable for automation) by utilising single-blow pressing instead of forging, by adopting NC plasma cutting machines, and by upgrading the quality requirements of components bought outside. Simplification of sub-assembly design was also regarded as useful to reduce the technical problems of automating the job (the first robot installation will involve the simplest sub-assembly). Despite the above changes, sensory control would still be needed. Potential inside this plant is large but only if sensors are successfully developed. The second case involved the welding of aluminium beer containers. This firm started developing their own automatic welding machines fifteen years ago, since no machine existed in the market. All these machines do the circular welds in the barrel (80-90% of the total weld track). One of the few manually welded parts involves a complex path in three dimensions. They are not willing to build a machine for this job because of its technical complexity, and they foresee the adoption of a robot. This will have to await improvements in the accuracy of their pressings (better than $\pm$ 0.5mm) and further development of sensors. Aluminium welding is very difficult (they do not know of any robot welding aluminium parts). Other potential uses for arc welding robots discussed were in railway wagon and bicycle manufacture.

Assembly systems can take a very large variety of forms. They range from the purely manual to the fully automated, with many hybrid versions in between. There are many options

to achieve automatic assembly. These can be divided into two essentially different approaches: conventional and robot assembly. In conventional automatic systems, assembly is broken down into a series of simple tasks which are then allocated to dedicated stations (workheads or PPD's performing one handling or joining tasks). In robotic assembly several tasks are allocated to versatile manipulators equipped with one or several tools or the ability to change them. Thus, the versatility requirements depend on the extent to which the concept of robotic assembly is applied. Very high versatility is required if one manipulator must assemble the whole product. Little versatility is needed if, instead, programmable manipulators perform only one task along an assembly line rather like in conventional methods. The performance requirements for assembly robots are higher than for any other application (see table 8.3). Fast short moves, high positional accuracy and high slewing speeds are all critical to assembly systems. Sensor directed control is highly advantageous since it will increase the potential for assembly automation. Force and tactile sensors would make possible difficult mating of parts, with less requirements for dimensional accuracy. Vision sensors would reduce the demands for parts presentation equipment. The trade-off between performance requirements and robot versatility is particularly apparent in assembly. The more robotic an assembly system is, the less accurate and less fast. A pick and place task would take five seconds if performed by a programmable multi-axis robot arm, and two seconds if performed by a high speed PPD arm (Abraham 1977, p126). Conventional assembly systems commonly have better than $\pm$ 0.5mm accuracy, whereas HTR's achieve around $\pm$ 1mm.

Researchers have begun to search for designs which could optimise the performance of robot assembly. Skinner (1975) and Kondoleon (1979) came to the conclusion that tool change should be minimised to achieve shorter cycle times. Various alternatives were visualised: (1) to use several tools in one arm; (2) to use a 'universal' tool or a combination of as many operations into one tool as possible; (3) to build several assemblies at once, and spread the tool change time over many units; (4) to use multiarm systems for product assembly. It is likely that any system configuration would only be appropriate for a restricted category of products, for no best universal design will ever be found. Conventional automation is generally appropriate for high speed assembly of small-to-medium size products (product volume less than 2048cm^3 or 12.7cm on a side. Nevins and Whitney 1975, p387). Abraham (1977) studied different configurations of adaptable programmable assembly systems (APAS) for various product lines (sixty product lines had some of the characteristics required for APAS such as product size smaller than 1 cubic metre, subcomponent weight smaller than 22 kilogrammes, many style variants, high volumes and small batches, not too complex and long product life expectancy (eg. small motors, compressors and outdoor lighting). He found that programmable low degrees of freedom arms and dedicated equipment arranged along a paced transfer line "is best for short cycle time products with limited style variations when labour savings and equipment cost are the key criteria" (p131). Downtime, however, is a significant disadvantage of this rather conventional configuration. He chose a system of programmable arms and special equipment arranged around circular

tables where the operation was divided into two: sub-assembly and assembly. He identified cycle time as the most sensitive parameter and a limiting factor of robotic assembly. A dramatic increase in the potential for APAS would occur if 1-2 second assembly cycle times are achieved. According to Nevins and Whitney (1978,p72) the most effective way to reduce costs and increase speed "is to make a small light-weight arm that has as few joints as possible".

The complexity of assembly stems from the number of parts handled by the system. To reduce the number of parts, suppliers of equipment generally decide on assembly of sub-assemblies. This, and the provision of buffer stocks between stations, are means of increasing reliability and reducing the implications of element failure. Other alternatives to simplify assembly are standardisation of product line (full or into families of close geometrical and dimensional characteristics), changes in product and component design, and improvements in the performance of component manufacture and inspection operations. The following is a list of requirements for automation of assembly (Ashley et al 1971, Richardson 1978, Horne 1978, Freudenberg 1978, and IPRODE Working Party on Automated Assembly 1979).

1. Selection of easier handling tasks by reducing the number of directions involved, adopting assembly by layers or stacks, and using simple peg hole insertions.

2. Avoiding difficult joining operations such as screwing.

3. Reduction in the number of parts by opting for different manufacturing operations or different materials. For example, substitution of several machined components

by one cast or moulded part.

4. Component material must withstand and be amenable to mechanical handling, such as feeding by vibration or other forces, without damage or marking, especially when appearance is crucial. For example, floppy, sticky, very light, very heavy, and delicate workpieces are difficult to feed mechanically.

5. Component shape must ease selection, orientation, feeding, positioning, and gripping. For example, component design must not allow nesting or entangling, should be symmetrical or grossly asymmetrical, and should have ample chamfers, gripping aids and other convenient features.

6. Component dimensions must be precise and consistent. Often the accuracy needed for automation is higher than the functional accuracy (that required for the proper operation of the product). Thus component manufacturing operations must be improved, or more precise operations chosen (injection moulding and diecasting are ideal for automated assembly whereas forging is not).

7. Component surface finish must be smooth and free from burrs, flashing, dirt, grease, swarf or other imperfections.

Assembly was the application discussed most frequently with potential users. Companies interested in mechanical assembly were those in the domestic appliances, small toys, automotive components, industrial batteries and confectionery industries. All of these preferred the use of conventional

semi-automatic machines for reasons of simplicity and reliability. All had experiences with the mechanisation of assembly and regarded it as a long progressive, and comprehensive process of change.

In one case, previous attempts to introduce fully automatic assembly of automotive instrumentation ended in complete failure. Utilisation dropped from eighty to forty percent because of continuous jamming of defective parts. They stopped using these machines and went back to traditional methods. Dramatic improvements in product and component design have now been undertaken. These include: widespread standardisation and modularisation of design encouraged by the motor car industry, replacement of machined by diecast parts, improvement of diecasting operations by the use of expensive dies and reduction in the number of parts by utilising plastic moulds (50% of material content is now plastic). Semi-automatic machines will soon be introduced for the assembly of a new product line. These are of conventional design and have microprocessor control with diagnostic and monitoring capabilities.

Another interviewee described the successful automation of battery cell assembly by conventional machines. They started paving the way for mechanisation fifteen years ago. Changes needed were all related to product, operations and component design. He stressed the need for inspection to reinforce the changes undertaken in outside, as well as inside suppliers. This interviewee considered the introduction of HTR's to be premature for his company. Another firm was about to introduce several machines designed and built by themselves for the semi-automatic assembly of miniature

car toys. Their main problem was the mechanical orientation and feeding of delicate parts since appearance was very important. Sensory systems have been studied (in collaboration with a university) and optoelectronic rather than TV sensors were selected for further consideration. PPD's are preferred to versatile manipulators.

A very special case of mechanical assembly was studied in one of the industrial visits: the sorting of various forms of chocolate into boxes. Sorting is broken down into simple tasks and then allocated to single purpose stations. Each station consists of inlet conveyors with orientating and positioning tracks (the plough system for orientation), and a PPD. The PPD picks the chocolate and places it into a particular position in a tray. Trays are transferred between stations by an outlet conveyor. According to the interviewee, the system chosen was mechanically driven, reliable, and fast. The fastest robots are hydraulically actuated but these are not allowed in the factory in the interest of hygiene ("all hydraulic systems, no matter how good they are, start to leak after a few months of use"). Pneumatic robots lack accuracy, and electrical ones are very slow. The accuracy needed is high since chocolate shape is varied and complex. Improvements to chocolate moulding techniques and tight control of environmental conditions had to be undertaken (the properties of chocolate make automation extremely difficult; a first attempt to automate in the 1960's failed because of the low precision of chocolate moulding). A robotic approach to assembly which makes use of sensors would have allowed for less accuracy and less peripheral equipment (in fact, another confectionary company is investigating the possibility

of using 160 PUMA robots with vision and tactile sensors to do this job. Marsh 1980b), However, this firm had abandoned their pattern recognition research programme and were now committed to achieve orientation and positioning by simple mechanical means. The demands of the operation are low for versatility and high for speed (30 boxes of chocolates per minute). Robots are not competitive here.

Robotic assembly was recently being introduced in the field of fork lift truck manufacture (the details of this new application were not disclosed for confidential reasons). A PUMA robot will operate in collaboration with seven newly designed peripheral devices. According to the interviewee the approach adopted is radically new, some patents have been produced, and will have a large impact on robotic assembly (offers to buy the system have been received). Command versatility and accuracy are high priorities ($\pm$ 0.25mm). The system will be interlinked with the firm's main frame computer to cope with the demands on programmability (300 different programmes are needed). No sophisticated sensors and no changes in the precision of components and product design were necessary.

8.3 Methodological and Organisational Compatibility

Piece goods manufacture can be organised in a wide variety of ways. A relatively large room for choice exists not only in the type of materials and operations, but also in the layout of machinery and the management of production. The flow of workpieces from primary component manufacturing operations to test, inspection and packaging can be organised into three basic systems: functional, flow-line, and cell

manufacture. These variants have attributes appropriate to different patterns of production and market demand. In a functional manufacturing system, machinery is laid out according to their type of operation. Separate groups of machines or manufacturing areas exist for each type of operation. All diecasting machines for example, are grouped together. Trimming, machining, assembly and so on are carried out in their own separate areas. Workpieces are processed by any machine inside a group, then stored (in-process stocks) and moved to another area for further processing. Functional systems are highly flexible since no machine is allocated to a particular product. These are appropriate for the highly dynamic environment of small-batch manufacture. In flow-line systems machinery is laid out according to a well defined combination of manufacturing operations and capacity requirements (Holmes 1979). These systems are therefore dedicated to a particular kind of product or, at most, to a family of products with very similar characterisitics. In contrast to functional systems, flow-line systems are appropriate for large-batch or mass production and allow for extensive mechanical integration of material handling functions. In a cell manufacturing system machinery is laid out into groups performing different manufacturing operations on a family of products. A diecasting machine, for example, is grouped together with quenching, trimming, drilling and inspection equipment. Workpieces must be grouped into families of similar characteristics which are then allocated to specific manufacturing cells (Group Technology). These systems, like the functional system, are appropriate for batch manufacture. However, their flexibility stems from a fast change-

over time and a better programming of production allowing for less in-process stocks. The time that materials take to flow through the system to become saleable products is reduced.

The requirements for robot versatility also depend on the particular methods and organisation of manufacture. This is particularly apparent in assembly as became clear in the last section. Unlike the automation of transfer in single operations, high positional versatility is needed from a transfer robot integrating several machines. In a flow-line system little demand formanipulative and command versatility exists, since part shape does not vary widely. If tranfer is broken down to simple tasks, positional versatility is not required and PPD's suffice. It is in the functional and cell systems where robot versatility is needed for the automation of various operations, In a functional system several machines of the same kind can be served by a robot. This reduces the flexibility of the system and puts strain on the programming of production. Furthermore, the demands for manipulative versatility in this type of organisation (any workpiece can be allocated to any machine) are not likely to be met by present-day technology. The cell system is the most appropriate for robot integration. Here, the versatility limitations of grippers and peripheral equipment are less significant, since group technology methods of production programming are used. In turn, the command and positional versatility of robots enhance the benefits of cell manufacture, positions and sequences are undetermined, and change-over times are shorter than with conventional automation. Just like robots, Group Technology is regarded

as necessary for the automation of small-batch production.

The most widely used method of organising batch manufacture is the functional system. Cell manufacture and group technology have been promoted for many years but controversy exists about their benefits (Norton and Fogg 1976, Leonard and Rathmill 1977, and PERA 1978). The introduction of robot manufacturing cells presents formidable problems. Changes in the layout of machinery which make use of more space are necessary. Present shops are commonly overcrowded, particularly in traditional areas such as forging and casting. Little chance exists here for re-arranging the layout of machinery. Radical modifications to traditional methods and organisations are also required. The large stocks and the flexibility associated with functional manufacture soften the impact of dramatic fluctuations in product demand, and make production planning easier. To be successful, cell manufacture must be introduced with fast reacting methods of planning and programming of production, information systems and organisations. These new practices are more demanding, and put strains on the managerial resources of traditional batch production shops. Modern firms with a high degree of orderliness and sophistication are likely to be successful adopters of robots and cell manufacture. As an interviewee put it: "firms with no computerised data processing systems, no modern control of production and disordered stocks and flow of materials are far behind robot automation".

Some early diecasting applications in the USA consisted of robots unloading two machines in functional systems. These systems did not spread because of the demands for changes in the layout of diecasting machines (the traditional layout and the fact that diecasting machines can be unloaded from one side only make changes in layout necessary). Another example of robot integrated functional systems was developed in a machining shop by Fujitsu Fanuc. This consisted of eight NC machine tools loaded and unloaded by a robot. The robot roves along an overhead conveyor to reach each machine. Examples of robot integrated cell manufacturing systems are almost entirely limited to experimental development. On the other hand, robot integrated flow-line systems are becoming a trend in large batch and mass production. Here, combinations of PPD's, SR's and servo controlled robots are used (Holmes 1979 and Sunding and Arnold 1977).

The majority of managers interviewed were aware of the benefits of cell organisation in component manufacture and assembly. They were also aware of its demands and almost invariably considered it as a long term possibility. One of the largest users of robots in diecasting in the UK did not regard cell manufacture as a feasible alternative at present, even though they already programme production in a fashion similar to group technology. The existing labour and trade union organisation is another obstacle. Trimming and diecasting operations are done in different areas of the plant where workers are represented by different shop stewards. Adoption of robot cell diecasting would imply a total relocation of equipment and lengthy negotiations. The risks are

too high and the benefits too uncertain. Another interviewee was experimenting with a simple diecasting-cropping cell for small products integrated by a PPD. This firm would adopt the cell system despite its larger cycle time if in-process stocks were reduced significantly and the cropping shop entirely eliminated.

A manager in charge of manufacturing policy in a large metal working group recognised the need for cell organisation and robots in small-to-medium batch production. He regarded adoption of these innovations as a slow process.. "Managers in charge of running factories are not in a position to make radical changes. They are far too involved in their normal tasks to be able to cope and understand new technology. "Only in green-field projects does the opportunity arise for sweeping changes in the methodological and organisational structure of a plant. One factory visited made large use of flexible automation and cell manufacture (various numerically controlled machines were in use but without robot integration). This was a new plant specially chosen as a test bed for all kinds of new ideas. Besides flexible automated manufacturing cells, other innovations in methods and organisation as well as in hardware were considered necessary and have been successfully applied (e.g. one trade union, only onepay rate negotiated, no bonus scheme, less specialised and more flexible job descriptions, no redundancy from technical change, higher status and more responsibility for foremen, only one canteen, new accounting methods, computerised production planning and programming, computerised warehouse and data scan system in the shop floor).

8.4 Economic Compatibility

Since robot technology can be applied across the whole spectrum of manufacturing processes the characteristics of potential user firms and industries vary widely. However, some concentration of robots in certain types of firms and industries can be noticed in the UK. The potential use of robots is largely determined by the general characterisitics of industrial sectors and firms (see tables A12.2 and A12.3).

Small and medium size firms have rarely been involved in robot adoption. None of the potential user firms visited were of a small or medium size either. Notable exceptions were several contractor firms using robots for unloading diecasting and injection moulding machines, and for spraying. Other sources reported small firms installing marble stone cutting, spraying, and arc welding systems (Allan 1980, Ward and Hollingum 1980, and Asea 1979). Small user firms were technically orientated firms linked to large manufacturing groups which had been able to secure relatively high volume and stable demand, and were enjoying expanding markets. In general, shops in large firms rather than contractors are in a better position to adopt robots. This is particularly true of transfer robots in component manufacture where change-over times are already long. Contractors have very unstable demand and low volumes of production, and any increase in the time to re-set a machine is undesirable. These firms have large constraints concerning labour, managerial and capital resources and their technological expertise is rather low. Thus, the concentration of a particular industry largely determines the potential for robot application. The diecasting industry in Europe for example, consists of a

large number of contractor firms and is less efficient than in the USA. This partly explains its lower rate of robot usage (Cakebread 1978). Other applications like spraying and arc welding may have faster change-over times, and may be more appropriate for the production runs of small contractor firms. Suppliers must be able to provide good back-up services in these cases, otherwise adoption is not successful.

High rates of success and large potential use in the short term were identified with very large firms and/or expanding markets. The most significant demand for highly versatile robots came from firms manufacturing earth moving equipment and fork lift trucks in their fabrication and assembly shops. These firms had a wide variety of models, few product lines, and low volumes, and were highly competitive at home and abroad. Successful applications were also found in firms which had recently experienced declining markets and/or lower shares of those markets. These were concentrated in industries making products such as electrical domestic appliances, sanitary ware, glass products (especially TV tubes), and components for the aerospace industry. With few exceptions, these sectors have reduced their shares of robot usage, and have no firm plans for further development.

Low technology firms that attempted robot adoption often failed. Firms in the wood working industry for example, found it difficult to service the equipment. No person had the skill needed to maintain the robot or was suitable for re-training (Up to recent times, this industry used very little machinery of any kind). These problems were present

even in firms rated as manufacturers of medium-to-high technology products. A firm in the electrical domestic appliances for example, had never installed a robot purchased in the early seventies. This firm belonged to a giant industrial group and yet it had not enough electronic technicians. Its engineers have never felt confident to commission the system which they regarded as over-sophisticated. The interviewee clearly stated: "Technology has surpassed the pool of skills of industry".

In contrast, firms using high technology processes such as NC machinery and computer control were highly successful and/or foresaw the adoption of robots in the short term. One of these firms, a large manufacturer of colour TV's, developed various models of computer controlled PPD's especially designed for this industry after having pioneered the use of servo controlled robots (it is interesting to note that this firm continues to use a Versatran robot for automating tasks for the first time. If this proves successful a more specialised robot is developed). They had fifteen graduates in electronics in their development department alone, and now export machinery around the world.

Generalisations concerning product volume and value added from the sample of firms visited were more difficult. Users in mass production were rare, and none were very successful. It appears that potential use of robots is marginally concentrated in high volume industries. However, high rates of success were attained in low volume production. These were the most recent applications of servo controlled robots. No potential use was identified in production of low value added goods, where robots have been highly

TABLE 8.1 - Classification of Manufacturing Operations (A)

1. Packaging, Storage and Distribution

2. Component Manufacture

2.1 Forming

2.1.1 Liquid Input

2.1.1.1 Metal
Sand casting
Shell moulding
Investment casting
Diecasting
Others

2.1.1.2 Plastic
Injection moulding
Extrusion
Blow moulding
Others

2.1.1.3 Others
Glass moulding
Others

2.1.2 Solid Input

2.1.2.1 Metal
Forging
High energy rate forming
Forging of sintered metals
Others

2.1.2.2 Plastic
Vacuum forming
Compression moulding
Others

2.1.2.3 Others
Glass forming
Others

2.2 Material Removal

2.2.1 Mechanical

2.2.1.1 Metal

2.2.1.2 Plastic

2.2.1.3 Others

2.2.2 Others
Chemical
Electro-chemical
Electrical discharge
Ultra-sonic
Laser
Others

Continued/....

TABLE 8.1 - Continued

2.3 Other Component Manufacture

2.3.1 Deposited Surface Finishing

2.3.2 Heat and Other Treatments

3. Assembly

3.1 Fabrication

3.1.1 Resistance Welding

3.1.2 Arc welding

3.1.3 Others
- Electron beam welding
- Electro-slag welding
- Laser welding
- Friction welding
- Others

3.2 Other Assembly (small part)

3.2.1 Mechanical Pinning and Fitting

3.2.2 Brazing

3.2.3 Adhesive Bonding

3.2.4 Wiring

3.2.5 Others

4. Test and Inspection

Notes:

A Similar classification can be found in Brown 1950, Arthur D Little Inc. 1965, and Bell 1972

TABLE 8.2 - Classification of Robot Systems According to Robot Task and Manufacturing Operation (examples are given)

Manufacturing Function			Handling Function		Transformation Function	
Manufacturing Operation \ Robot Task			TRANSFER	MANIPULATIVE	PROCESSING	ASSEMBLY
PACKAGING, STORAGE AND DISTRIBUTION			Palletising sacks of chemicals Loading glass bottles into boxes			
COMPONENT MANUFACTURE	FORMING	Liquid Input	Unloading pressure diecasting machines Unloading plastic injection moulding machines	Glass gathering and loading into press		Loading of inserts into pressure diecasting machines Loading of inserts into plastic injection moulding machines
		Solid Input	Loading/unloading presses Loading/unloading hot powder metal forging presses Loading/unloading glass forming machines	Open die forging Close die forging		
	MATERIAL REMOVAL	Mechanical	Loading/unloading metal cutting machine tools Loading glass cutting machines	Fettling Deburring	Grinding Pneumatic chipping Drilling Routing	
		Others		Polishing	Water jet cutting Flame cutting Polishing	
	OTHERS	Deposited Surface Finishing		Dipping and stuccoing of wax patterns for investment casting	Paint spraying Enamel spraying Enamel sprinkling Glass fibre and resin spraying Spraying of sealing and rust preventive compounds Metallising	
		Heat and Other Treatment	Loading/unloading of chemical treatment machines Loading of furnaces		Water jet cleaning	
ASSEMBLY	FABRICATION	Spot Welding	Loading/unloading of spot welding machines (pedestal welding)		Spot welding of motor car body panels	
		Arc welding			Welding of earth moving equipment subassemblies	
		Others	Loading/unloading of brazing and soldering machines			
	OTHERS	Small Part Assembly				Assembly of fork lift truck subassemblies. Assembly of typewriter subassemblies. Sorting of chocolates into trays
TEST AND INSPECTION			Dimensional checks			

TABLE 8.3 - The Technical Requirements of Different Applications (from Evans et al 1978, p32)

Requirements / Application	Fast Short Moves	High Slewing Speeds	High Positional Accuracy	Sensor Directed Control	Fast Programming	Off-line Programming
Unloading of injection/ diecasting machines	2.0	1.3	1.7	3.6	3.4	4.3
Loading/unloading of presses	1.9	1.4	1.9	3.0	3.1	4.1
Loading/unloading of machine tools	2.4	2.1	1.7	2.7	2.6	3.0
Aerospace Laminate Handling	3.3	2.6	1.0	1.3	1.9	1.7
Aerospace Drilling, Routing, and Fastening	1.9	2.2	1.2	2.0	2.0	2.1
Spot welding	1.2	2.3	1.7	2.7	3.0	4.0
Arc welding	4.2	3.5	1.2	1.9	2.7	3.2
Small part assembly	1.1	1.4	1.2	1.8	2.4	2.9
Average	2.2	2.1	1.5	2.4	2.6	3.2

Continued/.....

TABLE 8.3 - (Continued)

Keys:

1. Critical to the application
2. Highly advantageous for more effective and efficient use of robots
3. Offers some advantages but not absolutely necessary
4. May need this capability some time
5. Never need this capability

TABLE 8.4 - Approximate Feasibility Domains of Different Approaches to the Automation of Handling in Forming Operations

1. Plastic Injection Moulding

Machine Capacity	Automation of Mould Take Off By
200 Tonne lock force	Ejection and free-fall
200-600 "	PPD (e.g. 1 minute cycle)
600-200 "	SR, MTR or HTR
2000 "	Manual/mechanical aids

2. Pressure Diecasting

Machine Capacity	Automation of Casting Take Off By
400 Tonne lock force	Ejection and free-fall
400-500 "	PPD (e.g. 1 minute cycle)
500-800 "	SR
800-1600 "	MTR or HTR (e.g. 15-30kgs; 1.3 minute cycle)
1600-3000	Manual/mechanical aids (e.g. 50kgs)

3. Forging

Cycle Time (minutes)	Type of System
0.006-0.008	Longitudinal forging lines for small and simple components (transfer is achieved by ejection mechanisms, escapements and small PPD's)
0.014-0.063	Automatic single station die forging machines for small and simple components (transfer is achieved by ejection mechanisms, escapements, and small PPD's)
0.033-0.111	Press (100-500 ton capacity) loaded and unloaded by one or two PPD's or SR or by hand (100-250 grammes)
0.167-0.833	Press loaded and unloaded by one servo controlled robot

Source: Estimates and examples by Webster (1978), Cakebread (1978), Turnedge (1978), Phillips (1979), Konstantinov and Zankov (1974) and Konstantinov and Djamdjiev (1976).

CHAPTER 9

THE ADOPTION OF DIFFERENT ROBOT SYSTEMS

9 - THE ADOPTION OF DIFFERENT ROBOT SYSTEMS

9.1 Robot Characteristics and Adoption Pioneering

The relative advantages of robots to other alternatives improve with the increasing use of robots inside firms (the more robots exist in a firm, the more real the benefits of robot automation become. See table 3.1). At present the degree of versatility and standardisation of robot systems are still quite limited. Tools, peripheral equipment and software remain to a large extent inflexible and of specialized design. Consequently, the ability to automate highly dynamic processes, and the ease and speed of robot introduction are, in many cases, only marginally better than those of other approaches to automation. This is particularly true of complex applications which involve various tools and peripheral equipment.

In addition to the above stumbling blocks to robot automation, increasing versatility is often associated with lower performance, higher complexity, and poorer reliability. The majority of potential users interviewed preferred to wait for others to experiment before they considered even the most limited trials. Some of them had already studied proposals and quotations from robot suppliers, but lacked the confidence to take the risks of adoption. The main uncertainty lay in the reliability of the machines, particularly when they were to be subjected to hostile environmental conditions and to continuous operation. Managers complained about the lack of complex applications in normal operation in the UK which would assure them of the reliability of robot systems. They had also learnt about the need to develop other elements of

the system. An employee of a very large firm manufacturing automotive products clearly stated: "When you buy a robot you buy your problems. We do not have the facilities, nor the time, nor the resources to spend in developing a robot system." Suppliers of the less sophisticated equipment were also eager to pinpoint the negative side effects of versatility in high technology robots. Regardless of how sound these claims are, the fact that potential users have such views is one of the most important barriers to adoption.

These problems were particularly acute in the early days of robots. At the time, their design was not mature, and suppliers had little know-how and ability to service the diverse applications. The marketing policies of the UK pioneers exacerbated the initial difficulties of the robot business. As opposed to Unimation which sold very cautiously in the USA, HSDE and GKN conducted a policy of intense sales. Their ability to cope with the problems of each application was quickly surpassed. At least ninety percent of the applications of Versatran studied in the UK had been discontinued by 1978 (see appendix 10). As a result, former users have very strong views on "the failure of the professional robot suppliers to meet their own claims in respect of performance". Widespread failure in so many pioneering applications largely explains the long period of stagnant robot sales in the UK.

All robot makers had critical technical problems at first. Manufacturers had to undergo a long learning process before their products and services became technically and economically competitive. Nowadays, there is evidence that reliability and performance have been greatly improved (see figures A2.4 and 9.1). Successful firms have invaluable experience and

provide a more complete service (several are now providing entire robot systems). Newcomers must overcome this competitive edge. Dr. Craine (1978) put it to me bluntly:

> "Robots are less reliable than automatic machines, there is no doubt about that. They are more complex and more likely to go wrong. However, reliability now is much better than it has been in the past. This is where De Vilbiss think most of the people coming into the market have a long learning curve to go through. De Vilbiss did have to pass it and see no reasons why newcomers should not."

The most common technical faults were in the control and driving systems, particularly in the early handling applications (see poor reliability complaints in table A12.9). Then, Unimate and Versatran made use of step drum controllers which kept going out of sequence, and Trallfa tapes and circuit boards proved vulnerable to dust, heat and electronic noise. Hydraulic servovalves, available in the larger most sophisticated makes, were continuously leaking oil, especially in those applications with high temperature conditions. Three factors were fundamental for upgrading the reliability of robots: the adoption of electronic controllers making use of integrated circuits, the protection of control systems against environmental problems (e.g. air conditioned and pressurised control units), and the improvements in the quality of hydraulic systems (e.g. better fluid filtration, better servovalves, and more efficient cooling units). In the case of Unimation, dramatic changes occurred once step drum controllers were abandoned at the beginning of the 1970's (see figure 9.1). For example, a couple of pioneer users interviewed rejected the Unimate in the first trial. They were not willing to risk injury to humans and damage to expensive equipment as the machine kept going out of sequence. In a second trial when they tried the Unimate with a different controller, they

were fully satisfied and have continued to operate the robot successfully ever since (both made subsequent orders). Other users rightly complained about the cost of replacements since servovalves were continuously developing oil leakages (in one case sixteen servovalves were replaced in a period of eleven weeks!). Similar problems were reported by the former users of Versatran.

Pioneer adopters paid a very high price for versatility (see figure 9.2). Even though manufacturers first sold robots at a loss, these were very expensive machines (Unimation, for example, priced the first prototypes sixty four percent under their cost of $56000 each). Most of the people interviewed were extremely reluctant to pay for the versatility of robots, especially those that regarded it as highly redundant. Furthermore, tooling and peripheral equipment were in those days even less developed than they are today. As a result total system costs were very often much higher. This was, for the majority of the interviewees, unexpected and badly dented the image of robots as off-the-shelf automation.

Nowadays the situation is very different. The price of general-purpose robots has been maintained relatively stable. In addition, several specialist robots exist in the market which include a large proportion of the tooling (see figure 9.2c). Dramatic improvements in the economics of electronic components, brought about by large scale integration, have transformed the nature of robot manufacturing costs substantially. High versatility robots have benefited first and most from these improvements (see table 9.1). Consequently, changes in the relative price of different robot categories have occurred. The prices of small MTR's and HTR's, which

have less expensive manipulators and driving systems, have increased slower than the prices of other robot types (see table 9.2). The relative price of versatility, reliability, and performance has dropped.

At present, the control system remains a large proportion of the component costs of less versatile machines (see table 9.3). PPD's and SR's have started to adopt programmable electronic controllers (see chapter 5). In the future these will benefit from further improvements in the cost of integrated circuits. Reduction in the cost of manipulators and driving systems are very attractive if additional economies in the cost of materials of servo controlled robots are to be obtained. Since economies of scale in robot manufacture are insignificant below the level of 1000 robots per annum (Hall, 1978), a decrease in the number of axes in certain robots is attractive. Applications with low requirements for positional versatility and high requirements for load capacity will benefit most from such a change (e.g. transfer robots operating with one machine).

Robot manufacture consists largely of design, development, assembly and testing of equipment (components are generally manufactured by contractors to the specification of the robot firm). The costs of software, and of assembly of electronic controllers are large. Software costs have increased significantly, and constitute a large proportion of robot costs, especially in high technology robots (see table 9.4). The use of very large scale integrated circuits, and of high level languages offer the possibility of bringing down the relative cost of assembly of control units and the cost of software. Again high technology robots will benefit

most from these developments, although only marginally since increases in command versatility and software capability are common to all kinds of robot devices (see chapter 5).

The cost breakdown of advanced robot generations is different from that of present commercial robots. Control systems represent a larger share of component costs than is the case for generation one, since these include tactile and vision sensors (see table 9.5). Development will continue to result in more versatility at relatively lower costs. In 1978 the firm Brown Bovery estimated the price of a low cost vision system at ten to fifteen percent the price of a robot (£2,500. See Butler 1978, p. 49). Varvello (1980, p.29) forecast a much larger proportion by 1984: tactile and vision sensors would make up sixty percent of the cost of a robot. In 1972, Ghali (1972) estimated a price of about £150,000 for the most advanced prototypes in experimental development. By 1979, Thackray (p. 69) estimated the price of a robot with simple vision at about £50,000 or two to three times the cost of present HTR's. These systems have not been introduced to the market in significant numbers.

9.2 Labour Impacts

The impact of robots on direct labour is largely determined by the degree of automation and integration of an operation before and after adoption. Changes in the nature of jobs are radical when the transformation of workpieces previous to robot adoption is done totally by hand in a traditional organisation of labour. In contrast, little impact is felt when robots are introduced to transfer workpieces from one conveyor to another in a highly integrated factory.

The degree of automation of robot operations is implicit in the classification of robot tasks shown in table 8.2. Operations where robots are used to perform the transformation function are less automated than those where robots are used to perform the handling functions. Assembly robots replace humans in both transformation and handling tasks, though in some instances, complex parts may have to be handled manually when mechanical feeding is impossible. Processing robots replace the human hand as the guider of powered tools and rarely perform the handling functions of the operation, which remain manual. Manipulative robots can do transformation tasks guiding workpieces against powered tools (e.g. fettling and polishing) or sophisticated handling tasks in conjunction with automated machinery such as in forming (e.g. open die forging). Generally in either case all handling functions are automated when manipulative robots are introduced. Transfer robots are adopted into the most automated operations since they replace humans in handling tasks only. The degree of integration of manufacturing operations is less clearly identifiable. Mechanised transport between operations is common only in high volume and mass production plants. Generally, manual and semi-automatic assembly, spraying, and spot welding operations are broken down into simple operations and integrated by mechanical transport in a flow-line fashion. Automation of transport precedes full automation of the transformation function and as a result, people work in a tightly synchronised system. Like most of the other applications, there are cases where assembly, spraying and spot welding are performed in a stand-alone fashion. The introduction of both robots and mechanised transport would have greater

implications for the labour force in these cases than in the already integrated plants.

Unattractive jobs and working conditions and their resulting negative attitudes to work were the most commonly identified labour factors encouraging adoption according to the user-managers interviewed (see table A12.4). Physically strenuous and monotonous tasks; hot and noisy environments with a high concentration of fumes and vapours; and high absenteeism and labour turnover were characteristics common to the majority of applications visited. Shortages of direct labour were not generally a problem. These are, however, concentrated in the most skilled trades where tasks and working conditions are unattractive (e.g. spraying and arc welding).

The most widespread impact of robots on the nature of direct labour tasks is the reduction of physical effort. Work-pieces and tools can reach the limits of the lifting capacity of human beings. Power transmitted can exceed the human ability for tool guidance. These problems are worse in handling tasks where the requirements for speed and frequency of movement are high. In transfer tasks the longer the cycle the more appropriate manual operation is, with or without mechanic aids (see table 8.4). The opposite is true of manipulative and processing tasks where in addition to weight, high levels of momentum, pressure, and power make manipulation difficult to maintain for long periods. In particularly heavy tasks such as welding, grinding, and dipping and stuccoing of wax patterns in investment casting, the longer the cycle time the worse it becomes for manual operation. Not surprising legislation exist in such cases to prescribe minimum rest allowances. Assembly presents fewer problems

of strength. Effort must be identified with demands for maintaining high speed, frequent, and precise movements.

The psychological characteristics of labour tasks such as monotony were often pointed out as motives to adopt robots, particularly in transfer and assembly tasks (see table A12.4). These characteristics before and after the introduction of robots can not be discussed in depth in this study. However, important differences between the major categories of robot applications can be identified. Human attention in transfer tasks is not limited to the handling of workpieces, but includes tasks like monitoring of product quality, prevention of faults in the process by inspection and by inference of trends in the running of the system, and other auxiliary tasks (see section 8.1). While physical effort is reduced once robots are adopted, the operators still have to fill workpieces into vibratory feeders and magazines and put finished products in boxes or pallets for further processing. Responsibility and concentration may increase since the worker is in charge of more machines making sure quality is maintained in each of them. (The need for inspection is one of the important deterrents against robots, particularly in high value added production). Operators in tasks such as the unloading of injection moulding machines often have to stand idle waiting for the next product. In a one-mould-per-minute cycle for example, an operator would have only forty seconds before the next product is ready. With the adoption of robots, the operator is further removed from the product cycle. They now work in a longer "buffer storage cycle" and have time to do various tasks. The job becomes less monotonous and less tied to one machine, but

it also becomes machine paced. The operator does not start the product cycle any longer, and must keep the machines running (unless they decide to stop machines by not building up the buffer storages). Human attention in manipulative and processing tasks is directly connected to the transformation of workpieces. Responsibility and concentration rest on the worker's own ability rather than on the supervision of a machine. These are commonly regarded as the most skilled jobs. The process of mechanisation of these jobs virtually starts when robots are introduced, except for the manipulative applications in forming (e.g. forging). From there, the worker increasingly plays a supervisory role until he/she becomes removed from the product cycle, as in the transfer applications. The intermediate stages, those where the operator loads and unloads the workpieces continuously, are in my view the most negative concerning the labour task. Here, the most skilled portion of the job is allocated to the robot and the operator remains largely linked to the product cycle. Manipulative and processing robots in forming and material removal are generally introduced together with automatic feeding (i.e. the operator is removed from the product cycle). This is not so in deposited surface finishing and fabrication. In a very odd case in investment casting the operator had to load wax patterns into the robot wrist at the beginning of every product cycle. This was more the result of technical problems with the feeding equipment than of original design. In spraying and welding, loading and unloading of components into fixtures are the manual tasks remaining after robots have been introduced. These tasks already exist where conveyors are in use.

Here, the labour tasks of handling and transformation are allocated to different people. (Specialization and mechanical integration results in radical increases in output). Robots replace the transformation jobs paced by the conveyor: the processing tasks. In fabrication, the remaining tasks are more complex than in component manufacture. Welders still have to jig and tack-weld the components before robots take over. Particularly in arc welding, the complexity of the operation demands continuous expert supervision and correction. This will remain the case until the systems are improved to the point where automatic handling is feasible. The nature of the labour tasks before and after robot assembly is less well defined. Assembly tasks are generally identified as monotonous and tightly paced. No negative labour attitudes were mentioned as motives for the adoption of the assembly systems (see table A12.4). However, it was recognised that the further the breakdown of product assembly into simple tasks allocated to persons working on a flow-line, the more labour discontent. In traditional assembly lines, job content is low and unbalanced, and overmanning is common. Other approaches were being implemented with the aims of increasing the number of different assembly tasks per worker, and their independence from each others' performances (these can be regarded as analogous to robotic assembly). It is likely that manual tasks such as the feeding and assembly of difficult parts will remain after assembly mechanisation. The provision of buffer storages would soften the impact of these machine paced jobs.

With the exception of assembly, all applications are more or less associated with bad working conditions (see

table A12.4). In general, forming (diecasting and forging in particular), deposited surface finishing, heat and other treatments, and welding have the most obnoxious working environments. Most of the first UK handling robots operated with hot parts, particularly glass, in atmospheres with a high concentration of fumes and vapours. Almost all processing robots were installed in noisy areas with large contents of harmful vapours. Bad working conditions are not entirely determined by the nature of manufacturing operations. The design of machinery and the installation and use of special protective equipment can dramatically improve the environmental conditions at work. These improvements are the main targets of health and safety legislation. Regulations do not encourage directly the use of robots or any other form of automation. However, alternatives for improvement of working conditions are not always straightforward. By making the employment of human beings more difficult and expensive for certain operations, regulations improve the relative advantages of using robots, and indirectly encourage their introduction. Spraying of obnoxious substances is a typical example. Increases in the volume of air extracted necessary to reduce the concentration of vapours, result in higher levels of noise and energy consumption. Masks, ear mufflers, and other protective equipment make the labour task more difficult. These are unpleasant and compensation to wear them must be paid. In one case, workers did not accept working under pressurised atmospheres. On occasions, when outside atmospheric pressure was very high, they used to stop spraying altogether. Particularly obnoxious situations arise when spraying concave surfaces

or welding in enclosed spaces. (Some robots have been especially invented for these situations by Scandinavian firms: Trallfa and Unimate Apprentice). Many of the spraying applications visited had these characteristics (in these cases other approaches to automatic spraying are less effective). The use of robots was identified as necessary to remove humans from these tasks, and to eliminate all problems with health and safety regulations. The present small extent of robot adoption means that extraction can not be avoided in practice. Humans still mingle with robots at the spraying booth, and perform side by side the same obnoxious tasks intended to be eliminated by automation. In one instance, a worker was spraying the concave surface of bath tubs while a robot performed the less obnoxious task of spraying the outside surface (according to the interviewee visual inspection was necessary when spraying the concave surface).

The ratio of labour displacement is closely determined by both the marginal differences in the levelof automation and integration of an operation, and the extent of robot adoption. The cumulative labour-saving effect of a large number of robots results in higher ratios of displacement than is the case when only one robot is introduced. The average ratio of 1.7 workers per shift per robot obtained from the applications studied must be regarded as the displacement effect of robot experimental adoption (see table A12.7. Here, displacement ratios are considered at constant levels of output. If the increases in output achieved by robot adoption are considered, larger labour savings and potential displacement result). When assembly is excluded, displacement ratios rarely reach the level of two workers

per shift per robot (the average becomes 1.2 workers per shift per robot). Transfer, manipulative and processing robots introduced into mechanically integrated operations generally displace one worker per shift even when only one robot is adopted (e.g. transfer between conveyors, and spraying and spot welding where conveyors already exist). If mechanical integration is introduced at the same time as robots, displacement ratios are higher (e.g. 6 workers per shift per robot). Stand-alone transfer applications, and stand-alone manipulative and processing applications when handling tasks are also automated, generally displace one workers per shift also. In these cases, more than one robot must be introduced to achieve the potential ratio of displacement since tasks such as the filling of vibratory feeders remain. In some manipulative and processing applications, handling tasks are not automated. Here, displacement does not take place unless various robots are introduced (e.g. - grinding and arc welding). Smaller or larger ratios of displacement occur in special situations. Less than one worker per robot per shift can be displaced in transfer applications where cycle time is long enough for one person to attend various machines. This is typical of metal cutting operations involving medium-to-large components, particularly if NC machine tools are utilised. In one instance, robots offered little economic benefits to the firm since one person was in charge of loading and unloading four machine tools. On the other hand, more than one worker per robot per shift are likely to be displaced in transfer operations where several people are needed to perform the handling tasks because of the weight of the component. Furthermore, here

cycle times are likely to be long enough for a robot to serve various machines and achieve high ratios of displacement (e.g. more than 3 workers per shift). In general, those situations where tasks are strenuous, tightly paced or performed in hostile environments and consequently requiring reserve workers, have larger ratios of displacement. Assembly applications can have all those characteristics which result in very high levels of displacement. In one instance, assembly was organised in a flow-line fashion with workers doing specialised tasks linked by conveyors. The ratio of displacement was one worker per robot. In a second case, thirteen workers per shift per robot were displaced. Here, a robot and seven part feeding and presentation devices replaced a completely manual assembly system organised in a craft-like fashion.

The impact of robots on indirect labour tasks are closely associated with the complexity and sophistication of the application. The extent of fitting, setting , programming, and maintenance depends on the number of different grippers, special tools, and peripheral devices introduced. The effect of the level of sophistication of technology on the ease of indirect tasks is less clear cut. On the one hand, very simple technology such as mechanical systems and PPD's present relatively few problems. On the other hand, very sophisticated technology such as servo controlled robots with powerful software, ease programming and maintenance functions to a very large extent (e.g. programming by teaching, teaching in real coordinates, modular design of electronic circuits, and automatic fault finding). Transfer applications involving PPD's are perhaps the easiest to set. When

servo controlled and simple robots are involved, programming in transfer and manipulative applications becomes much more demanding. In processing applications this is not the case, since teaching is possible, particularly in spraying. Of the processing systems, arc welding is one of the most demanding, since teaching must be combined with programming of various parameters. Programming of assembly systems presents the most cumbersome problems. Teaching can become a long and tedious exercise. The use of standard high level languages incorporating common assembly functions will ease these problems and make adoption more likely. The question of who programmes the system largely depends on management and trade union policies, and the firm's available skills. Assembly is perhaps the only application where knowledge of a comprehensive programming language would be needed. It is significant that in one of the most difficult applications studied, arc welding, the operator was allocated the programming function.

9.3 Economic Profitability

The extent of profitability of different robot systems is central to the question of adoption. All but one of my interviewees stressed the search for improvements in the efficiency of operations as the main motive for robot introduction (see table A12.6). In the one exception, acute difficulties of labour recruitment left no alternative but the introduction of robots. Increases in labour productivity are the main economic benefits of robot introduction, but not the only ones. Advantages such as better quality and consumption of other resources result from adoption

(see table A12.8). Transfer robots, particularly in forming operations help to stabilise physico-chemical processes (e.g. diecasting, injection moulding and hot forging). Consistent and continuous running of these processes result in lower rejection levels, better energy efficiency and less tool wear. All manipulative and processing robots introduce machine consistency for the first time into operations entirely performed by humans with the aid of tools. Consequently, product quality and resource efficiency can be optimised and maintained at very high levels. Processes sensitive to a host of variables, particularly those obnoxious to humans such as dipping and stuccoing of wax patterns for investment casting, metallisation, and arc welding are greatly improved. Quality is a prime motive for robot adoption in these cases, in total contrast to the assembly applications.

Increases in labour productivity are, like the impact on skills and employment, related to the level of automation and integration of an operation before and after robot operation. Manual assembly, manipulative, and processing tasks, particularly for heavy jobs in bad working conditions have very low efficiencies. Introduction of robots into these operations may increase output as much as three fold, even though cycle time remains the same. The need for rest periods and reserve workers is eliminated once robots are introduced into these operations. Moreover, the remaining handling tasks like loading, fixturing and unloading are then carried out while the robot is working. Thus the transformation process, particularly if the cycle time is long, runs for a larger proportion of the available time. Smaller improvements in the output of manipulative, processing and

assembly operations result from robot adoption where mechanical integration of manual tasks or semi-automatic operation exist. Here, handling and transformation tasks have already been rationalised (e.g. spot welding of motor car body panels, conveyorised spraying and semi-automatic assembly). Labour productivity is, nevertheless, increased significantly since displacement, particularly for heavy tasks like spot welding, is large (see section 9.2). Transfer robots increase the utilisation of expensive machinery to very high levels (90-95%) by removing the operator from the product cycle completely. Marginal improvements in productivity depend largely on the operator's attendance before robots. Heavy tasks in hostile environments, forging and diecasting for example, tend to have low utilisation (60-70%) or large manning levels and consequenly, better potential for economic improvement. When these tasks are performed in continuous processes, as in glass manufacture, output may remain the same, but labour productivity increases dramatically due to the large ratio of displacement (this partly explains the high concentration of pioneering applications in the glass industry).

The magnitude of the investment in a robot varies with the cost of the standard elements, the cost of design, construction and development of special equipment, and the cost of debugging the entire system. This is related to the complexity of the operation or the need for robot versatility, different end effectors, peripheral technology and safety guards. Robot development is intended to increase the cost content of the standard elements of a system by increasing versatility and reducing the need for orientation and

positioning. At present, the cost content of the off-the-shelf equipment is still rather low (roughly 61% of total equipment cost. See table 9.6). In general, the more complex an operation is, the smaller the proportion of the cost that the standard robot represents and the larger the investment needed. Applications in component manufacture have a larger proportion of standard elements and require less investment than applications in fabrication and assembly. The cost content of the standard elements in a robot system also depends on the market potential and on the success of diffusion of particular applications. Excellent examples are processing applications such as spraying, spot welding and increasingly arc welding where end effector technology is readily transferred to different situations, and where handling functions remain manual (the price of these robots include tooling. See figure 9.2). The relative cost of these systems and the ease of their introduction has greatly been improved. Conversely, less sophisticated but rare systems demand relatively large investments (e.g. palletising). Transfer, manipulative and assembly systems operating with intricate workpieces will require special development as long as no "universal" grippers, tools, and peripheral equipment exist. The snowball effect of robot diffusion ↔ easier adoption plays a less significant role in these applications since the degree of standardisation which can be achieved is more limited.

The majority of user firms visited achieved a satisfactory payback period (see table A12.8). Those which did not, stopped using robots because of unreliability, low speed or oversophistication. Unsuccessful cases were concentrated in

early transfer applications. This was, however, due more to the particular make of the robot installed than to the type of application. Otherwise, there were no significant differences in the rate of success between different systems. The shortest payback periods were achieved in transfer and assembly applications. Assembly systems, despite their capital intensity, generally offer the largest rates of return on the investment even when plants operate in a one-shift system. Their marginal increases in output and their extent of labour displacement are much larger than those of the rest of robot applications. Transfer robots have the smallest economic advantage, but when PPD's and SR's are involved investment is relatively low. Since transfer applications usually operate on at least a two-shift basis, payback periods are short. All successful transfer systems visited operated on a three-shift basis and achieved less than one year payback periods. Processing robots represented the largest number of successful applications and had the longest payback periods. Those where conveyors and robots were introduced together, despite their large investments, achieved the shortest payback periods. Manipulative robots achieved low returns on the investment, due to their low labour displacement, low marginal increases in output and high capital intensity. Quality consistency played a very important role in the success of the manipulative applications visited (i.e. glass gathering and loading into a press for the forming of radar screens, and dipping and stuccoing of wax patterns in investment casting of turbine blades).

The profitability of robot investment has increased considerably since the introduction of robots into the UK at

the end of the 1960's. During this period labour costs have increased fourfold while the price of a Unimate 2000 robot, for example, has increased less than threefold. The cost of a Unimate 2000 robot has decreased 20% - 40% relative to labour costs * . However, this is perhaps the example where robot economics has improved best thanks to the performance of Unimation. When the situation is analysed in terms of aggregated robot categories and types of applications, the relative price changes are much less dramatic. The average price for all types of robots has decreased a mere eight percent relative to the average total labour cost to the employer in manufacturing industry (see table 9.7 and figure 9.3). Non-servo controlled robots have actually become less competitive, particularly those having large pay loads. Prices of servo controlled robots have increased at similar rates as those of mechanical engineering equipment, and thirteen percent slower than labour cost. Applications with a large robot cost content making use of servo controlled robots, particularly of small size, have significiantly improved their profitability. On this criterion alone, the most promising of all applications are assembly and arc welding of small-to-medium size products. (In the case of assembly, the fewer the number of parts involved the better). Furthermore, labour cost growth rates relevant to these systems, especially those of female workers in assembly, are higher than average. Here, robot economics are likely to continue improving rapidly.

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* When compared against the annual earnings of the top ten percent manual male workers (smallest growth rate) and the bottom ten percent manual female workers (largest growth rate) (Lawrence ed. 1980, p. 175 and 176).

9.4 Managerial Effects

A major stumbling-block for robots is the managerial effort demanded by their introduction. The degree of standardisation of a system represents the extent of engineering work spent before its installation. It represents the ease and speed at which the user is likely to put the equipment into normal operation. The demands for managerial effort are therefore associated to the complexity of the operation, and to the need for special development. According to its complexity, a conventional tailor-made assembly machine takes from six to eighteen months to design, build, set and debug. (The use of microprocessors is likely to reduce these lead times by two-to-five months). Other less complex equipment made to specification, such as special purpose spraying equipment, may take as short as five months to build (delivery of special components takes alone three months). According to some robot suppliers, the time required for building and debugging robot lines has been cut as much as fifty percent when compared to special purpose automation (one to six months). However, these lead times to robot introduction are relevant to simple, highly successful, and standardised systems supplied by established firms. In the absence of a steady demand for robots, robot firms take at least six months for delivery. (Small firms in particular must avoid large and expensive stocks of robots). Complexity and novelty, adding to supply problems, result in lead times to robot introduction as long as those of special purpose machinery. The majority of people interviewed experienced long and difficult periods of debugging, and spent significant effort in developing special equipment in collaboration

with robot suppliers (see table A12.9). The transfer and manipulative applications studied, except those where PPD's and SR's were used, showed a high concentration of problems (need for special grippers, peripheral equipment and safety guards). Most of these handling robots were pioneering applications introduced in the early seventies when experience was lacking. Demands for technical development were also high in the fabrication and assembly projects studied (arc welding and assembly). The complexity of these applications meant that numerous feeding and orientating devices had to be designed, built, and debugged, and that design changes in components and other manufacturing operations had to be carried out. Thanks to the abundance of spraying applications in the sample, processing robots showed a very low frequency of adoption difficulties. On only few occasions was new peripheral equipment introduced at the same time as the robots. Normally, peripheral equipment already exists in the plants and is fairly standard. This is also the case in spot welding.

Other demands on management and on indirect labour are associated to the type of robot adopted. Maintenance work is more difficult when servo controlled systems are involved. Those managers who introduced processing robots (all processing applications used servo controlled robots) frequently complained about the burden on the maintenance department, and the need for continuous training of technicians (training is usually carried out by the supplier. Only those established firms offer formal training courses at their facilities lasting from one to two weeks). The small extent of robot use inside firms, and the generally high turnover of

qualified maintenance personnel, exacerbate these problems, particularly if the firm operates on a continuous basis. Technicians can quickly forget what has been taught to them in training courses, since little opportunities for practising exists in firms with only a handful of robots (that is at present standards of reliability!). Despite all efforts for training in-house technicians, corrective maintenance was conducted by the supplier in the majority of cases. According to Mr. Engelberger, Director of Unimation Inc., five robots is the minimum for a company to develop in-house maintenance services. Even in the case of BL, the largest user of robots in the UK, a one-year contract for maintenance was signed with Sciaky, a supplier of spot welding robots (Scarbrough, 1981).

Radical organisational changes were rare in the cases studied. Some changes in the organisation of direct labour were necessary in those transfer, processing, and assembly applications where conveyors were introduced at the same time as robots, or where several robots were involved (this is in line with the extent of labour displacement). One of the most radical examples was the introduction of two glass forming cells. The initial job, the forming of laboratory glass ware, was entirely manual and highly skilled. It involved fourteen years of learning and advancement through fourteen different grades of skill. Two machines were specially designed to automate one of the glass forming tasks, and a robot was used to load/unload them from start-up. Two cells of two machines plus one robot and parts presentation devices, were installed. The sophistication of the set up and the low reliability of the robots in those

days meant that qualified technicians were employed full-time to perform the supervisory role and the filling of magazines with laboratory tubes (each cell displaced three craft workers per shift). If these robot cells had been introduced in greater numbers the plant would have needed a complete reorganisation. As it happened the firm was bought by an American multinational which transferred production to other plants in Europe. Production volume dropped dramatically to the point where the two forming cells were uneconomic to run and the firm returned to craft operation. In other transfer applications a potential user foresaw the need for labour reorganisation. Five injection moulding machines and three PPD's were about to be introduced in a new area for highly mechanised processes. A change from a system involving five grades of skills to one with only two grades was thought necessary. One skill grade would be in charge of supervision and setting, the other would be in charge of trouble-shooting and maintenance. This redefinition of jobs is necessary for enriching the job of direct workers, particularly when the final level of automation is high.

Besides the above demands, robot technology offers numerous managerial advantages. The motives for managers to embark on a robot project must be seen on a long term basis. Adoption pioneering involves far more problems than those which it solves. With time, the mastering of the technology and its widespread use yields the benefits pursued. Most of the people interviewed were eager to pinpoint problems of labour recruitment and control of performance as the prime managerial motive of adoption (see table A12.5). This was particularly noticeable in processing applications,

where obnoxious working conditions existed. In some situations, problems of recruitment did not exist because the firm trained their own workers. In these cases, very long training periods and high labour turnover were identified as factors encouraging adoption. Robots, for others, also provided the ability to increase or reduce production according to demand without labour implications. Legislation had made redundancy more difficult and expensive, and in a small and competitive labour market, redundancy had future repercussions in the firm's chances of recruitment. The best alternative, according to one interviewee was automation, since maintenance of employment in periods of low demand resulted in permanent overmanning. In a plastics firm each injection moulding machine was specifically assigned to one operator before robot adoption. Consequently, their absence resulted in the loss of a day's production for the respective machine. Here, robots were seen as an opportunity to increase the flexibility of labour allocation, and reduce the implications of absenteeism. For some managers the improvement of production scheduling and planning by introducing machine consistency, thus increasing the predictability of output, was an important incentive.

The extent to which the intended benefits of robot adoption were achieved is limited, since adoption has mostly involved a few robots. Recruitment problems may have been eased, but they are still present since workers still perform the operations, however obnoxious, where robots are used. Production scheduling and planning has become more difficult in situations where the initial operation was entirely manual (e.g. the introduction of glass forming cell

described above). The flexibility of humans working with tools is unbeatable. Mechanisation, of any kind, increases the rigidity of the system and the demands for careful planning. However, robots introduced in highly mechanised systems do not increase the change-over time significantly, and by removing the operator from the product cycle they facilitate the allocation of labour and improve the controllability and predictability of output (it is a paradox that those firms having long change-over systems and short production runs such as contractors of formed components are unwilling to add to their problems by automating, however small are the increases to the change-over time caused by robots).

9.5 Adoption Pioneering

The manner in which managers react to the question of adoption under high uncertainty owes as much to individual and social factors as to the compatibility and consequences of robot systems. The sole marketing efforts of individuals can largely explain managerial involvement in the transient period. In the early days the mere existence of supply shapes to a large extent the pattern of adoption (e.g. the success of spraying applications in Europe long before the USA and Japan). Persuasion is likely to come about if management and firms are open to risky experimentation or alternatively, where competitive pressures pave the way for the robot supplier. The majority of users interviewed responded to the call of the supplier. Some, however, imitated parent companies, or competitors in Britain and abroad, or had other special reasons. For instance one

managing director was motivated by reasons of prestige. He decided to acquire a robot after watching the "Tomorrow's World" TV programme on science and technology. Another managing director chose to test robots because the supplying firm was part of the same industrial group. Generally, successful pioneering applications can be identified with the activities of enthusiastic leaders with power to weather the storm that any new idea with large implications brings.

The qualifications, low status, and low wages of production engineers, and an excessive control of firms finance by accountants were given as reasons for the slow diffusion of robots in the UK. One interviewee explained the progressive attitudes of his firm on the basis that it was not controlled by accountants. "There is a commitment to apply new technology at a higher risk than otherwise. If a new development has engineering viability and long term potential, money is invested". Another interviewee thought British engineers had a "strong desire to keep things as they are, and an aversion to risk taking". Age and basic education were also identified as determining the inclination for pioneering adoption. The majority of people interviewed were senior staff engaged in production engineering and technical development departments, and had no university degree. Apart from stressing the role of the individual in adoption pioneering, no conclusions about the above widely held views can be reached from this survey since no proper international comparisons were made.

Fears of labour unrest have commonly been suggested as major deterrent for robot adoption in the UK. It is not possible to arrive at any firm conclusions about these

problems from a series of interviews with managers. Labour attitudes and acceptance have not directly played a major role in adoption pioneering. The majority of users reported a positive reaction from the workforce, and no failure was explained by persistent problems of industrial relations (see table A12.7). Some managers feared the complications of long negotiations and opted for introducing robots into new areas. Most of the managers interviewed favoured early consultations and negotiations with labour as the best managerial practice, but regretted that it was not implemented in their own case. On one occasion secrecy was the reason for not involving workers in the robot project. The firm belonged to an industry geographically concentrated with a high mobility of labour between competitive firms. Other reasons might have been the relatively little importance and the experimental nature of the robot projects. Generally, social inertia against participation and the effort which it demands can be regarded as major factors.

Consultations and negotiations resulting in formulae for sharing the benefits and softening the negative impact of robot adoption have become essential conditions. In the present situation of high levels of unemployment, managers realise that consultations are essential, even for experimental adoption, to secure future positive acceptance. One firm introduced a couple of robots in 1976 without the need for agreements on benefit sharing. When the firm was about to introduce its fifth robot in 1978, mounting pressures resulted in the implementation of a benefit sharing scheme. Interviewees often reported improved status and wages as a result of adoption, and the use of transfer and natural

wastage when displacement was necessary. When the size of the project is large and implications widespread, negotiations are inevitable and difficult. This was the case for one of the assembly projects studied. As part of the strategy to improve competitiveness, the firm had plans of concentrating production in one plant by introducing three systems and running them continuously. Long and difficult negotiations were expected (about one year long) to reach agreement on transfer, redundancy and job and wages redefinition. One of the negative consequences was the breaking of the social atmosphere that female assembly operatives had built up (according to the interviewee the need for companionship was one of the main incentives for mature women to work in the firm). Another interviewee learned from experience the need for consultations. The introduction of a flexible grade system, new injection moulding machines, and robots involved only four months of negotiations. In a similar situation when no early consultations were conducted, one year had to elapse before agreement to operate new machines was reached. The process of bargaining in robot adoption may also have a bearing on the type of system introduced. One manager was in the dilemma of adopting an expensive sophisticated robot to automate various tasks and have negotiations only once, or alternatively adopt one PPD to automate each task step-by-step and have negotiations every time.

Indirectly labour attitudes have played a crucial role in adoption pioneering. Attitudes to work have changed dramatically. Difficult recruitment and other labour problems have become increasingly associated with unattractive jobs

and working conditions. A general decline in the number of young people engaging in trades such as foundry work, forging, spraying, and welding was commented on by many of the managers interviewed. These trends were seen as the result of rising expectations stimulated by better education and living standards. In his own way, one senior interviewee described this picture of changing social attitudes:

> "In the old days workers took more interest in their job. They never thought there was anything wrong with their job and the environment (i.e. hot pressing). Perhaps this was partly due to penalties but also to a better industrial climate. When trade unionists and manager do-gooders started to say how bad the environment was, when the old people retired, the industry began to have problems and recruitment was more difficult. Management became more involved in administrative functions and less involved in the problems of the field. All these changes affected the quality of the operators and labour productivity decreased gradually. Now they are satisfied with an output that for past standard is rather low (e.g. 6000 pieces per day instead of the 12000 achieved before). There was a period three or four years ago (about 1974) when you could not get people because of the environmental problems, even unskilled people were difficult to recruit for this job".

A clear example of how much the decline of a trade can encourage automation was that of a firm making radar screens. Glass gathering and loading into a press used to be taught from generation to generation. The job involved years of training and few chances of acquiring the skill (usually only three people out of ten were successful). It was a hard job done in extremely hot conditions, in front of a furnace of molten glass. Increasing problems of recruitment started to be noticed in the 1960's. The average age of workers went up until the day when the last two workers decided to retire. There was no other alternative but the use of robots (Special purpose automatic machinery could have been installed but these are suitable for relatively

high volumes, about 250,000 pieces per annum. This firm produces 55,000 per annum only).

The most important conditions for adoption pioneering are the firm's policies on capital investment. In a policy statement for the advancement of mechanisation in 1975 an interviewee explained:

> "Finance will need to understand and support fully the mechanisation concept:
>
> a) Mechanisation is not cheap.
>
> b) Investments will have high production capacity over a long time therefore payback criteria will be longer than four to five years or we must use inflation accounting. If we had used this in the past we would be further advanced in mechanisation than we are.
>
> c) Inclusion of indirect costs and all other factors of production, supervision, technicians, toolmakers, etc., which will upset our traditional direct indirect ratios."

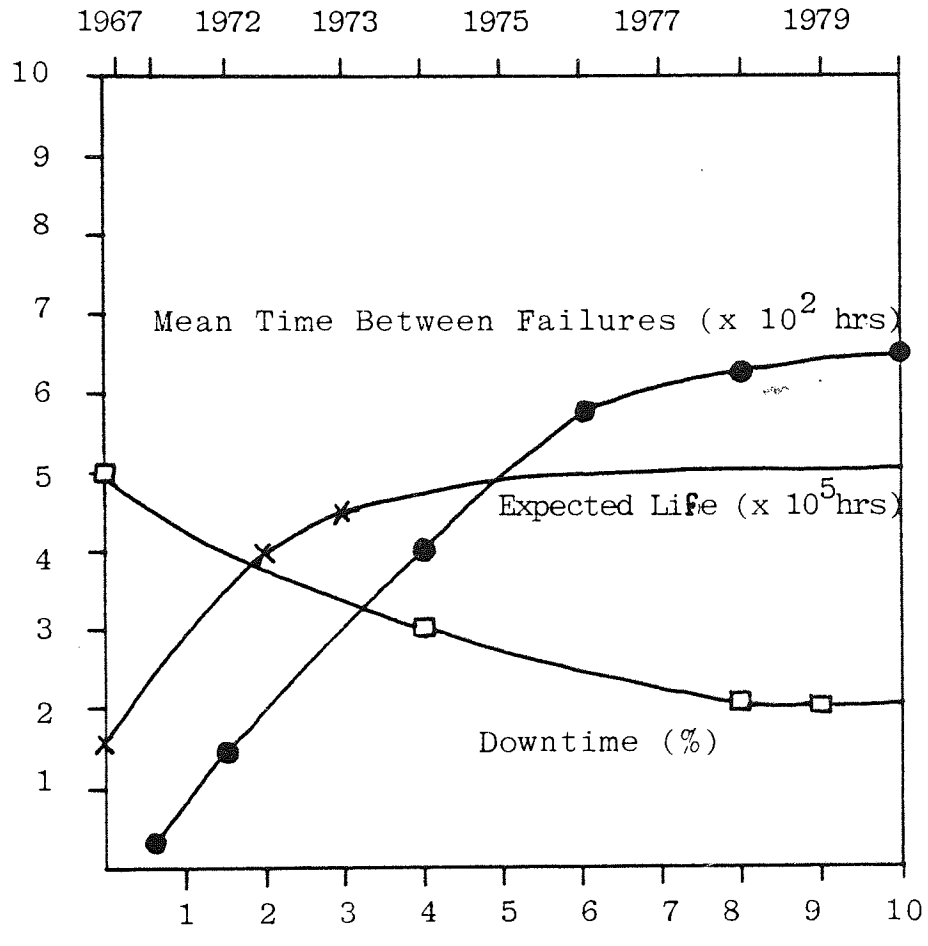
Rarely did the managers interviewed consider methods other than simple payback calculations solely based on displacement of direct labour. As opposed to discounted cash flows and inflation accounting, payback methods are appropriate for short term investment.

Pioneering adoption took place in firms with relatively low demands on capital. User firms required longer payback periods than the rest of the firms visited. The average payback period required by potential users was 1.9 years (1 to 2 years range) as compared to the 2.8 years required by users (see table A12.8). Those firms engaged in new applications such as arc welding and assembly regarded the robot project as an R&D investment. They demanded longer than average payback periods - in the region of three to five years. The economic situation of various British

industries has deteriorated with inflation, declining shares in their markets, and capital shortages. Some firms in the domestic appliances, TV tube processing, and metal component industries reported shortening of payback periods and more stringent procedures for investment appraisal than in recent years. Here, investment is limited to safe projects such as replacement of old machinery. Absolute certainty of achieving a one-to-two years payback period is demanded. Recently one domestic appliances firm reduced the payback period required from four to two years.

Figure 9.1 - Estimated Reliability of Industrial Robots (information from suppliers and other sources. For example, see Engelberger 1976d, Martensson 1976 and Weinstein 1978)

(a) Unimation Learning Curve (averages of various data)



(b) Others:

Trallfa (1974): Mean Time Between Service Calls = 600 hrs
Downtime = 4%

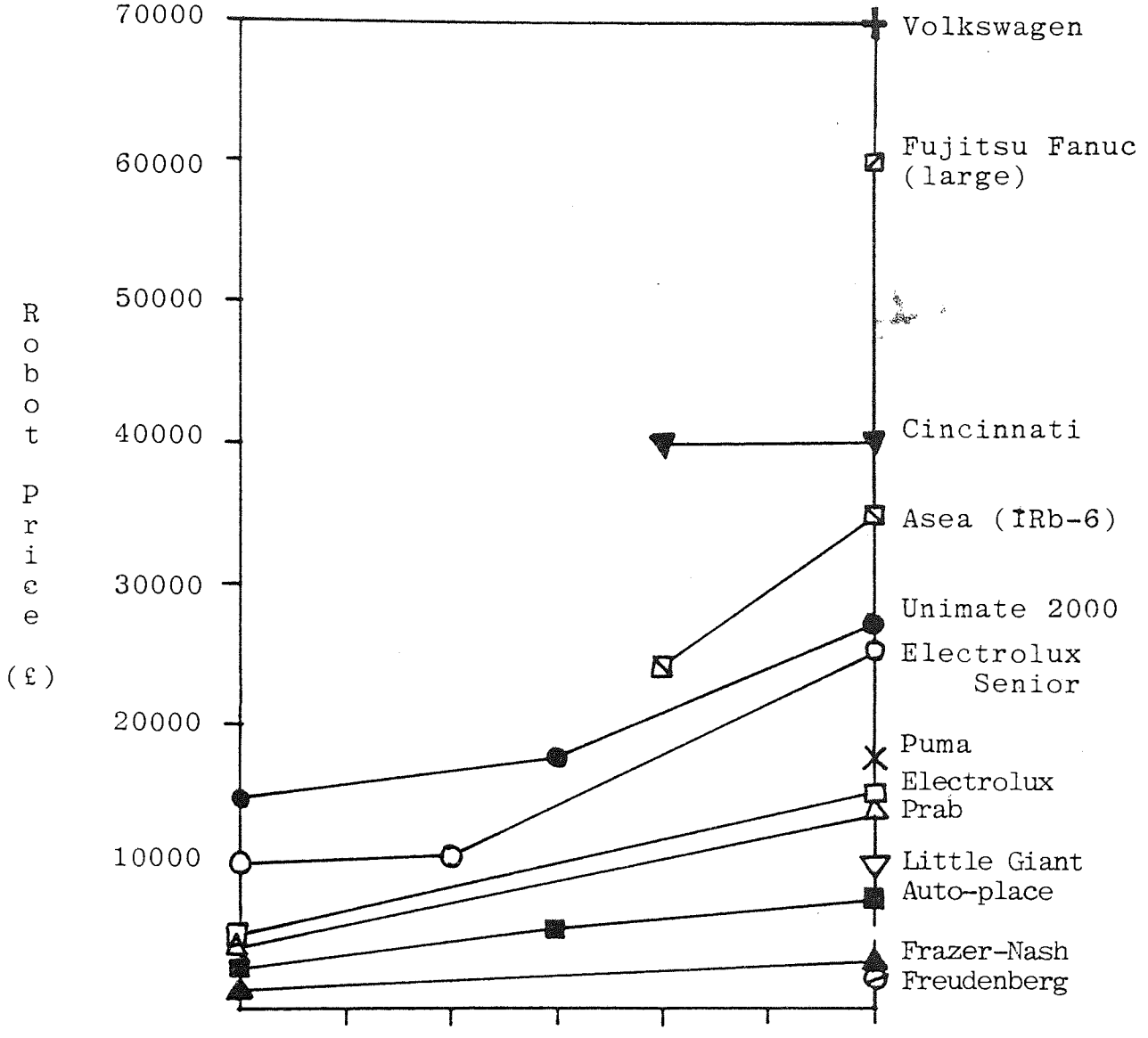
Unimation (1976): Mean Time to Repair = ½-2 hrs

Electrolux (1978): Downtime = 2%; MTBF = 500 hrs

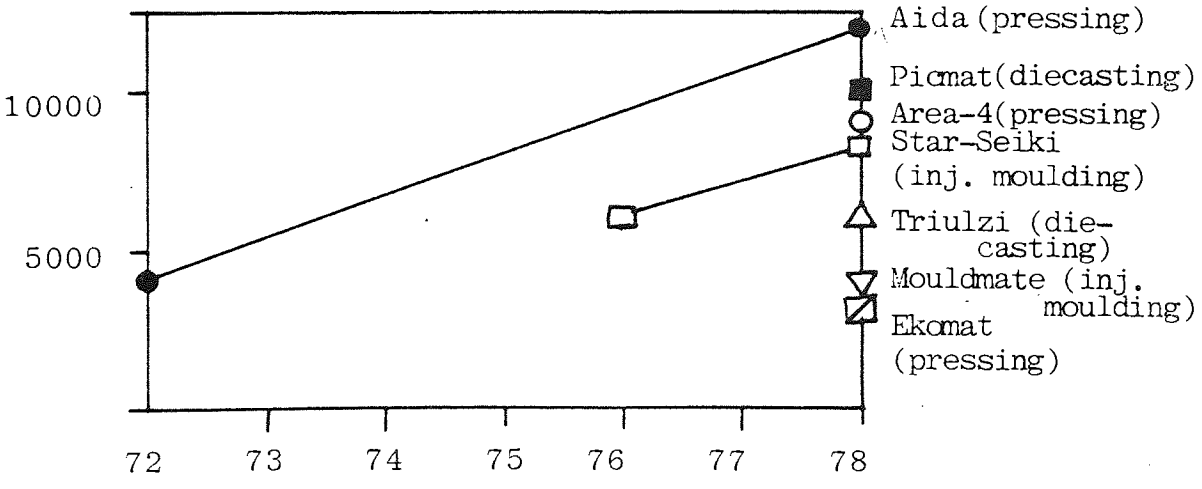
Asea (1979): Guaranteed downtime ≤ 3%

Figure 9.2 Price of Different Robot Makes (A)

(a) General Handling (HTR's, MTR's, SR's and PPD's)



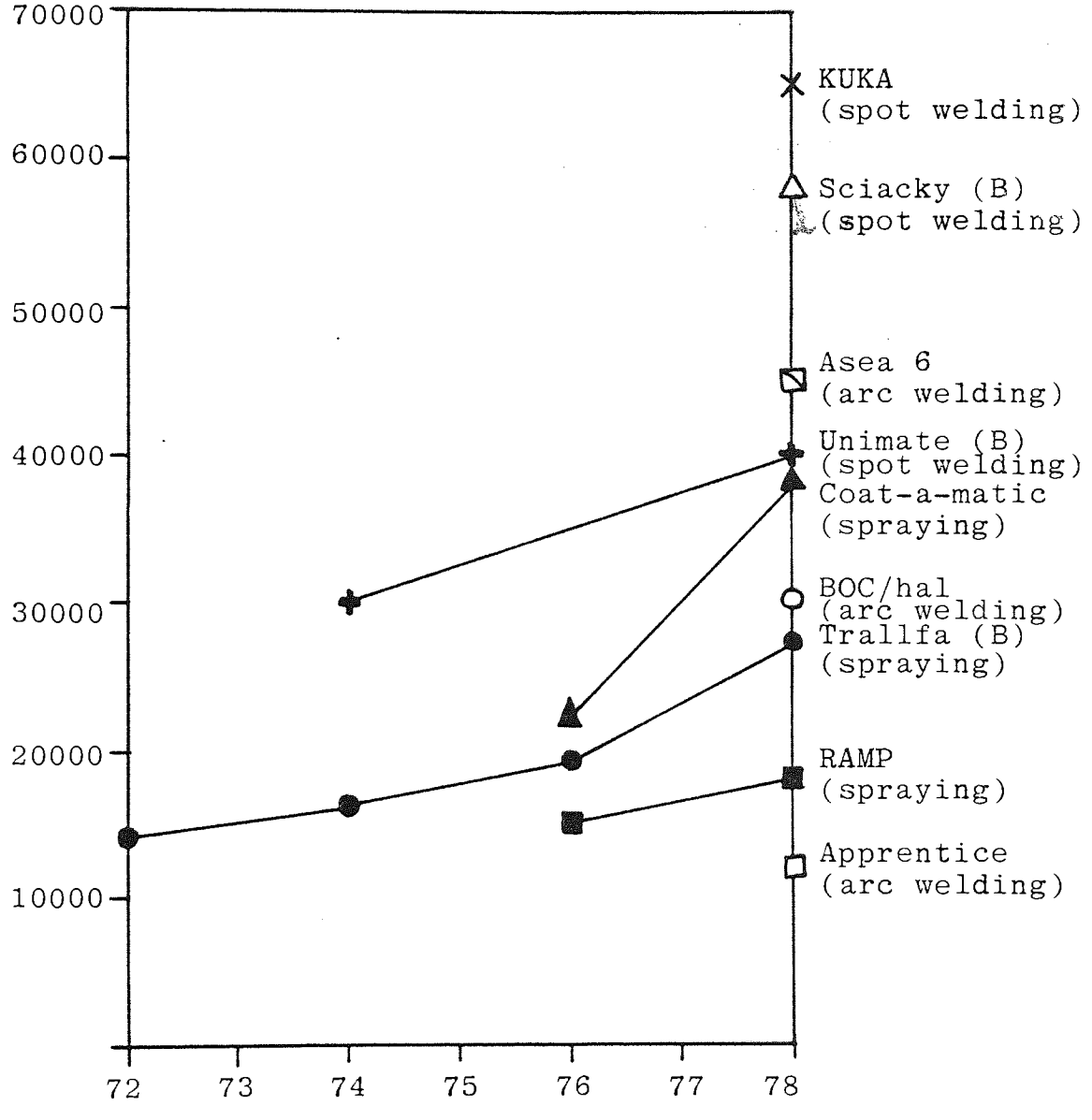
(b) Special Handling (PPD's and SR's)



Continued/....

Figure 9.2 (Continued)

(c) Processing Applications (MTR's and HTR's)



Notes: A Prices include special tools but no peripheral equipment

B Average of different models

TABLE 9.1 - Changes in the Cost Breakdown (%) of Components for Large HTR's (A)

Item \ Year	1962	1974	1978/9
Control System	75	35	20
Manipulator and Driving System	25	65	80

Notes:

A Estimated from Cakebread (1978)and Asea (1979)

TABLE 9.2 - Changes in the Relative Price of Different Categories of Robots (A)

	Small Robots (B)					Large Robots (C)				
	1972		1978		Price Index (E)	1972		1978		Price Index (E)
	Estimated Price (£)	Share (D) (%)	Estimated Price (£)	Share (%)		Estimated Price (£)	Share (%)	Estimated Price (£)	Share (%)	
PPD	1250	5	4000	8	3.2	2500	7	8500	8	3.4
SR	4500	19	12000	23	2.7	8000	22	25000	24	3.1
MTR	7500	32	15000	28	2.0	11000	30	27000	26	2.5
HTR	10000	43	22000	42	2.2	15000	41	45000	43	3.0

Notes:

A Prices do not include tooling and peripheral equipment

B For example: Puma, Apprentice, Electrolux Junior, Frazer Nash and Freudenberg

C For example: Cincinnati Milacron, Unimate 2000, Asea, Electrolux Senior, Pickmat and Star Seiki

D Share of combined price

E Price in 1978/Price in 1972

TABLE 9.3 - Cost Breakdown (%) of Components for Different Categories of Robots by 1978/79 (A)

Item \ Category	Small PPD	Small SR	Small HTR	Large HTR
Control System	61	57	39	20
Manipulator and Driving System	39	43	61	80

Notes:

A Estimated from: Freudenberg (1978), Webster (1978), Renkl (1978), Jones (1979), Cakebread (1978) and Asea (1979)

TABLE 9.4 - Contribution of Software (%) to the Cost of Different Robot Categories by 1979 (A)

Item \ Category	PPD	SR	MTR	HTR
Software	13	33	32	40
Manipulator, Driving and Control System	87	67	68	60

Notes:

A Report on assembly systems by a large metal components manufacturer

TABLE 9.5 - Breakdown of Component Costs (%) for Different Robot Generations (Forecasts) (A)

Item \ Generation	1	1.5	2-2.5	3
Control System (B)	29	38	66	85
Manipulator and Driving System	71	62	34	17

Notes:

A Estimated from Bryant and Caine 1974, pF2-14 and Varvello 1980, p25

B Includes: electronic parts, tactile and vision parts, sensory components and mini/micro computers.

TABLE 9.6 - Approximate Cost Content of the Standard Elements of Robots Relative to the Total Cost of Equipment for Different Applications (%) (from case studies in the robot literature and interviews with users and suppliers)

(a) A Sample of Various Applications

Application:	Range:	Average:
Palletising	50	50
Diecasting	83-93	88
Injection moulding	44-95	70
Pressing	67-71	69
Machine tool loading/unloading	63-92	78
Glass transfer	80-83	82
Component transfer in assembly	80	80
Spraying	47-68	58
Spot welding	45-81	63
Arc welding	64	64
Assembly (2-10 parts)	29-67	48

(b) General Application Categories

Category:	Range:	Average:
Transfer	44-95	75
Manipulative	-	-
Processing	45-81	61
Assembly (2-10 parts)	29-67	48

TABLE 9.7 - Price Indices for Labour, and Robots and Other Equipment

	Price of labour in manufacturing		Price of Equipment		Price of Industrial Robots (E)			
					Small size		Large size	
	Wages per week (A)	Total cost to the employer (B)	Metal working machine tools (C)	Mechanical Engineering (D)	Non-servo	Servo	Non-servo	Servo
1972	100	100	100	100	100	100	100	100
1973	113	118	108	107	-	-	-	-
1974	132	139	139	130	-	-	-	-
1975	172	182	182	167	-	-	-	-
1976	206	220	213	196	-	-	-	-
1977	216	237	252	228	-	-	-	-
1978	255	287	287	255	278	211	319	277

Notes:

A Rates per week for all sexes including juveniles (£27.27). Estimated from International Labour Office (1979, p408)

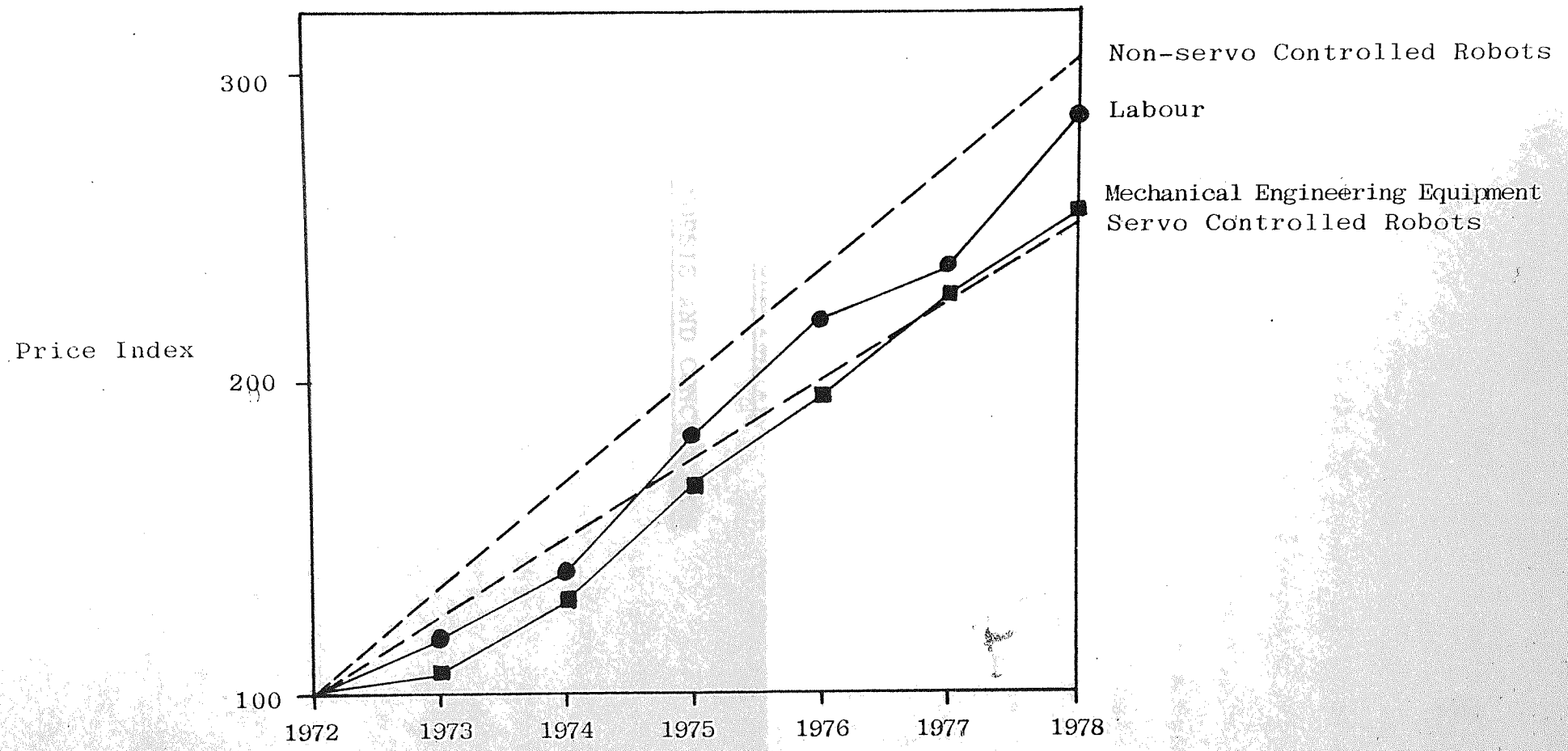
B Index of basic hourly wage rates adjusted for employers additional costs including national insurance contribution and surcharge. Taken from Flemming (1978, p9)

C Wholesale prices: index numbers of commodities produced in the United Kingdom (annual averages). Estimated from Ingram ed (1979, p466) and Lawrence ed (1980, p468)

D Wholesale prices: index numbers of output of manufactured goods (annual averages of home sales). Estimated from Ingram ed (1979, p464) and Lawrence ed (1980, p464)

E Averages of figures in table 8.2

Figure 9.3 - Rates of Growth of Labour and Equipment Prices (see Table 9.7)



CHAPTER 10

SYNOPSIS AND CONCLUSIONS

10 - SYNOPSIS AND CONCLUSIONS

10.1 Robot Advancement

The invention of robots owes as much to a trend towards more versatile machinery stimulated by technical developments (e.g. servo control and electronics) as to a drive to rationalise machine manufacture by producing standardised, off-the-shelf automation applicable to many situations. In practice the extent of versatility and standardisation of robot systems are limited by technical and economic constraints; the notion of a universal mass-produced robot is utopian.

The nature of robot inventive and innovative activites has radically changed under the influence of technological and economic forces. General purpose and modular robots for use in various applications played an important pioneering role in the early days of robots. Later, the success of certain applications triggered off the introduction of specialist robots. Less versatile but more standardised machines adapted to a particular area of applications with a large market have all the advantages of general-purpose robots, are simpler and less expensive, and are likely to achieve better performance and reliability.

Different generations of high technology robots with increased sensory perception and adaptability were being developed since the early 1970's. However, the direction of research and experimental development, like that of innovation, has changed dramatically. Reminiscent of its artificial intelligence and remote manipulation origins, early experimental work focussed on very complex sensory

systems and on manipulator arms. The problems along the path of producing economically feasible prototypes of advanced robot generations were generally underestimated. Later, efforts seemed rather more orientated towards short term practical problems, and towards a more integral development of robot systems. Sensory systems were increasingly conceived for industrial contexts, and work on particular applications and on other less developed elements of robot systems was intensified.

The successful adoption of particular applications by particular industries has sustained the robot business shaping development, supply, and manufacture. Robots were first introduced into the market for the loading and unloading of machine tools. Instead, American automobile firms introduced them into the technically simpler diecasting applications. Since then a strong partnership between the motor car and the robot industry has developed in those countries where the technology is most advanced.

The first signs of market development did not happen until processing robots were designed. Multiple spot welding lines for assembly of motor car body panels became the glamour area for robots in the beginning of the 1970's. This, and the success of spraying applications pioneered in Scandinavia to eliminate particularly obnoxious tasks, resulted in the relative decline of transfer as opposed to processing robots which has continued ever since. Later, manipulative (e.g. grinding and investment casting), new processing (e.g. arc welding, fettling and flame cutting), and assembly applications began to emerge.

In the second half of the seventies the manufacturing

capacity of individual robot firms grew substantially and the leader maker Unimation became profitable. New ventures stemmed particularly from the involvement of motor car firms in robot making. Manufacturers of diecasting and injection moulding machines also introduced large number of specialist PPD's. Large electronics firms were planning the introduction of minirobots for assembly. In general, the robot industry seemed to be leaving its infancy. With the accumulation of experience and the growth of individual robot firms, the cost of entry to the robot business increased significantly. Some large groups achieved quick entry by taking over small robot firms. Future ventures are likely to come from multi-national firms with experience and a gargantuan infrastructure for developing, making, marketing, and servicing high technology.

Successful firms have significantly reduced costs, improved reliability and have started to rationalise robot manufacture. At first robot design was not mature, and suppliers had little know-how and ability to service the diverse applications. Manufacturers had to undergo a long learning process before their products and services became technically and economically competitive. The problems of supply largely explain the slow speed with which robots have diffused everywhere. This is further evidence to support Rosenberg's arguments against a strictly Schumpeterian view of invention.

Robots were very expensive machines, even though manufacturers first sold them at a loss. Furthermore, tooling and peripheral equipment were, in the early days, even less developed than they are today. As a result, total

system costs were astronomical. This was often unexpected and badly dented the image of robots as off-the-shelf automation. Dramatic improvements in the economics of electronic components have transformed the nature of robot manufacturing costs substantially. The relative price of versatility, reliability, and performance has dropped. Small high technology robots which have less expensive manipulators and driving systems have benefited most, their prices have increased slower than the prices of other types of robots and the cost of labour.

10.2 Robot Adoption

Adoption is at the present stage, the most important limiting factor of robot advancement. Factors determining adoption can be used to explain to a large extent the international differences, and the differences in the advancement of different robot applications. The cost of labour and its rate of growth is of course an important determinant. The dramatic difference in the level of diffusion of robots between Sweden and the rest of the world, particularly Britain, are largely explained by these factors. However, no one single factor can entirely explain the level of robot diffusion. Adoption is a much more complex phenomenon, particularly in the early days of a technology. Adoption pioneering will tend to take place only when several conditions exist:

Firstly, when the technology is appropriate to the technical, methodological, organisational, and economic characteristics of the manufacturing firm (system compatibility). The extent of compatibility of the new technology with the system determines the

potential for robot adoption. This level of potential use is not static or fixed, but only structural changes in both robot technology and firms would modify it.

Secondly, when the advantages of adoption outweigh its disadvantages and are good enough to justify the investment of resources. The consequences of adoption on labour, management, and the firm, and the rate at which they are improved largely determine the speed with which the technology diffuses across industries and inside firms and reaches its potential level.

Thirdly, when the degree of compatibility of the firm with robots, and the consequences of adoption are recognised as worthy of the managerial involvement and the labour acceptance. The role of individuals and groups, and the atmosphere which prevails from their interaction and from the past performance of the firm set the final conditions for adoption pioneering. With no resources and no encouragement, managerial involvement and labour acceptance, even when the other conditions exist, are unlikely to be prompt. Adoption in these situations is relegated to the time when the forces of imitation, if diffusion succeeds, break the inertia of the system.

Different categories of robots can be identified. The manufacture of goods with geometrically defined shape or piece goods can be divided into operations of increasing technical complexity: (1) packaging, storage, and distribution, (2) component manufacture (forming, material removal, and finishing), (3) assembly (fabrication and small part assembly), and (4) testing and inspection. Robots can either

be used to automate the transformation process of a manufacturing operation for the first time (manipulative, processing, and assembly robots) or to automate the handling of materials in operations where the transformation process has already been automated (transfer robots). Transfer, manipulative, processing, and assembly robots can either be used to automate stand-alone operations or mechanically integrated operations. The degree of compatibility between these robot categories and existing manufacturing operations, and the consequences of their operation are substantially different.

The versatility and performance requirements for robots vary according to the complexity of manufacturing operations. The overall versatility requirements of transfer robots in stand-alone operations is rather low (e.g. loading and unloading of single machines). The main technical problem of transfer robots and of any handling system is the complexity of the component geometry. Manipulative or gripping versatility is a major requirement of these applications, particularly in material removal and assembly where workpieces are more intricate. Transfer robots are only appropriate for servicing slow-to-medium speed process machinery (middle range cycle processes). Manipulative and processing robots require very high overall versatility and performance. Parts of medium weight and complexity are appropriate for robot automation in forming and material removal (e.g. forging, deburring, fettling, and grinding). In contrast manipulative and processing robots in deposited surface finishing and fabrication are appropriate where components have very complex geometry (e.g. dipping and stuccoing of wax patterns in investment casting, paint and enamel spraying, and welding). In general, manipula-

tive and processing robots are more appropriate the longer the product cycle is. The versatility and performance requirements of small part assembly are the highest of any other application. As in the case of transfer, assembly robots are appropriate for middle range product cycles. Small part assembly and fabrication are plagued with problems of inconsistent component dimensions. Sensor directed control would be highly advantageous for easier mating of complex parts and reduction of the need for accuracy and parts presentation equipment. Changes in product and component design would also be needed to simplify adoption.

The versatility and performance requirements also depend on the methodology and organisation of manufacturing operations, and on the different patterns of production and market demand. In a flow-line system of manufacture, few demands for versatility and high demands for performance exist (large-batch or mass production). Transfer tasks for the integration of different operations can be broken down and allocated to PPD's, and process machinery can be inflexible and of special design. In a functional and cell system, transfer robots used in the integration of machinery and process machinery require high levels of versatility. Present-day technology is unlikely to cope with the demands for manipulative versatility of functional systems (small-batch production). The cell system of manufacture is indeed the most compatible with robot technology (medium-batch production). Here, the versatility limitations of grippers and peripheral equipment are less significant, since group technology methods of production programming can be used. In turn, the command and positional versatility of robots enhance the benefits of

cell manufacture.

In general the compatibility of robot versatility depends on the basic design criteria of the manufacturing system. With present-day technology versatility is rarely accompanied by top performance, thus it is not compatible with systems where productivity is the top priority. For example, the more robotic an assembly system is (allocation of several tasks to a highly versatile manipulator), the longer the time needed to assemble one product becomes.

Above all, robot technology must be compatible with the general characteristics of the firm. Successful adopters and potential users had one or several of these characteristics: expanding markets, successful sales at home and abroad; relatively high technology process and products; relatively high volumes and stable demand; and good supply of labour, managerial, and capital resources. These characteristics were rarely present in small and medium size firms. Small and successful adopters were all technically orientated firms linked to large manufacturing groups which had been able to secure relatively high volumes and stable demand, and were enjoying expanding markets. Small and unsuccessful adopters were low technology firms making low value added products. High rates of success and large potential use were identified with large firms. Potential use, particularly for transfer robots, was marginally concentrated in high volume industries. However, processing and assembly systems were successful in low volume industries with a large variety of models and few product lines. Applications with fast changeover time such as processing applications where workpiece handling is not automated (e.g. arc welding and spraying) are more appropriate

for the pattern of production commonly found in small firms.

The main incentives for the adoption of robots are the profitability of the investment and the ease of management of direct labour derived from the elimination of unattractive jobs and working conditions which stimulate negative attitudes to work. Other factors such as the ease of supervision, monitoring, and control of performance, and improved product quality play an important but secondary role.

The profitability of robot investment is largely determined by the increase in labour productivity which results from increases in output and reductions in labour costs. Increases in output are most impressive where robots automate the transformation process for the first time in stand-alone operations (assembly, processing, and manipulative robots). In situations where heavy jobs and/or bad working conditions exist, these robots are also associated with high ratios of labour displacement even when handling tasks remain manual (e.g. glass gathering, grinding, and arc welding). The largest increases in labour productivity occur where handling tasks are also automated (e.g. small parts assembly). Smaller improvements in output result where robots automate the transformation process in mechanically integrated operations. These applications are also associated with low ratios of displacement, except where heavy tasks or bad working conditions are involved (e.g. spot welding of motor car body panels, conveyorised spraying, and semi-automatic assembly). Increases in labour productivity are less impressive where the transformation process has already been automated (transfer robots). The extent of output increases is largely determined by the level of utilisation of machinery before transfer robots are

introduced. Heavy tasks in obnoxious environments are associated with low levels of utilisation. Here, transfer robots increase labour productivity significantly.

Difficult recruitment, high absenteeism, high labour turnover, and frequent breaks in production are closely associated with unattractive jobs and working conditions. The most widespread impact of robots on the nature of direct labour tasks is the reduction of physical effort in obnoxious environments. These factors have greatly encouraged the adoption of transfer and manipulative robots in forming and heat treatment (e.g. diecasting, forging, and glass handling), and of processing robots in deposited surface finishing and fabrication (e.g. spraying and welding). Incentives of this nature have not played an important role in material removal and assembly. These tasks are less associated with problems of strength and obnoxious working conditions but, especially where unskilled jobs are involved, have connotations of monotony and boredom.

The major stumbling-blocks for robot adoption are the managerial efforts and the total system costs. The degree of versatility and standardisation of robot systems, and hence the managerial and economic advantages associated with their introduction are still quite limited. Although development activites are making progress in this direction, tools, peripheral equipment, and software remain, to a large extent, inflexible and of specialized design.

The degree of standardisation of robot systems depends on the complexity of the application, on its potential market, and on the extent to which it has been successfully adopted (this is a kind of snowball effect: degree of standardisation

$\longleftrightarrow$ level of diffusion). The lead times for introduction of simple or highly successful systems have been cut as much as fifty percent when compared to special purpose automation. More complex applications take as long to introduce, and cost nearly as much as special purpose machinery. Applications where handling is automated exhibited the highest concentration of development problems, particularly those in assembly. The end effector and peripheral technology of processing applications, especially those where handling remains manual, is readily transferred to different situations. Here, the degree of standardisation of the system grows faster as its diffusion advances. As standardisation increases adoption in turn becomes relatively cheaper and easier, and paves the way to further diffusion. Excellent examples of these are spot welding, spraying, and increasingly arc welding systems. Transfer, manipulative, and assembly robots operating with intricate workpiece require special development as long as no 'universal' grippers, tools, and peripheral equipment exist; the need for them is avoided; or the potential market is not large enough to sustain special supply.

At present, increasing versatility is often associated with higher complexity, lower performance, and poorer reliability. Maintenance work is more difficult when servo controlled robots are involved and training is necessary. The small extent of robot use inside firms, and the generally high turnover of qualified personnel, exacerbate these initial problems. In most cases the firm depends entirely on suppliers to provide corrective maintenance. As users learn, versatility should be less and less associated with high complexity and poor reliability.

The impacts on direct labour depend on the extent of robot adoption. Labour impacts are therefore particularly important for sustained adoption. The larger the number of robots introduced, and the larger the marginal differences in the level of automation and integration of an operation before and after adoption, the greater the impacts on labour (the ratio of labour displacement, changes in skill requirements, and need for labour reorganisation). On the one hand, in stand-alone transfer applications and in stand-alone manipulative and processing applications, especially where handling is not automated, displacement does not take place unless various robots are introduced. On the other hand, fully automated assembly applications replacing several manual tasks organised in a craft-like fashion may displace as many as thirteen workers per shift and demand a complete reorganisation of labour.

As the level of automation increases, the responsibility and concentration required from a job rest more on the supervision of an increasingly complex machine than on the worker's own ability to perform the transformation of a workpiece. The intermediate stages, those where the operator loads and unloads the workpieces continuously, particularly where mechanical integration exist, are in my view the most negative concerning the labour task. Here, the most skilled proportion of the job is allocated to a machine and the operator remains largely tied up to it. Once the operator becomes removed from the product cycle the job starts to become again less monotonous and less tied to a particular machine although it becomes machine paced. An operator-supervisor does not have to start the product cycle any longer, but must keep

machines running by building component and product buffer storages.

The impact of robots on skills is less significant where the transformation process has already been automated, particularly where manual tasks are integrated by conveyors (e.g. transfer from conveyor to conveyor, and loading/unloading of process machinery). Elimination of heavy tasks in obnoxious environments is a further bonus. When robots automate the transformation process for the first time, more skilled jobs are eliminated (manipulative, processing, and assembly robots). The most radical changes in the nature of the job happen where handling is automated at the same time as robot adoption (manipulative and processing robots in forming and material removal, and small part assembly). Where handling is not automated the worker becomes closely tied to the robot system, except where mechanical integration of processing tasks already exist. Here robots replace the more skilled jobs paced by the conveyor, and the jobs of the workers loading/unloading components to and from the system remain (e.g. spot welding of motor car body panels and conveyorised spraying). In fabrication the remaining handling tasks are more complex than in component manufacture (this partially explains why they remain manual). Furthermore, in applications like arc welding present-day technology still requires skilled welders for teaching, supervision, and correction.

10.3 Explanatory Factors

At the end of the sixties research and experimental development on robots was more advanced in the UK than in any

of the European countries. Similarly, British firms transferred American technology and introduced robots into the market at a time when little interest existed in Europe. This is in stark contrast to the British position ten years later and is further evidence to support the hypothesis that Britain may well suffer from a tendency to innovate quickly, but have a slower rate of acceptance, and end up with the most limited diffusion (Kennedy and Thirlwall 1972, p 58). Other pioneer countries like Japan, USA, and Sweden have managed to advance the technology comparatively quickly and have continued to be leaders. This is evidence against the hypothesis that, "in countries which are pioneers, diffusion tends to be slower" (Ray 1974, p 19).

Pioneering experimental work on advanced automation seems to have suffered from drastic cuts in SRC finance for artificial intelligence research. Without any doubt, the magnitude and quality of British public support for robotic R&D, when compared to the Japanese, American and West German programmes, are the main reasons for its slow and erratic progress.

The market for robots in the UK did not develop as expected. Furthermore, the marketing policies of the UK pioneers exacerbated the initial difficulties in robot supply and manufacture. As opposed to Unimation which sold very cautiously in the USA, HSDE and GKN conducted a policy of intensive sales. Their ability to cope with the problems of each application was quickly surpassed. Widespread failure in many pioneering applications largely explains the long period of stagnant robot sales which followed. The band-wagon effect, generally identified in the literature as a stimulus for diffusion, can also act as a strong deterrent for unsuccessful innovation.

The majority of user firms achieved a satisfactory payback period. However, profitability alone does not explain the differences in diffusion of robot systems. (Differences in payback periods achieved by successful applications were small). The shortest payback periods were achieved in transfer and assembly. Transfer robots in stand-alone operations (the second most successful category with about thirty five percent of all robots) are the least capital intensive, especially where PPD's and SR's are involved, and firms usually ran for at least two shifts. Furthermore, they remove operators from the product cycle of one machine and are normally associated with obnoxious tasks and working conditions. Despite their capital intensity assembly systems offered the largest rates of return even when firms operated on a one-shift basis. Assembly robots, as opposed to the simpler transfer robots concentrated in forming, present extreme technical difficulties related to complex component geometry (assembly accounts for less than four percent of all applications). Processing robots were less profitable but achieved successful operation more frequently. The success of processing robots in finishing and fabrication where handling is not automated such as in spraying, spot welding, and arc welding has resulted from a combination of several conditions (These systems account for about fifty percent of all applications and have the fastest rate of growth):

1. Their technology is less constrained by workpiece geometry. Parts presentation equipment is limited to fixtures which are loaded by hand, and end effectors are other than gripping tools which do not require radical modification when workpieces

change (as opposed to small parts assembly the transformation process is specialized).

2. Parts presentation equipment had to be improved (e.g. better accuracy) but to a large extent it already existed.

3. As a result of their greater independence from workpiece geometry, their technology is more readily transferred to different situations. This and a large market potential favoured a faster and more extensive standardisation of systems. Consequently, adoption became easier and relatively cheaper as their diffusion advanced.

4. As a result of their greater independence from workpiece geometry they have faster change-over than other operations of similar complexity. They can be more attractive in small-to-medium batch production and diversified product lines (except where fixtures are very complex like in spot welding of cars), consequently more compatible with small-to-medium size firms.

5. Generally they are associated with obnoxious tasks and working conditions.

6. They may replace more skilled jobs with specialized handling tasks and have large ratios of displacement. However, the most widespread systems are those introduced into already rationalised operations. Those eliminate specialised transformation tasks tightly paced by conveyors and leave handling tasks manual (e.g. spraying and spot welding). In stand-alone operations like arc welding the remaining handling

tasks still require skilled welders at present.

Manipulative robots were the least profitable due to their low labour displacement, low marginal increase in output, and high capital intensity (output was in the cases studied constrained by other technology). Quality consistency played a very important role in these cases.

The profitability of robot investment has increased considerably since the introduction of robots in the UK. The average price for all types of robots has decreased eight percent relative to the average total labour cost to the employer in manufacturing industry. Prices of servo-controlled robots have decreased thirteen percent slower than labour costs. Applications making use of small servo controlled robots with a low content of peripheral equipment have significantly improved their profitability. On this criterion alone the most promising of all applications are arc welding, palletising, and assembly of small-to-medium size products (in the case of assembly the fewer the parts involved the better). Furthermore, labour cost growth rates relevant to these systems, especially those of female workers in assembly, are higher than average.

Individual and institutional factors are important in exaplaining further the diffusion of different systems and the international differences in the level of robot diffusion (particularly each country's ability for adoption pioneering).

Labour acceptance has not played a direct role in adoption pioneering, except perhaps in Sweden where workers and trade unions have been known to demand strongly the elimination of certain jobs by any means including automation. However, indirect attitudes to work have been crucial. Rising

expectations stimulated by better education and living standards in highly industrialised countries have resulted in difficult problems of recruitment for certain occupations. These have greatly encouraged automation in recent years. Alternatively a check on these labour supply problems and on the need for automation has been achieved by large influxes of migrant workers from poorer countries. Large proportions of foreign workers from developing countries are important explanatory factors of the low level of diffusion in countries like the FRG, France and the UK. For example, the FRG, despite having the highest labour costs, has a very low level of diffusion and the largest proportion of workers from developing countries. Other countries with very high levels of diffusion like Sweden and Japan have restricted immigration despite the fact that in the past they foresaw acute labour shortages.

Changing social attitudes have also stimulated increasing legislation for workers' protection and codetermination at work. Health and safety regulations do not directly encourage automation but make the employment of workers for certain jobs more difficult and expensive. Sweden, the USA, and the FRG are countries where these trends seem to be more noticeable. Similarly protection of employment and increased industrial democracy may encourage automation as the shedding of labour in conditions of variable demand become more difficult. On the other hand, this legislation can also make the introduction of automation more difficult. The need to provide safeguards has made robot systems more capital intensive and more difficult to introduce.

Labour acceptance may have not been a widespread con-

dition in the pioneering stages of robot advancement but the situation is changing rapidly. Consultations and negotiations resulting in formulae for sharing the benefits and softening the negative impact of robot adoption have become essential conditions even for experimental adoption. This is a sound basis for securing the future acceptance of robots.

Successful pioneering applications can be identified with the activities of enthusiastic managers, and more importantly with an environment conducive to innovation. The firm's policies on capital investment have as decisive a role in determining the profitability of robots as the total labour costs. Pioneering adoption took place in firms with relatively low demands on capital. All pioneering firms regarded the robot projects as risk investment with long term benefits, and demanded longer than average payback periods (e.g. three to four years).

Encouragement for robot adoption by a firm takes place alongside successful economic performance at home and abroad. In Britain, the performance of the motor car industry and its machine builders explains, more than any other factor, the present state of robot supply, manufacture, and use. This industry played a relatively meagre role as a pioneer user. Instead the domestic appliances, sanitary ware, and glass industries introduced robots in the early days. Later, all these industries suffered from declining shares in their markets and ceased to be agents of robot diffusion. In stark contrast, Italy has recently enjoyed growing motor car, machine tools, and domestic appliances industries. The innovation policies of Fiat alone largely account for the level of robot diffusion in Italy.

Recent signs of a rise in robot demand can be largely identified with spot and arc welding applications. The motor car industry became the main user by 1978 thanks to the decision to use robots to build the new BL Mini Metro. However, in contrast to the most successful car making countries, British car makers remained uninvolved in robot manufacture. This is perhaps the result of its position in the international market and consequently its small chance for exporting its own car manufacturing technology which will increasingly consist of industrial robots. Firms fabricating agricultural machinery, earth moving equipment, and fork-lift trucks were the main areas of growth in arc welding and assembly in the UK. Interest in assembly was also growing in firms in the electrical and electronics industries. The average number of robots per firm has been and still is pretty low in the UK. Robot adoption is still largely an experimental activity.

10.4 Policy Implications and Recommendations for Further Research

At present the impact of robots on productivity, and their positive and negative social implications are relatively insignificant (except perhaps in car body assembly lines). In the long term, however, investment in robots, and the strategy followed for their development and diffusion may substantially influence a country's capacity to make and sell products and machinery for national and international markets.

Robots and flexible automation have been primarily envisaged as the means to mechanise small-batch manufacture. The potential benefits of mechanisation lie in the enormous

size of this sector of the economy, and in its present labour-intensity. Unfortunately, formidable problems must be solved before the level of automation in this sector can be increased. With some exceptions, the structure of firms in this sector seem to be rather incompatible with present-day robot technology. It is more likely that manufacturing technology in industries with higher volumes, more stable demand and a strategy for product diversification will become more versatile under the influence of recent technical developments. Industries with a higher concentration like the motor car industry must continue to play a pioneering role in the development of robots and flexible automation. Success in doing this and efforts to transfer the technology to less strong industries in small-batch manufacture is a more feasible alternative.

In Britain the most fundamental need is that of bringing the motor car industry back into successful operation at home and abroad. A partnership between motor car and robot builders will continue to be an important mechanism for robot advancement elsewhere. There are several other important areas for action, but without this partnership the robot industry in the UK will continue to be handicapped. Other nations' car-robot makers have started to enjoy the benefits of early pioneering development by exporting their technology.

Other partnerships between users and makers of robot technology are evolving and will produce future successful applications. The identification, formation, and promotion of such partnerships are the most important areas for action from both government and private industry. It is essential

for public and private policy to be orientated towards applications which are not yet fully developed and which have a large future potential. Although adoption is the limiting factor in the diffusion of successful systems at present, its main problems are closely related to problems of supply (e.g. degree of standardisation, reliability, serviceability, complexity, and risk). Priorities must be given, particularly for public funds, to start building the infrastructure of supply and manufacture especially orientated to areas of long term economic importance. On the basis of size and labour intensity these are likely to be in material removal and assembly. Research, experimental development, and manufacture of future successful applications must begin in, and be conducted by the industries which will use them.

Supply and manufacture of successful applications, except for the early transfer of Versatran and Unimate, started late in the UK. In the face of an incipient domestic demand, indigenous robot makers have been overpowered by the competitive advantage of foreign manufacturers with more experience. Measures encouraging demand for present commercial robots are important, but they must be selective. These measures must be orientated towards (1) strengthening the infrastructure of native suppliers and of licensees of foreign robots manufacturing and developing their technology in the UK; (2) reducing the risk and improving the availability of resources needed for robot adoption by small-to-medium enterprises, especially for large projects; and (3) favouring the dissemination of information and the transfer of technology. Public funds must be invested in facilities for experimental development, testing, advising,

demonstrating, education, and training rather than be channelled into handouts to users. The rate of success of adoption will suffer if the commitment needed from the user is reduced, but will rise if the risk of failure is diminished and the availability of venture capital is improved.

Research and experimental development in universities and research institutes must take a more cohesive and determined form. University laboratories must remain autonomous and focused on basic and applied research and on generalised problems of robotics (e.g. mechanics, control, and artificial intelligence). However a kind of academic-consultant establishment like the IPA in the FRG, and the SRI International and the Charles Stark Draper Laboratory in the USA may also be successful in Britain. These institutions can be a useful meeting place for industrial and academic experimental development; useful in the sense that they can provide the legal and institutional environment to commercialise the fruits of development faster than would otherwise be the case. The areas of research must have the integrated nature and the industrial orientation that robotics research and experimental development has in Japan, the USA, and the FRG (a.g. research on sensory systems, software, control, end effectors, peripheral equipment, performance evaluation, standardisation, safety, and particular applications).

Efforts to build an indigenous capability for making robot technology may gain from concentrating research, experimental development and manufacture on future successful applications such as flexible manufacturing systems (FMS) and adaptable programmable assembly systems (APAS). Work

on these applications started in Japan and USA in the first half of the 1970's. However, the UK has a latent capacity in these areas, and there is time and scope for creating indigenous technology which can be exported in the future. In contrast to past successful applications which resulted in a shift from general-purpose to specialist robots, integrated transfer (FMS) and assembly (APAS) systems are constrained by the geometry of the workpiece. The chances are that innovation will advance at a slower pace in these areas and that versatility will have to be seen in the context of product families. A further drop in the degree of versatility of robot systems may be needed if high levels of standardisation are to be achieved in material removal and assembly (product orientated robot systems). This is particularly true of assembly where processes are highly diverse and dictated by the product.*

The final configuration of FMS and APAS is likely to be more of a proprietary, and thus confidential, nature than is the case for processing robots. This is a potential area of difficulty if public funds are to be used in the development of entire systems. Alternatively public promotion of partnerships of robot makers and users can be orientated to develop standard blocks for building those systems. This has been the policy of designers of special-purpose assembly machines for achieving a certain degree of versatility and standardisation. Similarly standard block elements with a high degree of versatility can be used to build robot assembly

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* The SRC has recently launched an R&D programme which resembles similar programmes abroad, and has the characteristic outlined here.

systems. Such block elements may be families of grippers, arms, joining tools, interfaces, control units, parts presentation equipment, sensory systems, and software.

The UK government has already begun a project to build automated small-batch manufacturing cells, and has supported manufacturing of assembly robots (i.e. the Puma robot). Further efforts to bring together experts on robotics and experienced builders of special-purpose assembly systems and of other components must be made. The glamorous and far-fetched world of robotics has been in conflict with the pragmatic and more commercial world of conventional assembly. Little cross fertilisation of ideas and experiences has taken place. It is a real tragedy that these worlds have been largely alienated from each other when in reality robot technology is evolving under the tight constraints of industrial applications, and when conventional assembly is getting more versatile. Robot systems are likely to be hybrids of versatile and special-purpose assembly systems (e.g. systems with servo and non-servo controlled axes, with special parts presentation equipment to feed some parts, and some sensory controlled arms to feed others). Collaboration between these two types of automation builders is likely to reduce the time needed for learning and development of feasible technology.

Selection of particular product families to which assembly systems will be first adapted must be made by a thorough and systematic search across and inside industries. Initial exploratory projects are necessary if development funds are not to be wasted in building systems with future technical, economical, and social difficulties. In this

respect, British researchers can learn from the experiences of the US exploratory projects on assembly and their programme of technology transfer to industry, and from the FRG efforts to social and technical design (see for example Abraham et al 1976 and 1977a and b, and Battelle Institute 1978). Exploratory projects on the economics of automatic assembly of various products must take into account the differences of structure and relative performance of British manufacturing industry. Studies of the structure of various industries are decisive in estimating the potential use of assembly and other robots. Research should focus first on the most successful sectors of British industry. Manufacturing of earth moving equipment, fork-lift trucks, and agricultural machinery are some examples of successful areas which could give a strong boost to assembly and other systems (e.g. FMS and arc welding). Efforts must also be made from the start to involve the component supply industry for motor cars. Sub-assemblies such as gear boxes and carburettors may have to be selected for development soon. Large obstacles will have to be overcome in industries of low concentration, like the component supply sector of the motor car industry, to achieve the standardisation of design needed for automatic assembly.

The electrical instrument and electronics industries have already started to invest in assembly projects. These are some cases where the proprietary nature of the systems and the high competition of these industries are likely to obscure developments with a veil of confidentiality. If forms of transferring the technology to other sectors can be found, greater benefits will derive from development efforts.

Another sector which can play a pioneering role in robot development and manufacture is the aerospace industry. The British aerospace industry, like its American counterpart, could concentrate on the development of new manipulative and processing robots (e.g. rivetting and routing of aircraft frames) and of computer-aided manufacture in general. This industry could be the centre for development of the kind of flexible automation which could more readily be transferred to the small and medium-batch sector of manufacturing industry which is less technically orientated.

The configuration of robot systems, particularly those with a high level of integration (e.g. FMS and APAS) could take various forms according to the priorities attached to different aspects (e.g. cycle time versatility, reliability, serviceability, and job content). It is important that the interests of the workforce must be properly represented when design and experimental development is undertaken. The configuration of a system should be influenced by the content of the labour tasks created or eliminated (avoiding for example the intermediate levels of automation where operators, particularly in short cycle applications like assembly, are closely linked to one machine). In turn, the system configuration will largely determine the kind of hardware elements which are most appropriate to be built, and the range of possibilities for labour organisation available when the system is introduced into production (e.g. the ease with which direct manual tasks can be combined with setting and programming of the system).

Increased participation of various interests may seem an obstruction to robot development and diffusion. This is

an effective way of dealing with the social implications and of improving the adoption of robots and consequently, a sound basis for sustained diffusion. A lot of effort and resources must be invested into devising the kind of organisation and methodology which would deal with these issues. The motivation to do so is only likely to be encouraged by increased pressure and urgency from groups representing the interests of workers (e.g. trade unions). The training of competent people and the provision of general guidelines to influence the design and introduction of robot systems is the responsibility of trade unions. Public funds invested in exploratory projects and in the development of pilot systems must contribute to the development of these skills.

On the basis of its size and low level of automation, assembly is the most critical area concerning the social implications of robots. Assembly has all the characteristics necessary for the fast take off which has been persistently predicted of robotics. It has the largest and fastest growing economic incentive for robots. In principle its high labour intensity and fast growing labour costs (particularly where female workers are involved) make automation very attractive in economic terms. At the same time these systems would have the highest ratios of displacement, and would eliminate jobs which though monotonous are not related to obnoxious physical conditions, and are considered as valuable opportunities for social contact (e.g. assembly jobs to which mature women are recruited). Assembly also has the strongest technological push of all applications, since developments in electronics are making small and versatile

systems cheaper than other equipment and labour. Furthermore assembly has a large proportion of female and unorganised labour with less muscle to influence the terms on which the systems are introduced. On the other hand, assembly has the most difficult technical problems, demands the largest capital investment, and requires the most extensive changes in component and product design. It therefore has the obstacles which may turn a rapid take off into a progressive change. There seems to be plenty of time and scope to study systematically the commercial and social implications of various systems in various areas, to shape their design and development, and to find the best ways of dealing with the inevitable negative impacts of their introduction.

Breakthroughs in system design and sensory control, and opportunities to undertake extensive product redesign can give further impetus to assembly by robots. These conditions are likely to arise in a future economic boom once the present recession and restructuring of huge sectors of the economy are over. The present recession may also undermine the bargaining power of unions and may encourage women, under the influence of more conservative ideologies, to return to the home. This will further facilitate a wider and faster spread of robots. Robot diffusion will be disruptive or evolutionary depending on how much organised labour can participate in shaping future investment in new plants, and negotiate on behalf of the unemployed. However, the question is not whether robots will be successful, socially or commercially and thus worthy of development effort, but in what forms they should evolve, and how they should be used.