TRENDS AND IMPACTS OF COMPUTER INTEGRATED MANUFACTURING

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THE SECOND IIASA ANNUAL WORKSHOP ON COMPUTER INTEGRATED MANUFACTURING: FUTURE TRENDS AND IMPACTS

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and

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FOREWORD

The Annual Workshop of the IIASA-Project on Computer Integrated Manufacturing (CIM) was held in Stuttgart, FRG, from 18-20 July, 1988. This was the second in the series of annual meetings after the Ivalo (Finland) workshop in 1987. The co-host of the workshop in Stuttgart was Professor H.-J. Warnecke of the Fraunhofer Institute of Production Technology and Automation. It was co-sponsored by Carnegie-Mellon University, USA, and the Japanese Committee for IIASA. The aim of the workshop was to analyze technological trends, diffusion patterns, and economic and social impacts of CIM as well as to review the work accomplished by IIASA and its collaborators.

The workshop was attended by 52 participants from 18 countries and 3 international organizations (OECD, ECE, UNIDO). A total of 24 presentations were delivered, including 3 keynote presentations by Prof. Warnecke (FRG), Dr. Kozar (CSSR), and Prof. Jaikumar (USA).

Prior to the Stuttgart Workshop, the CIM Project had a small expert meeting in Prague, CSSR, co-hosted by the Research Institute for Mechanical Engineering and Production Economy (VUSTE) and the Central Research Institute for Technological and Economic Information (UVTEI) of the CSSR. This meeting was devoted to technological trends in CIM and to forecasting future applications of CIM technologies. It was supported by a Delphi-style questionnaire, which was answered by 14 experts from 9 countries. The results of the Prague workshop and the Delphi study are reflected in some papers presented in Stuttgart by IIASA.

This volume combines the Proceedings of the two workshops, presenting the key papers of each of them. The papers are organized in the following way:

Part 1 consists of the three keynote papers presented at the Stuttgart workshop.

Part 2 consists of papers which describe technological and basic economic factors of CIM applications and diffusion.

Part 3 deals with the diffusion trends, employment and other macroeconomic impacts of CIM technologies.

Finally, the fourth part addresses managerial and organizational impacts of CIM technologies.

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Technology, Economy, Society	Computer Integrated Manufacturing

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KEYNOTE PAPERS OF THE SECOND ANNUAL WORKSHOP

Integration of information and material flow in a pilot plant - development and experiences

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Project aims

The integration of information technology into industrial development and manufacturing is a worldwide phenomenon, the technical and economic effects of which are of great importance for the continued development and competitivity of production technology in Germany. Work is underway in this area in all corners of the globe. Functional hardware and software components with integrated production facilities are already available, improved hardware and software (databases, networks) allow existing separate solutions to be linked together. The result is,

- a shorter reaction time to changes in the product, equipment and customer requirements
- a higher degree of complexity in production without the partly artificial and time consuming division into production stages caused by the limited scheduling capabilities prevailing at present
- a more efficient use of the machines through better planning and supervision, manufacture with reduced numbers of personnel and ingenious maintenance concepts, and, consequently, reduced production costs.

CIM is, however, not an organizational and technological advance which can be achieved overnight. Once initial developments have been completed they must be integrated and partly updated. For a successful CIM installation, therefore, a modular concept, specific to the firm in question must be developed. This individuality must apply to the functional modules themselves as much as to the problem solving within the modules. Slogans such as "You can't buy CIM off the peg", "CIM is a concept - not a program" contribute to a large degree to the existing confusion. Only one thing is certain: as the expense of introducing CIM is not related to the number of employees in a firm, generally speaking only large firms can afford such an organizational project. The continued existence of small and medium-sized firms is, therefore, very much in danger:

- Thanks to CIM, large firms are now in a position to become more flexible than smaller firms, in so far as concerns both the fulfillment of deadlines and product specifications of the client, and the use of the capital invested. Thus the essential competitive advantage of medium-sized firms is lost.

- As quantitive growth is possible only within certain limits, large firms - in order to even out the effects of rationalisation on the workforce - are expanding production not to each production centre/factory but throughout the whole firm. Suppliers are therefore finding fewer and fewer product niches.

The future assurance of medium-sized firms can therefore likewise only succeed with the help of CIM : their motto must be - better, cheaper, faster and still more flexible than large firms. There is no alternative. To "carry on as we always have" is out of the question. In other words: only when medium-sized firms have been made receptive to the CIM philosophy and when meaningful solutions have been developed and adapted to their specific applications, will this new technology provide a wider circle of firms with equal opportunities for the future with positive socio-political consequences. Otherwise CIM may be the instrument of the creation of a disastrous monopolization of the whole potential of manufacturing technology.

Small and medium-sized firms obtain their advice/information almost exclusively from computer manufacturers and software houses. Thus, the user is unable to obtain any independent advice: computer manufacturers have no company-specific solutions to offer, only computer-specific concepts, which must be "company-neutral". If CIM has to be integrated into different work places with operation-specific equipment, then the firms, wishing to introduce CIM gradually, must have available to them extensive expertise in the field. Moreover, a lot of demonstration and training is required. At the moment, however, the people affected in the various operational areas are still not properly prepared for this technology. They are often neither able to develop solutions for computer integrated manufacture in their product area, nor capable of operating the necessary CIM components. For potential CIM users - above all the small and medium-sized firms - it is therefore extremely important to witness practical and concrete demonstrations of the problems, advantages and possible solutions, and to obtain objective problem, technology and branch specific assessments of solutions, in order to be able to help in the corporate decision-making process.

The aim of the "Fabrik-2000" CIM demonstration (Factory 2000) by the Fraunhofer-Institute for Manufacturing Engineering and Automation (IPA) is, therefore, to demonstrate practical and concrete solutions of computer integrated manufacture and its advantages especially for the potential users in medium-sized firms, in order to enable the introduction and application of computer integrated manufacturing. On the basis of a demonstration manufacturing plant with a continuous production process, CIM demonstrations, seminars and training programmes and conversion support are to be carried out. With the help of the installed and deliberately heterogeneous manufacturing and computer systems, various solutions for closed CIM chains, from the design through manufacture and assembly up to quality assurance must be implemented, in order to enable a general representation of the individual subareas of 'computer integrated manufacture'.

The target groups are all categories of persons involved in the area of computer integrated manufacture:

- Managers must be offered a gradual conceptual knowledge of the installation: What is the form of the firm-specific and problem-adapted CIM solution and how can this be most economically transcribed?
- CIM users must be trained in problem solving systematics and in the use of new hardware and software components, programming languages, data base languages etc.
- Technology consultants must be provided with an objective updating of their knowledge.
- CIM trainers must deal in greater depth with special problems in training and qualification, and if need be discuss them together.
- Building on what they know, students must provided with a comprehensive understanding of the problem: in what overall context is the selective existing detailed knowledge to be placed?

Based on this concept, this initiative represents no threat to commercial consultancy firms: Here for the first time a complete field of technology is to be put into operation. The operation-specific advice, which is connected with the training/instruction, is only made possible or experienced by the initial kindling of enthusiasm. "Fabrik 2000" is also supported by the BMFT in its national initiative "CIM-Technology-Transfer-Centres".

If one considers the main emphasis of the tasks to be the transfer of CIM expertise, the organization of seminars for training and further education, the organization of CIM demonstrations and information events, the CIM advice and testing of general CIM solutions or subsystems, then the following positive results are to be expected from "Fabrik 2000":

- transfer of knowledge research - industry and vice versa
- the support above all of medium-sized firms with advice on organization, structure adaptation, effects on the workplace, qualification requirements etc...
- synergy effects via well-balanced procedures
- synergy effects via purposeful information exchange between user - research - producer - company consultant
- positive feedback from industrial practice to student training.

Product and system layout

The "Fabrik 2000" CIM demonstration will show combined extracts from the areas of mechanical production and electronic production. Fig. 1 (F2000) shows the manufacturing procedure. Over the longer term the most important aim is the integration of new modules and the flexibilization of existing components. In this process, the knowledge and the possibilities of the individual areas of the institute will be increasingly made use of.

The finished product from this procedure is a pyramid, consisting of an aluminium base, an electronic module, divided into two printed-circuit boards and a transparent die-cast apex (see Fig. 2 F2000). Both the aluminium base and the mounting of the printed-circuit boards are to be chosen individually: the base can be chosen from several basic models , for the electronic module the colours and lighting sequence of the LED modules have to be redefined for each case.

Fig. 3 illustrates the present layout of the "Fabrik 2000" CIM
demonstration.

"Machining centre" cell consisting of

- a BZ 20 4 axis machining centre by Steinel
- a WABCO-HITACHI robot for automatic loading of workpieces and for the changing of the fixtures
- a central area for the presetting of the tool
- a central commissioning area for workpiece pallets and fixtures
- a SIEMENS SICOMP WS 20 cell computer with FMC cell control software.

For reasons of cost, the fitting out of the machining centre with pallet changers, a circulating storage and a central clamping and setting-up place is at present not possible. In order, nevertheless, to fulfill the future requirements of low-labour manufacture, hydraulic fixtures for the clamping of workpieces and an industrial robot for the handling of workpieces are to be installed, appropriate to the range of workpieces to be machined.

The transport tasks between the central workpiece presetting place, inventory and machining centre are carried out by the FTS (IPAMAR).

"Commissioning station" cell, consisting of
- a Dürr P 100 portal robot
- a COMPAQ 386 cell computer
- a transfer point for the FTS
- a special control software.

The commissioning station automatically assembles the components of the electronic module, arranged in the magazine, for manufacturing or transport lots. In the commissioning station the components of the electronic modules are stored by type in flat or upright magazines.

"Assembly station", consisting of
- a HAUSER portal robot
- an ADEPT TECHNOLOGY adept one assembly robot
- a gray-scale vision system
- a transfer point for the FTS
- a HEWLETT PACKARD Vectra cell computer
- a special control software.

The usually costly re-equipping of industrial robots for new assembly cycles means that the production of very small lots and batches of workpieces is uneconomical. For "Fabrik 2000", therefore, an assembly cell with two industrial robots was developed, so as to allow the complete automation of the re-equipping procedure:

The portal robot lifts the transport pallets with the printed-circuit boards and component magazines from the FTS and places them onto a free pallet. After the gripper has been changed, the portal robot takes the magazine from the transport pallet and positions it in the work space of the assembly robot (adept one) or on the buffer points in the cell. The work space of the adept one is divided into two areas of 180 degrees each. While the adept one is carrying out mounting or soldering operations on one side of its work space, the portal robot is re-equipping the other side of the work space for the module of the next printed-circuit board (cf. Fig. 5 F2000).

The image recognition system installed is used consistently in order to arrange the grippers and the peripherals as simply and universally as possible. The image recognition system works exclusively parallel to the robot process and has thus no negative influence on the cycle time, on the contrary, it reduces the cycle time by correcting the jointing position of components with tolerance faults :

In order to recognize the position and the orientation of the parts, the portal robot exchanges the gripper for a camera and is thus able to recognize the parts position and orientation on the flat magazines from any point in the work space using the vision system. The adept one takes the components from the flat magazines and measures the position of the terminal wires using the vision system. As a camera is brought parallel to the gripper by the robot, this can be carried out during the movement from the pick-up point to the assembly point. The vision system calculates the correction value for the jointing process parallel to the robot movement. If the arrangement of the terminal wires of the component is outside the tolerance for the contact spacing of the printed-circuit board, the component is tilted in the gripper, the terminal wires are sequentially assembled in the printed-circuit board and at the same time straightened.

The robot controls contain no type-specific or variant-specific programs. The cell computer, which directly coordinates the axis control of the portal robot, processes the robot used for the handling of the pallets, magazines, and printed-circuit boards in accordance with an optimization program. The program guarantees the shortest possible path for the adept one between the pick-up points of the magazines and the assembly position.

The assembly robot works with a specific program module. This module entails
- taking the part from the pick-up point
- optically measuring the part
- assembling the part in the assembly position using the correction data.

For each individual product to be mounted, the program is generated by reproduction of the program module. For the processing of a program module the control contains the following data:
- the pick-up point for the magazines from the cell computer, in addition the relative coordinates of the parts on the magazine via the image recognition
- the parts data from the master computer or from the CAD system
- the assembly position from the CAD system via the master computer
- the jointing correction data during the execution of the program through the parallel image processing.

The program is generated parallel to the assembly of the previous product, so that it is available without any loss of time. The soldering program is generated from the jointing points and the component data (contact spacing, number of terminal wires).

The assembly cell thus offers the following advantages, in comparison with conventional separate solutions:
- economical assembly automation of the smallest number of pieces through automatic set-up without cycle time loss
- non-exact positioning preparation and jointing of tolerance faulty components without any loss of time as a result of the installation of image recognition
- complete assembly of even smaller numbers of pieces
- immediate automatic assembly of completely new products without programming
- avoidance of cell down-times
- shortest cycle times through path optimization.

"Transport" cell, consisting of
- the autonomous vehicle IPAMAR
- a cell computer
- the planning and control system.

The production process of the future requires a transport system, which reacts flexibly, even to unforeseen events such as the failure of a cell or blocked travel paths. The present transport systems are not suitable for this task, as true flexibility via rigid connecting paths (fixed control wires) and limited planning possibilities. With the IPAMAR autonomous vehicle, a transport system

was developed by IPA, which offers a high degree of flexibility:
- graphic design of the travel paths in a planning system
- no fixed layout
- guidance of the vehicle without the need for guide wires, and thus coverage of various production areas as well as office spaces
- flexible response to interruptions in the production proces
- intelligent circumvention of obstacles.

The layout planning system enables the user to input the travel path in graphic form. The basic representation contains the highly simplified hall layout with production cells, load transfer stations and the travel path. A simulation system tests the movements of the vehicle and uncovers mistakes using fictitious travel tasks. By the means of a simple operation, adaptation to a modified layout is quick and problem-free.

The central task of the transport system arrangement is the management of travel tasks, and coordinating the generation of travel programs. Tasks can be received from the manufacturing master computer at any time and, when required, processed. Should the need arise, the transport unit can be completely independent from the manufacturing master computer, thanks to an additional manual input possibility of travel tasks in the arrangement of the transport system itself. With the help of a preset travel task, an optimal path can be planned, based on the travel path layout. This action brings into play certain techniques of graph theory, the optimizing criteria of which can be selectively defined.

The interface to the vehicle represents the travel program which is automatically generated by the transport computer, transmitted via infra-red wireless data transfer to the vehicle and there executed autonomously. The travel records form the core of the travel program, and define the movements of the vehicle. In addition to these, support point measurements, sensor controls and docking procedures are individually preplanned and integrated into the travel program. The SOFT-WIRE guiding system does not need any special guidelines, marks or send facilities in the environment in order to define the position.
- A rough position definition liable to drift errors, results through the upward integration of the path travelled via the path and angle sensors.
- At regularly spaced-out predefined places in the hall there is a support point measurement using ultra-sound sensors for drift compensation.
- For the fine positioning when approaching the load transfer station, an opto-electronic sensor is installed, which determines the position error during the approach procedure.
- Through the knowledge of the side misalignment the position accuracy can be still further increased via a servo-telescopic control of the load transfer module.

Communication

Evolved company structures lead to heterogeneous EDP concepts, which, based on the function-orientated DP solutions for individual subareas, make overall integration difficult from both the hardware and the software point of view. It is necessary to enable computers from different manufacturers to communicate with each other. Therefore, either a standardized communication system or a case-specific solution for the communications problems which arise has to be worked out. Both methods are used at present. On the one hand, for example, General Motors have been working since 1980 in collaboration with a number of users and manufacturers on the definition of a standard for manufacturing communication (MAP), on the other hand there are on the market a number of communications products for the most variegated communications tasks. As the standardization of MAP has still not been fully attained and cost-effective MAP communications products therefore are still not available, each user has to work out a concept which fulfills his own communications tasks, without creating problems for a subsequent transfer to a future standard product.

These considerations are the starting point for the definition of the communication system in "Fabrik 2000". Based on a heterogeneous hardware structure (mini computer, personal computer, process computer, etc...), such as is normally found in manufacturing companies, a system architecture for the communications was created, which, starting from a wideband backbone, integrates various subnetworks with regard to their access method (ETHERNET, TOKEN BUS), their transfer method (wideband, baseband) and the network software used (NOVELL-PC-Netz, DECNET), and enables the subsequent installation of communications products with the MAP standard (cf. Fig. 7). Components from ALLEN BRADLEY are used as the wideband backbone (cf. Fig. 8). The following network products are used in parallel on this backbone:

- VISTA-LAN (Allen Bradley)
- DECNET (Digital Equipment)
- NOVELL-PC-Netz (Novell).

VISTA-LAN is a network based on the TOKEN BUS principle. Via appropriate interface facilities (NIU - Network Interface Unit) the asynchronous transmission between different serial V24 interfaces is achieved. In addition the possibility exists of starting a virtual connection on individual V24 pins inside the VISTA-LAN, via the TOKEN BUS controllers (Allen Bradley) installed in the personal computer.

DECNET, a network based on the CSMA/CD principle, enables a transparent connection between different DEC computers and supports all levels of the ISO/OSI model. The coupling of the ETHERNET baseband system installed on the backbone is achieved in accordance with the basic communications task in three ways:

- **Transparent DECNET/DECNET connection via backbone**
  The DECNET protocol is modulated via an ETHERNET modem (MICOM) directly to a free channel of the wideband system, and can be retransmitted to each terminal connection point of the backbone via a further ETHERNET modem in the baseband area, and made accessible to an application.

- **Connection of the PC network DECNETDOS/NOVELL**
  Via an ETHERNET controller (MICOM) a PC can be coupled directly to the baseband ETHERNET. Through the use of the DECNETDOS software (DIGITAL) the linking of the PC as a node in an existing DECNET network is possible. At the same time the PC can communicate via a TOKEN BUS controller (Allen Bradley) with the wideband backbone. NOVELL-PC-Netz is used as the network software. The coupling of both network software products to a gateway function of the PC takes place via a special coupling program.

- **Connection of virtual DECNET terminals with VISTA-LAN.**
  The virtual DECNET terminals are connected from the baseband ETHERNET to V24 terminals via a terminal server (DIGITAL). The connection to the interface facilities of the VISTALAN (NIU) takes place via simple V24 jumpers.

NOVELL is a PC network, which functions in accordance with the fileserver principle: One or more PCs are installed as the central data station(s). These stations can be used as a virtual mass storage from all the work stations connected to the network. Access is achieved via virtual drive designations. The NOVELL network software is independent from the installed network hardware and the access procedure.

The communication between the manufacturing master computer (VAX 11/780) and the PC orientated cell computers of the individual manufacturing facilities takes place either
- via a V24 connection, which is transmitted from the manufacturing master computer via the baseband ETHERNET, the terminal server and the NIU in the VISTALAN and from there via a second NIU again in a V24 terminal, which is directly connected with the cell computer or via
- a file transfer based data exchange between the manufacturing master computer and the file server of the NOVELL-PC-Netz using the DECNETDOS/NOVELL gateway.

The information transmitted is available at any time to the individual cell computers using the NOVELL network software. For the communication between the manufacturing master computer (VAX 11/780) and the process computers, installed for the cell control, the baseband/wideband-ETHERNET connection is provided via the ETHERNET modem. Via this communications channel the most diverse network protocols can be transmitted transparently. For process computers of the VAX family DECNET is used, otherwise a protocol such as TCP/IP can be used.

For the subsequent introduction of a communication in accordance with the MAP standard an incidental frequency channel of the wideband is provided. Existing communications channels can then be gradually rearranged on MAP. Should the need arise, appropriate gateways must be provided for the coupling of both communications systems.

Planning and control

When trying to introduce a network and thus to reduce the cost of gathering, storing and processing information, it is also useful to be able to maintain and modify certain data stocks at any one time at a single place in the firm. One must not be tempted, to make planning and control systems too susceptible to errors and faults: a fault in one area must not affect operations in other areas. Care must therefore be taken, to create smaller and faster control loops, which can work independently of the other areas for a certain length of time.

The manufacturing requirements planning systems (MRP) installed up until now are however, in spite of undoubted efforts at integration from the functional point of view, characterized by a planning which on the one hand provides only small leeway and on the other hand permits only limited feedback on the higher order planning level at any one time. A uniformly dense state of information cannot, therefore, be achieved exclusively through information technology integration throughout the firm alone. What is also needed is a functional universality up to the process level and a constant relevancy of data on all corporate levels. Only when the horizontal and vertical information technology integration is supported via programs, when the routine work is taken on or at least lightened, can an employee intervene in the control process of the whole firm.

Expressed simply: each hierarchy of the firm needs its own programs, files and computers, which must of course be integrated with hardware and requirements in an overall concept. These programs must also bear the increased work content in an integrated production system calculation. So, for example, the manufacturing requirements planning systems have up until now, been subdivided into material requirement and a connected capacity planning, which are looked after by.completely different and often spatially separated employees. This separation of the requirement and the capacity aspects leads to planning results, which, with regard to their quality for integrated production systems, are unacceptable. Far shorter process times and smaller supplies can be achieved without danger to the readiness to deliver, through simultaneous consideration of requirement, capacity and transport. The advantage of this way of looking at things is that, process specifications are already created on the higher corporate/planning levels, which need only be further refined, not basically rearranged, at the subsequent levels.

A further example of this modified work content is workshop control: the manufacturing tasks generated by the production planning must be periodically transferred to a manufacturing master computer. There ensues with the help of detailed parts lists and detailed work plans, a solution of the production tasks in a succession of detailed activities and the assignment of all auxiliary devices needed for the activities. The complete detailed task thus created must, in the context of fine planning, be allocated to a resource and the capacity allowed for. At the same time the availability of all resources needed for the implementation is to be guaranteed at the outset. Therefore even for this resource a plan and a time schedule are to be made.

The requirement for independent control loops gives rise once more to the idea of a (decentral) EDP supported control station. An example is the concept of EDP supported control stations for short term manufacturing control. Accordingly the planning and control concept for "Fabrik 2000" was designed as a multi-stage control station concept. Fig. 9 illustrates this hierarchy.

The activities of the planning level can be outlined as follows:
- allocation of approved tasks to individual resources/transport equipment
- instigation of production
- supervision of the completion of the task as regards quantity, time limit, costs and quality with the help of reported operational data
- intervention in the event of deviations from the planned task completion.

The control level executes the following steps:-
- transfer of the approved job program
- extension of the tasks by transport tasks and auxiliary device preparation tasks
- job release
- job instigation.

On the control level there ensues
- NC program distribution
- NC data management

- material flow control
- production data evaluation.

The executive level comprises
- the on-line control of the individual cells
- the relaying of information to the process
- the reporting of the actual production.

Planning level: GRIPPS (graphic supported integrated manufacturing requirements planning system).

Against the background of "Fabrik 2000" the "GRIPPS" system was developed for the planning. The innovative character of this system results from the introduction of the multi-stage simultaneous planning, which enables an optimized stock with considerably reduced cycle times. Essential characteristics of simultaneous planning are for example:
- derivation of secondary requirements and thus the preparation of the material flow objects needed from capacitively matched manufacturing tasks
- definition of the manufacturing tasks with the help of a simultaneous consideration of quantities and time limits (stocks, requirements) and capacities (capacity offer/competition)
- daily update of the planning specifications.

A requirement of simultaneous planning is the construction of a specific planning structure. This connects the (in conventional systems separated) product or planning structure (parts lists) with the capacity or material flow structure (work plans) in graphic representation arranged according to capacitive and scheduling viewpoints (Fig. 10). At the same time, material flow objects, which compete for the limited available capacity of a capacity unit, are grouped together in a capacity group.

An essential consideration for a high-capacity MRP system is the job-specific preparation of all necessary information. In order to guarantee a data organization without data redundancy, GRIPPS was implemented on the basis of the present relational database ORACLE with SQL standard and in C. This system works via a user-friendly interface, which enables the generation, display and modification of data via specific screen masks.

Control level: ATEXI (Job scheduling in automated, flexible manufacturing systems).

ATEXI is a dialogue orientated program system, which satisfies the difference between the operational manufacturing requirements planning and the operative control of the automated manufacturing process. ATEXI consists of the two subfunctions system task generation and operation times.

In system task generation first an availability check is carried out for the preset manufacturing tasks with regard to the required
- raw material or semi-finished positions
- manufacturing aids and
- NC programs.

For the raw material or semi-finished positions a reservation is carried out. Subsequently the manufacturing tasks with positive availability are split into so-called system tasks. System tasks represent the generated subsets of the manufacturing tasks in accordance with manufacturing or transport lots. They form essential input information concerning the operation times.

The operation times carry out the time-slot and place assignments of the operations on the work stations for the approved system tasks. This takes place periodically in normal operation (e.g. daily). In the event of failure, a new requirement orientated schedule can be initiated. The load sequence of the system tasks is established with the help of priorities, which are calculated either externally preset (e.g. from authorized representatives) or by means of priority rules.

The sequence planning and machine assignment is carried out simultaneously, taking into account the actual capacity situation of the work stations, the workpiece carriers, the production aids, and the means of transport. During the scheduling of the tasks to be planned, that one will be chosen, from amongst the machining stations, which displays the least idle time. In this way a high utilization of the system is ensured.

Before, however, an operation is definitively planned, it is checked to see if the necessary production aids are available in the requirement period. If they are free, but not in the place required, a transport task is generated. In assembly tasks, in the context of the time limits, the preparation of the assembly components must be initiated. To that belongs both the removal and the combination of the component requirement relating to the task and the transport of the parts to the assembly station.

Task scheduling results in detailed tasks. Detailed (system) tasks are fixed in time and place, taking into consideration the actual
situation as regards capacity, for the implementation of machining, assembly, measurement, commissioning and transport procedures.

Control systems: PROPOSS (event orientated control of highly automated production plant) The event orientated production process-control system PROPOSS was developed for the information and control technology integration of overall subsystems in highly automated manufacture. PROPOSS is an integrative component of a workplace control system and fills the generally existing gaps on the executive level.

PROPOSS uses as input values system tasks which are generated on the control level. PROPOSS works with an event orientated process model, which undertakes the initialization of the real-time process control of the transport, inventory, assembly or machining processes based on the machining cycle time of the system tasks. In accordance with the degree of automation of the system to be controlled there takes place a further subdivision of a process into activities to be initiated separately (e.g. install FTS 123 into block path 27, transfer part xyz to the transfer point of machine A).

PROPOSS generates a generalized process operational sequence description from the preset system tasks by event graphs, the nodes of which can be either detailed tasks or individual activities, according to the degree of automation of the system to be controlled. The respective sequence nodes are determined with the help of a graduated decision process, taking into account the actual process state and preset process conditions (e.g. activity a must be terminated before the beginning of activity b).

PROPOSS works with a production process image. The allocation of all machines, buffer space, means of transport, and storage facilities for workpieces and production aids is known at each point in time.

PROPOSS checks the implementability of planned detailed tasks, as also the individual activities to be carried out inside a detailed task on the basis of the actual manufacturing situation.

PROPOSS contains modules for fault classification and automatic fault treatment. According to the type of fault, either alternative strategies can be initiated, or an error message is given at the next highest planning level.

Experiences

Inevitably the benefits of the implementation of "Fabrik 2000" have up until now accrued mainly to IPA itself. The aims of "Fabrik 2000" would be unsuccessful, however, if "Fabrik 2000" was seen and used merely as a means to an end, as a playground for the acquisition of proficiency. Therefore, "Fabrik 2000" was understood right from the beginning to be a pilot project for a CIM application. Development inside the company follows as for a customer project.

The experiences so far can be summarized in the two main areas of
material flow/information flow and project organisation/people.

Material flow/Information flow

- Provide a reliable universal overall concept, which is carried out without modification step by step (Material flow: geometry, speed, throughput; Information flow: data content/format, hardware)
- Keep an eye on all interfaces - there is always a part of the interfaces to be dealt with personally.
- Guarantee manufacturer independence through open architectures.
- Physically check which components show performance capacity and compatibility (black box),
- promises are often unfortunately very different from the actual facts.

Project Organisation/People

- Include all colleagues early on, CIM solutions depend on the detailed knowledge of colleagues at all levels.
- The coordination of the interfaces is the task of the project management. The implementation of the individual cells as 'black boxes' is the responsibility of the project partners.
- Entrust the responsibility for the CIM project management to the higher echelons (executive board, higher management) and tighten up the project organization, otherwise area optimization and thoughts of competition reduce success.

Outlook

The next steps to realization affect the completion of ordering and final assembly cells and the customer specific definition of the products via a CAD system. In the ordering cell the 'grip in the box' should be put into effect at the same time. In the middle term there is the connection between varnishing and quality assurance.

But in order to avoid the creation of a museum, "Fabrik 2000" will
also in the future be subject to strict considerations of return on investment. Each investment must be justified in the context of the overall aims of the institute. At least in the medium term a significant contribution margin must be provided via the training to be made available.

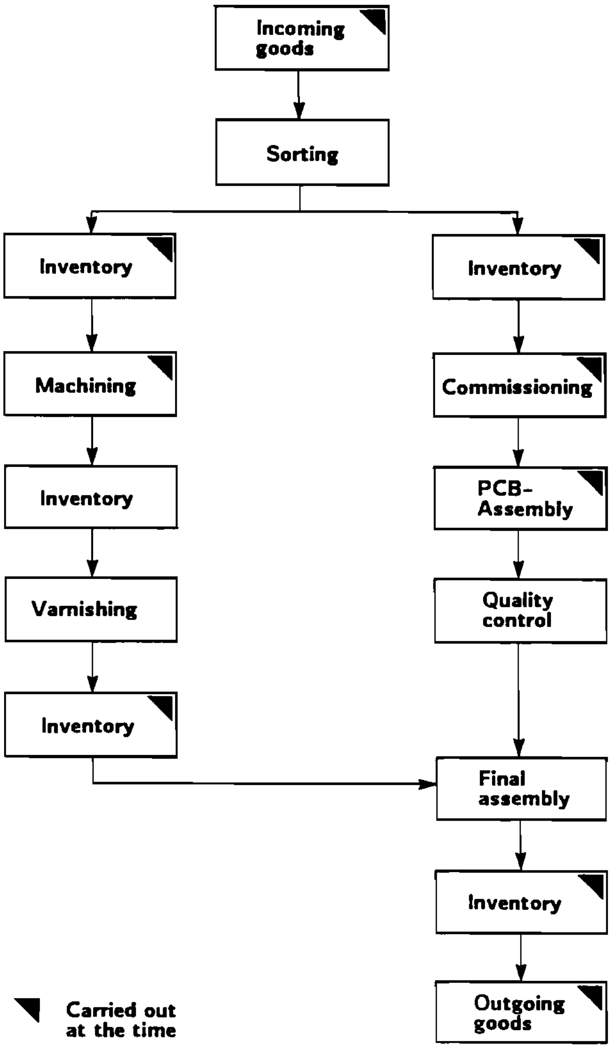


Fig. 1 Manufacturing Sequence

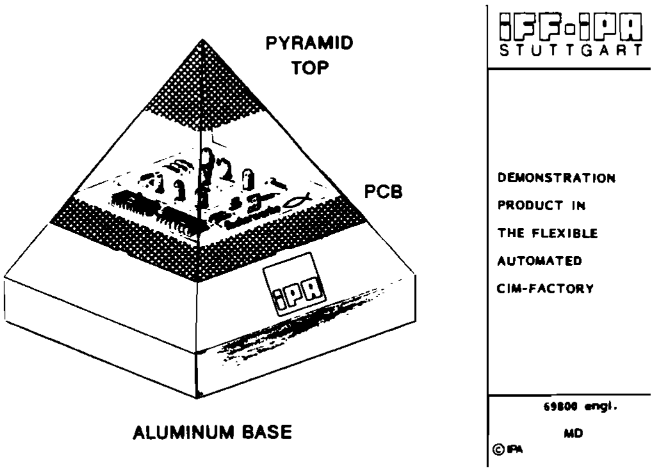


Fig. 2. Finished Product

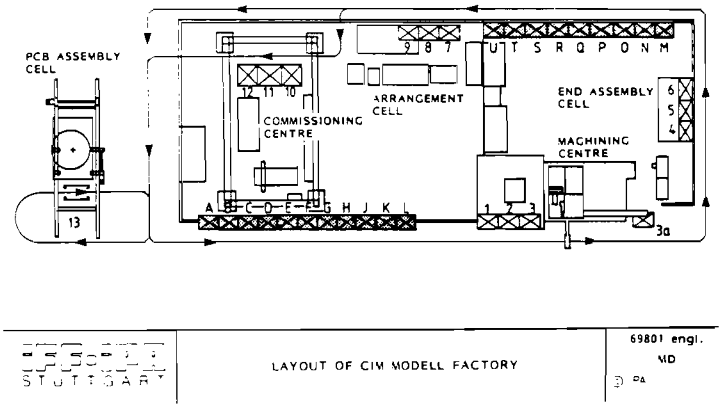


Fig. 3. Layout

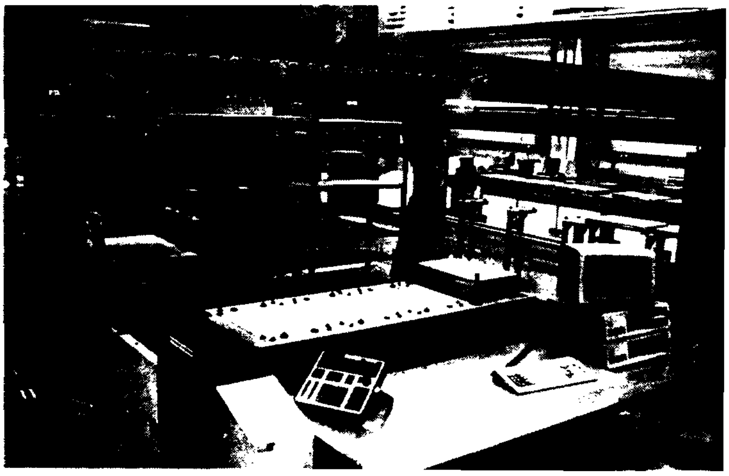


Fig. 4. Commissioning Station

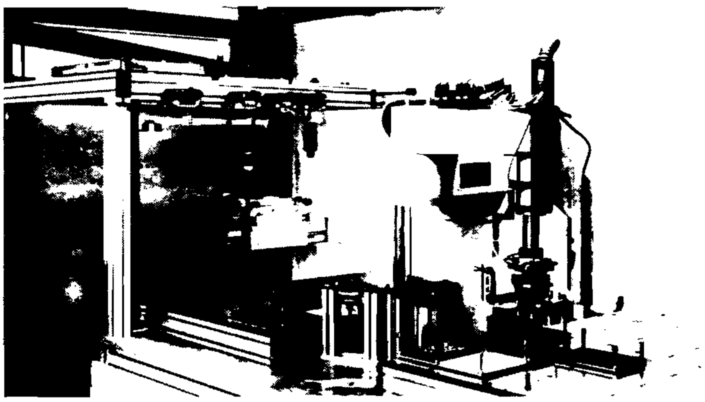


Fig. 5. Assembly station

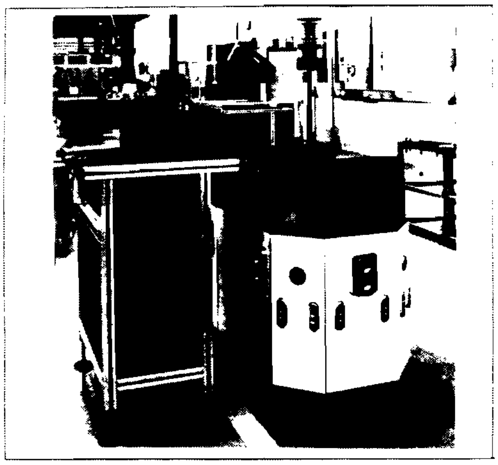


Fig. 6. IPAMAR

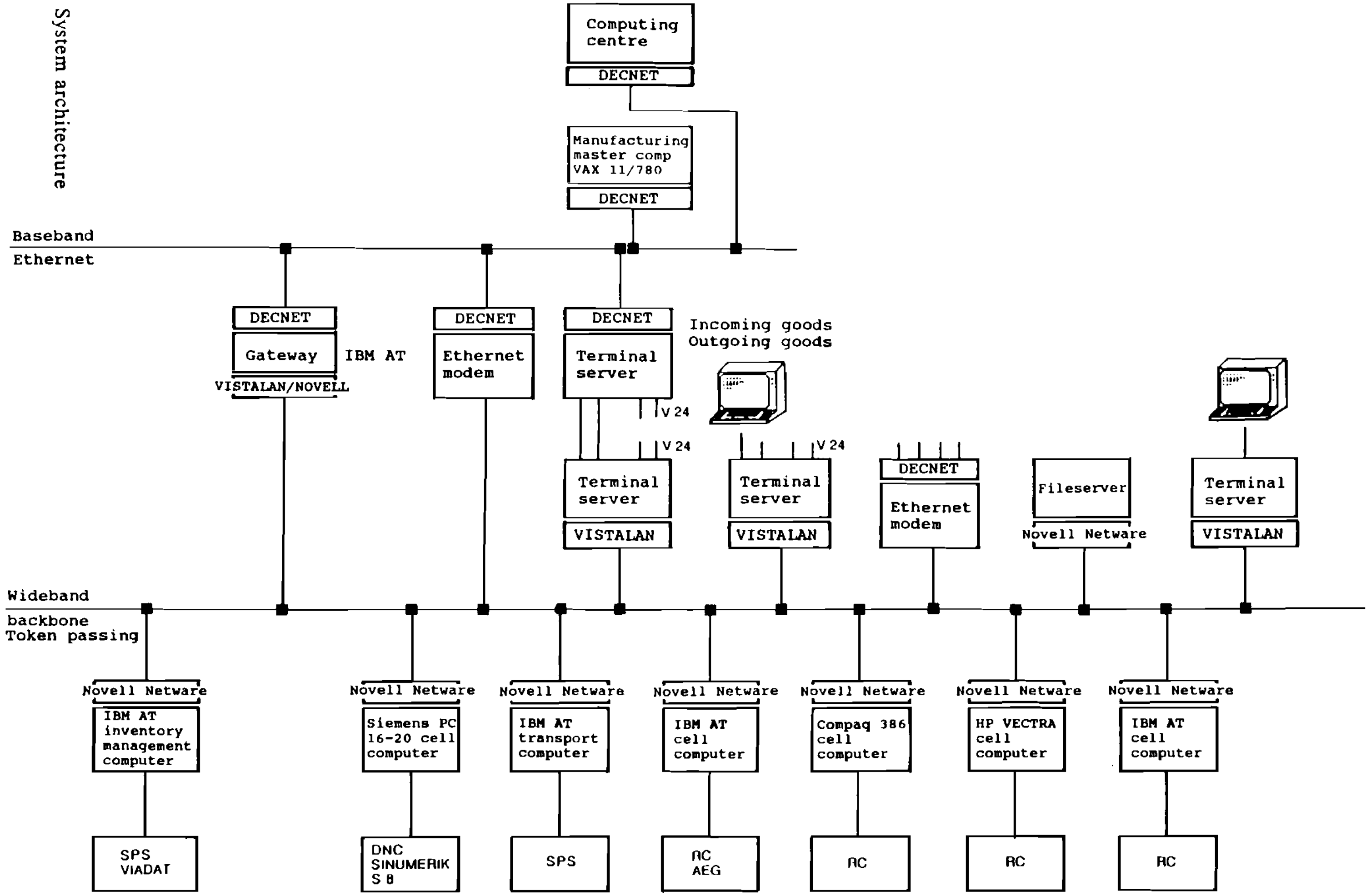


Fig. 7. System architecture

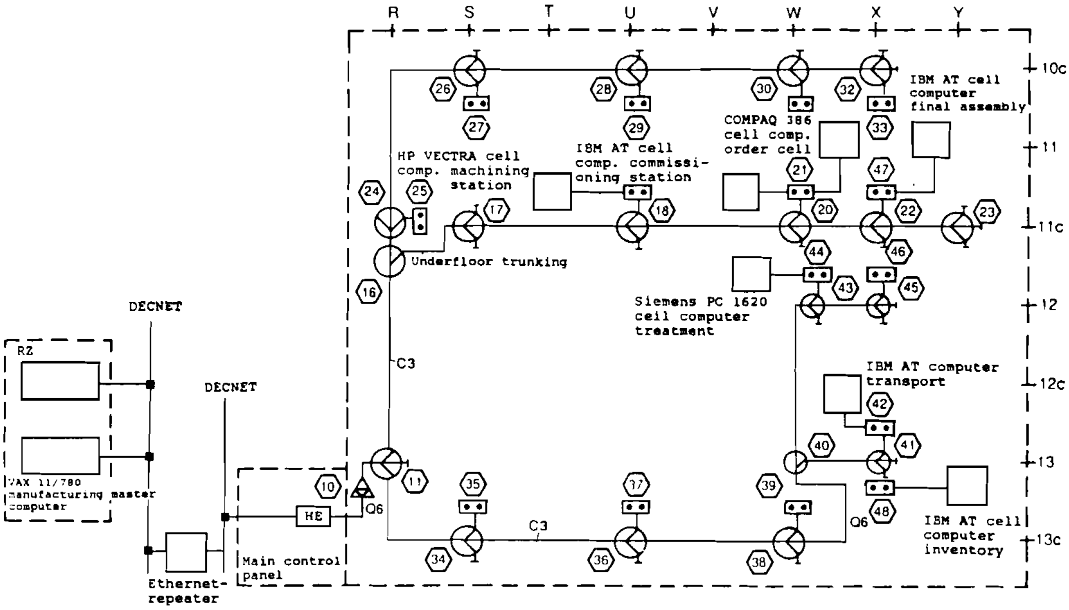
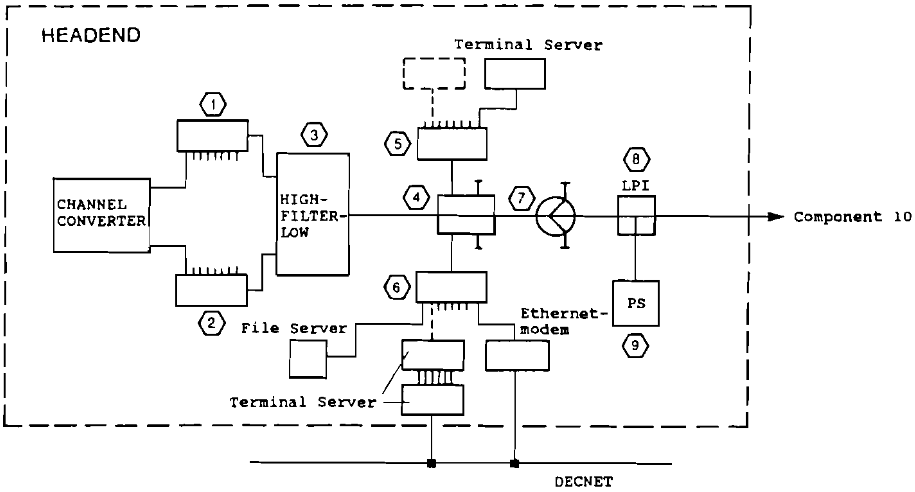


Fig. 8. Wideband data network



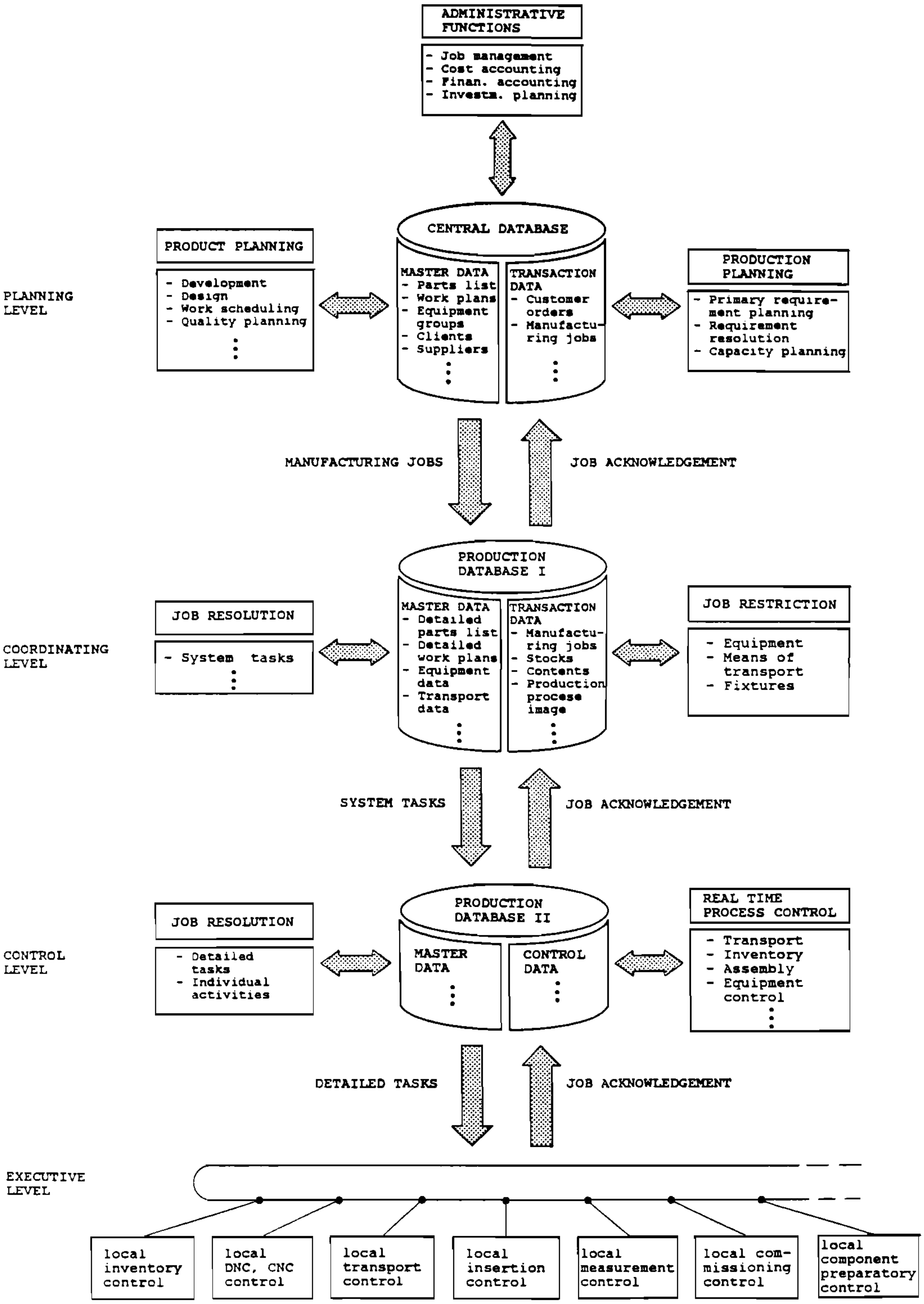


Fig. 9. Planning and control hierarchy

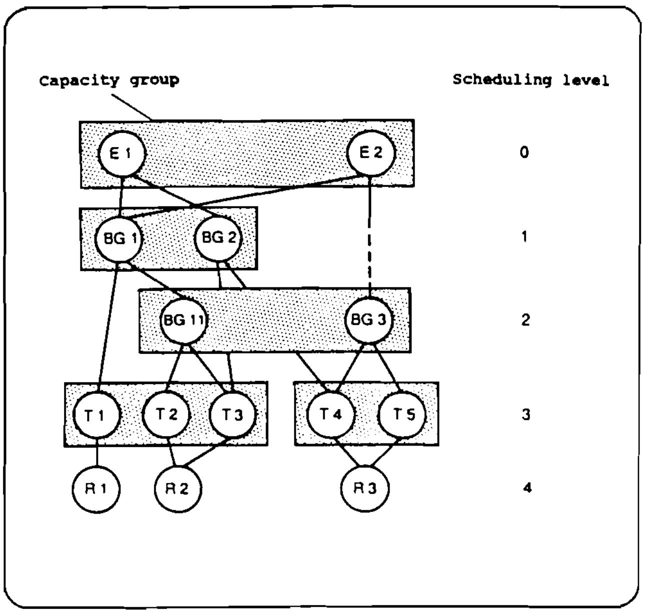


Fig. 10. Specific planning structure GRIPPS

IIASA CIM WORKSHOP, 1988, Stuttgart

TRENDS AND IMPACTS OF CIM IN PLANNED ECONOMIES

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The very basic approach to flexible automated manufacturing is the same in planned economies as in market oriented economies. The basic objectives of flexible automation and CIM are also identical: product and process flexibility,a substantial increase of productivity, insurance of standard quality, energy and material savings, reduced labour intensity, etc.. Another factor that is becoming more and more important is integration. Developmental stages and trends that will be discussed later in the paper are also identical.

On the other hand there are definite differences that can be identified in the following areas:

- conditions existing prior to the introduction of flexible automation
- evaluation of economic effects
- forms of indispensable international cooperation
- enhancement of the role and function of the human factor /long term education and development, including retraining/
- concept of an automated plant as a synthetic result of a comprehensive application of flexible automated manufacturing.

Many of these differences, however, are due to the fact that the truly most effective ways of CIM applications are currently being sought, rather than to the existence of different principles on which the two types of economies are based.

1. PRINCIPAL ROLE OF FLEXIBLE AUTOMATION AND CIM

Highly dynamic development of science and technology will in a relatively short time, create conditions for an introduction of new technology generations into all sectors. In this context, mechanical engineering industry should accommodate the changes of its own technology and, at the same time, provide technological means for other sectors.

Within mechanical engineering industry, not only generation changes are to be expected in technology, i.e. transition from manufacturing processes based on cutting to chipless technologies and mastering of the methods of processing new materials. Our efforts will be aimed at achieving the shortest and simplest transition from the initial raw material to the final product not only from the point of view of increased productivity but also minimization of losses due to material waste, that is to the application of wasteless technologies and, thus, environmental protection.

In manufacturing processes, mechanical engineering industry is entering a period of transition from the hitherto basically mechanical manufacturing to automated and even automatic manufacturing. Thus, fundamental changes occur both in the structure of engineering plants and in individual activites. Electronics and based on it computers and control technology have opened ample room for automation. We are witnessing rapid introduction of automation into all spheres of the society's life, particularly into the operation of manufacturing.

Industrial automation represents a basic developmental trend in engineering processes and organisms. Automation surmounts not only the limits determined by man's physical abilities but also the limits of his mental activity. It makes it possible to establish the states of processes which cannot be intercepted by man's senses and to select, on this basis, optimal modes of work etc. Consequently, products which cannot be manufactured by means of mechanical equipment can be now manufactured and the required growth of output and related growth of pruductivity can be ensured. Monotonous, unskilled and routine work is eliminated, man's position becomes fundamentally different and general humanization of work occurs.

The introduction of flexible automation to discrete production has improved and increased the production capability to a much larger extent than all the other new technologies and their combinations, be it other advanced technologies, new materials and alloys, new methods of organization, etc.. Furthermore, automation of production and manufacturing processes has called for automation of production planning, for the design and development of new SW systems and data bank systems.

Application of automation to manufacturing processes has called for a comprehensive integration of all autonomous systems, organizational and economic aspects into the wholly new, system based concept, i.e. the concept of comprehensive automation of industrial production.

This capability to integrate production, including all the pre-manufacturing and post-manufacturing stages into a total, functional and automated system has marked a new development of industries, namely of engineering and electronic industries. In most European countries with planned economy CIM and automated manufacturing have been incorporated into the state policy of technological development.

National programmes of application of flexible automated manufacturing, including CIM, have been designed and are currently being implemented in all Euroean socialist countries, incl. Yugoslavia /no data is available on Romania/. All these programmes include - either in the form of subprogrammes or autonomous programmes - programmes of development of industrial robotics.

These programmes are currently being updated. Three main trends have been identified:

- an overall application of flexible manufacturing systems /FMS/ ranging from a production line to workshop and eventually the whole manufacturing section

- development and installation of CAD/CAM systems

- development of CIM and automated plants.

At the same time qualitative differences between individual developmental stages discussed in chapter 3 of this paper are currently being studied and verified.

As for the higher developmental stages, incl. CIM, the following performance factors are expected to play a major role:

- increased productivity by at least 500 - 600 %
- decreased pay-back time to 2,5 - 4 years
- increased overall operation time of automated equipment to 18-20 hours per day
- shortened time between project design and project launching /less than 24 months/
- decrease in labour intensity by 60 - 70 %
- reduced costs of material by 20 - 40 %

- reduced product development time by 50 - 75 %
- five fold increase of productivity of project designers, product designers and engineers
- reduced development costs by one half
- lead time reduction by 50 %.

2. INTERNATIONAL COOPERATION

Demands of flexible automated production and namely its integration go beyond the capabilities of individual national economies of the CMEA countries. Consequently, two important documents were signed in the 70s - an intergovernmental agreement between all member countries concerning a further development of uniform and compatible HW and SW /including peripherals/ for production and manufacturing process control and an agreement concerning cooperation in the field of automation of engineering functions. Later, in the 80s two general agreements concerning cooperation in the field of industrial robotics and FMS were signed.

Another evidence of the high priority the member countries of the CMEA attach to the development of flexible automation, is the incorporation of the programme of "Comprehensive automation" into the "Overall programme of scientific and technological progress until the year 2000" adopted by member countries in 1985. Comprehensive automation is becoming one of the major technological, but also economic and social tasks of all countries involved in the programme.

The programme of "Comprehensive automation", part 2 has been devised to speed up the development and application of flexible automation in industry and national economy. The internal structure of this international programme provides conditions for a joint, highly specialized development and production of individual components, modules and systems, incl. an automated plant.

In July this year prime ministers of the CMEA countries met in Prague to discuss new developments. At this conference it was decided that major efforts should be aimed at the so called "Comprehensive targeted projects". In the field of overall automation one such project is a design, development and operation of automated engineering and electronic plants until the year 2 000.

In this process the CMEA countries expect to make use of not only their mutual cooperation but also of an effective cooperation with other industrially advanced countries. This cooperation however, is rather limited due to a variety of restrictions and impediments. It is believed, however, that the steady trend of advances will bring this highly effective and benefitial cooperation still further.

3. DEVELOPMENT PHASES

Similarly as in other industrially advanced countries also in the CMEA countries, the early 70s witnessed a lot of research and development activities in the field of flexible automation /FMS and industrial robots/. The development attained so far can be described by the following phases:

The first phase spans over the period 1971 - 1977 and is characterised by the advent of NC machine tools, first generation of industrial robots and handling devices /manipulators/, the very first automatic logistic systems and the first generation of FMS.

Characteristic factors of the second phase /1974 - 1984/ are robotized workstations, AGV applications, automation of measuring and inspection operations, automated NC programming, second generation of FMS, robotized manufacturing systems.

In the course of the third phase the main efforts have been and are being geared to the diffusion of the CAD, CAP and CAM systems, automation of PPS, development of a hierarchical production control system, automation of assembly processes, application of flexible automation to the plant's main production. The phase originated in 1978 and will go on till the early 90s.

The fourth phase is the phase of CIM, its philosophy, its architecture and concepts, modular HW and SW, development of the third generation of FMS and the second generation of FAS, and experimental implementation of flexible automation involving the whole production plant. This phase came to being in 1982 and wil go on till the late 90 s.

The fifth phase will generate new advanced architecture of an automated production plant /APP/ by means of a comprehensive modernization of the existing plants into APPs. The new APP architecture and structure will be gradually adopted by all major industries.

over which
The time horizon/full CIM and APP should be accomplished can be put at 10 to 15 years or even more. The main factors influencing the prospect of such accomplishment are - modularity, portability, compatibility, standardization and increased production efficiency with every single partial project.

The development of flexible automation in the mechanical engineering industry is subject to the trends of complex automation characterized by both high level of standardization and high measure of integration of various components of manufacturing systems. This is a fundamental transition from the gradual improvement of production organisms and processes taking place within these organisms through partial, relatively idependent innovations of individual components towards complex innovations of higher order.

It appears so far that moral life of the lowest organisms subject to complex innovations /at the level of workshop or a manufacturing section/ is some 15 to 20 years; in the meantime, innovation of individual components of shorter service life is undertaken, e.g. 7-8 years with respect to NC machine tools.

Because of that it is very important that basic prerequisites for economically acceptable solutions are included already in preparatory works for the project of flexible automation as efficiency of the manufacturing system can be substantially influenced at the stage of system concept and design.

Any introduction of flexible automation to industrial processes must be followed by immediate integration. Properly select hardware and software provide favourable conditions for an efficient process integration. New aspects of labour division between pre-production and production functions have been identified and integrated in the CAD/CAM systems. It has become apparent, however, that a comprehensive solution of flexible manufacturing throughout the entire plant /CIM/ is a must today.

4. AUTOMATED PLANTS

The ultimate goal of any comprehensive automation is the design and a step-by-step development of an automated plant. It is a sort of a climax, a synthesis of all the concentrated and long-term efforts. The scientific and technological goal of all the work involved in the development of an automated plant consists in a stepwise automation of all the essential functions and their simultaneous integration with respect to both the material and information flows.

The automated plant of the 90s will have both highly automated even automatic units and sections, as well as less automated processes and areas.

The 90s will witness a further transition from the rather low level of flexible automation to an advanced level and new needs of integration arising from the implementation of CA - technologies, i.e. CAD, CAP, CAM, CAQ, CAI, CA - production planning and management. CIM itself will represent a qualitatively new step.

In most cases an automated factory will be a result of a modernization process starting at the workshop level and proceeding upwards. The aim of such a process will be a truly harmonious development of all plant functions and a reduction of labour intensity.

Every comprehensive automation process will always be ca out as a dynamically developing process within a dynamically developing manufacturing environment.

5. GENERAL FINDINGS

Our practical experience with various forms of flexible automation over the last twenty years has yielded the following findings:

- changes in production due to new
  - technology
  - technical means
  - organisation
  - process control
  - management
  - professions
- existence of activities common to manufacturing processes within the context of growing automation and robotization
- automation applied to one function brings about automation of other functions

- long term production programmes assume a more significant role
- there is a growing specialisation on part of manufacturers and a definite local concentration of particular production
- complexity of flexible automation projection based on efficiency criteria
- trend towards modernizing plants /starting at shop floor level and proceeding upwards/ without discontinuing production
- modularity of both HW and SW
- emergence of new jobs and professions
- decrease in the number of employees
- step-by-step integration
- broad cooperation between industry and R and D.

6. EXPECTED TRENDS

The following is the summary of the goals and phases of CIM and APP development described in the previous chapters of this paper:

a/ dynamically growing automation of production and manufacturing systems

b/ implementation of the principle of modularity with standardized technological and information interfaces

c/ development of manufacturing systems towards CIM and APP

d/ comprehensive automation involving all automated plant functions

e/ modernization of the existing plants aimed at a systematic automation of all the main plant functions

f/ integration of all progressive manufacturing processes into the process of comprehensive automation

g/ dynamic growth of integration needs

h/ growing role of highly skilled labour

i/ need of a systematic and effective international cooperation.

NOTE: Major quantitative data is included in the IIASA analyses and studies presented elsewhere.

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FROM FILING AND FITTING TO FLEXIBLE MANUFACTURING: A STUDY IN THE EVOLUTION OF PROCESS CONTROL

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88-045

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INTRODUCTION

Manufacturing technology is, in essence, the technology of process control. It is machines, human labor, and the organization of work brought together in the control of a manufacturing process. While the nature of process control can be quite different in different industries, a common theme that seems to emerge from a study of process control is the evolution of manufacturing from an art to a science. Inasmuch as the long term viability and manufacturing competence of a firm is intrinsically tied to how one manages this evolution, it is important to understand the factors that drive it. The object of this paper is to attempt to arrive at such an understanding.

One finds, in the metal fabricating industry, a great variety of process control technologies being practiced at any time. For this reason, and because the industry is very large and has a long history, we have chosen it as the base from which to study evolving patterns of process control in the mosaic of machines, labor, and the organization of work. Because aggregate data at the level of the industry does not lend sufficient relief to the shifts in this picture, we have taken, as our unit of analysis, the firm.

Within the firm, we study the evolution of process control from the perspective of the work station. It is here that technology and work come together and manufacturing takes place. Because we are interested in a particular aspect of technology and work, i.e., manufacturing's shift from an art to a science, we also examine the thinking behind the ideas that have shaped process control and the cognitive components of work.

Our study focuses specifically on the segment of the metal fabricating industry engaged in the manufacture of small arms. A number of major manufacturing innovations have had their seeds in this industry--development of machine tools at the Woolwich Arsenal, interchangeability of parts at the Whitney and Colt factories, Taylorism at the Watertown Arsenal. Our purposes are abetted by the considerable scholarship devoted to the study of this industry and by the existence of a single firm, Pietro Beretta, whose history includes the assimilation of each of these manufacturing innovations.

Founded in 1492, and controlled by the same family for fourteen generations, Beretta has been engaged in the manufacture of firearms for almost five hundred years. While the product has not changed much, the processes for making a rifle have. Thus it provides as close to a controlled experimental study of the evolution of process control as one could have. Though Beretta originated none of the major metal fabricating innovations, it was quick to adopt every one of them.

To understand how the transformation in manufacturing technology has come about, we will visit the arsenals where the various innovations originated--the Woolwich Arsenal in England, and the Colt factory and Watertown Arsenal in the

United States--and the people responsible for them. What they thought about and what they did is the story of process control in the metal-working industry. It will become apparent, as the story unfolds, that process control has evolved in a succession of epochs, each characterized by a fundamental shift, or "revolution," in the organization of work and the nature of the firm. The story is told from the perspective of the individual at a machine, where process control is effected and the changes can be seen most vividly.

The six epochs we have identified are:

(1) The invention of machine tools and the English System of Manufacture (1800);

(2) Special purpose tools and interchangeability of components in the American System of Manufacture (1850);

(3) Scientific Management and the engineering of work in the Taylor System (1900);

(4) Statistical Process Control and the dynamic world;

(5) Information processing and the era of Numerical Control;

(6) Intelligent systems and Computer Integrated Manufacturing.

Our discussion is divided into eight sections, which deal respectively with the origins of the firearms industry, its progression through each of these six epochs, and our conclusions about the nature of the progress that has been made. It begins with Beretta.

The first change in the technology of manufacturing firearms came some three hundred years after Beretta started making guns. It came in the form of the English System of Manufacture, which was introduced at Beretta consequent to the Napoleonic conquest of the Venetian Republic and the establishment of a state run arms factory at Brescia.

Much of our understanding of how the nature of work changed with the introduction of the English system comes from a visit to the shop of Henry Maudslay, in the second section of the paper. Sufficient records of this founder of the machine tool industry and trainer of many an English mechanic exist to allow us to form a picture of what the workshop of the late eighteenth and early nineteenth centuries looked like.

A visit to the Colt Armory, in the third section of the paper, illuminates the next half century of progress. Elihu Root, at the Colt factory, brought to a high state of refinement a system of manufacture based on the notion of interchangeability of parts and the development and use of special purpose machinery. The "American System," as it was called, was showcased at the Crystal Palace Exhibition in 1851 and, within twenty years, had been adopted, in whole or in part, by most of the armories in Europe. Beretta adopted the entire system, contracting with the American firm Pratt and Whitney to build a complete factory in Gardone.

In section four, we deal with the Taylor System, which had profound implications not only for the firearms industry, but for all of manufacturing. To explain the changes brought about in the workplace by this system, we turn to Hugh Aitken's detailed explication of the introduction of the Taylor System at the Watertown Arsenal.

Company records for Beretta are sketchy for this period. We know that following the First World War, Pietro Beretta completely renovated the factory, introduced machinery compatible with the innovation of high-speed tool steel, and incorporated the principles of scientific management as enunciated by Fayol and Taylor. We know little about how Taylorism was adopted by Beretta; indeed, beyond such aggregate statistics as the plant's expansion to three times its size and its realization of a tenfold increase in productivity over a period of fifteen years, we know little of Beretta's progress during the Taylor era.

The next three sections deal with the postwar epochs--the Dynamic World, the Numerical Control era, and the dawning of the age of Computer Integrated Manufacturing. As Beretta was by this time a leader in the technology of arms manufacture, the discussions of these epochs focus specifically on the Beretta factory.

Together, these latter epochs constitute a fundamental shift in the paradigm of production--from a world view of managing material processing to one of managing intelligence. It is to this shift, which heralds a radical departure in the way we conceive of manufacturing and holds many lessons for all of metal fabricating, that we wish to draw the reader's attention. While the explication of the first three epochs is interesting and establishes a perspective on the evolution of process control, it is in promoting an understanding of the nature and impact of the latter three that this paper makes its principal contribution.

There is a consistency in the circumstances of these six epochs as they were experienced by Beretta.

(1) Each epochal change represented an intellectual watershed as to how people thought about the manufacturing problem.

(2) Most of the gains in productivity, quality, and process control achieved by Beretta in its five hundred year history were realized during the assimilation of the six epochal changes and very little between them.

(3) Each epoch entailed the introduction of a new system of manufacture; the machines, the nature of work, and the organization all had to change to meet a new technological challenge.

(4) It took about ten years to assimilate the change incurred by each epoch.

(5) Every change represented the solution of a process control problem whose process variance was perceived to be highest.

(6) All of the changes were triggered by technology developed outside the firm.

It is obvious that each of the epochal changes would affect all of the metal fabricating industries, and they did. But by examining these changes at the level of the work station in a single firm concerned with the manufacture of a single product, the firearm, we can see their impact in sharpest relief and observe a consistency that suggests powerful lessons for the management of technology. Our objective in scrutinizing a variety of historical records is not to trace the origin of ideas in process control, or even the full impact of these ideas on manufacturing, but rather to analyze how they have affected process variance--the measure of "out-of-control"ness that a process is designed to contain--and how the reduction of this variance has led towards a science of manufacturing.

Let us begin with a product consisting of two or more metal components that must be bonded together. The manufacture of such a product will entail two processes, (1) a metal-fabricating process in which the individual components are formed, and (2) an assembly process in which the separate components are brought together. For purposes of this paper, it will suffice to say of the latter that it consists in a sequence of operations in which two or more components are selected, located, fitted, and bonded together. In following the evolution of process control, we are principally concerned with the former operation, metal-fabricating.

The purpose of a metal-fabricating process is to bring about a transformation, according to closely prescribed specifications, in the form, physical characteristics, or finish of a metal component. A measure of the effectiveness of a process is the ability of the set of people, machines, and procedures that impinge upon it to meet the specifications established for the component the process is intended to produce. Some degree of variation is implicit, inasmuch as the performance of a process is never perfect. Sources of variation can lie in people, machines, and procedures, as well as in the object being fabricated. Control of variation is process control. Thus, the study of process control is the study of the kinds of variances that can occur, the sources of these variances, and the means by which they can be managed. A measure of the effectiveness of process control is the degree to which variances are minimized.

In measuring the characteristic being transformed for a specific lot of components produced by a particular process, the frequency of occurence for a given measure will follow the distribution in Figure 1. The mean of the distribution, the standard deviation, and the desired standard of performance are of interest to us. The difference between the mean and the desired standard tells us how close we have come to satisfying our requirements; it is a measure of the accuracy of the process. The standard deviation, as a measure of dispersion, tells us to what degree the process is capable of repeating the desired performance; the smaller the dispersion, the more capable the process is of repeating the desired performance. It is a measure of precision, and is due to limits in the ability both of a machine to execute identical performances and of the persons and procedures that direct the machine. Variance due to machines is defined as repeatability, variance due to people and procedures, reproducibility.

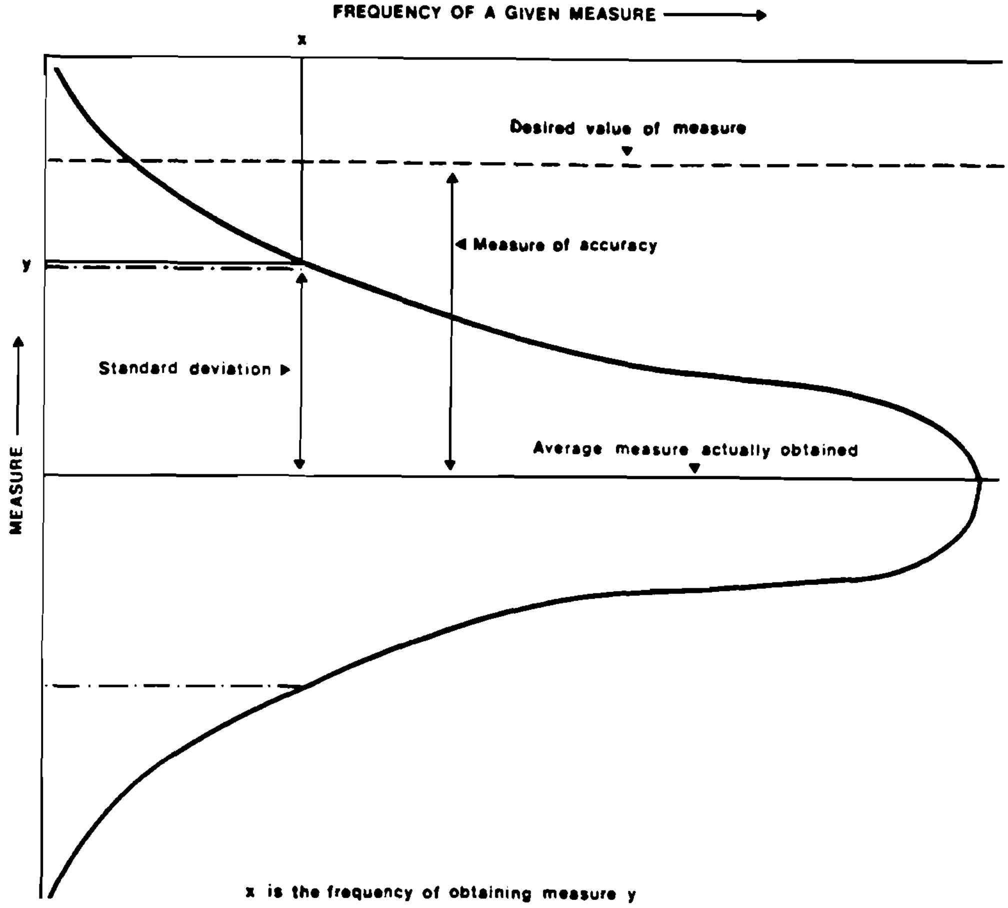

Figure 1: Frequency of occurence for a given measure.

If we measure, for the same component as above, the means and standard deviations for sequential lots, we would find that over time the mean of the process keeps changing. The standard deviation of the mean of the process, defined as the <u>stability</u> of the process, is a measure of how well it performs over time. <u>System variance</u> is the net variance due to accuracy, precision, reproducibility, and stability.

All of the measures of variance assume that we have not made any adjustments to the process. In practice, we always make adjustments to a process when something goes wrong, and a process that accommodates such adjustments is obviously desirable. Accuracy, as we noted earlier, is the systematic bias in a process, stability, the manner in which that bias shifts over time. To the extent that we can adjust the process we can correct the bias and bring it closer to the desired standard. The capability of a process to make dynamic adjustments and correct for bias is termed adaptibility. A measure of adaptibility is the variance between system variance and variance in repeatability.

The requirement for adaptability is quite different depending on whether we want to make one component or a large number of identical components. To be adaptable with a sample of a single component a process must have a high degree of accuracy. More important in a process for producing large numbers of identical components are precision and stability, as we can compensate for accuracy by making adjustments. The greater the stability of a process, the less frequently it will have to be adjusted.

Before proceeding with our discussion of the evolution of process control, we need to define one further notion, that of versatility. Inasmuch as it has nothing to do with variances in product characteristics, versatility is quite different from the notions discussed above, yet it has important implications for process control. Versatility is the ability of a process to accommodate variety in process specifications. As greater versatility usually reflects greater complexity in a task, the sources of variance can be expected to increase.

As we shall see, the six epochs represented attempts to tackle specific problems in the management of system variance--accuracy, precision, reproducibility, stability, versatility, and adaptability. It will become apparent that the ethos of process control required to manage each of these is quite different. It is extremely difficult for a firm to manage the conflicting demands of two successive process control paradigms; the management of technology requires a quick transition from one to another.

We will shortly examine the relationship between technology and work in each of the six epochs, attending closely to Table 1 (A-C), which summarize some of our findings along dimensions that will hopefully provide some insight into the nature of these epochal shifts.

	English System	American System	Taylor Scientific Management	Dynamic World	NC Era	Computer Integrated Manufacturing
Number of Machines	3	50	150	150	50	30
Minimum Efficient Scale (Number of People)	40	150	300	300	100	30
Staff/Line Ratio	0:40	20:130	60:240	100:200	50:50	20:10
Productivity Increase Over Previous Epoch	4:1	3:1	3:1	3:2	3:1	3:1
Rework as Fraction of Total Work	.8	.5	.25	.08	.02	.005
Number of Products	Infinite	3	10	15	100	Infinite

Table 1 (A-C): Comparison of six epochs in process control.

	English System	American System	Taylor Scientific Management	Dynamic World	NC Era	Computer Integrated Manufacturing
Engineering Ethos	Mechanical	Manufacturing	Industrial	Quality	Systems	Knowledge
Process Focus	Accuracy	Repeatability	Reproducibility	Stability	Adaptability	Versatility
Focus of Control	Product Functionality	Product Conformance	Process Conformance	Process Capability	Product/ Process Integration	Process Intelligence
Instrument of Control	Micrometer	Go/No-Go Gauges	Stop Watch	Control Chart	Electronic Gauges	Professional Workstation
Organizational Change	Break-up of Guilds	Staff/Line Separation	Functional Specialization	Problem Solving Teams	Cellular Control	Product P3 Process Program

Table 1 (B)

	English System	American System	Taylor Scientific Management	Dynamic World	NC Era	Computer Integrated Manufacturing
Standards for Work	Absolute Standards on Products	Relative Standards on Products	Work Standards	Process Standards	Functional Standards	Technology Standards
Work Ethos	"Perfection"	"Satisfice"	"Reproduce"	"Monitor"	"Control"	"Develop"
Skills Required	Mechanical Craft	Repetitive	Repetitive	Diagnostic	Experimental	Learning Generalizing Abstracting
Control of Work	Inspection of Work	Tight Supervision of Work	Loose Supervision of Work/ Tight Supervision of Contingencies	Loose Supervision of Contingencies	No Supervision of Work	No Supervision of Work

Table 1 (C)

GUN-MAKING IN GARDONE -- THE FIRST THREE CENTURIES

For three hundred years after its inception gun-making in Gardone changed little. But elsewhere, spurred by the development of machine tools in the latter part of the eighteenth century, innovations were introduced in both the techniques and organization of work involved in gunsmithing. By contrasting the practices related below to those described in the subsequent sections on the English and American systems of manufacture we can begin to understand the changes that Gardone had to catch up with.

In the 1880s in Gardone locking mechanisms were made in shops that were little changed from those of three hundred years earlier. The three plates in Figure 2,[1] taken from Diderot's Encyclopedia, show the shops and the kinds of tools and measuring instruments then in use. Although the shop illustrated in the plates was where assembly was done, shops that fabricated components would not have looked much different. There would be a forge to make small components and a crude drilling machine, but there would be no planer machines to do metal cutting. Hammers, chisels, and files were the principal tools, calipers and wooden rules the only measuring devices.

Shops kept models of locking mechanisms from which the craftsmen worked, constantly comparing the component being manufactured with the model. Components were hand forged, filed to shape, fitted together, and then hardened. The bulk of the work in these shops consisted in filing and fitting pieces. The assembly process was imprecise, a matter of repeated trial and error and adjustment.

Although models were far and away the primary means by which artisans communicated design intent, some designs were replicated in primitive drawings, which circulated among the masters. The engravings shown in Figure 3 are from the introductory plates of Verschiede Stucke Fur Buchsenmacher by Johann Christoff Weigel, probably the most widely circulated and influential gun design book of the span 1650-1750.[2] The drawings are remarkable in that they carry no specifications or dimensions. Only design intent and functionality are communicated, the interpretation of the design by the master serving as the basis for construction of the mechanism.

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[1] Diderot's Encyclopedia, Arquebusier," plates II, III, IV. Reproduced courtesy of the Kress Library of Business and Economics, Baker Library, Harvard Business School.

[2] Verschiedene Stucke Fur Buchsenmacher, 1702. Originally in Plusiers Models des plus nouvelles manieres qui sont en usage en l'Art d'Arquebuzerie, Paris, 1660. Reproduced from Diderot's Encyclopedia, "Arquebusier," plates V, VI, courtesy of the Kress Library of Business and Economics, Baker Library, Harvard Business School.

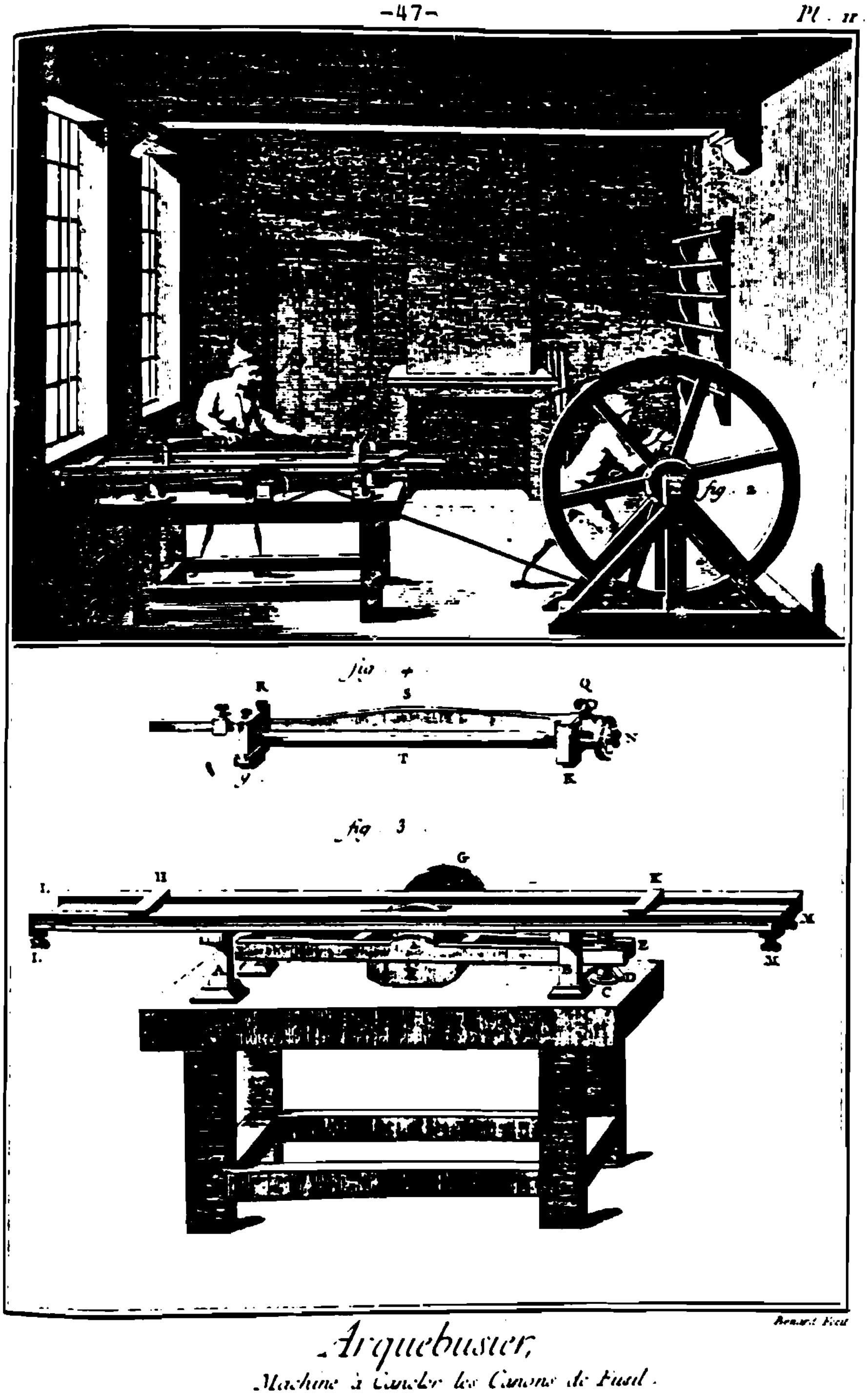
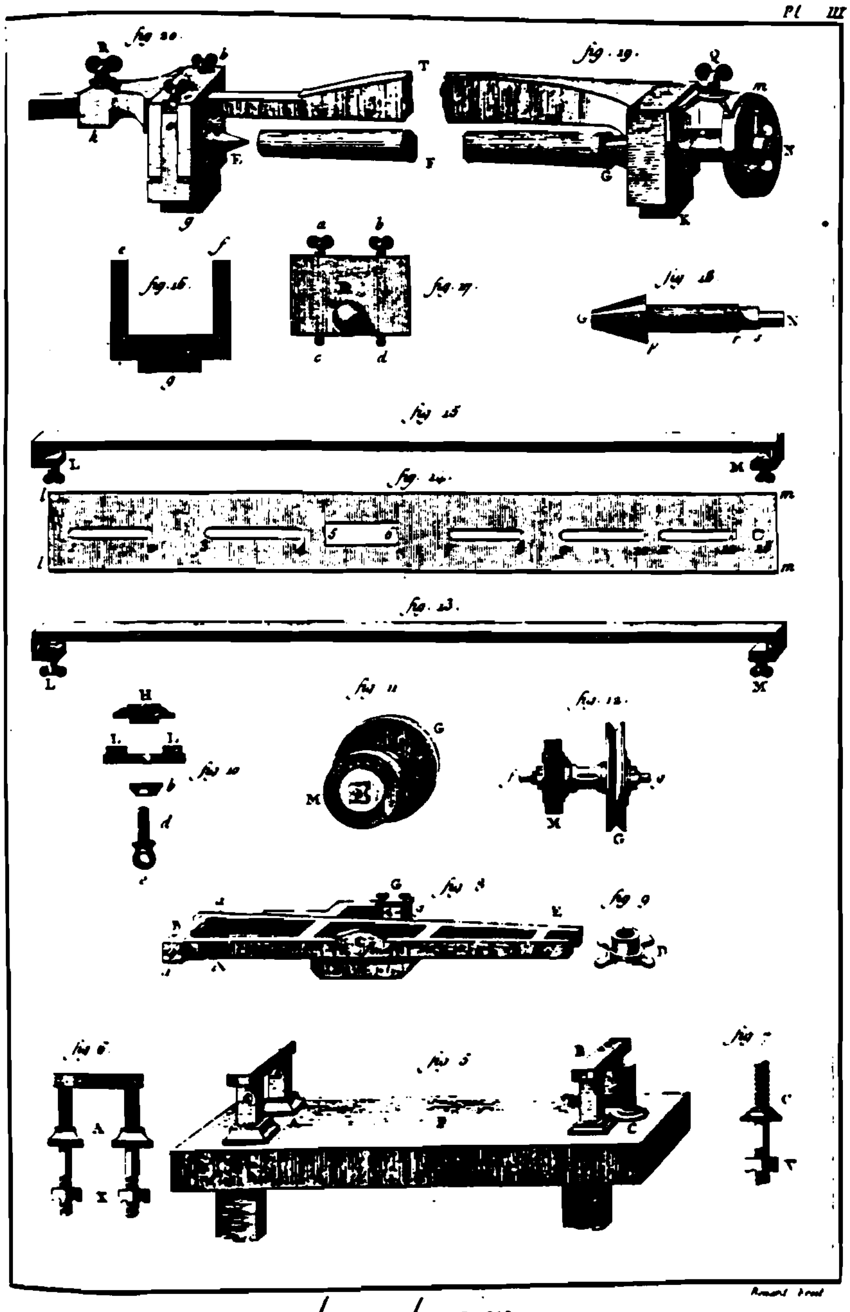


Figure 2: Early shop, tools, and measuring instruments for gun-making.

Pl. III

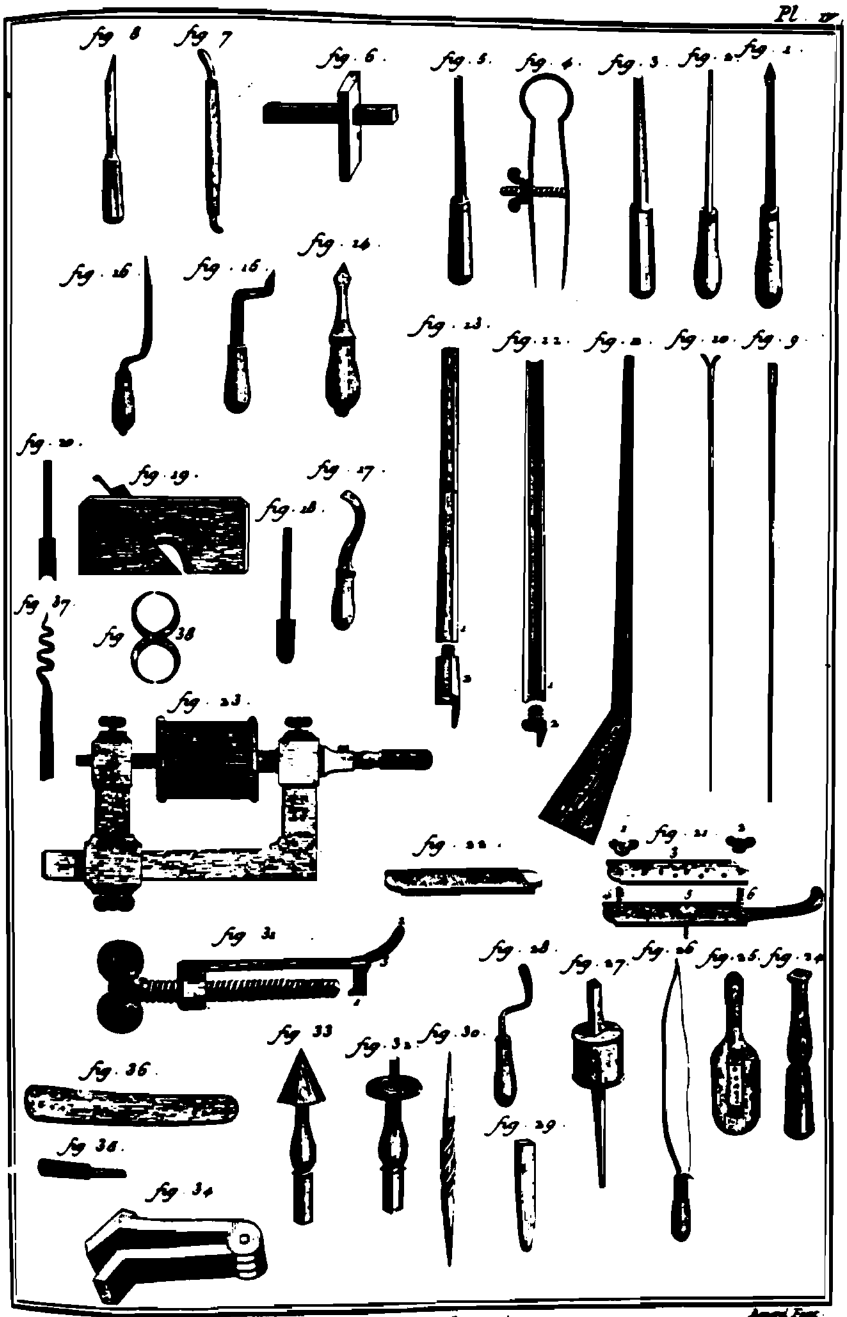


Benard fecit

Arquebusier,

Développements de la Machine à Caneler

Pl. IV



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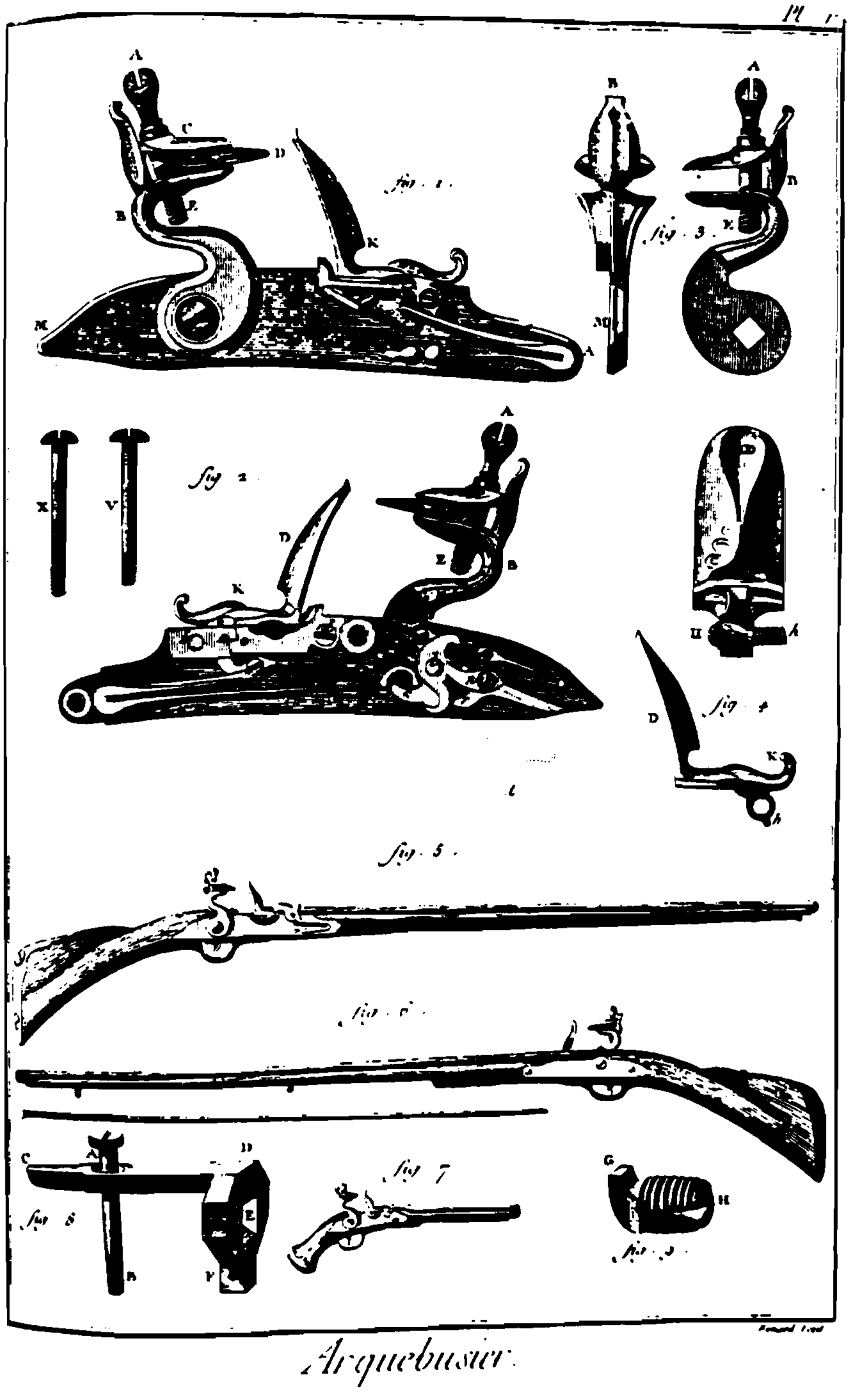
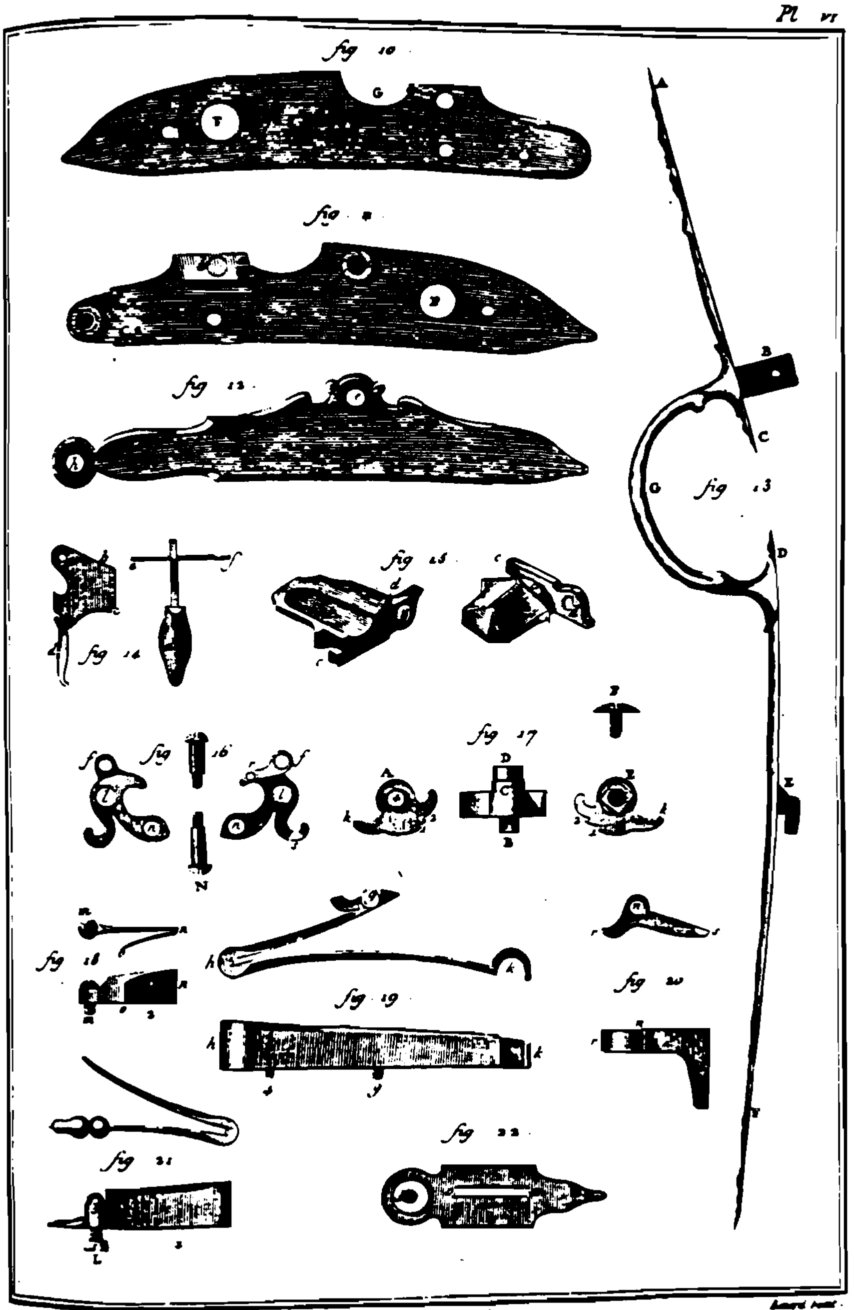


Figure 3: Early gun design drawings.

Pl. VI



Arquebusier.

International distribution of designs for gunsmithing dates to 1635, the year of publication of the first book of patterns by Phillipe Daubigny. The custom proliferated rapidly in France and, after about 1700, in Germany as well. It was the German books that exercised a strong influence in Brescia. By the end of the first quarter of the eighteenth century, the classical Brescian designs had been abandoned by gunmakers in favor of the new fashions then dominant in Germany and Austria. Brescian gunmakers adopted not only German gun architecture and external structure, but also German mechanisms.

Production involved the master, the model, and a set of calipers. If there were drawings, they indicated only rough proportions and functions of components. Masters and millwrights, being keenly aware of the function of the product, oriented their work toward proper fit and intended functionality. Fit among components was important, and the master was the arbiter of fit. Apprentices learned from masters the craft of using tools. Control was a developed skill, which lay in the eyes and hands of the millwright.

A master's shop employed about eight people. Annual production was about 260 locking mechanisms. Although the pace of work was usually quite leisurely, the productivity of these shops could as much as quadruple during peaks of demand.

Whereas barrel making shops were functionally focused and organized around five classes of workmen--forgers, borers, smoothers, filers, and finishers--shops engaged in the construction of locking mechanisms had a product focus. The work in these shops consisted in bringing the components together and obtaining the right fit. Everyone in the shop was involved in all stages of the production process, which consisted of forging, filing, fitting, and polishing. As the principal activity, fitting, involved filing and fitting two or more components and polishing the composite workpiece, we see that the fabrication of components and their assembly were closely intertwined.

Given the organization and activity of these shops, what can we say about system variance? Note that the construction of locking mechanisms at this time involved only the use of hand tools and vises. There were no jigs to properly align or locate components. With no machinery to speak of, considerations of precision and stability are moot. Reproducibility accounted for all system variance, which was very high. With only calipers and wooden scales, and control totally in the hands of the craftsman, the standard deviation of error was as large as one-sixteenth of an inch.

With such high variance, one cannot think of the manufacture of a number of items together, only of the making of each individual item. The fit between mating components is impossible to achieve without having both physically present. Accuracy is achieved here through the adaptability of the craftsman in appropriately adjusting the contours.

Note two important aspects of the process we have been examining.

(1) An assemblage of components was required to fabricate and assemble a single product. The craftsman had to view each item independently of other items.

(2) The measure of skill lay in degree of adaptibility, i.e., the ability of the craftsman, or operator, to adjust to a wide variety of conditions, and the speed of adjustment necessary to obtain the required accuracy. The speed of adjustment between high skill and low skill could be as large as four to one.

With adaptability of the operator being so important, it was only natural that managerial response was directed towards increasing skills and maintaining a skilled workforce. Systems that developed adaptive skills flourished, and the master-journeyman model survived for many centuries.

As adaptive skills are really contingent responses to a wide variety of work conditions, procedures cannot readily be transferred. A journeyman had to learn by observing the indiosyncratic behaviors of the master. The master could solve the most difficult of problems, and fashioned each product such that quality was inherent in its fit, finish, and functionality.

It should be noted that adaptibility is a response to the inability of a process to obtain adequate accuracy, precision, reproducibility, and stability. Thus it is a symptom of a deeper problem. Process improvement entails eliminating the need for adaptability and thus the very skills of the master. Suffice it to say, for the moment, that to reduce system variance at this stage it would be necessary to:

(1) introduce more accurate measuring instruments so that one could obtain constant feedback on the state of the product and thereby strengthen adaptive response;

(2) devise tools that would lend greater control, and thus, precision, to the process of metal cutting; and

(3) simplify product designs to reduce variance due to reproducibility.

A fundamental shift in the focus of technological attention is inherent in all these requirements.

THE ENGLISH SYSTEM OF MANUFACTURE

The machine tool industry was born in England in the late eighteenth and early nineteenth centuries through the agency of English mechanics who devised tools that added greater precision to the process of metal cutting and introduced accurate measuring instruments that helped them achieve a high class of workmanship. The building and use of tools was the focus of their attention. The tools themselves, being general purpose, could be used to fabricate a variety of workpieces. The apprentices who trained in the shops of the great English mechanics were much sought after, many having become skilled in the use of instruments and machines. Their skills being applicable to the building of many different workpieces, apprentices focused on the tools they used rather than on the products they fabricated.

With the development of machine tools, the functionality of a product could no longer be viewed together with the process used to make it. With their separation, the process took on a life of its own, enabling process improvements to be made independently of product contraints. This was the intellectual leap that freed the development of technology from the constraints of the product. Once it occurred, the flowering of technology was very rapid. Within fifty years, the technological landscape was revolutionized. The seeds of the new system of manufacture that would utilize the new technolgy were sown by a young mechanic, Henry Maudslay, who worked at the Woolwich Arsenal.

Tools for the Woolwich Arsenal

The tools being built by Maudslay around 1789 were a source of great wonder to his fellow workers. A born craftsman, whose skill was the pride of the entire shop, Maudslay supplemented dexterity with an intuitive power of mechanical analysis and a sense of proportion possessed by few men. He exhibited a genius for accomplishing his ends by the simplest and most direct means.

Of all his phenomenal achievements, Maudslay is best known for the development of the slide rest, and its combination with a lead screw operated by change gears (Figure 4).[3] One of the great inventions of history, it is used in almost every machine tool.

Like most great inventions, the slide rest was a product of many minds. Leonardo da Vinci had made crude drawings of it. Besson's screw cutting lathe,

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[3] Illustrated Machine-Tools of 1885 (Manteno, Ill.: Lindsay Publications, 1981), 60-61. From Hutton, F. R., Report on Machine-Tools and Wood-Working Machines (Washington: Government Printing Office, 1885).

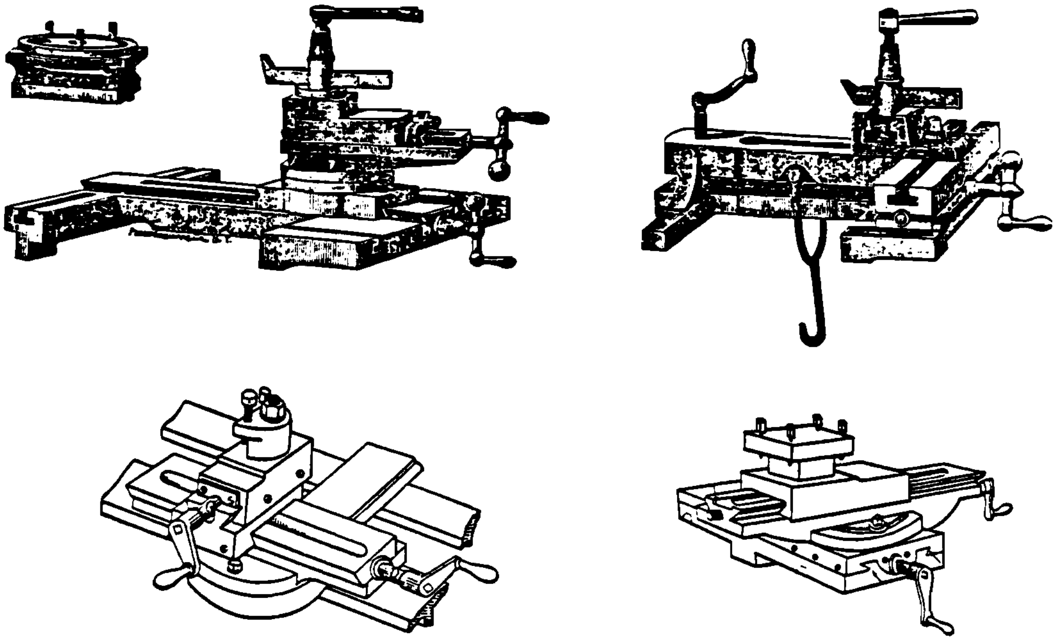

Figure 4: The slide rest, circa 1885

built in 1569, shows a lead screw.[4] An illustration of an early slide rest, shown as Figure 5, is taken from Diderot's Encyclopedia.[5] Samuel Bentham anticipated the combination of slide rest and lead screw operated by change gears.[6] "When the motion is of a rotative kind," Bentham wrote in his 1793 patent, "advancement (of the tool) may be provided by hand, yet regularity may be more effectually insured by the aid of mechanism. For this purpose one expedient is the connecting, for instance, by cogged wheels, of the advancing motion of the piece with the rotative motion of the tool."[7] But it was to

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[4] Woodbury, R. S., Studies in the History of Machine Tools, "History of the Lathe to 1850" (Cambridge, Mass.: The M.I.T. Press, 1972), 56.

[5] Diderot's Encyclopedia, "Tourneur," plate XXXVII. Reproduced courtesy of the Kress Library of Business and Economics, Baker Library, Harvard Business School.

[6] Roe, J. W., English and American Tool Builders (New York: McGraw-Hill, 1926), 38.

[7] See British patent records. Patent No. 1951, dated April 23, 1793.

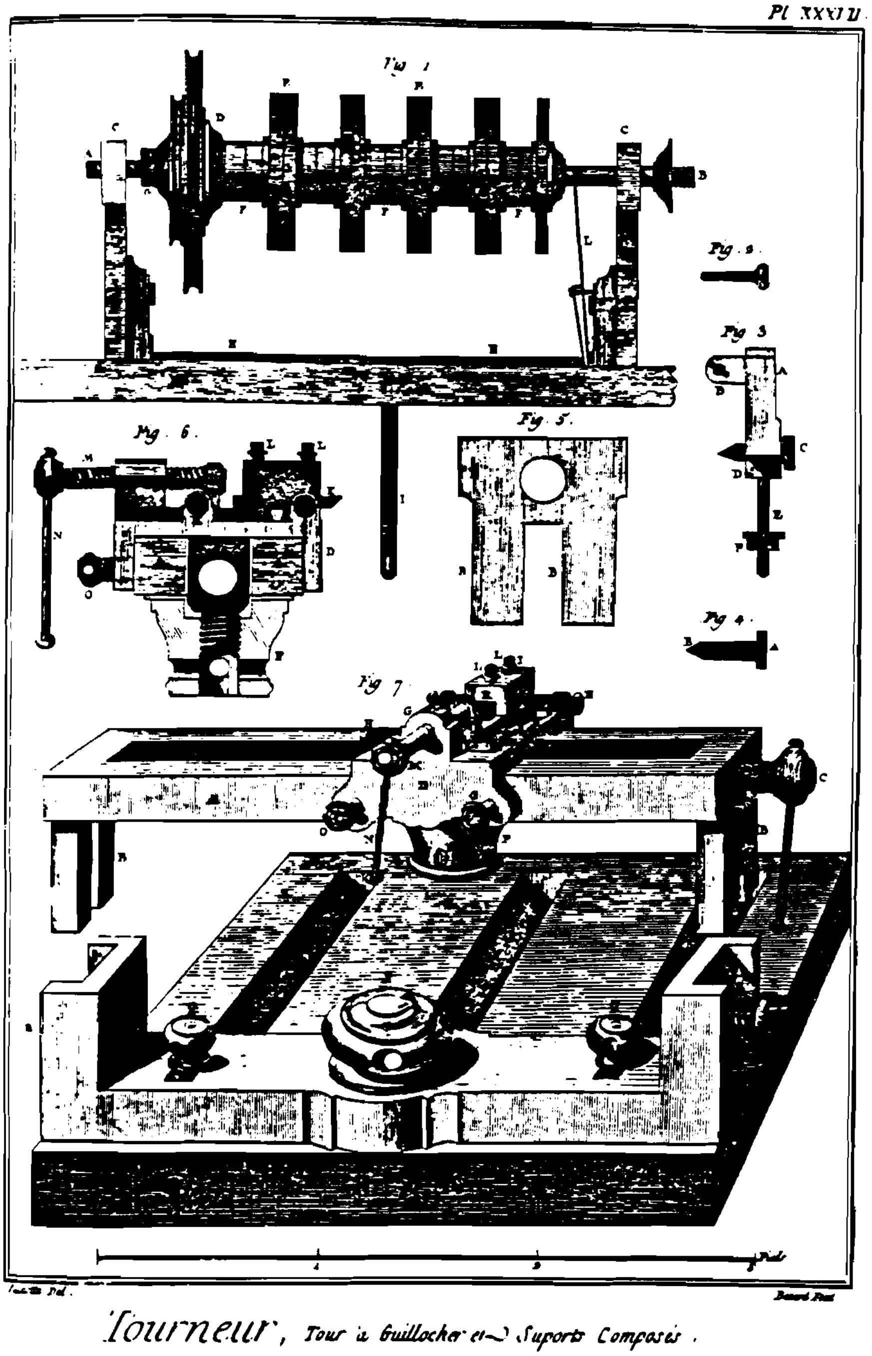

Figure 5: An early form of the slide rest.

Maudslay that the distinction of actually designing and developing the first power-driven and controlled lathe fell.

To take the place that it did in industry, the lathe had to possess a number of features, enumerated by Robert Woodbury below, which Maudslay was able to to synthesize.

> An industrial lathe must have: first, the ability to machine an iron or steel workpiece of a substantial industrial size. In order to meet this requirement the lathe must itself normally be made of iron or steel and have its various parts of dimensions such that it can withstand the stresses set up in it by cutting the ferrous metals. . . .
>
> Second, the industrial lathe must also be supplied with a source of power and means of its transmission to the workpiece and to the cutting tool adequate for cutting iron and steel at rates which are economical. This requires a suitable headstock spindle with means for its drive, and a tool carriage with its feed.
>
> Third, the industrial lathe must itself be constructed with adequate rigidity and precision so that it is capable of producing a precision nearly equal to its own in the workpieces turned upon it. . . . Rigidity in a lathe is provided partly by the material of which it is made and partly by the design of its parts, but precision depends also upon the accurate construction of certain of its features, especially the spindle bearings, the guideways, and the lead screw. The precision actually needed in the industrial lathe at any given period is somewhat greater than that required for the work to be done on it.
>
> Fourth the industrial lathe must have flexibility. Only a few machine shops in the mid-19th century could afford to have specialized machine tools, such as a boring engine, a screw-cutting machine, or a gear-cutting machine. Most shops had to depend upon a lathe, a planer or shaper, and a drilling machine. . . . To achieve flexibility the lathe needs at least change gears for both screw cutting and longitudinal feed of the tool, cone pulleys or some other means of varying the speed of the workpiece and the cutting rate, a sliding tailstock to take work of different lengths, and a chuck or a face plate for boring or for other turning not possible with the workpiece mounted between centers.[8]

The machine that Maudslay built in 1800 (Figure 6)[9] was, according to Roe, "distinctly modern in appearance. It has a substantial, well-designed, cast-iron bed, a lead screw with 30 threads to the inch, a back rest for steadying the work, and was fitted with 28 change wheels with teeth varying in

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[8] Woodbury, R. S., Studies in the History of Machine Tools, "History of the Lathe to 1850" (Cambridge, Mass.: The M.I.T. Press, 1972), 96-97.

[9] Ibid., 104. From British Crown Copyright, Science Museum, London.

number from 15 to 50."[10] Maudslay built lathes for screw cutting on which he cut some of the best screws to that time. One of these "was principally used for dividing scales for astronomical and other metrical purposes of the highest class. By its means divisions were produced with such minuteness that they could only be made visual by a microscope."[11]

His many inventions notwithstanding, Maudslay's importance lay less in the development of machines than in the founding of the machine tool industry and the radical transformation of shop floor practice. "I believe it may be fairly advanced," wrote Holtzapffel, "that during the period from 1800 to 1810, Mr. Maudslay effected nearly the entire change from the old, imperfect, accidental practice of screw making to the modern, exact, systematic mode now generally followed by engineers."[12]

"Maudslay's standard of accuracy," Roe observes, "carried him beyond the use of calipers."[13] In his workshop, Maudslay kept a highly accurate bench micrometer, which he referred to as "The Lord Chancellor." About sixteen inches long, the micrometer had two plane jaws and a horizontal screw, a scale graduated in inches and tenths of an inch, and an index disk on the screw graduated to one hundred equal parts. "Not only absolute measure could be obtained by this means," remarked Nasmyth, "but also the amount of minute differences could be ascertained with a degree of exactness that went quite beyond all the requirements of engineering mechanism; such, for instance, as the thousandth part of an inch."[14]

Nasmyth further observed that "the importance of having Standard Planes caused him (i.e., Maudslay) to have many of them placed on the benches beside his workmen, by means of which they might at once conveniently test their work. . . . This art of producing absolutely plane surfaces is, I believe, a very old mechanical 'dodge.' But, as employed by Maudslay's men, it greatly contributed to the improvement of the work turned out. It was used . . . wherever absolute true plane surfaces were essential to the attainment of the best results, not only in the machinery turned out, but in educating the taste of his men towards first-class workmanship."[15] Whitworth would later assert "the vast importance of attending to the great elements in constructive mechanics,--namely, a true

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[10] Roe, J. W., English and American Tool Builders (New York: McGraw-Hill, 1926), 41.

[11] Autobiography of James Nasmyth (London, 1883), 140.

[12] Holtzapffel, Vol. II, 647.

[13] Roe, J. W., English and American Tool Builders (New York: McGraw-Hill, 1926), 45.

[14] Autobiography of James Nasmyth (London, 1883), 150.

[15] Ibid., 148-149.

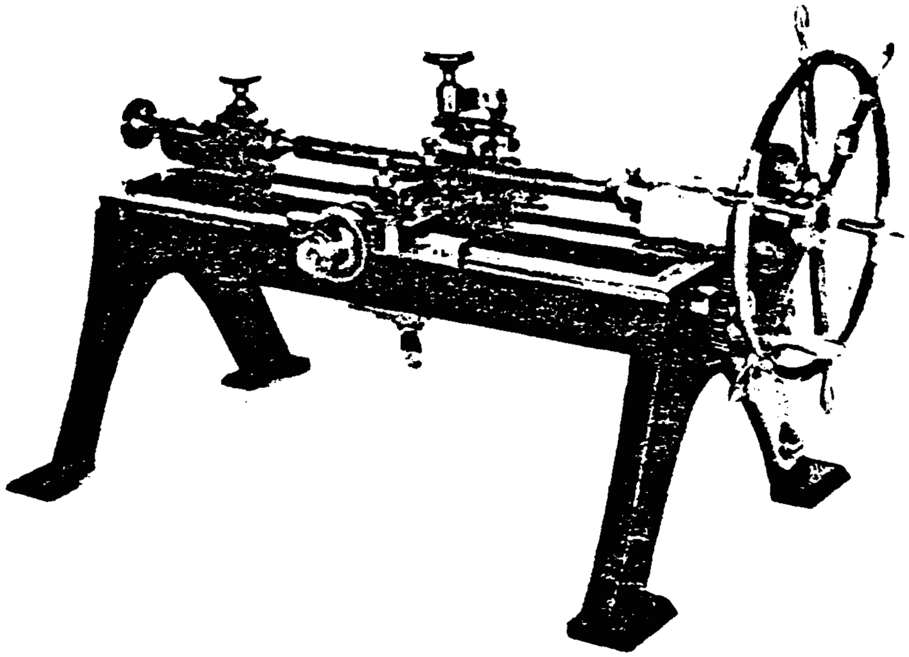

Figure 6: Maudslay's lathe, circa 1800.

plane and the power of measurement. The latter cannot be attained without the former, which is, therefore of primary importance. . . . All excellence in workmanship depends upon it."[16]

This taste for accuracy and workmanship was Maudslay's lasting legacy. Through his workshop, which employed several hundred men at one time, passed nearly the entire coterie of great machine tool builders. Clement, Roberts, Whitworth, Nasmyth, Seaward, Muir, and Lewis showed, throughout their lives and in a marked way, Maudslay's influence upon them. The methods and standards of Maudslay and Field, spread by the former's workmen into the various shops of England, made world leaders of English tool-builders.

Under the leadership of the "Maudslay men," all of the great metal-working machine tools achieved a form that remained essentially unchanged for nearly a

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[16] Presidential Address. Institution of Mechanical Engineers (1856), 125.

century. England enjoyed unquestioned leadership in the machine tool industry, supplying nearly all of the machine tools used in France and Germany, whose own machine tool development lagged a generation or two behind.

The influence of the English mechanics was not limited to the building of machinery. Their mode of apprenticeship had produced a cadre of individuals who conceived a new system of manufacture, a system whose foundation rested on Mechanical Engineering and whose roots lay in principles of measurement and accuracy and the ability to meet tolerances. Theirs was not a skill based on knowledge of the functions required to manufacture a specific product, but rather knowledge of tools and of scientific principles of measurement skills. These skills, and the general-purpose machine tools being produced at the time, could be applied to a variety of products. The accuracy, precision, and productivity of general purpose machine tools was greater than that of hand tools and other product specific tools then in use in the various industries. This system of manufacture quickly came to predominate in machine shops in England and soon spread throughout the rest of Europe.

The Engineering Drawing

The engineering drawing, as a medium of communication in engineering work, did not exist prior to 1800. Engineering work was defined by a physical model of a product that was to be reproduced. In the manufacture of a rifle barrel, for example, a worker would ensure that the dimensions of the barrel he was working on corresponded to those of a model barrel by using calipers to transfer measurements from one to the other. Because each worker needed his own model barrel to work from, the greater the number of workers a shop had, the greater the number of model barrels it had to supply. As it was impossible, given the standards of accuracy of the time, to make all model barrels identical, the manufactured barrels, too, were all different.

La Geometrie descriptive, written by Gaspard Monge in 1801, was the first formal treatise on modern engineering drawings. In it, Monge developed the theory of projecting views of an object onto three mutually perpendicular coordinate planes (such as are formed by the front, side, and top of a cube) and then revolving the horizontal (or top) and profile (or side) planes onto the same plane as the vertical (front) plane. The fundamental theory of all orthographic (mutually perpendicular) projection is derived from the descriptive geometry of Monge.

Monge showed how drawings need to be dimensioned. Dimensions, the size specifications added to the shape description as provided by the orthographic drawings, consisted of the numerical values of the measurements directed to the proper location on the part and the relevant surfaces or locations on the object. For drawings to replace models as a medium of communication, one needed accurate measuring instruments. The English system of manufacture, with its basis in measure, created a variety of such instruments.

Together, mechanical drawings and the English system altered the organization of work. With an objective *standard* of performance (a mechanical drawing), which was the same for every worker, models were no longer needed. Work could be compared to the desired standard using an objective measure of performance, the micrometer (Maudslay's "Lord Chancellor"). The master was no longer needed for guidance or approval; the worker could obtain the former from a drawing and verify his work with the appropriate measuring instrument.

With clear specifications of what is required and an objective standard with which to compare performance, we would expect system variance due to accuracy to be markedly reduced. With workmanship a prized objective and no longer product specific (a workman trained to turn out a metal shaft for a horse-drawn carriage could now turn out a rifle barrel as well), we would expect the guild system to collapse. As workers needed no longer be ingratiated to a master, but were free to leave as soon as they had developed the necessary skills, we would expect to see a market develop for skilled labor. We will see all of these things happen at Beretta. What the merchants of Brescia and Venice and the Doges managing the Venetian Arsenal could not do, the mechanical drawing and micrometer achieved in a span of fifteen years.

Gardone Shops for Barrel-Making

Gardone became part of the Napoleonic French republic on 21 September 1792. As the revolution had deprived the French aristocracy of political and economic power, so the Napoleonic era had a profound effect on Gardone gunsmithing.

The cooperative artisan organization of Gardone, considered "antidemocratic" by the francophile municipal authorities, had been completely dismantled. Anyone could now engage in the various professions, or "arts," of barrel-making. The barrel-master under the guild structure was, under the English system, replaced by the machine operator. Under this system, each person was responsible for all aspects of making a component.

The English system of manufacture introduced to Beretta during the French occupation transformed the arms factories in Brescia. The French had found that with drawings and general purpose machines they could have one large factory instead of many small shops. The new, state-owned arms factory established in Brescia to maintain the supply of arms to the French army was furnished with the latest machinery, imported from France, and operated under the factory system of production. For the first time, the masters had to contend with a radically different technology and organization of work. Marco Cominassi writes of the factory:

> The work force of the Imperial-Royal Factory in Gardone consists of 180 skilled workers, not counting apprentices or the women who work there; together they could produce two thousand barrels a month. A huge building, property of the public treasury, serves as the residence of the supervisors and agents, and of the captain when he comes here from Brescia; here, too, the iron that is advanced to the workers is given out, and where they bring the finished product. The barrels are proved in the presence of the captain.
>
> The work is divided up among five classes of craftsmen, called the forgers, the borers, the smoothers, the filers and the finishers. Each of

> these groups elects a leader who retains office for three years, and lives in Gardone without ceasing to participate in the work; these leaders, under the presidency of the captain, form the administrative council of the factory.
>
> The forgers receive their iron in flat rectangles purified under the drophammer; they wrap it around the mandril by force of fire and hammer so that the two long edges are fused together and form a barrel. . . .
>
> The barrel having been roughed out and certified as perfect by a supervisor, it passes on to the borers, who use water-driven machinery (see Figure 7)[17] to clean out the scaly bore with rough circular files, first narrow, then of ever greater diameter, until the required size is reached. But since the borers cannot make the bore perfectly cylindrical with their instruments, the barrel passes next to the smoothers, who subject it to subtle and careful labours. The external finish is then entrusted to the filers who, with a diligence that is partly a specialty of this factory, reduce the barrel to final shape by bringing in into contact with a large water-powered sanding disc. Next comes the polishing phase, done by the finishers with special files, and finally the fine-polishing is done with various abrasives by the women. The breechers, those who fit the sights and the proofers constitute an appendix to the five classes of above-named craftsmen.[18]

The effect of the machinery and organizational structure of the state-owned factory at Brescia was like a shock to Gardone. The productivity of the factory and the quality of the muskets it produced for the military far exceeded that of the shops of the Gardonese artisans. Artisans at the state-owned factory were, with but three years of training, turning out a product far superior to that being turned out by masters who had devoted a lifetime to their art. Only the mercantile contracts of Beretta kept the masters in business at all. Their markets in the Levant were being lost to French, English, and Belgian competitors. If Beretta and the other shop owners were to remain viable, they would have to modify their activities. It would not be easy to assimilate the changes that had occurred in the industy, but the Gardonese had little choice but to try.

Pietro Antonio Beretta attracted a number of newly trained artisans from the state factory. He purchased three new machine tools and expanded the scope of activities within his shop, which grew from eight to forty people and enjoyed

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[17] Morin, M., and R. Held, Beretta: The world's oldest industrial dynasty (Chiasso, Switzerland: Acquafresca Editrice, 1980), 203. From Treatise on Portable Firearms and Edged Weapons (Vienna: Imperial-Royal Printing Office of the Court and State, 1829), plates III, V.

[18] Ibid., 199-202. From "Notes on the Arms Industry in Gardone in the Trompia Valley," Giornale (Imperial-Royal Lombard Institute for Science, Letters and Art).

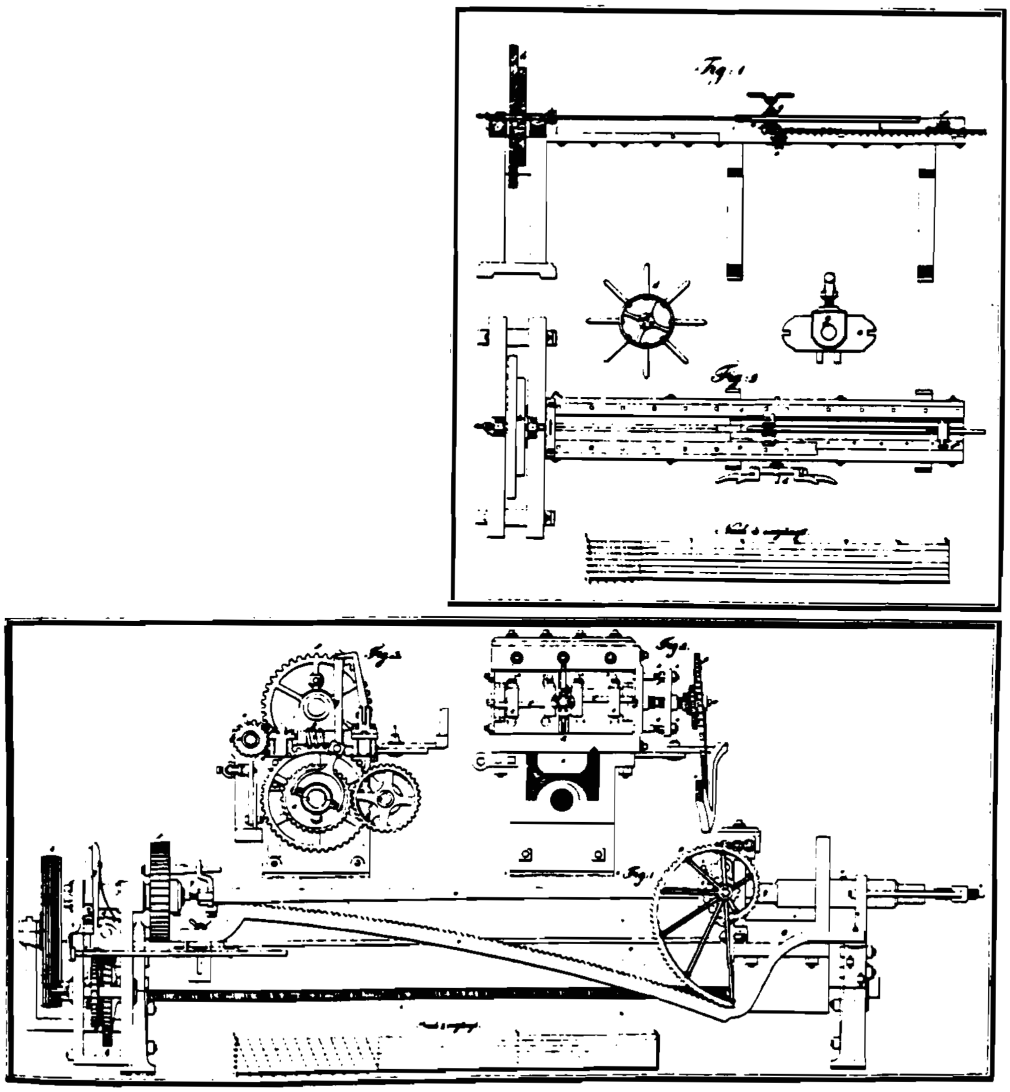

Figure 7: A Barrel-borer (square figure) and Asymtotic barrel lathe (rectangular figure), circa 1829.

a four-fold increase in productivity. The greater size and increased productivity of the rejuvenated shop represented an order of magnitude increase in productive capacity.

In 1815, Beretta travelled widely, establishing contacts with importers, wholesalers, and retailers. The network he established was woven tighter by his son, Giuseppe, who achieved the unification, in a single factory, of the complete manufacture of a firearm.

The importance of the attention of the master to product quality gave way to the availability of operators trained under the new system. It was the availability of the skills of the latter that became the new constraint on growth. This constraint would not be long-lived, though. It was, as we shall see, soon to be relaxed by the introduction of the American System of Manufacture.

THE AMERICAN SYSTEM OF MANUFACTURE

While the English were evolving a system of manufacture whose ethos was accuracy, a new system, based on precision and interchangeability (of parts) was being developed in the United States. Implicit in the exploitation of interchangeability of parts is a need for a large number of identical components. In fact, one only thinks about interchangeability when such a need exists. With the emphasis of their system on accuracy, English mechanics and engineers made parts to fit (i.e., to mate with one another). The better the fit, the better the workmanship, with "perfection" being the objective. As "fit" was achieved by concentrating on the relationship between components, one made parts one at a time.[19]

Interchangeability, by contrast, relied on the existence of clearance between parts. The greater the clearance, the easier it was to make parts interchangeable. Thus, the objective of interchangeable manufacture was to move from perfection of fit towards the greatest possible clearance without losing the functionality of the product. In doing so, the intellectual problem changed from that of generating perfection of fit to one of managing clearances between components. These concerns are at opposite poles.

Clearances allowed for variances, and the management of these variances was the hallmark of the American System of Manufacture. Interchangeable manufacture allowed for the separation not only of fabrication and assembly, but also of the different operations in fabrication from one another. Managing variances entailed prescribing limits and then achieving the precision imposed by these limits by developing machinery that was constrained in its operation and a system of gauges that would insure that fabricated parts were indeed interchangeable.

The simultaneous introduction of special purpose machines and systems of gauging and inspection had the effect of reorienting the thinking of engineers away from the making of individual components toward the development of systems for manufacturing large lots of components. Charles Babbage, in his celebrated work, On the Economy of Machinery and Manufacture, was the first to distinguish the English and American systems on the basis of making versus manufacturing. Engineering problems were radically different between the two systems. The essential feature of precision manufacture was exact duplication utilizing matched or common fixtures, tools, and size gauges. Workpieces were produced

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[19] Paul Uselding discusses the differences between the two systems of manufacture and their relation to precision and accuracy in "Measuring Techniques and Manufacturing Practice," Yankee Enterprise: The Rise of the American System of Manufactures O. Mayr and R. C. Post, eds. (Washington, D.C.: Smithsonian Institution Press, 1981), 109-110.

to fit these fixtures, tools, and gauges and not to exact size relative to a universal standard of measurement.

Although the first complete manufacturing system based on interchangeable parts, a system for making pulley blocks, was built by Brunel, Bentham, and Maudslay at Portsmouth in 1795, their achievement did not alter the intellectual ethos of technological achievement in England. Development of the system was left to the Americans. Our concern with interchangeability in America is not with its origins, which are the subject of some debate, but rather with its effects on the nature of work.

The Whitney Factory

Eli Whitney, in carrying out a contract for the manufacture of firearms secured from the United States government in 1798, employed much the same techniques as other gunsmiths of the time. His stocks were made by hand shaving and boring and his barrels were forged by hammers upon anvils and finished with rude drills and grindstones. The lock parts (see Figure 8)[28] were ground and drilled, filed approximately to patterns, and fitted together. Whitney's innovation was to make the lock parts more uniform by the systematic use of hardened jigs and classify the work on a more intelligent and economical basis.

Assembling the lock parts was considered a crucial test of interchangeability. Because they could not be filed or milled after hardening, lock parts were traditionally assembled and fitted soft and then marked or kept separate to avoid mixing after hardening. In order to be assembled after hardening, lock parts had to be made interchangeable.

Whitney systematized the work of firearms manufacture by making the parts in lots of large numbers and employing unskilled labor to file them to hardened jigs. Operations in his factory are described by Wilma Pitchford Hays.

> The several parts of the musket were, under this system, carried along through the various stages of manufacture, in lots of some hundreds or thousands of each. In their various stages of progress, they were made to undergo successive operations by machinery, which not only vastly abridged the labor, but at the same time so fixed and determined their form and dimensions, as to make comparatively little skill necessary in manual operations. Such were the construction and arrangement of this machinery, that it could be worked by persons of little or no experience, and yet it performed the work with so much precision, that when, in the later stages of the process, the several parts of the musket came to be put together, they were readily adapted to each other, as if each had been made for its respective fellow. A lot of these parts passed through the hands of several different workmen successively, (and in some cases several times returned, at intervals more or less remote, to the hands of the same workman,) each

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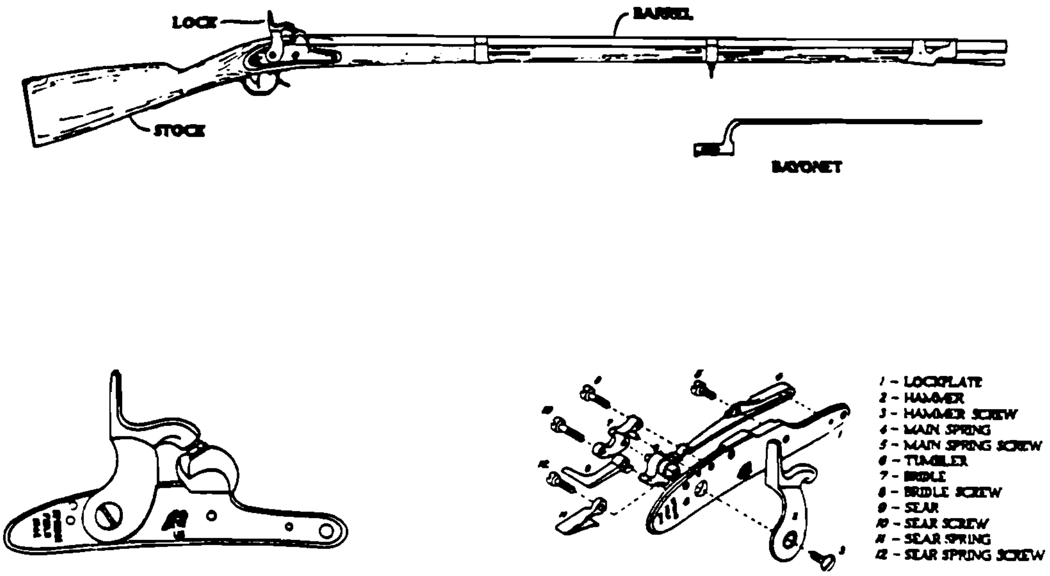
[28] Smith, M.R., <u>Harper's Ferry Armory and the New Technology,</u> (Ithaca, N.Y.: Cornell University Press, 1985), 87. Drawing by Steve Foutz.



LOCK

LOCK-EXPLODED VIEW

Figure 8: Lock parts for U.S. Model 1842 musket.

performing upon them every time some single and simple operation, by machinery or by hand, until they were completed. Thus Mr. Whitney reduced a complex business, embracing many ramifications, almost to a mere succession of simple processes, and was thereby enabled to make a division of labor among his workmen, on a principle which was not only more extensive, but also altogether more philosophical than that pursued in the English method. In England, the labor of making a musket was divided by making the different workmen the manufacturers of different limbs, while in Mr. Whitney's system the work was divided with reference to its nature, and several workmen performed different operations on the same limb.

It will be readily seen that under such an arrangement any person of ordinary capacity would soon acquire sufficient dexterity to perform a branch of the work. Indeed, so easy did Mr. Whitney find it to instruct new and inexperienced workmen, that he uniformly preferred to do so, rather than

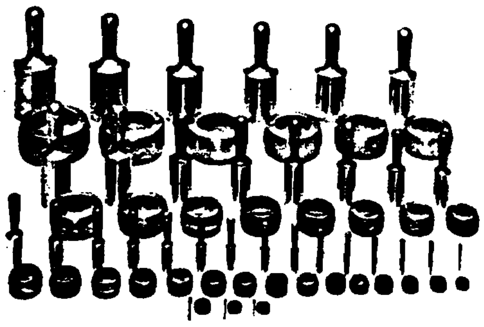


Figure 9: A set of "go"-"no go" gauges.

> to attempt to combat the prejudices of those who had learned the business under a different system.[21]

As a means to ensure precision in barrel manufacture, Whitney introduced "go" and "no go" gauges Figure 9).[22] The smaller of the two plugs was to fit into the barrel. If it did not, or if the large plug did fit into it, the barrel was rejected. Imposition of explicit standards improved the quality of arms and, in the 1830s, the Ordnance Department began supplying manufacturing gauges to contractors.

Of Machines and Men

Of this period, Fitch wrote that

> so far as machinery had been introduced, its construction was rude, and its use exceptional. Hand-shaving and chiseling for the stocks, and hand-forging, grinding, and hand-filing for the metal parts, constituted nearly all of the work.

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[21] Hays, W. P., Eli Whitney: Founder of Modern Industry (New York: Franklin Watts, Inc.,), 53-54.

[22] Mayr, O., and R. C. Post, eds., Yankee Enterprise: The Rise of the American System of Manufactures (Washington, D.C.: Smithsonian Institution Press, 1981), 113. From the Brown and Sharpe Manufacturing Co.; Smithsonian Institution Neg. No. 81-202.

> Apart from all consideration of the earliest usage of specific machines, it must be said that their introduction did not make itself felt as a great industrial agency until within twenty-five years past, in instance of which it may be stated that in 1839, there were at the Springfield armory about six men to one machine, and the ratio at other works seems to have been equally large; for of the private armories most reputed for early improvements one is stated at this time to have had but a single milling-machine, and that a rude one; and at another armory a single gang-saw profiling-machine was the principal stocking machine in use. It was some fifteen years later before the manufacture of milling, edging, and other important gun machinery was conducted on a scale sufficiently extensive for the general outfitting of large armories.[23]

The use of this machinery coupled with the use of water power to drive it had combined, as we saw in the earlier description of the Whitney factory, to reduce the skill requirements, though not necessarily the cost, of labor. Fitch observed that

> relative to the skill required in the manufacture (of guns), since most of the work is special and done by the piece, few of the operatives may, in any case, be placed under the schedule caption of ordinary laborers. The foremen upon the several jobs or sub-contracts (who may be usually rated at 1 foreman to 30 or 40 operatives), the blacksmiths and the machinists proper, the tool-makers and the barrel-straighteners, are considered skilled workmen, but the machine-tenders and other operatives, however proficient in their special duties, are not so considered. The skilled men thus specified will generally constitute less than 20 per cent of all. But in many factories much of the machinery is tended by experienced men, drawing the wages of skilled workmen, and the employment of unskilled labor, often adduced as an advantage due to improved machinery and the interchangeable system, seems largely available only on heavy contracts, when it may be utilized with a careful system of oversight. Machinery may contract the province of certain skilled trades . . . but the . . . increased fineness and accuracy required in the manufacture of fire-arms demands the most skillful and experienced oversight, and unskilled labor can only be employed with the best results upon limited portions of the work. Thus we find that at most of the larger armories the greater proportion of the operatives draw the wages of skilled men.[24]

The system lent itself to piece work, and we find that many arms manufacturers subcontracted much of their work, either bringing contractors into their plants to work under local supervision, or sending the work out to smaller shops.

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[23] Fitch, C. H., Report on the Manufacture of Fire-Arms (Washington: Government Printing Office, 1882), 7.

[24] Ibid., 8.

The Colt Armory

Thanks to an instructive visit provided by Haven and Belden, we can see how the various aspects of the interchangeable system came together in the arms factory established in Hartford by Samuel Colt.

> (The new armory) was finished and operations commenced in it in the Fall of 1855. As will be observed by the diagram, the ground plan of the principal buildings form the letter H. (See Figure 10.)[25]
>
> . . . the entire manual labor of the establishment is performed by contract. The contractors are furnished room, power, tools, material, heat, light, in fact all but muscle and brains. . . . The contractors number some scores--some particular manipulators requiring only their individual exertions, while others employ from one to forty assistants. Many of them are men of more than ordinary ability, and some have rendered themselves pecuniarily comfortable by their exertions. . . .
>
> . . . The whole of this immense floor space is covered with machine tools. Each portion of the fire-arm has its particular section. As we enter the door the first group of machines appears to be exclusively employed in chambering cylinders; the next is turning and shaping them; here another is boring barrels; another group is milling the lock-frames; still another is drilling them; beyond are a score of machines boring and screw-cutting the nipples, and next to them a number of others are making screws; here are rifling machines, and there the machines for boring rifle-barrels. . . Nearly 400 (machines) are in use in the several departments. . . .
>
> It is unnecessary to describe all the operations performed by the machines; a few will render the whole understandable. Taking the lock-frame, for instance; they commence by fixing the center, and drilling and tapping the base for receiving the arbor or breech-pin, which has been previously prepared--the helical groove cut in it, and the lower end screwed--once grasped is firmly fixed into position, furnishing a definite point from which all the operations are performed, and to which all the parts bear relation. The facing and hollowing of the recoil shield and frame, the cutting and sinking the central recesses, the cutting out all the grooves and orifices, planing the several flat surfaces and shaping the curved parts prepare the frames for being introduced between hard and steel clamps, through which all the holes are drilled, bored and tapped for the various screws; so that, after passing through thirty-three distinct operations, and the little hand finishing required in removing the burr from the edges, the lock-frame is ready for the inspector. The rotating, chambered cylinder is turned out of cast-steel bars, manufactured expressly for the purpose. The machines, after getting them the desired length, drill center holes, square up ends, turn for ratchet, turn exterior, smooth and polish, engrave,

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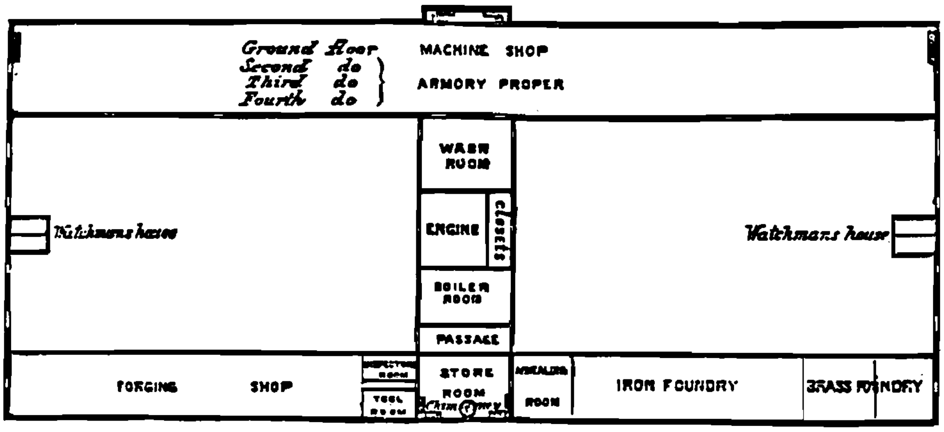
[25] Haven, C. T., and F. A. Belden, A History of the Colt Revolver (New York: William Morrow & Company, 1940), 352.



GROUND PLAN OF THE ARMORY.

Figure 10: Floor plan of the Colt Armory in Hartford, Connecticut, 1855.

bore chambers, drill partitions, tap for nipples, cut pins in hammer-rest and ratchet, and screw in nipples. In all there are thirty-six separate operations before the cylinder is ready to follow the lock-frame to the inspector. The barrel goes through forty-five separate operations on the machines. The other parts are subject to about the following number: lever, 27; rammer, 19; hammer, 28; hand, 20; trigger, 21; bolt, 21; key, 18; sear spring, 12; fourteen screws, seven each, 98; six cones, eight each, 48; guard, 18; handle-strap, 5; stock, 5. Thus it will be observed that the greater part of the labor is completed in this department. Even all the various parts of the lock are made by machinery, each having its relative initial point to work from, and on the correctness of which the perfection depends.

. . . (The upper floor) is designated the Inspecting and Assembling Department. Here the different parts are most minutely inspected; this embraces a series of operations which in the aggregate amount to considerable; the tools to inspect a cylinder, for example, are fifteen in number, each of which must gauge to a hair (see Figure 11);[26] the greatest nicety is observed, and it is absolutely impossible to get a slighted piece of work beyond this point. On finishing his examination, the inspector punches his

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[26] Mayr, O., and R. C. Post, eds., Yankee Enterprise: The Rise of the American System of Manufactures (Washington, D.C.: Smithsonian Institution Press, 1981), 78. From the collections of the Division of Military History, National Museum of American History; Smithsonian Institution Neg. No. 62468.

> initial letter on the piece inspected, thus pledging his reputation on its quality. . . .
>
> On their final completion, all the parts are delivered to the general store-keeper's department, a room 60 feet wide by 190 feet long, situated in the second story of the central building, and extending over the rear parallel. All the hand-tools and materials (except more bulky kinds) are distributed to the workmen from this place; several clerks are required to parcel the goods out and keep the accounts; in fact, it is a store, in the largest sense of the term, and rather on the wholesale principle at that. On the reception of finished, full sets of the parts of the pistols, they are once more carried up to the assembling room; but this time to another corps of artisans. Guided by the numbers, they are once more assembled. . . .
>
> . . . We have followed (a rifle) . . . through about 460 separate processes of manufacture, which, in the usual course pursued would have occupied from three to four weeks of time. . . .
>
> . . . During the time of our visit we were informed that scarcely less than one hundred thousand weapons were at that moment in the various stages of progress, yet the whole number of employes was little less than six hundred who, by the aid of mechanical contrivances, turn out an average of two hundred and fifty finished arms per diem.
>
> In rough numbers it might be stated that supposing the cost of an arm to be 100, of this the wages of those who attended to and passed the pieces through the machines was 10 per cent, and those of the best class workmen engaged in assembling or putting together, finishing and ornamenting the weapons was also 10 per cent, thus leaving 80 per cent for the duty done by the machinery. . . .
>
> . . . A majority of the machinery was not only invented, but constructed on the premises. When this department was commenced, it was the intention of the Company to manufacture solely for their own use. Some months since, applications were made by several foreign Governments to be supplied with machines and the right to operate them. After mature deliberation, it was concluded to supply the orders, and on the day of our visit we saw a complete set of machinery for manufacturing fire-arms, that will shortly be shipped to a distant land. The Company have now determined to incorporate this manufacture as a branch of their regular business.[27]

In the American arms factories, as exemplified by the Colt Armory, the foremen were contractors who hired their own help as subcontractors to produce the various parts of the gun. When a man had made his contract, he was provided with a machine and left on his own to complete the order. Many of the improve-

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[27] Haven, C. T., and F. A. Belden, A History of the Colt Revolver (New York: William Morrow & Company, 1940), 352-358.

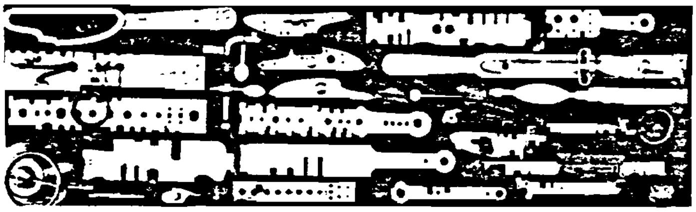

Figure 11: A set of inspection gauges for U.S. Rifle Model 1841.

ments in metal working methods, most of them undocumented, derived from the zeal of individuals who applied their ingenuity to the machine in front of them in order to realize the savings that would result from increased productivity. The Royal Commission on the American System reported that "in the adaptation of special apparatus to a single operation in almost all branches of industry, the Americans display an amount of ingenuity combined with undaunted energy."[28] These improvements were seldom patented. Most became common knowledge, and were appropriated by others who carried the improvements still further.

With the emphasis of manufacturing during this period on interchangeability of parts, the focus of control shifted from product functionality to product conformance. Though still patterned after a model, a piece was expected to conform not just to the pieces it was to mate with in a given rifle, but to those same pieces in every gun of a given design. Accuracy in this system, which might be as close as a thirty-second or sixty-fourth of an inch, was ensured by an elaborate system of patterns, guides, templates, gauges, and filing jigs.

Writing in 1880 on the degree of uniformity then being achieved Fitch observed that

> if gun parts were then called uniform, it must be recollected that the present generation stands upon a plane of mechanical intelligence so much higher, and with facilities for observation so much more extensive than existed in those times, that the very language of expression is changed. Uniformity in gun-work was then, as now, a comparative term; but then it meant within a thirty-second of an inch or more, where now it means within half a thousandth of an inch. Then interchangeability may have signified a great deal of filing and fitting, and an uneven joint when fitted, where now it signifies slipping in a piece, turning a screw-driver, and having a close, even fit.[29]

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[28] Mayr, O., and R. C. Post, eds. Yankee Enterprise (Washington, D.C.: Smithsonian Institution Press, 1981), xii.

[29] Fitch, C. H., Report on the Manufacture of Fire-Arms (Washington: Government Printing Office, 1882), 4.

As product conformance relied on repetition, the focus of process control became repeatability; that is to say, each execution of a process was expected to produce precisely the same part. Quality was achieved through 100% inspection for functionality.

The American System Abroad

Robbins and Lawrence, a machine tool builder that had perfected the use of the American system, seeing the commercial potential of their work, exhibited their guns at the Crystal Palace Industrial Exposition in 1851, where the rifles garnered an award and attracted such attention that Parliament was induced to send a commission to the United States to study "the American system" of interchangeable manufacture and secure the machinery necessary to introduce it at the Enfield Armory near London. The company received an immediate order for 20,000 Enfield rifles with interchangeable parts and one hundred and fifty-seven metal working machines to equip the armory at Enfield.[30] With this order, Robbins and Lawrence became the first large-scale exporter of machine tools.

When Samuel Colt set up his own integrated factory near London, the American system was placed on display and soon held in awe by all the major arsenals in Europe. Pratt and Whitney, one of the major machine tool builders who supplied the Colt factory, was soon receiving orders from almost every country in Europe for machinery (see Figure 12)[31]
with which to set up factories.

Giuseppe Beretta had seen the superiority of the new system of manufacture in the Prussian arms factories, which had acquired from Pratt and Whitney the entire manufacturing system, lock, stock and barrel. Not wanting to fall behind, Giuseppe Beretta, in 1860, had Pratt and Whitney build an integrated factory in Gardone. With this one stroke, he had the largest arms factory in all of northern Italy. The two hundred workers in the Beretta factory were soon turning out eight thousand sporting guns and three thousand military rifles per year.

In 1881, Beretta was awarded a medal for its innovations in the factory system. It was the only firm that took in iron and wood through one door and sent out finished arms through the other. The company sold not only in Italy, but throughout the world, particularly in the regions of the East. Its precision of manufacture was such that the company was able to offer a guarantee against any and all breakdowns and defects for one year. Beretta introduced a number of new products and watched its volume of manufacture grow.

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[30] Roe, J. W., English and American Tool Builders (New York: McGraw-Hill, 1926), 138.

[31] Illustrated Machine-Tools of 1885 (Manteno, Ill.: Lindsay Publications, 1981), 142. From Hutton, F. R., Report on Machine-Tools and Wood-Working Machines (Washington: Government Printing Office, 1885).

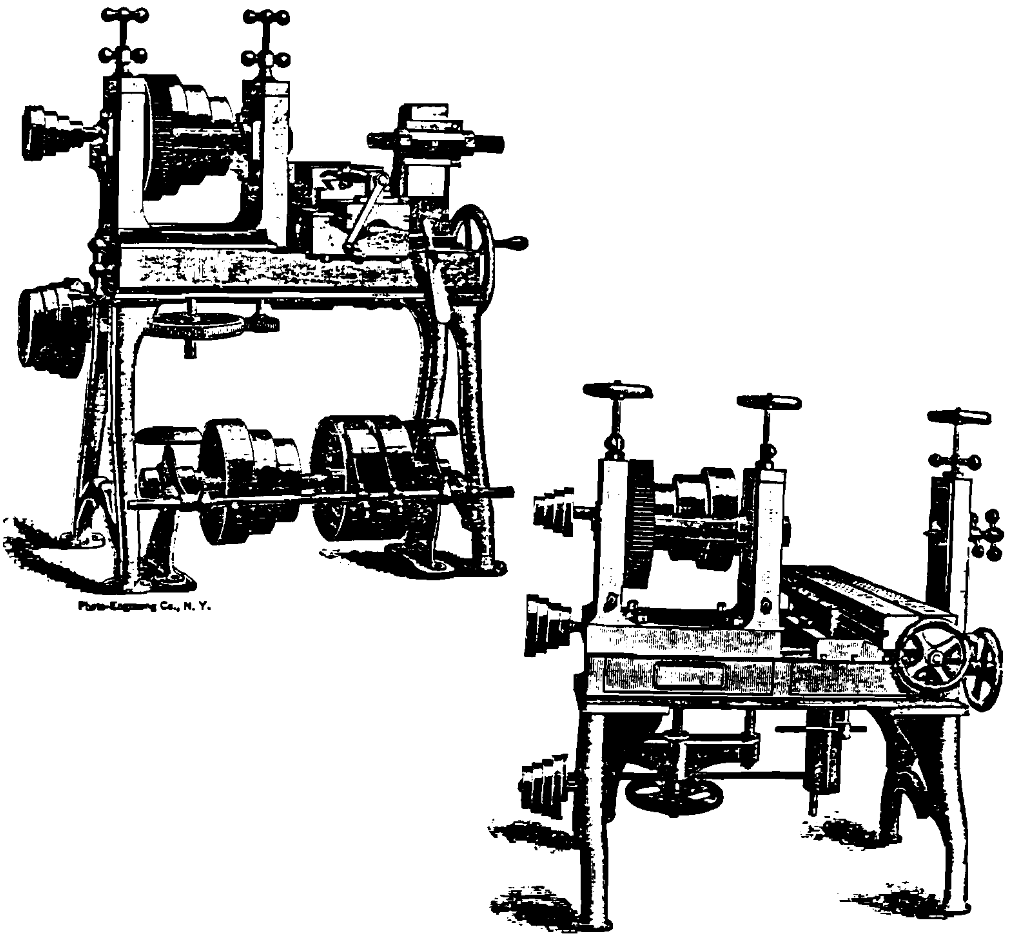

Figure 12: Milling machines for gun-making, circa 1885.

The one drawback in all of this progress had to do with the nature of work. The activities at the workstation, as we saw earlier in the description of the Colt factory, did not require much skill. There were now two kinds of workers:

those who built, maintained, set up, and improved machines; and those who turned out parts by the hundreds every day. Together, the separation of staff and line work, the specialization of line work, and the elimination of skill at the work station had the effect of creating a competitive market for labor, which tended to depress wages. Gardone saw its first strike by workers, which interrupted work for several days, in 1878. The subsequent organization of unions and establishment of a labor cooperative considerably improved the tenor of workers' lives.

Work was now reduced to managing machines and output. Labor was a corporate entity that executed procedures; engineers conceived of the tasks. The separation of conception and execution of work was now complete. Mechanical work could now be abstracted, studied in isolation from the plant, and then developed in the plant and reproduced by other workers. Mechanical work was becoming a science.

Although it was conceived as a system for the manufacture of interchangeable parts, the American system's major contribution to process control was the notion of mechanization of work. Whereas the English system saw in work the combination of skill in machinists and versatility in machines, the American system introduced to mechanisms the modern scientific principles of reductionism and reproducibility. It examined the processes involved in the manufacture of a product, broke them up into sequences of simple operations, and mechanized the simple operations by constraining the motions of a cutting tool with jigs and fixtures. Verification of performance through the use of simple gauges insured reproducibility. Each operation could now be studied and optimized.

In the context of the American system, it was necessary to attend not only to the construction of special purpose machines, but also to the interrelationships among them. In order to design and build a collection of special purpose machines for manufacturing a component one had to conceive of an entire system of manufacture. This entailed being an architect of a collection of mechanisms, as well as bringing scientific principles to the study of mechanisms. Manufacturing was now "front-end" loaded, that is to say, the most significant aspects of cost and quality of components was established prior to the production of the first unit. The importance of special purpose machinery to such a system cannot be overstated.

Over the next hundred years, these simple mechanisms would be elaborated, eventually becoming self-acting and capable of great precision and versatility. As understanding of the principles of mechanization became diffused with the increasing specialization of machines, variability of work returned once more to labor.

The next major intellectual watershed would be crossed when the new science of machinery was extended to human labor. Application of the principles of machine movement to human work yielded a new "scientific management" of work, whose impact on the organization of work at the Watertown Arsenal we will now examine.

THE TAYLOR SYSTEM

To Frederick Taylor falls the distinction of doing for work what a century of refinement had done for machinery. Taylor recognized that the machinery available at the end of the nineteenth century was capable of more than workers were getting out of it. Worker-related activities, he realized, were limiting the speed and efficiency that could be achieved by the machines. The idea that these human activities could be measured, analyzed, and controlled by techniques analogous to those that had been successfully applied to physical objects was the central theme in what Taylor was to put forth as a theory of "scientific management."

As conceived and practiced by Taylor, scientific management was concerned with industrial work, particularly the work of machine shops in metalworking establishments. Taylor was concerned almost exclusively with organization at the shop level, from the superintendent and foreman down.

Although he shared with Church, Halsey, and Towne in the United States, and Slater Lewis in Britain, an interest in incentive wage payments as a means of increasing productivity, Taylor took a different approach. He viewed work as an object and studied it as if it were a physical, mechanical entity. In the Taylor scheme of things, job times were determined not by past experience but with a stop watch. Standard times were to be set for each job, and a standard rate of output determined. This involved two elements: job analysis, and time study.

Job analysis consisted in breaking each job down into small elements, and distinguishing those elements that were essential for the performance of work from those that were superfluous, or "waste." The waste was to be eliminated. Once the elements essential for the performance of work had been isolated, they were classified functionally in order that different aspects of the job could be carried out by functional specialists. For instance, a machinist assigned the task of turning down a piece of metal to certain dimensions on a lathe might find that his cutting tool needed sharpening. Taylor considered the skills associated with sharpening tools to be functionally different from the skills of a machinist, and, consequently, separated them. Similarly, it was not part of the machinist's job to determine correct speed or the correct angle of a cut. Even more obviously, it was not part of his job to obtain materials or tools from the storeroom, or to move work in progress from place to place in the shop, or to do anything but turn the piece of metal on his lathe. Job analysis, as Taylor interpreted it, almost invariably implied a narrowing of the functions included in the job, an extension of the division of labor, a trimming off of all variant, non-repetitive tasks.

The second basic element in Taylor's system was time study. After a job had been analyzed into its constituent operations, these were timed with a stop watch. By adding the elementary times for each operation, a total time for the whole job was calculated. Operations were classified into two types: machine time, and handling time. Machine times could be precise, as they depended on physical characteristics of the metal being worked, the cutting instrument, and the machine tool. Handling times, which referred to the time taken by an operator to set up work on the machine and remove it after the work was completed, varied widely among operators.

Nor were the machines themselves neglected by the Taylor system. Inasmuch as the speed of operators was largely determined by the speed of the machines as driven from a central location by belts, pulleys, and shafts (see Figure 13),[32] Taylor considered the standardization and control of these systems at their optimal level of efficiency essential. To this end he prescribed methods for scientifically determining correct belt tensions and providing maintenance, and established the activities of belt maintenance and adjustment as a separate job.

Taylor employed Henry Gantt and Carl Barth to assist with the specification of optimum cutting speeds. "Taylor succeeded in determining empirically," explains Aitken,

> by a prolonged series of experiments, the optimum relationship between all the variables that influenced the rate at which metal could be cut on a lathe: the depth of cut, feed, speed, and type of tool, the hardness of the metal, the power applied to the machine, and so on. These results were plotted on graph paper, giving a set of geometric curves from which the proper speed of the lathe could be determined when the values of all other variables were known. This method of solving the roblem was, however, to slow and inconvenient for ordinary shop use. Barth . . . reduced the relationships discovered by Taylor and Gantt to a mathematical equation and transferred the functional relationships involved to specially made slide rules, which made it possible to determine the correct speed of a machine tool quickly and with all the accuracy required for practical use.[33]

Together with job analysis and time study, this systematization of machinery introduced a level of precision previously unknown. With the application of these concepts, work could truly be said to be standardized.

Taylorism at the Watertown Arsenal

The Watertown Arsenal, at the beginning of the twentieth century, employed some two hundred and fifty people in its machine shops and another fifty in its foundry. The general condition of the Arsenal at that time is described by Aitken.

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[32] Illustrated Machine-Tools of 1885 (Manteno, Ill.: Lindsay Publications, 1981), 68. From Hutton, F. R., Report on Machine-Tools and Wood-Working Machines (Washington: Government Printing Office, 1885).

[33] Ibid., 33.

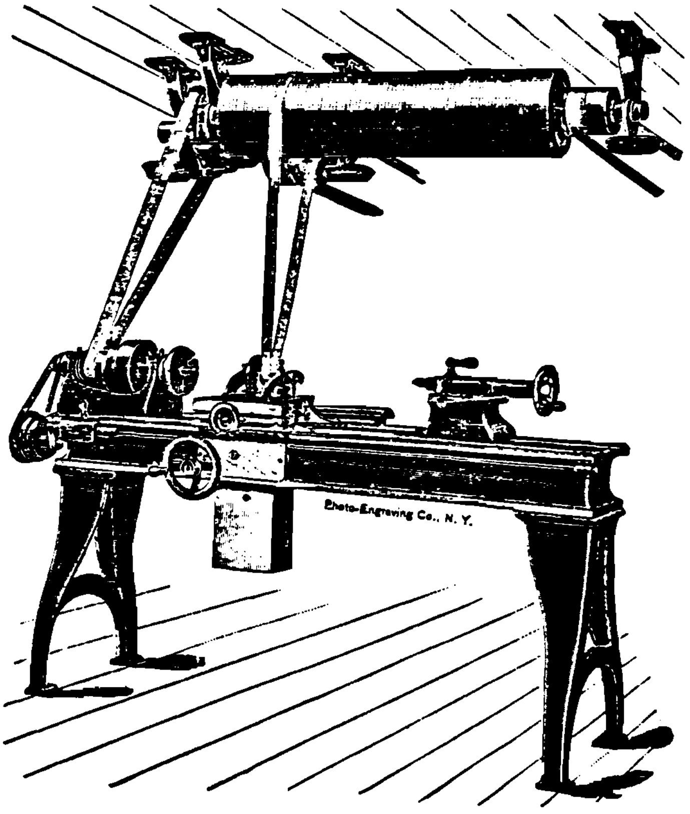

Figure 13: Belt-driven lathe, circa 1885.

> Forty percent of the machine tools had been in service for fifteen years or more, and many of them for over twenty years. All had been designed when carbon tool steel was the only type of tool steel available, and the system of belts and pulleys had been set up on that basis. Throughout the plant there was a serious shortage of small parts, such as belts, straps, and clamps. Handling facilities, such as cranes and trolleys, were inadequate. . . . (In the foundry) the only mechanical assistance available to the molders were two cranes and a few pneumatic rammers. For the rest, the work was entirely by hand. . . .
>
> . . . There was a headquarters office staffed by clerks, whose principal function was correspondence, and an engineering division, an innovation introduced . . . in 1908, which was responsible for the making of cost estimates, the preparing of blueprints, and similar tasks. . . . In the day-to-day operations of the arsenal the master mechanic and foreman were largely left to their own devices to allocate jobs and get out the work.

> . . . Apart from its organizational defects, the machine shop at Watertown was technically far from up-to-date in 1909. Into this machine shop there was introduced a major innovation, high-speed tool steel, probably the most revolutionary change in machine shop practice within the memory of anyone living at the time. . . .
>
> High-speed steel was no minor change which could be introduced in one section of the arsenal and then forgotten. The whole arsenal had to be geared to the pace which it set. (Colonel) Wheeler took a lathe which, using one of the old-style carbon steel tools, could be made to remove a maximum of two hundred pounds of metal from a casting in an eight-hour working day. He put a high-speed tool in the lathe and set it to work on the same job under the same conditions, except that the speed, feed, and depth of cut were altered to suit the new tool. The lathe removed precisely ten times as much metal--two thousand pounds--in the same period of time. This was probably an exceptional case, for the usual increase seems to have been 200 or 300 per cent.
>
> It was possible for a machine shop to purchase a stock of high-speed tools, use them in its metal-cutting operations, and yet continue to turn out work at much the same rate as before. . . . A shop which did this would find the results disappointing; the only obvious change would be that the tools would not need to be reground so frequently. To purchase high-speed tools was one thing; to use them correctly, so that their full potentialities could be realized, was another.
>
> A machine shop which adopted high-speed steel and knew what the new steel could do was faced with the necessity of a complete reorganization. First, few of the machine tools built to use the old steels could be run at the pace and with the power which the new steel demanded. Hence the necessity for rebuilding and redesigning machine tools, systematizing belt maintenance and repair, and increasing power capacity. Secondly--a considerably more intractable problem--few of the machinists and foremen who had grown up in the carbon steel era had any conception of what the new steels could do. Hence the necessity for Barth's slide rules and the prescribing _by management_ of speeds and feeds which, to men of the older generation, were literally fantastic. And third, since the use of high-speed steel meant very large reductions in machining times, handling times (the time taken to set up a job in the machine before machining and to remove it afterwards) came to represent a higher proportion of total job times.[34]

Hence the necessity to examine the labor component of work, specifically the uncertainty introduced by labor. System variance was due not so much to the accuracy and precision of machine tools as to labor's ability to reproduce a given procedure. Fortunately, Taylor paid as much attention to the procedures of manufacture as to the processes.

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[34] Aitken, H. G. J., _Taylorism at Watertown Arsenal_ (Cambridge: Harvard University Press, 1960), 86-87, 102-103.

After consulting with Colonel Wheeler, the superintendent of the arsenal, Carl Barth, a protege of Taylor, undertook a "complete reorganization of the whole shop management along the lines of the Taylor System," an endeavor that "fell into four parts or phases: (1) reorganization of the storeroom and toolroom, (2) creation of a planning room and establishment of a routing system, (3) respeeding and standardization of machine tools, and (4) installation of an incentive wage system based on time study and task setting."[15] Aitken elaborates.

> The first point of attack was the storeroom . . . . A new system for accounting for stores issued was instituted . . . to provide automatic checks against excessive or duplicate issues of materials. Barth also recommended the installation of the "double bin" system, whereby two separate but adjoining bins . . . were used for each article in store, one the receiving and the other the issuing bin. When all of the articles in the issuing bin had been distributed, it became the receiving bin and what had been the receiving bin became the issuing bin. As the bins were successively emptied, the tags showing all issues from them were sent to the property division, where they were checked against the stock sheets. This simple but highly effective system provided an automatic inventory of stores: the quantity of an article on hand was verified each time the issuing bin for that article was emptied.
>
> The tool room also was reorganized. . . . The toolmaking section was separated from the tool-issue section and a foreman appointed to supervise the manufacture and care of tools. . . . Orders (were) placed for the standard Taylor tool forging and -grinding equipment. . . . A special allotment (was made) . . . for the installation of tool-managing facilities. . . . (This) was supplemented . . . by a further allotment for the purchase of high speed tools . . . .
>
> An important series of changes made during the same period was the establishment of standard procedures for the inspection and maintenance of the belting which drove the machine tools. (Barth) recommended the purchase . . . of a . . . belt bench, a set of . . . belt scales, and a . . . wirelacing machine. . . . At the same time a special belt-maintenance gang was formed, and its foreman . . . sent for instruction. . . . A great deal of the old belting was replaced with new and in some cases heavier belting. This made it possible to run machines at higher speeds and with greater power, so that full advantage could be taken of the cutting powers of high-speed steel, and also prepared the way for Barth's later standardization of cutting speeds and feeds. By the end of April 1910 the belt-maintenance system was in full operation and belt failures during working hours had been practically eliminated.
>
> . . . It was decided that two . . . gun carriages should be the first products to be put through the machine shop 'under the Taylor system.' This

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[15] Ibid., 88, 91.

meant . . . that their manufacture would be routed from the planning room, since Barth had not yet begun his work on the machine shop and no time studies had been made. The two six-inch carriages were to serve as pilot projects, principally to give the planning room staff and the machinists their first taste of centralized routing.

A considerable amount of preparatory work was necessary. Assembly charts were drawn up, containing a detailed analysis of the operations required to produce each component that went into a complete gun carriage. On the basis of these charts the planning room decided upon the sequence of operations which each component was to follow, the dates at which each operation should be started and completed, and the order in which each component should be moved from workplace to workplace, up to final assembly. These individual analyses were then brought together on a single route sheet, which formed the master timetable for the whole project. . . . The route sheet was then turned over to clerks, who prepared the individual job cards, move tickets, and so on which would be required for the execution of the work. These cards, together with the master route sheet, were then passed to the route-sheet clerk, who filed them ready for use when required. . .

. . . By the middle of April 1910 practically all of the work in the machine shop was being routed from the planning room. . . .

While the planning room was getting into action, Barth took up the . . . rehabilitation of machine tools. This involved four principal phases: th diagramming of the individual machine tools, the rebuilding and redesigning of obsolete or unsuitable tools, the standardization of ancillary equipment, and the prescribing of speeds and feeds. . . . An extensive series of tests on different types of high speed-steel was conducted and, during a slack period of work early in 1910, the opportunity was taken to relocate a number of the machine tools, to bring together in one section of the shop all equipment of the same type. Several of the larger machine tools were provided with individual electric motors, while the smaller ones were arranged so that they could be driven in groups. . . .

Diagrams were prepared for all machines in the machine shop, showing the driving arrangement, feed gears, and so on. This process necessitated the measuring of all the machines, their gears and pulleys, and the study of the diagrams to insure uniformity and the proper relationships in their speeds and feeds. A considerable amount of redesigning and rebuilding was done, particularly of cone pulleys and gears, first on the lathes and then on the drills, planers, shapers, slotters, and other machines.

At the same time arrangements were made to standardize all the ancillary equipment used on the machine tools. The sockets for boring bars were standardized so that all boring bars would fit all sockets, and the slots in the faceplates of the lathes, planers, and other tools were cut to a single size. All the tee bolts were made to fit this standard slot, to avoid any delay in finding the right bolt for a particular job. To achieve uniformity in cutting tools, the workmen were forbidden to grind their own tools . . . . Instead, the toolmaking department was to forge and grind all tools to the standard Taylor specifications and by the use of Taylor-designed equipment. The tool posts on the lathes were altered and strengthened so that they could be used with these tools.

From August 1910 until . . . June 1912, Barth spent four days each month at Watertown. These monthly visits were entirely taken up by work on the preparation of slide rules for the machine tools and in instructing the planning room in their use. . . .

(Dwight) Merrick was hired to carry out time studies, by means of a stop watch, of the various jobs in the machine shop and to teach time-study work to certain members of the planning room staff. These time studies had three chief purposes: (1) to simplify work by the elimination of superfluous motions, (2) to set a standard time in which each job ought to be done, and (3) to provide the basis for a payments scheme which would furnish an incentive for the workmen to do the job in the standard time. Merrick's work was essentially an extension of the improvement and standardization work which Barth had begun. What Barth had done for the machines, Merrick was now to do for the men.

. . . Merrick's task was considerably more complicated than anything Barth had undertaken. Barth could examine a machine tool, change its gears and its belting, and reset it to run at a higher speed in complete confidence that the machine would do what he wanted it to. But Merrick had to take some account of the fact that the men would not work at the pace he prescribed unless they wished to do so. He had to face the problem of motivation.

The answer which the Taylor system provided to this problem was an incentive-payments scheme. If you wanted men to work at a certain pace, you promised them a financial reward if they did so; the problem was no more complicated than that. . . .

Taylor doctrine did not entirely overlook the possibility that the introduction of time study in a plant might cause trouble. The stop watch had not yet become a symbol of all that was detestable to organized labor in the Taylor system . . . but it was already realized among the Taylor disciples that the purposes of time study could easily be "misunderstood" . . . . It was considered vital that no time studies be attempted until all working conditions had been brought up to a high level of efficiency and standardized at that level. There were two reasons for this. First, if conditions were not standardized, then the job itself was not standardized and could not be scientifically timed. It would serve no purpose to set a time on a job today if tomorrow the machine might be running at a different speed, or if the workman had to wait around at the window of the storeroom until his material was ready, or if he had to leave his machine idle while he ground his tools. And secondly, it was believed that there would be less resistance to time study if the men being timed had grown accustomed to seeing a whole series of changes being made in their working conditions, all of which made their work easier. . . .

> . . . Unlike other parts of the Taylor system which, as soon as they were installed, affected the organization and operation of the entire shop, time study was introduced gradually and almost imperceptibly. . . .
>
> . . . Merrick continued in regular employment at Watertown until June 1913, by which date several of the arsenal's employees had been trained to take his place as time-study experts. By the end of June 1913 . . . the Taylor system at the arsenal was on a self sustaining-basis. . . . It was the arsenal's regular system, and all that remained was to extend and complete it.[36]

In 1900, Frederick Taylor and Maunsel White demonstrated their high-speed, chromium-tungsten steel at the Paris Exposition.[37] Though it ran red hot, the metal did not soften or dull. As the structure of the machines at that time could not withstand the stresses induced by the forces of running so hot, heavier machines, five times as powerful, were built to exploit this innovation. Taylor and White took Europe by storm, and soon Taylor's notions of scientific management were well publicized. The ascendancy of the American System of Manufacture and its culmination in the Taylor System were now well known. By the turn of the century, the leading engineering journals were full of the new gospel and supporting their preachments with examples of successful innovation.

Beretta's Belated Adoption of Taylorism

Taylorism arrived late at Beretta. With the death of Giuseppe on 24 June 1903, Pietro Beretta became head of the firm, a position he held until his own death in 1957. The latter Beretta greatly enlarged the factory, equipped it with the most modern equipment, and brought out many innovative products. Under his direction, the firm rose to international prominence in less than three decades.

Beretta installed three hydroelectric plants on the Mella River, the first in 1908 and the last in 1939, which continue to contribute to the firm's energy requirements to this day. With the availability, after about 1910, of machine tools capable of using high-speed steel, Beretta gradually began renovating the equipment in his plant (see Figure 14).[38]

Then, a sharp decline in demand for sporting rifles in the years preceding World War I created a crisis among the manufacturers in the Trompia Valley. In the lull before the storm, Beretta and his chief engineer, Tullio Marengoni, threw themselves actively into the development of new designs. A patent entitled

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[36] Ibid., 95-101, 106-107, 110, 112, 119.

[37] Landes, D. S., The Unbound Prometheus, (Cambridge, England: Cambridge University Press, 1969), 297.

[38] Morin, M., and R. Held, Beretta: The world's oldest industrial dynasty (Chiasso, Switzerland: Acquafresca Editrice, 1980), 230. From the last pre-war Beretta catalogue.

Figure 14: The Beretta factory, circa 1939-1940.

"Innovations for Automatic Pistols," obtained by Beretta in 1915, was the conceptual cradle for a family of weapons that would make the company renowned the world over. Although with the war production of military arms shot up, there was no physical expansion of the facility. Some modern machines were added, but Taylorism did not take hold at Beretta until the late 1920s. From 1919 until 1922, life in Italy was torn and threatened by all manner of violence. Beretta was one of the few factories in Brescia that was not taken over by rebellious workers during this time.

Rationalization of production was the talk of Europe in the 1920s. Although the teachings of Taylor and Fayol found a receptive ear in Pietro Beretta, Taylorism was not adopted at the Beretta factory until 1928, when machinery acquired from the firm Fabbrica d'Armi Lario (called FALC), in Camerlate, near

Como, was transferred to Gardone, necessitating a reorganization of the plant and layout. The size of the firm subsequently doubled, and with the increased scale came the functional specialization of Tayorism.

The Ethiopian war of 1935 and Italian intervention in Spain the year after brought a flood of large orders for Beretta's highly successful automatic pistol, the Model 34. Taylorism and mass production of the Model 34 fit well together, and the new organizational form took hold at Beretta.

It is difficult to say whether Beretta's rapid growth resulted from the implementation of Taylorism, or from the requirements for mass production of the Model 34, which led naturally to the introduction of Taylorism. Indeed, it may be that there is no connection at all. But occur together they did, and the result was a dramatic increase in labor productivity. Methods engineering was introduced and, though the size of the work force only doubled, the size of the staff group increased three-fold. Most of the impact of methods engineering was in the reduction of rework, which dropped from 40% to 25%.[39]

At Beretta, as elsewhere, the ethos of work was fundamentally altered by Taylorism. In the Beretta factory separation of line and staff was complete; the stop watch, the efficiency expert, and productivity measures were there to stay. Though belatedly, Taylorism had met Beretta and now they were one.

Let us now examine the changes wrought by the Taylor system on the work station and process control at the work station.

(1) The scope of work was restricted under the Taylor system. Material handling, tool sharpening, belt tightening, oiling machinery, work set-up, and other secondary activities were no longer done by the operator but by specially trained people, each of whom performed only a single function. Such functional specialization was not new. It extended to secondary operations a concept begun with the American system of manufacture.

(2) Worker discretion was eliminated. The Barth slide rule specified exactly how an operation was to be performed and tasks were set by an "efficiency expert." Work was broken down into small parts and standardized. There was "one best way" to perform a task, which was specified by an outside observer, and the worker's sole responsibility was to execute the procedure that constituted that one best way. System variance was reduced by eliminating worker discretion and making the task reproducible. This was Taylor's lasting contribution.

(3) Control of work was now in the hands of management, which could compare the quantity of work performed against a predetermined standard and monitor worker effort. Much has been written on the aspects of management control

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[39] It should be noted that 40% rework does not mean that 40% of the parts were rejected. If only 10% of the parts were rejected, but it took four times as long to repair them, we would have 40% of total work as rework.

of work and the setting of standards. Senate testimony on Taylorism at the Watertown Arsenal documents much of the resulting antagonism between management and labor.[48]

With Taylorism, we had crossed another intellectual watershed--the study of procedure of manufacture independently of the process of manufacture. How one set up a tool on a machine was largely independent of the process, hence, tool set-ups could be studied in their own right. The efficient layout of a plant was now independent of what was made. Such separations gave rise to the field of Industrial Engineering, which was quite distinct from its parent, Mechanical Engineering.

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[48] Hearings before the Special Committee of the House of Representatives to Investigate the Taylor and Other Systems of Shop Management (3 vols., 62nd Congress, 2nd session, Washington, D.C., 1912).

THE DYNAMIC WORLD -- STATISTICAL PROCESS CONTROL

In the 1950s, following the establishment of NATO, Beretta was licensed to manufacture the semi-automatic Garand M-1 rifle. A decade earlier, the Garand had transformed the manufacturing system at the Springfield Armory. It would do the same at Beretta, but with a difference.

Most of the equipment at Springfield when it received the contract to manufacture Garands was of World War I vintage. Because the armory had lagged behind in the adoption of the new technology, which emphasized the integration of multiple operations in a single machine, a massive program of equipment renovation and plant modernization had to be undertaken. (See Figure 15 for photos of the machinery used to manufacture the Garand at Springfield,[1] and Figure 16 for an illustration of the machining operations required on a particular piece.)[2]

Beretta's contract, coming a decade later, after the Second World War, had an impact that went beyond the renovation of equipment. The M-1 required tolerances greater by an order of magnitude than any the company had previously experienced, and the specified degree of interchangeability of components was 100%. Machines for producing the Garand had to possess both accuracy and precision. Beretta chose to build its own machines on principles established by Garand. As Beretta was not a machine tool builder, this experience exerted a profound influence on both the company's manufacturing system and its organization of production.

Monitoring Variation and Its Sources

Because the machines that Beretta built did not have the process capability of, for instance, the Kingsbury multi-station machines for drilling and reaming, the machining process had to be constantly monitored for any deviation from the prescribed process settings. Machines with a tendency to "wander" demanded a new technique to enhance process capability. Thus it was that statistical process control, invented in the United States in the 1930s, was adopted by Beretta before it was ever used at the Springfield Armory.

Though it seemed, at the time of its introduction, an innocuous enough change, statistical process control (SPC) radically altered the organization of work at Beretta. Meant to ensure process stability, SPC required only that process behavior for a sample of parts be recorded on charts at specified intervals of time. Yet we shall see how, over a period of only five years, it

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[1] Modern Small Arms (Cleveland, Ohio: Penton Publishing Co., 1942), 8, 11.

[2] Gun Manufacture (New York: McGraw-Hill, 1942), 121.

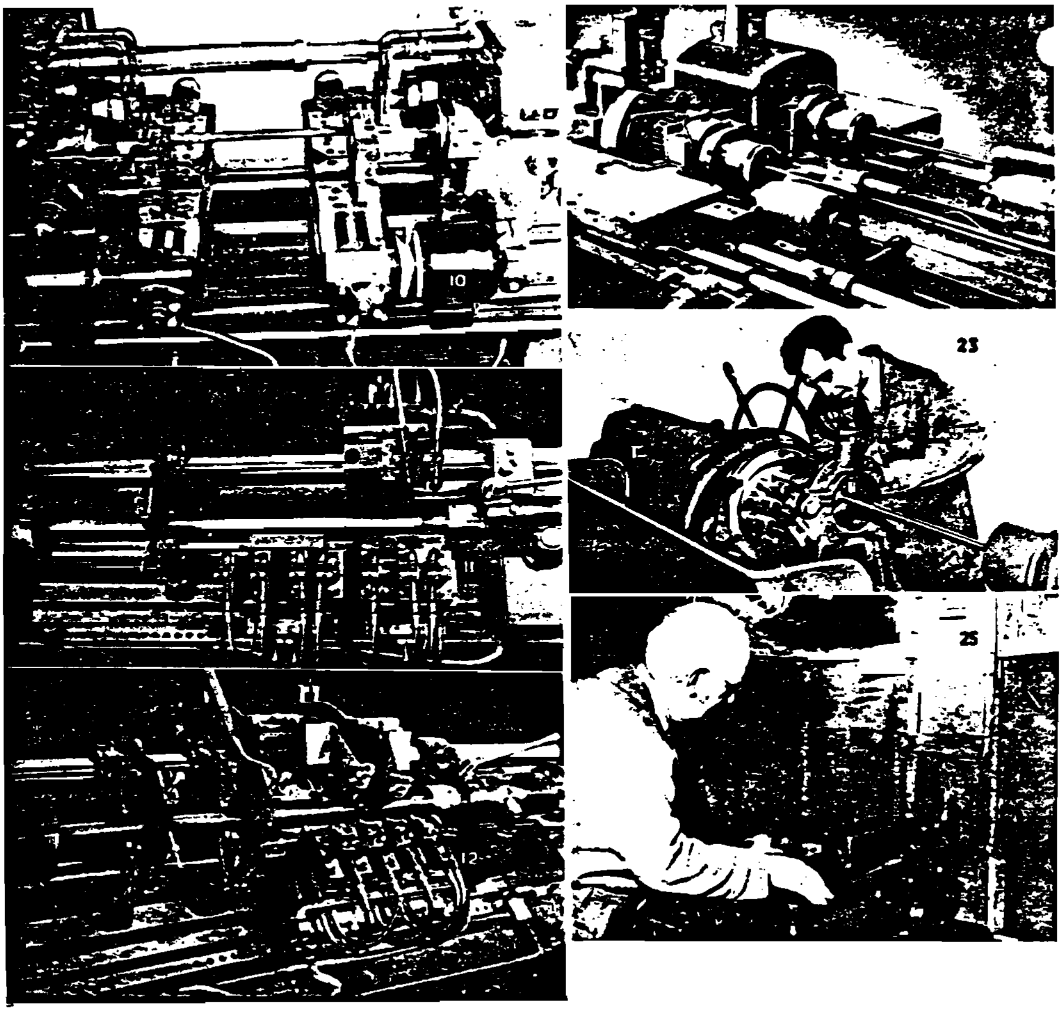

Figure 15: Machinery at the Springfield Arsenal for milling (10), rough turning (11 and 12), rifling (22), chambering (23), and testing (25) the Garand M-1.

Figure 16: Sequence of machining operations for the Garand safety.

changed the ethos of manufacturing management at Beretta and with it the organization of work.

Before the Garand, rifle parts were, almost without exception, made by means of a tedious succession of single machine cuts supplemented by hand operations. Tolerance requirements for a variety of operations on the M-1, as can be seen in the operations sheet (Figure 17), are .001 inches.[3]

Finish reaming and rifling operations, for example, require that particular attention be paid to tool sharpening. The reamer is ground dry on a standard tool and cutter grinder with a grit wheel that removes .001 inch of material at the rate of .0002 inches per pass. Bore and grooves must be absolutely smooth, to a tolerance of .001 inch. The dimensions of both are inspected at every inch along the length of the barrel by means of star gauges, gauges with expanding fingers that transfer their readings to a vernier caliper at the end of a long rod. A spring attached to the star gauge ensures uniform pressure when expanding the measuring points, thus eliminating variations due to the inspector's touch. Fixtures devised to facilitate production included the use of multiple set-ups, quick clamping arrangements, and special indexing devices.

Beretta, when it commenced manufacture of the Garand, had the advantage of hindsight--a decade of experience at Springfield. In electing to build its own fixturing, gauging, and tool systems, the company was effectively blazing a new trail in high precision manufacture. Although the machines Beretta built could hold the required tolerances, they had to be constantly monitored to prevent excursions from the process limits. This is where statistical process control came in.

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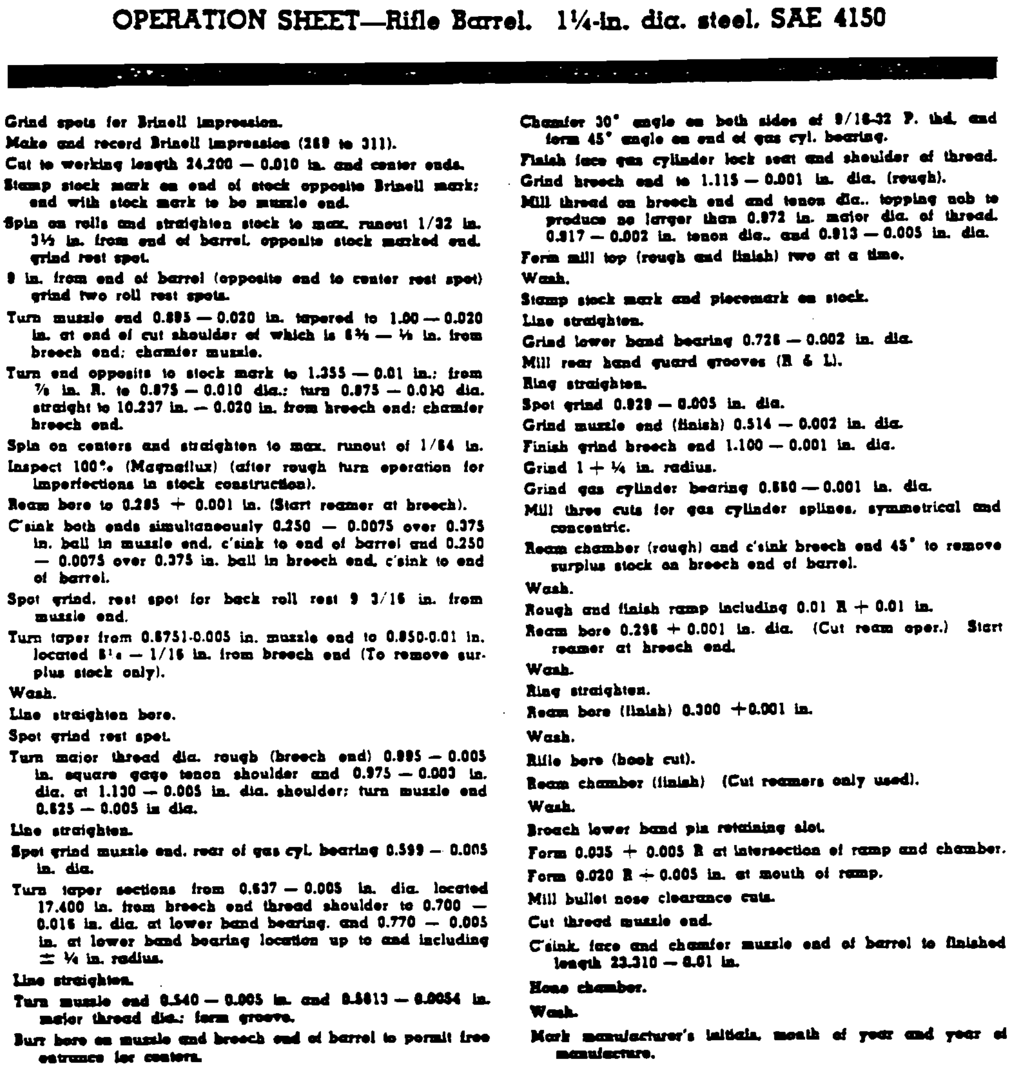
[3] Gun Manufacture (New York: McGraw-Hill, 1942), 117.



OPERATION SHEET—Rifle Barrel. 1¼-in. dia. steel. SAE 4150

Grind spots for Brinell impression.

Make and record Brinell impression (269 to 311).

Cut to working length 24.200 — 0.010 in. and center ends.

Stamp stock mark on end of stock opposite Brinell mark; end with stock mark to be muzzle end.

Spin on rolls and straighten stock to max. runout 1/32 in. 3½ in. from end of barrel, opposite stock marked end. grind rest spot.

9 in. from end of barrel (opposite end to center rest spot) grind two roll rest spots.

Turn muzzle end 0.895 — 0.020 in. tapered to 1.00 — 0.020 in. at end of cut shoulder of which is 6¾ — ⅛ in. from breech end; chamfer muzzle.

Turn end opposite to stock mark to 1.355 — 0.01 in.; from ⅞ in. R. to 0.875 — 0.010 dia.; turn 0.875 — 0.010 dia. straight to 10.237 in. — 0.020 in. from breech end; chamfer breech end.

Spin on centers and straighten to max. runout of 1/64 in.

Inspect 100% (Magnaflux) (after rough turn operation for imperfections in stock construction).

Ream bore to 0.285 + 0.001 in. (Start reamer at breech).

C'sink both ends simultaneously 0.250 — 0.0075 over 0.375 in. ball in muzzle end, c'sink to end of barrel and 0.250 — 0.0075 over 0.375 in. ball in breech end, c'sink to end of barrel.

Spot grind, rest spot for back roll rest 9 3/16 in. from muzzle end.

Turn taper from 0.8751-0.005 in. muzzle end to 0.850-0.01 in. located 8¼ — 1/16 in. from breech end (To remove surplus stock only).

Wash.

Line straighten bore.

Spot grind rest spot.

Turn major thread dia. rough (breech end) 0.995 — 0.005 in. square gage tenon shoulder and 0.975 — 0.003 in. dia. at 1.130 — 0.005 in. dia. shoulder; turn muzzle end 0.625 — 0.005 in dia.

Line straighten.

Spot grind muzzle end, rear of gas cyl. bearing 0.599 — 0.005 in. dia.

Turn taper sections from 0.637 — 0.005 in. dia. located 17.400 in. from breech end thread shoulder to 0.700 — 0.016 in. dia. at lower band bearing, and 0.770 — 0.005 in. at lower band bearing location up to and including ± ¼ in. radius.

Line straighten.

Turn muzzle end 0.540 — 0.005 in. and 0.5813 — 0.0054 in. major thread dia.; form groove.

Burr bore on muzzle and breech end of barrel to permit free entrance for centers.

Chamfer 30° angle on both sides of 9/16-32 P. thd. and form 45° angle on end of gas cyl. bearing.

Finish face gas cylinder lock seat and shoulder of thread.

Grind breech end to 1.115 — 0.001 in. dia. (rough).

Mill thread on breech end and tenon dia., topping nob to produce no larger than 0.972 in. major dia. of thread. 0.917 — 0.002 in. tenon dia., and 0.913 — 0.005 in. dia.

Form mill top (rough and finish) two at a time.

Wash.

Stamp stock mark and piecemark on stock.

Line straighten.

Grind lower band bearing 0.728 — 0.002 in. dia.

Mill rear hand guard grooves (R & L).

Ring straighten.

Spot grind 0.929 — 0.005 in. dia.

Grind muzzle end (finish) 0.514 — 0.002 in. dia.

Finish grind breech end 1.100 — 0.001 in. dia.

Grind 1 + ¼ in. radius.

Grind gas cylinder bearing 0.880 — 0.001 in. dia.

Mill three cuts for gas cylinder splines, symmetrical and concentric.

Ream chamber (rough) and c'sink breech end 45° to remove surplus stock on breech end of barrel.

Wash.

Rough and finish ramp including 0.01 R + 0.01 in.

Ream bore 0.296 + 0.001 in. dia. (Cut ream oper.) Start reamer at breech end.

Wash.

Ring straighten.

Ream bore (finish) 0.300 +0.001 in.

Wash.

Rifle bore (hook cut).

Ream chamber (finish) (Cut reamers only used).

Wash.

Broach lower band pin retaining slot.

Form 0.035 + 0.005 R at intersection of ramp and chamber.

Form 0.020 R + 0.005 in. at mouth of ramp.

Mill bullet nose clearance cuts.

Cut thread muzzle end.

C'sink, face and chamfer muzzle end of barrel to finished length 23.310 — 0.01 in.

Hone chamber.

Wash.

Mark manufacturer's initials, month of year and year of manufacture.

Figure 17: Operations sheet for Garand rifle (Springfield Arsenal).

The principles of statistical process control assume that machines are intrinsically imprecise, that is, that an identical procedure will produce different results on the same machine at different times. The degree to which the results vary will depend on the capability of the machine to maintain precision. The variation will always be more or less, but never zero.

The sources of variation are of two kinds, random and systematic. Systematic sources of variation produce errors that have an assignable cause and introduce a particular bias. Tool wear, for example, leads to less metal reduction in subsequent pieces as the amount of tool feed gets smaller. Random sources of variation produce errors that, due to a multiplicity of causes, can be neither observed nor controlled.

If we can observe a process and identify when a systematic error occurs, we can assign a cause and make the necessary correction. This observation can be accomplished by using a <u>control chart</u> (Figure 18).* The control chart is based on the premise that all random processes have a particular pattern. The frequency distribution of a given dimension, for instance, might be expected to follow, in statistical parlance, a normal distribution in which 99.5% of all measurements will fall between two limiting values, called confidence limits, that lie three standard deviations above and below the average value of the distribution. When the dimension falls outside the defined limits (i.e., an "out-of-control" situation is encountered), there is a high probability that the excursion is due to a systematic error for which we can try to find an assignable cause. Having identified the cause, we can then take corrective action and bring the process back under control.

The control chart is an attention focusing mechanism. It selectively presents, to an operator who has a number of different things to attend to, only those situations that are critical and require immediate attention. Introduced by an engineer on the frame line at Beretta, it reduced rejects dramatically, from 15% to 3%.

It might be helpful, at this point, to clarify the concepts of process capability and process stability. The precision a machine is capable of is, as noted above, defined by the standard deviations of the random variation in its performance. It is a property of the machine. The tolerance required by workpiece might be more or less than a machine is capable of achieving. Process capability is the relationship between the precision of the machine and the tolerance required by a workpiece. A common measure of process capability is defined by the ratio: tolerance/6 * the standard deviation. Process stability refers to the frequency with which a process goes out-of-control. It is a measure of machine reliability, and is unrelated to process capability. A machine might be very capable but unreliable, or vice versa.

At Beretta, machine reliability was being monitored and measured by the mean time between systematic errors. (See Figure 19.) As systematic errors have assignable causes, and as the control chart focuses attention on every possible assignable cause, one is led naturally to <u>manage contingencies</u> in the process.

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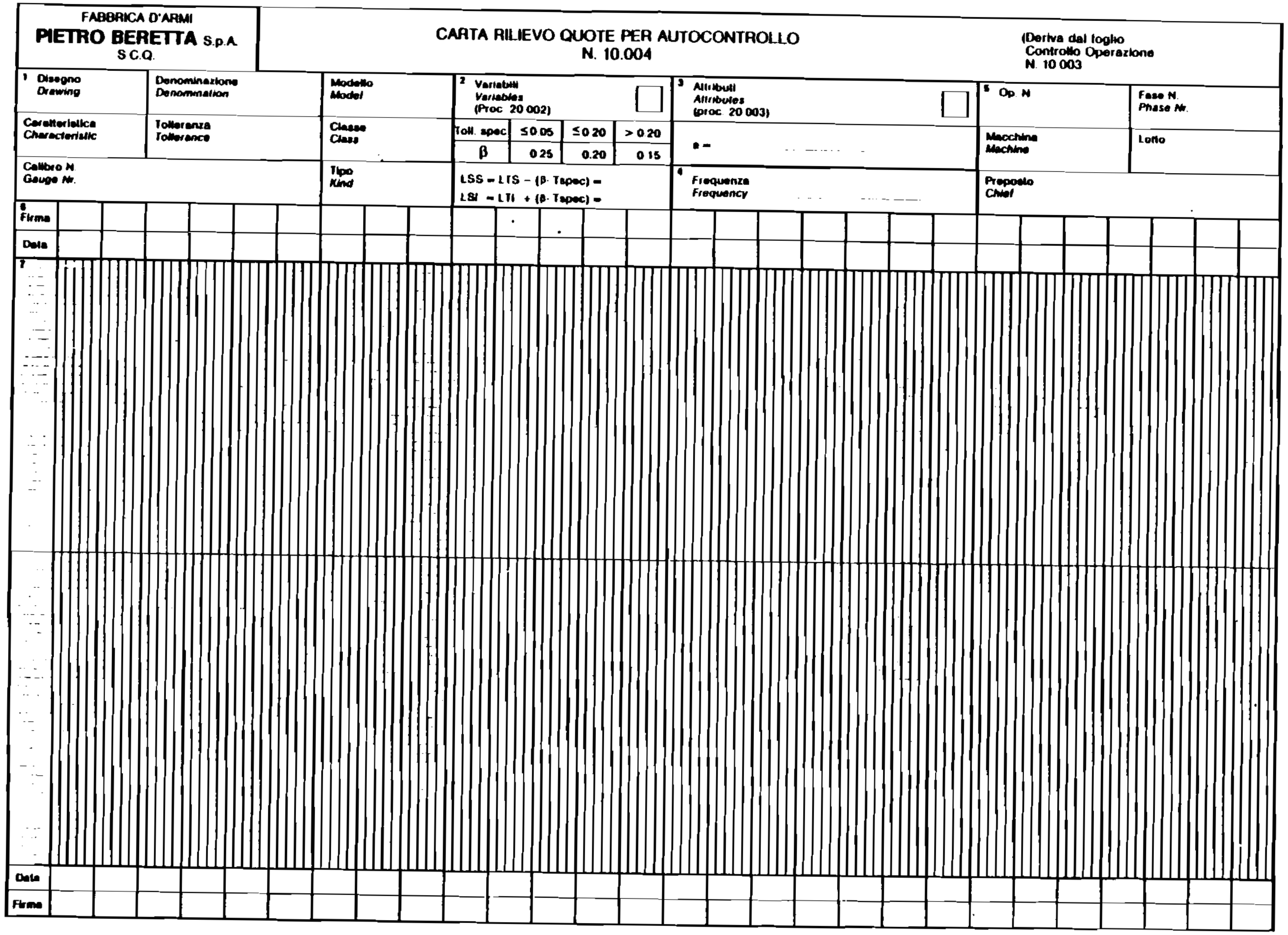
*Source: Pietro Beretta, Gardone, Italy.



FABBRICA D'ARMI
PIETRO BERETTA S.p.A.
S.C.Q.

CARTA RILIEVO QUOTE PER AUTOCONTROLLO
N. 10.004

(Deriva dal foglio
Controllo Operazione
N. 10 003

1 Disegno *Drawing*

Denominazione *Denomination*

Modello *Model*

2 Variabili *Variables* (Proc. 20 002) ☐

3 Attributi *Attributes* (proc. 20 003) ☐

5 Op. N

Fase N. *Phase Nr.*

Caratteristica *Characteristic*

Tolleranza *Tollerance*

Classe *Class*

Toll. spec	≤0.05	≤0.20	> 0.20
β	0.25	0.20	0.15

a =

Macchina *Machine*

Lotto

Calibro N. *Gauge Nr.*

Tipo *Kind*

LSS = LTS − (β· Tspec) =
LSI = LTI + (β· Tspec) =

4 Frequenza *Frequency*

Preposto *Chief*

6 Firma

Data

7

Data

Firma

Figure 18: Process control chart used by Beretta.

To reduce the mean time between systematic errors one needed to find ways by which the sources of the errors could be eliminated. The application of SPC provided one way by which errors could, over time, be observed, better understood, and eventually solved. Manufacturing's evolution from an art to a science now included a systematic way of learning by doing.

The success of the method on the frame line led to its use in other areas; over a five year period, process control charts were introduced at more than eighty stations. All critical operations employed a process control chart and an operator responsible for monitoring the process.

Let us consider the work station for a moment. With statistical process control, day-to-day management attention was redirected from the quality of a product to the performance of a process. Concern was no longer with mean performance, but with the "outliers," the out-of-control situations; not with worker effort, but with machine variance. Inasmuch as semiautomatic machines controlled the pace of operations anyway, the shift in focus from worker effort to machine variance would seem rational. Yet Beretta was unique among small arms manufacturers in making this shift in operations. We will shortly see why.

Semiautomatic machines automated tool movement, thus reducing labor in manufacture. They also separated the work of operator and machine, enabling each to perform different functions independently of one another. This provided operator slack, which could be used either to monitor the machine or to operate more than one machine. The inclination to increase labor productivity would suggest that an operator be assigned two machines; while one machine is busy cutting metal, the operator could be setting up the second. This was the strategy adopted at Springfield for Garand production.

Such a strategy is reasonable as long as machines are extremely reliable (i.e., the mean time between defects is large). When this is not the case, when we have machines subject to periodic excursions from the process parameters, we not only experience greater rates of rejects and downtime, but contingencies on one machine affect the production output of others. During the early years of Garand production at Beretta, operator slack time was occupied by statistical process control tasks for all critical operations.

If the volume of output is controlled by the speed of the machine and the only controllable element at a work station is the minimization of problems with the machine, operator attention quite naturally should be on the stability of the process. That processes change over time is implicit in such an ethos of work. The essence of a process is its dynamic characteristics. This is in stark contrast to the earlier Taylor view, which cast all problems in essentially static terms. In the Taylor world, there was "one best way" to do something and, having specified it, work was defined by performing it in that way forever more. In the dynamic view, work is defined in terms of identifying problems and diagnosing and solving for them. Supervision of work in a dynamic environment consists not in monitoring effort but in facilitating change.

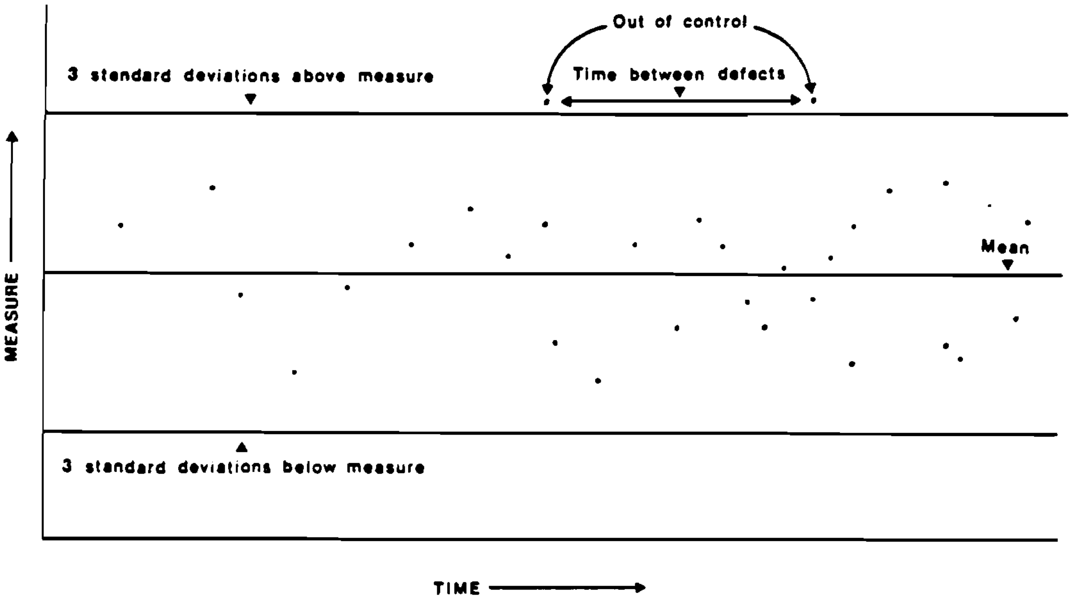


Figure 19: Mean time between systematic errors.

The Quality Control Function

What began as means for controlling rejects on Beretta's frame line became, over a period of five years, a new system of manufacture. Quality Engineering replaced Industrial Engineering as the dominant ethos. Now, for each phase of the production process, the Quality Control Service established:

- points in the production process requiring intervention;
- instruments to be used;
- norms to be followed in identifying and correcting deviations;
- procedures for determining the costs of quality control, scrap, and re-work; and
- responsibility and authority of the individual to whom the controls were entrusted.

Quality Control was responsible for quantitatively measuring the natural variability of every machine and the degree of fidelity of every tool, verifying tool conformity to design, and identifying possible causes of systematic error. Through a statistical analysis of the collected measurements (Gauss distribution and confidence limits) the natural tolerance of a machine could be calculated and registered and a control method designed for accepted processes.

The quality control system that was established included: frequency of measurement of particular dimensions during manufacture; estimation procedures of process performance, together with methods of diagnosis, if warranted; and procedures for correction of the process by operators, as well as conditions under which machines should be stopped and examined by Quality Control. A quality control supervisor was responsible for eight to ten machines and for day-to-day control of the process in the plant. There were three other staff groups in Quality Control:

- o Testing, which was responsible for certifying product quality and ensuring conformance to product specifications;
- o Metrology, which was responsible for the control of tools, the calibration of measuring instruments, and preparation of control instruments; and
- o External Supply Control, which was responsible for the control of raw materials and partially completed products supplied by outside vendors, as well as for selection of outside vendors.

As might be expected, scrap and rejects were dramatically reduced--from 25% to 8%. Labor productivity improvements were not that significant, 25% over five years, and capital intensity was unchanged. In light of this, one might question our characterization of this change as a revolution.

From a Static World to a Dynamic One

The intellectual history of process control had seen a shift from a static world view to a dynamic one, in which continual change and improvement were the raison d'etre of management. If constant improvement was the focus of management attention, why didn't such improvement translate into productivity or quality improvements? The answer lies in the performance specifications of the products themselves, and the introduction of new products with ever greater tolerance requirements. Consider the Garand. Beretta was able to improve upon this rifle with a new calibre barrel, a new type of magazine and feeding system, and a new sear, called the BM-59, that allowed fully automatic fire upon selection. This arm was adopted by the Italian Army in three different versions.

Though labor productivity was little changed at Beretta, several characteristics of manufacture changed in fundamental ways. The composition of the work force changed, with quality control becoming an integral part of manufacture and commanding a larger staff. The staff line ratio went from 60:240 to 100:200. The organization of work changed, with production of each major component organized as a synchronous transfer line. The barrel line, for example, became a synchronous shop with twenty-four people, nine of them quality control personnel.

A synchronous line is one in which all of the operations required to manufacture a component are rationally laid out, with sequential operations located next to one another on the shop floor. Buffer inventories between operations are kept very small (equal to one hour or less of work). Throughput time, that is, the time between the start of the first operation on a workpiece and the completion of the last, is greatly reduced by synchronous lines. Because throughput time is short, problems can be caught quickly and corrected before a lot of pieces requiring rework are created. One obvious benefit is that the quality of components is improved. Another, more subtle benefit is that diagnosis and problem solving is now carried out by examining the work station not in isolation but as part of the entire system.

Consider a problem at operation 5 in a process whose assignable cause is at operation 3. In a conventional shop with a lot of buffer inventory, the prior stations might be working on different batches of products and may have had a new set-up, while the batch of products having the problems might have been made on a different shift. Looking for assignable causes in such an situation would likely be fruitless, as the circumstances under which the problem arose would have changed. In a synchronous line with low buffer inventories, one can examine the entire system for the causes of problems. While this increases the scope of the problem solving domain, it also involves more than one operator (i.e., a team) in the problem solving effort. A shift in the organization of work has occurred. Now when the search for assignable causes and solutions for a problem calls for a team effort, a team can be brought to bear.

Together, synchronous lines and statistical process control drive an organization towards an ethos of process improvement that includes a view of an integrated process. Latter day advances in similar concepts, such as Just-in-time production in Japan, have amply demonstrated the success and radical transformation of work wrought by such systems.

Let us now contrast with those effected by earlier innovations the principal changes in the nature and organization of work brought about by the introduction of statistical process control.

(1) As we noted earlier in the discussion of Taylorism, the management of work was the management of effort. With statistical process control it shifted to management of attention. It was the "outliers" in a process that were now of interest to management; only by attending to these could one hope to improve productivity or quality. Attention, a cognitive ability, stressed information processing and diagnostic skills. Learning about outliers could only take place when problems were recognized, described, and solved, and this, of necessity, could only take place at the work station with the help of the operator. Discretion and control of work, which were earlier removed from the operator, were restored.

(2) Under Taylorism, besides the obvious management task of making sure procedures were executed as planned, the principal management task was coordi-

nation. With functional specialization of labor, one had to be a concert master to ensure that the firm, as a whole, functioned efficiently. The planning center, which served this coordination function, was the nerve center of productive activity. With SPC, the Quality Control department took over the principal functions of manufacturing management. Concern for schedules and production output was subordinated to concern for quality and process improvement.

(3) The synchronous line forced an integrated view of the entire system of manufacture. Whereas the intellectual underpinnings of Taylorism were reductionism and specialization, that of SPC in a synchronous line was integration.

(4) Information management of process parameters was institutionalized. With the introduction of SPC there was, for the first time, explicit recognition and separation of the information about operating process parameters and the physical processing of material. The separation of information about a procedure from the procedure itself was the intellectual watershed crossed by statistical process control. Now it was possible to observe and study the efficacy of procedures.

It would not be very long before one could completely separate information processing from material processing. This would come in the form of the next technological breakthrough, numerically controlled machines.

THE NUMERICAL CONTROL ERA

Beretta acquired its first numerically controlled (NC) machines in 1976. These machines functioned automatically, performing operations and changing tools according to numerically coded instructions. Although this technology had begun to spread through Italy at the beginning of the decade, its presence was isolated. Its primary users were companies that manufactured small quantities of products of high value. With the introduction of microprocessors, controllers went down in cost and up in reliability, making NC technology viable for large scale use. Beretta introduced these systems into the high volume production (200 to 400 pieces per day) of small- to medium-size products.

Beretta regarded the automation of tool changing, which meant that what had formerly been accomplished with a transfer line could now be accomplished with a single machine, as the single most significant benefit of NC technology. The NC machines (see Figure 20),[1] which combined the versatility of general-purpose machines and the productivity of special-purpose machines, also overcame limitations imposed on particular components by the specialization of transfer lines. But they were expensive. At the time, the best Beretta was able to obtain was a four-year payback, and some had an eight-year payback.

"As you can see," said company president Ugo Beretta, "it was not what you would call a brilliant investment. But we had to do it sometime. We could have waited, but we could not turn back the clock. It was a very new technology, with electronics and computers, and we had to understand it. Instead of waiting, we decided we would go ahead and buy a machine tool company and learn the new technology. So we bought MIVAL, a small machine tool company with expertise in this field."[2]

Numerical Control had evolved out of a program funded by the United States Air Force in the late 1940s. Although the first commercial products were offered a decade later, there was no significant penetration of NC systems until controllers became more economical and reliable in the 1970s. A shift in the essence of NC control--from coded tapes and hard-wired decision circuits to executive software and microprocessors--simplified the operation and programming of NC systems and made machine tool control faster and more flexible.

The work cycle of NC machines--the set of motions that determines the selection of tools, their proper positioning in three dimensions relative to a workpiece, the feeding of workpieces, the flow of coolant, etc.--is recorded as a series of codes on punch tapes, magnetic tapes, or in semiconductor memories. Played back, these instructions put an NC machine through its paces, be

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[1] Source: Advertising brochure, Pietro Beretta, Gardone, Italy.

[2] Personal communication.

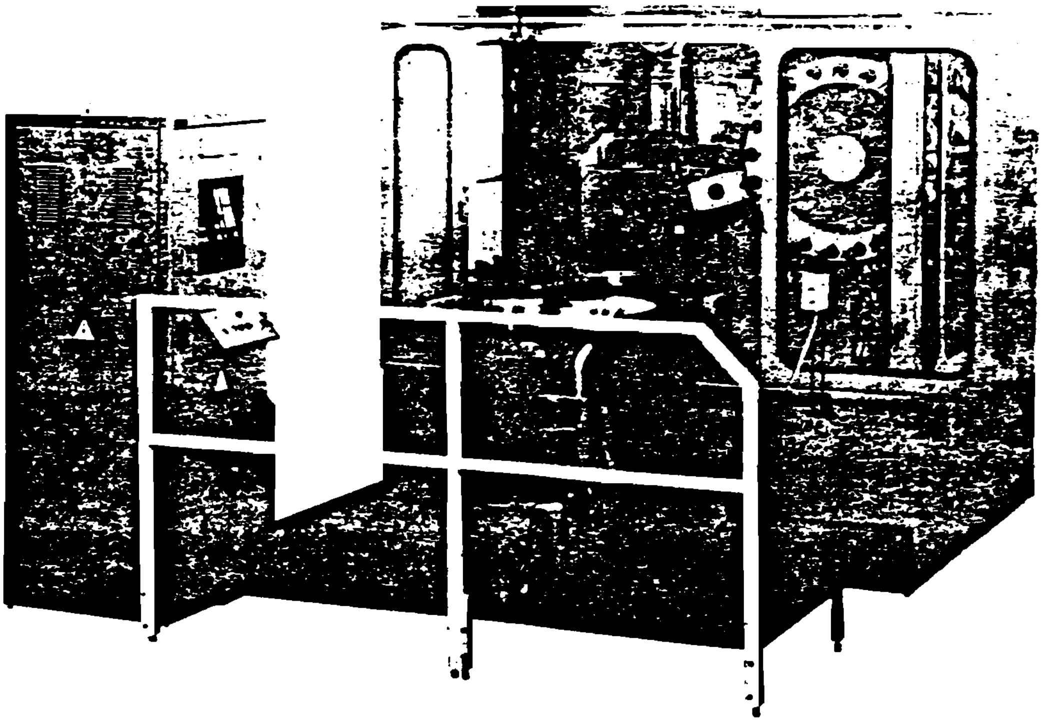

Figure 20: MIVAL horizontal machining center.

they drilling, grinding, cutting, punching, milling, or some combination of these.

The motions a machine tool must go through to produce a part are described in detail, mathematically, in accordance with the blueprint specifications of the part. This reduces the entire process of producing a part, including the skill of the machinist, to a formal, abstract expression, which, when coded and translated by a microprocessor, activates a machine's controls. Every movement, however slight, has to be formally, explicitly, and precisely articulated. With such programmable automation, a switch in products no longer entails physical set-up changes to retool or readjust the configuration of the machines, only a switch in programs. Thus, NC technology combines the versatility of general purpose machines with the precision and control of special purpose, or self-acting, machines.

"In the past," observed <u>The American Machinist</u> in 1973,

> humans were both translators and transmitters of information: the operator was the ultimate interface between design intent, as incorporated in a drawing or instruction, and machine function. The human used mental and physical abilities to control machines. Today, computers are increasingly becoming the translators and transmitters of information, and numerical control is perhaps most representative of the kind of control that plugs into the greater stream with a minimum of human intervention. Historically, numerical control certainly has been the most significant development of the electronic revolution as it affects manufacturing.[3]

Advanced control techniques variously allow NC machines to record utilization and cutting tool life, reduce set-up efforts and time, compensate for errors, inspect surfaces and make automatic adjustments, allow operators to modify their programming on the shop floor, record events of the last minute or two prior to a failure, and perform self-diagnosis. Coupled with greater sophistication in machine tool design, numerical control made possible the development of stand-alone machining and turning centers capable of shift-long, untended operation.

NC technology, after two decades of failure, came into its own with the advent of microprocessors. Microprocessor technology made controllers at once extremely powerful and relatively inexpensive, and its greater computer power made possible sophisticated yet flexible and "user friendly" operator interfaces.

The earlier problems of NC technology were partially due to the programmers' limited formal knowledge of the machining process. A lot of the tacit knowledge possessed by operators was not accessible to them. This limited understanding of variations in machinability, tool wear, and part material properties, together with inadequate control strategies for coping with these shortcomings, significantly constrained early implementations of NC technology. But it was only a matter of time before more of the tacit knowledge implicit in operator skills became precise, explicit procedures capable of dealing with a variety of contingencies.

NC Technology at Beretta -- From Synchronous to Cellular

What happened to the organization of work in the Beretta plant after the installation of NC machines is interesting. In the transfer-line, the average cycle time for a product was two minutes. Half of this was attributable to the machine, the other half to the operator. With the automation of tool changing, a variety of operations could be done by a single machine, but the overall cycle time increased. The cycle time required to perform the operations of three machines would be 3.6 minutes, three of which would be machine time. Thus, the NC machine replaced three machines, but took almost twice as long to produce a single part.

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[3] Noble, D. F., Forces of Production (New York: Alfred A. Knopf, 1984), 221(n.).

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                0.6 min.   0.3 min.      1.0 min.
Machine 1 ========== =====  xxxxxxxxxxxxxxxxxxxx

                                 0.6 min.   0.3 min.       1.0 min.
Machine 2                        =========  =====  xxxxxxxxxxxxxxxxxxxx
                                   Part      Tool     Tool Movement
                                  Setting   Setting
                                 (Manual)  (Manual)    (Automatic)
```

Figure 21: Time cycle for two operations = 1.90 min. or an average of 0.95 min./operation.

One can see that an operator of this NC machine would be idle 85% of the time. By allocating two machines to a person, operator idle time could be reduced to 66%. (See Figure 21.) The greater the machine component of the cycle time, the larger the cluster of machines around the operator. This leads to a cellular rather than synchronous plant layout.

In a synchronous line with one-minute cycle times, an operator performed a fixed, unchangeable routine. The nature of the work was determined by "hard automation," the jigs, fixtures, and cams that governed the performance of the operation. With hard automation, considerable effort was expended to get the jigs and fixtures right the first time. "Quality" was front-end loaded in the hardware design, and quality control was a process of monitoring and tending the machines and tools.

The scope of activity at any given work station was very small, and the pace of work was established by the machine. The principal intellectual activity on the line consisted in monitoring machine performance and diagnosing problems when they occurred. Because a problem at any one station on a synchronous line could stop all subsequent operations, thus exacting a high cost in productivity, a large and centralized set of resources was allocated to problem solving. At Beretta, this allocation was seen in the growth of the Quality Control department.

A cellular plant layout significantly increases the scope of activities for which an operator is responsible. The twelve operator stations in the barrel line layout shown in Figure 22 are responsible for one hundred and sixty-eight operations.[*] On average, each operator is responsible for fourteen operations. This compares with an average of three operations per person on a typical indexing machine in a transfer line used to manufacture, for example, the Garand rifle. Thus we have a five-fold increase in the scope of activities.

Source: Pietro Beretta, Gardone, Italy.

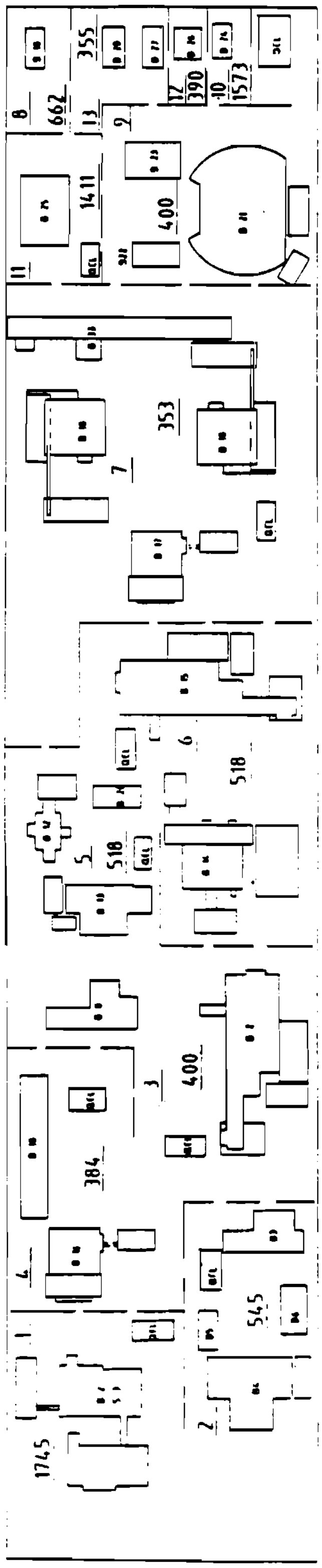

Figure 22: Beretta barrel-line layout.

We find, too, that the nature of the work changes. An NC operator works not with physical objects, but with information. The object of attention and medium of work is a computer program. Whereas the operator on a synchronous line was interested in observing the behavior of a process, the operator in a manufacturing cell composed of NC machines is interested in observing the behavior of a procedure.

Softening "Hard" Automation

NC machines are characterized as "soft," or programmable, automation. Operators write programs that precisely specify, down to the most minute detail, a sequence of operations that involve a choice of tools, the length and direction of tool movement, and the speeds and feeds of machine controllers. These sequences are contingent on some measured condition, such as tool wear and compensation.

Soft automation possesses five distinguishing characteristics.

(1) Specificity of procedures -- The degree of detail with which a procedure must be specified is at least one order of magnitude greater than with hard automation. The number of lines of program code required to machine the barrel shown in Figure 23 is 6,300.[5] For every possible contingent condition, such as the different variations in the dimensions of a casting, we need a response in the form of a clearly defined procedure. Because the computer is static and functionally blind, capable only of moving a tool in three dimensional space and changing its course at prescribed points, the procedures must be written as if to guide a blind person restricted to a small set of activities in a finite space. The specificity of the procedure, together with removal of the person from the immediate environment of work, renders the activity more abstract and scientific.

(2) Adaptibility to change -- Programs can be changed as easily as erasing a sentence and typing a new one in a manuscript. Such a change in a computer program results in a new procedure. Hence, quality is no longer front-end loaded, but subject to constant change and improvement that can be observed, monitored, and modified at the work station. Because change does not entail the design and construction of new hard automation we see more frequent and incremental changes in procedures, which do not require centrally allocated resources, being introduced at the work station. Thus work at a station no longer involves just monitoring performance, but improving it as well.

(3) Versatility of operations -- Operations at a station are only restricted by the configuration of the part being machined, i.e., whether it is prismatic or rotational. NC machines can perform operations on either one of these two classes of products, but not on both. Within each class, the machines can perform almost any operation, restricted only by the availability of tools in the tool magazine and the tolerances they are capable

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[5] Pietro Beretta blueprint, Pietro Beretta, Gardone, Italy.

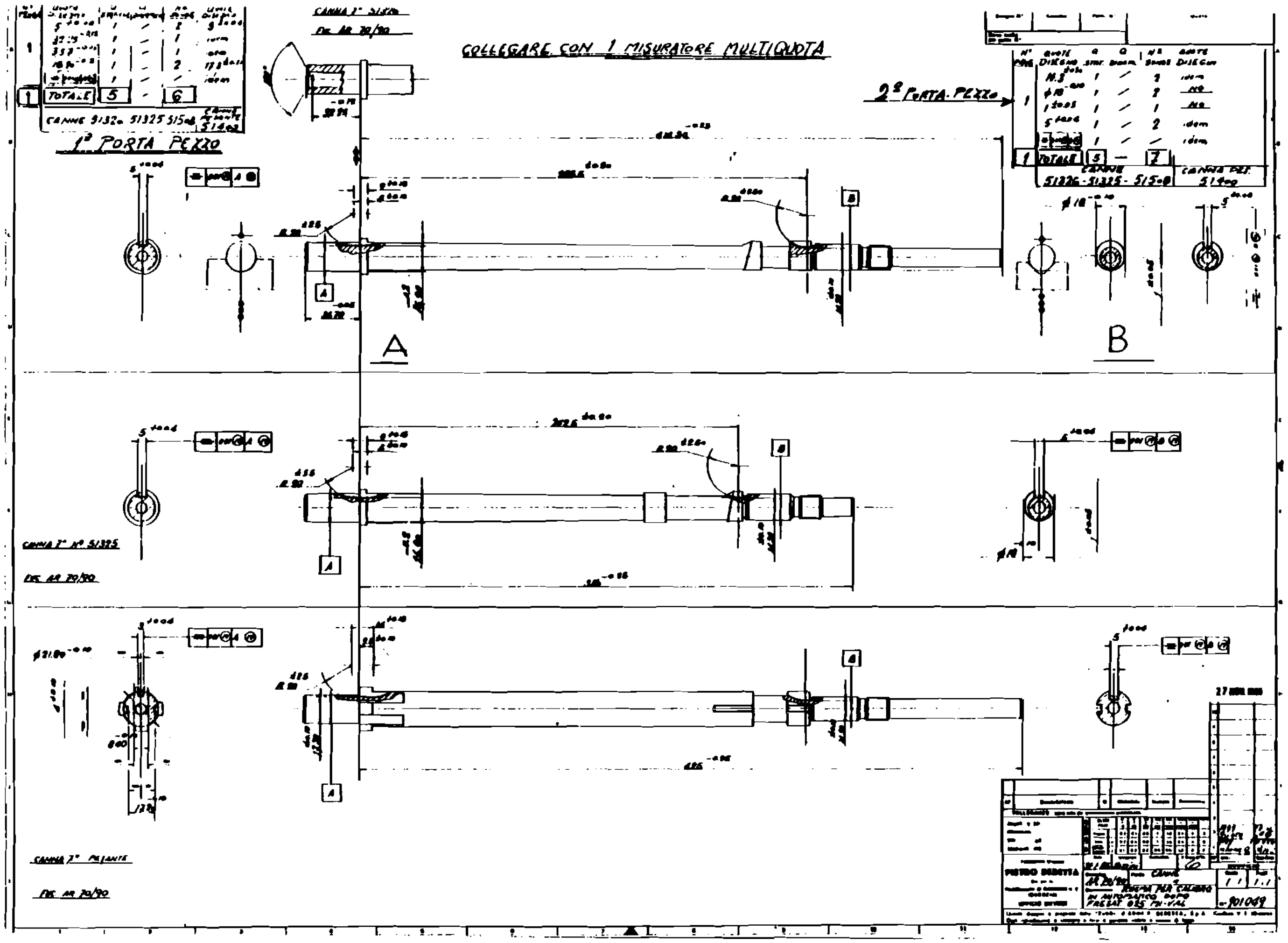

Figure 23: Blueprint r a Beretta barrel.

of maintaining. This avoids the large fixed cost associated with special-purpose machines by enabling a variety of new products to be machined at a single work station. Thus the scope of activities at an NC work station is expanded to include the introduction of new parts and processes. Precision, adaptability to change, and versatility of the machines have rendered the nature of work at a work station more scientific and abstract, more comprehensive, and subject to continual change.

(4) Reproducibility -- Once a program is written, the machine controller is capable of executing the program flawlessly forevermore. This suggests that the better able a program is to deal with contingencies in operation, the less need the machine will have for a skilled operator. An operator writing a procedure is, in effect, "cloning" him or herself. If the cloning is perfect, the operator is left with no job at all, or at best a very uninteresting job. This phenomenon creates a managerial imperative to constantly introduce new products and processes in order to keep skilled people in the organization occupied, or suffer possible disintegration into an organization without the skills to innovate.

(5) Transportability -- A reproducible program's use is not restricted to the machine on which it was developed. It can be used on any identically configured machine, and it can be copied at no cost. Thus, once a program is written, parts can be subcontracted to any small job shop with equivalent equipment without a great deal of concern for quality. Quality is assured by the raw materials and the programs that govern the parts' fabrication.

Reproducibility and transportability permit the scale of a manufacturing enterprise to be small, and assure the growth of the enterprise without the addition of skilled people. The five characteristics of information intensive processing--precision, adaptability, versatility, reproducibility, and transportability--suggest a complete restructuring of the organization of work and the nature of the firm.

Do we find such changes in practice? The substantial impact of the NC machines on quality, and the concomitant enhancement of the quality control organization, were benefits that Beretta had not fully anticipated. Management of quality with transfer line technology, with engineering and manufacturing separated, had consisted in monitoring and control. With NC technology, management of technology grew to encompass methods engineering and moved manufacturing a giant step closer to a science.

With its base of experience in automation, Beretta decided, when computer numerically controlled (CNC) machines became available, to completely convert its machine tool base to this newer technology within six years. Abetted by cost reductions that accompanied the spread of this new technology, Beretta had, by 1984, installed more than two hundred CNC machines on which more than 90% of its metal work was being done. Total value added cost in manufacturing, due to better quality products and substantially less overhead, was reduced from sixty-six cents on the dollar to sixteen cents on the dollar.

NC and QC -- The Impact of Numerical Control on the Quality Organization.

To understand the impact of NC machines on the organization of work one need only look at the changes in the quality organization. The object of attention, as noted above, is no longer how a process behaves, but rather how a procedure behaves. Increased microprocessor control of activities and on-line analysis of tool wear and tool compensation were providing automatic feedback, enabling cybernetic control of machining. With control of the process automated to such an extent, the nature of quality management was bound to shift.

Figure 24 shows an electronic gauge used for some turning operations at Beretta.[6] An operator introduces machined parts into the gauge, which measures four different dimensions. The measurements are automatically fed into the FANUC controller, which integrates them with data on parts previously produced. The NC machine has some built-in variability, and the sensor has measurement error. We would expect that parts would not be identical, but would range randomly within certain bounds of precision. We need a procedure that, taking account of this random variability and the historical data, can detect a systematic change (jaws misaligned) or a trend (tool wear). Having detected a change, we need to make an adjustment to the cutting program. The machine then automatically adjusts the appropriate tool movement.

In order to have the machine make the adjustment automatically, it is necessary to understand all the steps in the cutting operation. The step at which the adjustment is made must be appropriate as a point of intervention to accommodate a change, and the kind of change must be appropriate to the procedure. Statistical sampling, techniques of inference, and methods engineering are all integrated within one procedure.

We can see, in the example above, that methods engineering and quality control are one and the same. The Industrial Engineering of the Taylor era and the Quality Engineering of the SPC era have now been subsumed in a new discipline, Systems Engineering. In 1979, Beretta formalized Systems Engineering as the Quality Control Programming Section and charged the head of the section with responsibility for all of its manufacturing procedures. Data analysis, experimentation with new procedures, and evaluation of new technology, as well as documentation of all that went on in manufacturing, fell under the purview of this section, which grew quickly to twenty-two people, becoming the largest group in the quality control organization.

The principal responsibilities of the Quality Control Programming Section are outlined below.

(a) The group was charged with analyzing the individual phases of a production process (machines, operators, work methods, and working conditions) to ensure their conceptual fit in order to guarantee quality, and to determine

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[6] Pietro Beretta blueprint, Pietro Beretta, Gardone, Italy.

INCISIONE

Disegno N° | Complessivo | Parte N°

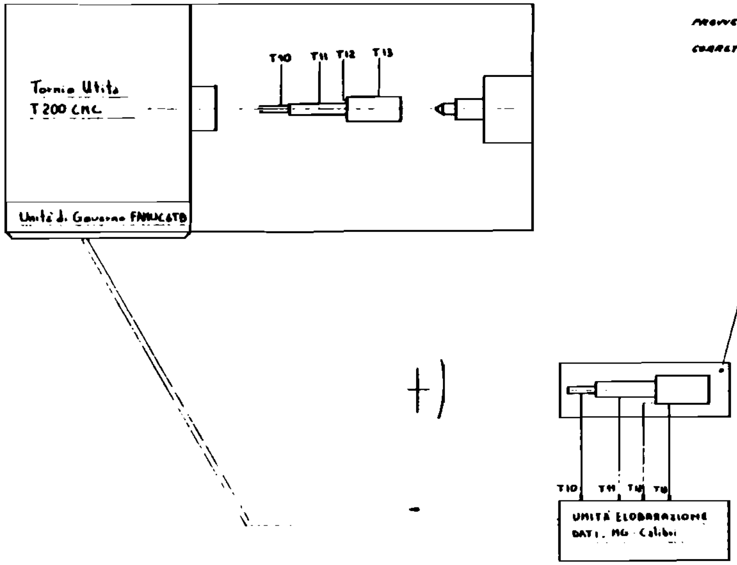
Serve anche per parte N°

CICLO DI MISURA

L'OPERATORE PROVVEDE A DEPOSITARE IL PEZZO PRELEVATO DAL TORNIO DIRETTAMENTE SULLA STAZIONE DI MISURA CHE È INTERFACCIATA CON L'UNITÀ DI GOVERNO DEL TORNIO.

ESEGUITO IL CONFRONTO CON I VALORI DI RIFERIMENTO IMPOSTATI PROVVEDE TRAMITE SEGNALI IN BCD A VARIARE IL VALORE DEI CORRETTORI UTENSILI INTERESSATI

IL CALIBRO DISPONE DI: 9 MISURATORI DIAMETRALI
3 MISURATORI LONGITUDINALI



Particolari previsti sul calibro:

Canna 225 compresi nuovi modelli
" 746
" BM59
Tromboncino 225 (57080)

NB Il calibro può essere utilizzato inoltre per particolari simili a quelli citati.

TOLLERANZE

FABBRICA D'ARMI
PIETRO BERETTA
S.p.A.
STABILIMENTO DI GARDONE V.T.
(BRESCIA)
UFFICIO METODI

Data 4-12-85

Oggetto: Schema funzionamento calibro elettronico interfacciato con CNC UTITA e correttori utensili

Foglio 1/1

N° 300926

whether the preparation of each phase was consistent with overall project development.

(b) The group was also charged with analyzing all available means of production for the purpose of quantitatively measuring their natural variability (machines) and level of fidelity (tools), and for eliminating, for every operation, every possible cause of systematic error by: verifying tool conformity to design (metorlogy); testing with a tool that precisely met design specifications; and producing pieces in a quantity such that tool wear would not degrade quality. Through a statistical analysis of the collected measurements (Gauss distribution and confidence limits), the natural tolerance of a machine could be calculated and registered, a specific procedure could be accepted or rejected on the basis of its ability to maintain the required tolerances, and a control method could be designed for accepted processes.

With on-line, 100% inspection, the inspector should be at the work station where diagnosis of problems takes place based on information derived from every part in production. This suggests that the quality control and methods engineering functions are now being done at the work station by the operator. The distinction between line and staff is sufficiently blurred by this shift as to render arguable whether the line-staff concept is still meaningful. As we can see in the barrel line illustration, each of the twelve workstations has a quality control bench. On this line, each operator is both quality inspector and methods engineer. The operators formally report to the Quality Control Programming Section, and are responsible for, and have authority to make changes to, procedures.

The shift to managing information and procedures was not an easy one for Beretta. "It was," averred Ugo Beretta, "the biggest change in the culture of the plant that I have ever seen."[7]

Each operator is a manager of a cell, and there is no supervision of work. Operators no longer monitor the performance of machines, but rather control the performance of a group of machines run by computers. To do so, they need to understand the relationship between computer programs and physical output. They also need to understand the interaction of all aspects of a system of machining. The principal medium of communication is no longer a blueprint, but printed output.

The use of the electronic gauge (Figure 24) is a particularly telling observation in manufacturing practice. In the blueprint for the barrel (Figure 23) there are no tolerance or measurement specifications, only four parameters, labelled T10, T11, T12, and T13. These specifications are replaced by control programs, each of which represents a relationship between some set of historical measures and the required response. To specify these control programs, the operator has had to become a systems engineer, comfortable with data base manip-

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[7] Personal communication.

ulation and control algorithms. The transformation of work has been quite radical indeed.

How did this transformation affect operations at Beretta? For a start, the company grew three-fold in eight years without a net increase in the workforce, and was still capable of handling excess capacity. Having drastically reduced manufacturing costs, Beretta began manufacturing rifles for its two major competitors, Browning in England, and FLN in Belgium. In 1985, the Beretta Parabellum 9mm won the company the United States Army contract for a replacement pistol for the venerable Colt 45. The contract stipulated that a new factory be constructed in the United States. The reproducibility and transportability of its NC programs assured Beretta of being able not only to make money at a bid price less than half that of the second place bid, but also to start up an entirely new factory in Accokeek, Maryland within eighteen months.

NC technology simultaneously enhanced flexibility, quality, and productivity. Beretta realized a ten-fold increase in the number of products that could be produced on the line, with a concomitant reduction in rework and scrap from 8% to 2%, and a three-fold increase in labor productivity. Implicit in the simultaneous increase in number of products and quality of workpieces was an integration of product and process knowledge.

The workplace ethos had changed again. It was now more than just monitoring machines; it was controlling them, as well. Electronic gauges replaced control charts. The skill required was more than diagnosis. One had to experiment with procedures and learn. Adaptation replaced stability as the process focus. System Engineering replaced Quality Engineering as the dominant engineering ethos. Information technology had come of age.

COMPUTER INTEGRATED MANUFACTURING -- THE DAWNING OF A NEW AGE

Just as Beretta had completed the renovation of manufacturing machinery in its plants yet another new technology began to emerge. Robots for loading and unloading parts in machines, untended mobile carriers for transporting pallets from one part of a plant to another, and flexible manufacturing cells capable of a ten-fold increase over traditional machinery in the variety of parts that could be made were all making their debuts, and with them came the potential to automate the manufacturing process from one end to the other, from loading machines, through changing, setting, and operating tools, to unloading processed parts.

In 1987, Beretta engineers introduced, as pilot projects, two new technologies: a flexible manufacturing system (FMS); and computer-aided design/computer-aided manufacturing (CAD/CAM, the integration of computer-aided design and CNC machines).

Beretta's FMS

The first project was the installation of a flexible manufacturing system for manufacturing a major gun part--the "reciever."

A flexible manufacturing system is a computer-controlled configuration of semi-independent work stations, connected by automated material handling systems, designed to efficiently manufacture more than one kind of part at low to medium volumes. The system designed for production of the Beretta receiver (shown in Figure 25)[*] consists of three CNC machining centers connected by a material handling system that incorporates a conveyor arranged in a loop. The loop constitutes a buffer area where pallets on which the workpieces are mounted keep moving until the machine required for the next operation becomes available. The system is capable of fabricating forty-five discrete parts. With the exception of inspection, all system operations are under computer control.

In most FMS installations, incoming raw workpieces are fixtured onto pallets at a station. Once information on a fixtured workpiece (typically an identifying number) has been entered to inform the FMS controller that the workpiece is ready, the FMS supervisor (computer) takes charge, performing all the necessary operations to completion in any of a number of machines, moving workpieces between machines, responding to contingencies, and assigning priorities to the jobs in the system.

The supervisor first sends a transporter to the load/unload station to retrieve the pallet. The loaded pallet then keeps moving in a loop until a machine becomes available to perform the first operation. When a shuttle (a position

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[*] Pietro Beretta blueprint, Pietro Beretta, Gardone, Italy.

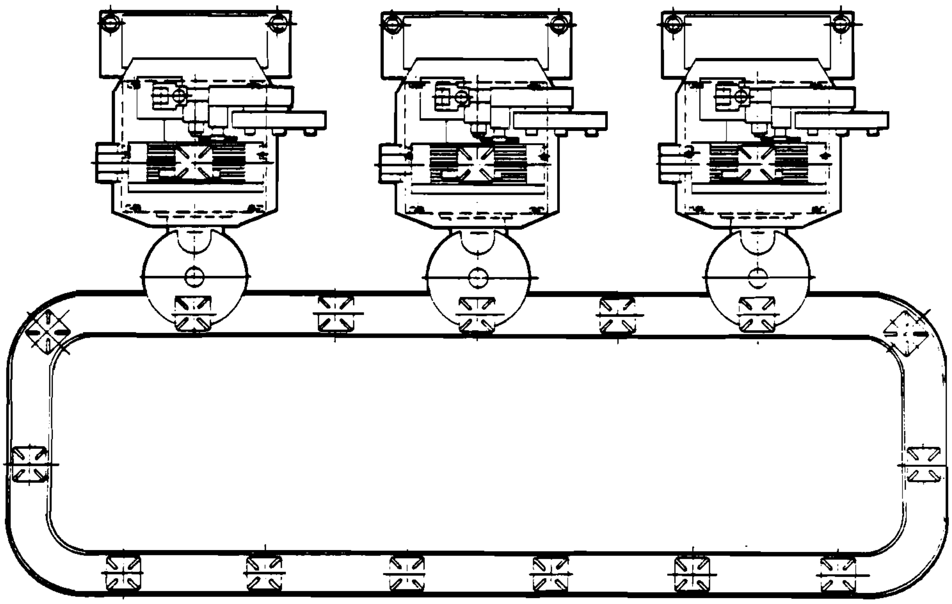

Figure 25: FMS receiver-line at Beretta.

in the queue) is available, the transporter stops and a transfer mechanism removes the pallet, freeing the transporter to respond to the next move request.

Parts received by the machine must be accurately located relative to the machine tool spindle. The inspection to accomplish this can be done manually, using standard instruments, or by coordinate measuring machines. The appropriate machining offsets are calculated from the measurements and communicated to the supervisor.

Meanwhile, the supervisor has determined whether all of the tools required for the machining operations are present in the tool pocket and requested needed tools from either off-line tool storage or a tool crib/tool chain within the system. When all the required tools are loaded, the supervisor downloads the NC part program to the machine controller from the FMS control computer.

The process of making sure that the part is, in fact, what the computer thinks it is is termed qualifying the part. Qualifying includes making sure that all previous operations have been completed, that the part is dimensionally within tolerance limits, and that it is accurately located. Tools, too, must be qualified. Tool geometry, length, diameter, and wear are all examined, either manually or under computer control. When both the workpiece and the tool have been qualified, the tool, part, or program offsets necessary to correct for systematic error have to be established.

When the set-up activities are completed, machining begins. The FMS monitors the tool during machining. If it breaks, a contingent procedure is invoked. Some advanced FMSs have in-process inspection and adaptive control, by which we mean that a continuous measurement of metal removal is taken to determine whether it is within defined process parameters. Compensating corrections for any deviations are made during machining. Adaptive control in FMS is still very rudimentary and technically quite difficult with present day technology.

The finished, or machined, part is moved to the shuttle to await a transporter. After being loaded onto the transporter, the pallet moves to the next operation, or else circulates in the system or is unloaded at some intermediate storage location until the machine required for the next operation becomes available.

The computer controls the cycles just described for all parts and machines in the system, performing scheduling, dispatching, and traffic coordination functions. It also collects statistical and other manufacturing information from each station for reporting systems. As all the activities are under precise computer control, effects of part program changes, decision rules for priority assignment, contingent control, and part-portfolio mix can be captured.

The old line for making receivers is shown in Figure 26.[1] The forty-one machines in this line compare with twenty-four in the new FMS line, configured as eight, three-machine cells. The number of cells was dictated by the volume of work.

Each cell in the FMS receiver line fabricates a complete receiver, and is managed by a single worker. The FMS reduces minimum efficient scale by an order of magnitude, and is flexible and versatile enough to accommodate other prismatic parts as well as receivers.

It will eventually be possible to load a machine on the FMS line at the beginning of a shift with thirty-five pallets, each containing a blank receiver, and have the entire lot completely machined by the end of the shift without an operator being present. Although untended operation has not yet been achieved at Beretta, it is not only possible, as a number of Japanese machine tool vendors have shown, but achievable in the next decade. When it comes, it will in all likelihood once again radically alter the nature of work.

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[1] Source: Pietro Beretta, Gardone, Italy.

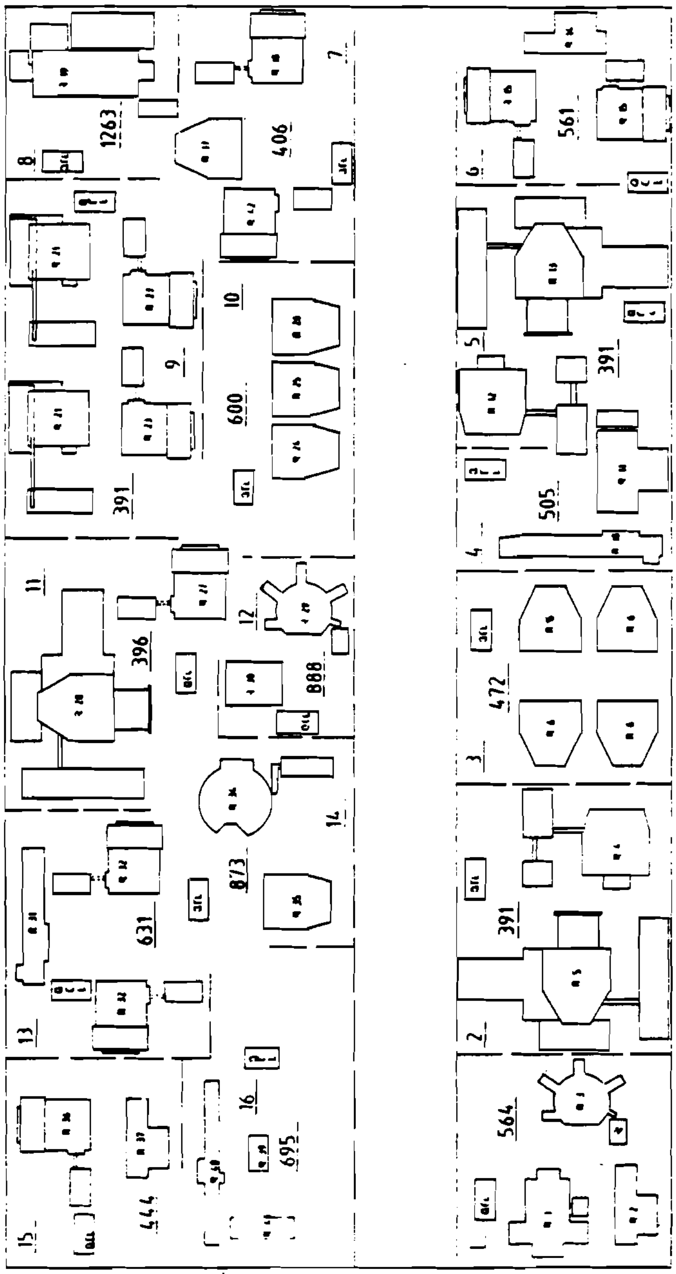

Figure 26: Original receiver-line at Beretta.

What we can expect from a world of untended flexible manufacturing is summarized below.

(1) The worker is likely to be completely separated from the physical elements of work--metal, lubricants and oil, executing procedures, and turning out parts. Work will, instead, become an act of conception, of creating new products and processes.

(2) All of the tools, fixtures, and programs needed by a system will have to be conceived, built, and developed before it can make the first product. Thus, all of the controllable costs will be sunk before the first product comes off the line. After this, the unit cost will be the same whether the firm makes one unit or many.

(3) In order to achieve untended manufacture, the craft of machining needs to be developed into a science of manufacturing. Every possible contingency needs to be anticipated and an appropriate response provided in the form of a tightly specified procedure.

Problem Solving in FMS

Master mechanics working with general purpose machines usually accrued years of experience, during which they accumulated a wealth of idiosyncratic knowledge about how to perform in a wide variety of circumstances. They talked in terms of a "feel" for the machine, the tools, and the parts they worked on. It was through this feel that they were capable of producing parts of very high accuracy. Watching them work, one had a sense that they recognized errors (e.g., vibration or chatter, structural deformation due to thermal forces) as they were happening and adapted their procedures to compensate for them. This, in engineering terminology, is an advanced form of adaptive control in an ambiguous environment. Such error recognition and compensation requires either a very elaborate database with a complex web of relationships, such as the experiential knowledge of the skilled machinist or a scientific understanding of the machinery, sensor, and controller technology.

With the advent of numerical control machines, the master machinist was often replaced by a less skilled operator. This does not imply that contingencies were somehow removed from the machining process. All the new machines did was follow explicitly well defined procedures in the form of computer programs. One could experiment with these procedures until one obtained a good part.

The far-reaching effects of this technology were control over the process, repeatability, and reprogrammability. Dynamic contingencies remained a part of the environment, and skill was still required to identify and eliminate errors. Neither the computer control systems, nor the lesser skilled persons employed to operate them, were capable of recognizing systematic errors in these machines. The "feel" for the machine was absent. New skills, those of manipulating abstract procedures and entities and recognizing, and learning from, the relationships between procedures and tolerances, were required.

FMS technology and "unmanned" machining compounds the accuracy problem. Workers are entirely removed from the machining area, machining being done using multiple machines with multiple tools, and inspection done off the machine. As an FMS is merely a number of standard NC machines connected by an automated material handling system, it has all of the problems common to NC machines. But it also lacks the stand-alone NC machine's constant attention from a machine operator, who can compensate for small machine and operational errors by realigning parts in a fixture, tweaking cutting tools, etc. The programs lack the skilled machinist's capacity for accommodating large variations in castings. Determining the source of an "out of tolerance" problem in an integrated FMS can be very difficult. The error might be the result of any one or a combination of factors, such as tool wear or interface alignments (e.g., tool/spindle, part/fixture, fixture/pallet, pallet/machine). Proper diagnosis entails knowing which tools were used on which workpieces on which machines, and, if more than one part program was used, which was in use when the problem occurred.

The level of complexity involved in problem diagnosis is an order of magnitude greater than in a manually tended machining center. Thus, if an NC machine is once removed from the "feel" of machining, an FMS is twice removed. To understand the difficulty associated with diagnosing problems in an FMS an analogy is useful. Consider the task of writing, for a person of limited vocabulary and using only the English language, the instructions for drawing a picture of a donkey. If this exercise proves easy enough, then consider the following: each of three people is to be given instructions for drawing a different part of a donkey (using different vocabulary and syntax) and their drawings are to be brought to a central location where a fourth person will be required to assemble them. Now, if a fifth person were to inform you that the donkey looks like a horse, how would you go about correcting the problem and issuing new instructions.

Why, you might ask if problem diagnosis is so difficult, do we use FMSs for fabrication of high accuracy parts. It is simply because of controllability, reproducibility, and reprogrammability. Once we have solved a problem and written the appropriate code, the system will reproduce the procedure forever. Reprogrammability allows us to perform experiments on the line to correct for errors. If the procedures are set up right, codification of the experience gained and of alternatives taken and rejected becomes possible. In a restricted domain, such knowledge can be transferred to other processes, products, tools, etc. In order to move from an art to a science, we need to understand the streams of knowledge that make up the science. It is not the case that the problem solvers are no longer skilled. In fact, they are highly skilled; only the domain in which the skill operates is different, having become more abstract than real.

Where a number of contingencies can arise, it is important to be able to recognize, diagnose, and learn from the resulting errors. With such a high plane of technical intelligence required, operators have to be trained in the scientific method in order to better understand how various machine tool errors can cause parts to be out of tolerance, how to measure and correct these errors, and how to make accurate parts. A key to successful, accurate machining is the cutting tool--geometry, cutting edge preparation, accurate position control of the cutting edge to shank, proper inspection of new tools, and accurate equipment for sharpening and presetting.

An operator is usually alerted to possible machine tool errors through discovery of an error in the final form of a part. These errors, be they in size, shape, location, or surface finish of a part feature, can result from one or a combination of errors in three broad classes--mechanical, thermal, and operational. These are elaborated in Figure 27. Both mechanical and thermal errors can be further classified as attributable to aspects of either a machine or a part.

One is also concerned with the frequency of errors. Errors can be systematic (static), whereby they occur with approximately the same magnitude each time the manufactuing task is performed, or they can be random (dynamic/fluctuating), occurring each time with different magnitudes and without an apparent pattern. (See Figure 28.) Many of these errors can be avoided by good shop and machining practices, maintenance discipline, and an awareness of how fixture design, poor tool setting, and other actions can affect system performance.

When tolerance bands are broad, error avoidance is enough to keep a shop running smoothly. Exploration of machine tool errors and diagnostics do not play a significant role in day-to-day operations and skills will not be required of shop floor personnel. But in a changing environment, in which new parts and part programs are being introduced and tolerance bands are very small, error avoidance alone is not likely to remove all errors. Detailed examination of machine tool will be required to locate sources of mechanical and thermal error, determine their magnitude, and identify their mechanisms. It is possible to segregate these into static and dynamic errors through a number of tests. Static errors are significantly easier to deal with than dynamic errors. If, for example, a machine tool has a bed that sags slightly at one end when the table is moved over it, and if only one axis is affected, it might be possible to reprogram offsets in another axis to compensate for the sag while cutting. Dynamic errors, whose sources are usually thermal, are the most difficult to handle, requiring very careful analysis of alternative procedures. Their solution requires the "feel" of a master machinist, the logical mind of a software programmer, and access to extensive databases of information on similar problems.

With this transformation of the operator into a "knowledge worker," the blue collar image of factory work is no longer appropriate. The intellectual assets needed by a firm to create new products and processes become the dominant driver in manufacturing competence. Thus, management of these assets becomes crucial to a firm's viability.

Beretta's CAD/CAM System

An understanding of what these assets are can be gleaned from an analysis of the second project Beretta undertook, CAD/CAM integration. This project consisted in having both the design for the locking system of a rifle, and the NC programs needed to directly fabricate its parts, carried out on an engineering workstation. The three engineers assigned to this task were provided

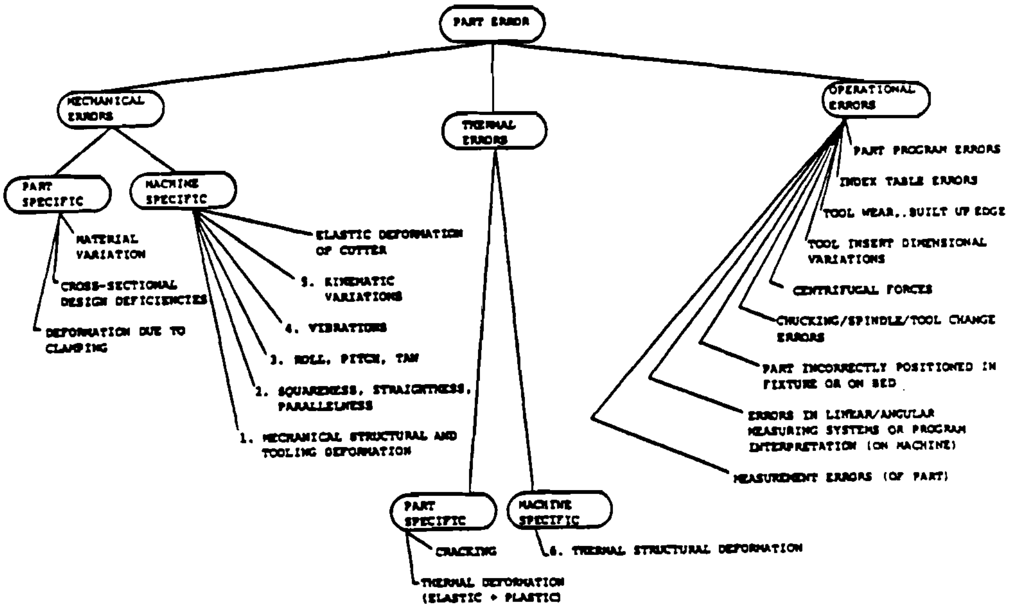

Figure 27: Sources of error in an FMS.

with a workstation with a color graphics terminal that displayed icons intended to facilitate component design. The component design had to satisfy both product functionality requirements (such as safety, efficient kinematic interaction, ability to withstand stress, and ease of assembly and disassembly) and manufacturability constraints (such as required tolerances, clearances between components, simplicity of parts configuration, etc.).

The locking system consisted of twenty-six different parts. Some of these were selected from a catalog of components, others had to be specifically designed. Software vendors supplied a number of different computer programs capable of manipulating parts geometries. These were used to create designs, move them around on the screen, and fix them to specific locations as if one were actually physically assembling them in three-dimensional space. Other computer programs simulated the movement of the triggering mechanism and the kinematic linkages associated with it. The forces exerted on the mechanism during firing and the resulting stresses were also simulated by computer programs.

An engineer working with a number of different parts geometries could create and test different alternatives, settle on a tentative design, and then examine the manufacturing impacts of each part. A host of manufacturing related computer programs could then be used to create the NC programs needed to machine the components and even graphically display the tool path of a metal cutting program on the screen. When satisfied with the design, the engineer could

	SYSTEMATIC/STATIC	RANDOM/DYNAMIC
Part-Specific Mechanical Errors:	Material variation. Cross-sectional design deficiencies. Deformation due to clamping.	Material variation Deformation due to clamping.
Machine-Specific Mechanical Errors:	Elastic deformation of cutter kinematic variations Roll, Pitch, Yaw. Squareness. Straightness. Parallelness. Mechanical, structural and tooling deformation.	Elastic deformation of cutter vibrations.
Part-Specific Thermal Errors:	Thermal deformation	Cracking. Thermal deformation.
Machine-Specific Thermal Errors:	Thermal, structural deformation.	Thermal, structural deformation.
Operational Errors:	Part program errors. Index table errors. Centrifugal forces. Errors in linear/angular measuring systems or program interpretation (on machine).	Index table errors. Tool wear, built-up edge. Tool insert dimensional variations. Chucking/ Spindle/ Tool change errors. Part incorrectly positioned in fixture on bed. Errors in linear/angular measuring systems or program interpretation (on machine). Measurement errors (of part).

Figure 28: Classification of FMS errors.

transfer the program to a machining center and have the components fabricated automatically.

The CAD/CAM pilot project proved that the concept was viable. Three people had designed in as many months what normally took nine people a year to develop. This represented a reduction in person months from one hundred and twelve to nine.

The components used to test the feasibility of the concept were, by design, quite conservative, but the engineers realized that by building a variety of analytical models they could create a very powerful design tool. By simulating performance in real-time they learned much about how the different aspects of product design and process interacted. They were able to discern problems in these interactions and even to codify design rules for manufacturability.

The immediate organizational response to the CAD/CAM project was to regard this design tool, like all the other innovations the company had adopted, as a productivity enhancement tool. This is was, but it was also something more; it was a knowledge enhancement tool. The system possesses the potential to make an expert more of an expert and, as it accumulates information, models, and design rules, to enhance the intellectual assets of the firm. It can be argued that such systems are themselves part of a firm's intellectual assets.

If the enhancement of intellectual assets is critical for manufacturing competence, and if CAD/CAM integration has the ability to achieve it, in what dimensions might we discover useful insights?

Obvious dimensions are those of organizational memory and analytical capabilities. Such systems are capable of maintaining, and providing on-demand access to, vast stores of information. They can perform a variety of calculations and simulate behavior to reduce uncertainty in product and process performance. Taken together, these capabilities constitute powerful productivity enhancement tools.

A particularly important dimension that such tools add to a firm's intellectual assets might be called <u>system intelligence.</u> Prior to CAD/CAM integration, organizations solved product/process problems by taking recourse to the respective experts in each area. Each of these experts represents a vast store of functional knowledge in a specific area. Over time, organizations have learned how to effectively manage the knowledge of these functional experts, and devised mechanisms for resolving the conflicts that arise between them over which sets of alternatives are better in a given situation. This knowledge of how to manage knowledge is sometimes called tacit knowledge, or organizational intelligence.

In CAD/CAM integration, we have begun to include information on, and models of, functional expertise. This information enables us to systematize, examine, and learn from interactions between functions in such a way that issues are more sharply focused and patterns of interaction become recognizable. System intelligence, then, is the recognition and understanding of the interactions between functions, and a surrogate for organizational intelligence as it relates to product/process performance.

Creating functional models of products and processes, validating them with experience, and manipulating them in the process of design is an emerging form of engineering--knowledge engineering. While this term has been used in association with the acquisition of knowledge for so-called "expert systems," we suggest a more encompassing definition, to include the variety of functions that we see emerging as a broader engineering discipline.

On Putting It All Together

While Beretta has not as yet integrated its CAD/CAM and FMS technologies (i.e., has not moved to computer integrated manufacturing, or CIM), a few things are already clear. The organization of work will see another radical shift. While the engineering ethos in the NC era was one of systems science, in the CIM era we see knowledge and the management of intelligence as the primary domain of activity. The professional workstation has replaced the simple electronic gauge. The creation of new products and processes, being versatile, is the primary driver. The ability to generalize and abstract from experience in order to create new products is the skill required. As Beretta has thus far built only one FMS cell and designed but a single locking mechanism using CAD/CAM, this may seem like idle speculation. Yet evidence from Japanese systems operating unattended at night suggest that this is clearly the direction. My own studies of more than one hundred FMS systems operating worldwide corroborate this evidence. (Table 4 provides a comparison of the NC based factory with one using FMS.)[18] The following are among the conclusions drawn from that research.

> The management of FMS technology is taking place in a different manufacturing environment, and thus consists of new imperatives.
>
> Build small, cohesive teams. Very small groups of highly skilled generalists show a remarkable propensity to succeed.
>
> Manage process improvement, not just output. FMS technology fundamentally alters the economics of production by drastically reducing variable labor costs. When these costs are low, little can be gained by reducing them further. The challenge is to develop and manage physical and intellectual assets, not the production of goods. Choosing projects that develop intellectual and physical assets is more important than monitoring the costs of day-to-day operations. Old-fashioned, sweat-of-the-brow manufacturing effort is now less important than system design and team organization.
>
> Broaden the role of engineering management to include manufacturing. The use of small, technologically proficient teams to design, run, and improve FMS operations signals a shift in focus from managing people to managing knowledge, from controlling variable costs to managing fixed costs, and from production planning to project selection. This shift gives engineering the line responsibilities that have long been the province of manufacturing.
>
> Treat manufacturing as a service. In an untended FMS environment, all of the tools and software programs required to make a part have to be created before the first unit is produced. While the same is true of typical parts and assembly operations, the difference in an FMS is that there are no allowances for in-the-line, people-intensive adjustments. As a result,

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[18] Jaikumar, R., "Postindustrial Manufacturing," Harvard Business Review, 64, No. 6 (November-December 1986), 73.

		Before	After
	Types of parts produced per month[1]	543	543
	Number of pieces produced per month[1]	11,120	11,120
	Floor space required	16,500 m^2	6,600 m^2
Equipment per system	CNC machine tools	66	38
	General purpose machine tools	24	5
	TOTAL	90	43
Personnel per system three shifts	Operators	170	36
	Distribution and production control workers	25	3
Average processing time per Part[2] days	Machining time	35	3
	Unit assembly	14	7
	Final assembly	42	20
	Total	91	30

[1] To make the comparison useful, I have held these figures constant.
[2] This includes time spent in queue.

Table 2: Performance of one factory before and after automation.

competitive success increasingly depends on management's ability to anticipate and respond quickly to changing market needs. With FMS technology, even a small, specialized operation can accommodate shifts in demand. Manufacturing now responds much like a professional service industry, customizing its offerings to the preferences of special market segments.[11]

We have come full circle. The new manufacturing environment looks remarkably similar to the world of Maudslay; only the world of work has changed. The holy grail of a manufacturing science begun in the early 1800s and carried on with religious fervor by Taylor in early 1900s is, with the dawning of the twenty-first century, finally within grasp.

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[11] Ibid., 76.

CONCLUSIONS

Having examined each of the six epochs of process control we can see that there is a certain consistency among them in terms of what changes. Technological demands, the organization of manufacturing to meet these demands, and the nature of work are affected in each epoch. We also see that the shifts involved in the transition from one epoch to the next are intellectual shifts. Each epoch brings a new way of posing a problem and solving it. To the extent that a firm competes by acquiring, developing, and managing know-how, these intellectual shifts become technological imperatives. One might argue that the shifts themselves are socially determined, and that technology is a social product. Nevertheless, insofar as we live in a competitive world, we must, once one of these shifts has occurred, adapt to the technological imperatives imposed by it.

In examining how the nature of work is affected by these intellectual shifts we have shown, in this paper, that a firm's response must go beyond a radical restructuring of its organization to address the intellectual underpinnings of what gets done in the world of work.

We have shown that the first three epochs--the English, American, and Taylor systems--related to the material world of mechanization. Each saw the manufacturing world as a place of increasing efficiency and control, substitution of capital for labor, and progress through economies of scale. These objectives were obtained through an engineering focus on machines and what could be done with them. The role of labor was increasingly seen as one of adapting to the machines and the contingencies of the environment, ultimately, of being yet another machine. Concurrently, the machines themselves became more elaborate, capable of ever greater precision and control. Yet the single principle that seemed to underlie these developments was increasing mechanical constraint.

Abbot Usher, a historian of technology, observes that

> some of the impressive improvement of machines consists of refinement of design and execution. The parts of the machine are more and more elaborately connected so that the possibility of any but the desired motion is progressively eliminated. As the process of constraint becomes more complete, the machine becomes more perfect mechanically. . . . The general line of advance takes the form of substitution of the more intense for the less intense forces, grading up through a long sequence that begins with types of human muscular activity. . . . There is a steady increase in potential (energy): we have to deal with a transition for machinery worked at a very low potential to machinery run at very high potential. The change in potential itself requires more and more careful constraint of motion because

> these highly intense concentrations of energy could not be applied to mechanisms until adequate control was possible.[12]

This world of mechanization reached its zenith in 1950. Already, one could hear rumblings of a brave new world. In 1946, Brown and Leaver laid out, in a Fortune magazine article entitled "Machines Without Men," a blueprint for a new industrial order.[13] They had made the intellectual leap from mechanization to information processing. Norbert Weiner, in a prescient analysis of the power of information processing, gave credence to Brown and Leaver's world view. Though it would be another forty years before we would see the first automated factories without men, the seeds for the emergence of a new paradigm were planted.

It is appropriate that James Bright completed his landmark study, Automation and Management, in 1958, for that year marks the end of the era of mechanization. Bright observed that

> the average manufacturing system of 1956 . . . can be regarded as no more than a crude assemblage of unintegrated bits of mechanism. These mechanisms themselves may reflect the utmost in the mechanical art of our times. Still, when collected under one roof and directed toward a particular production end, they are anything but a machine-like whole. . . .
>
> . . . A hundred years from now the average factory of our day may be regarded as having been no different in philosophical concept from the factory of 1850. . . . (Process) "design" has meant the colectoin of equipment for a production sequence--not the synthesis of a master machine.[14]

The glue that made a collection of machines a manufacturing system was people processing information. The lack of integration Bright speaks of and the intelligence needed to make machines function has been the focus of the subsequent three epochs. In the dynamic view, the NC era, and computer integrated manufacturing, we see a reversal of the trends of mechanization: increasing versatility and intelligence; substitution of intelligence for capital; and economies of scope. Machines have been increasingly seen as extensions of the mind, and as meant to enhance the cognitive capabilities of the human being. This paradigm shift is what this paper is all about. The versatility of information technology and freedom from mechanical constraint suggest a new managerial imperative.

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[12] Usher, A. P., A History of Mechanical Inventions, (Cambridge: Harvard University Press, 1954 rev. ed.), 116.

[13] Noble, D. F., Forces of Production (New York: Alfred A. Knopf, 1984), 68-70.

[14] Bright, J. R., Automation and Management, (Boston: Harvard University Graduate School of Business Administration, 1958), 16.

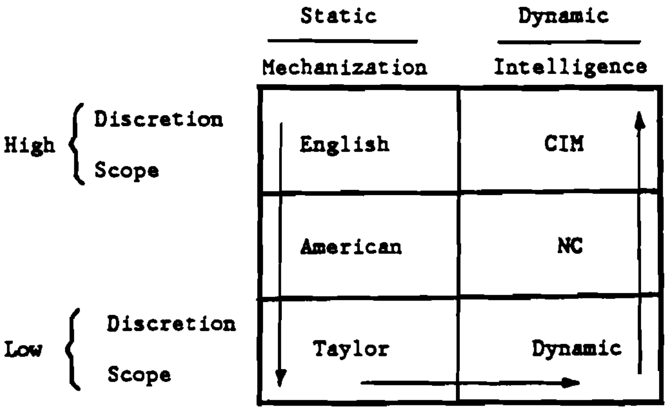

Figure 29: Work, mechanization, and intelligence in the evolution of process control.

The systems of the epochs characterized by integration and intelligence are seen as man-machine cooperatives. To understand the significance of this shift, let us imagine the technology in the extreme. Consider a small group of engineers working coorperatively via a connected system of work-stations on designing, and writing the manufacturing software for producing, on any defined configuration of machines located anywhere in the world, all of the components for a new rifle. Having created the requisite procedures, the rifle can now be produced in whatever quantity is desired. Machine capacity and materials have become commodities, to be bought and sold at whatever price one can obtain.

We are not there yet, you say. Yes. But why not? What is holding us back is <u>not</u> increasing mechanization, but the greater intelligence in the form of precise and complete sets of contingent procedures. This is the technological imperative today.

The one incontrovertible trend we see through the six epochs of process control is the evolution of manufacturing from an art to a science. Each of the six epochs focused on a particular aspect--accuracy, precision, reproducibility, stability, adaptability, and versatility. In the early epochs, we developed measures, then gained control of the process. Next, we mastered variability, first in the machine, then in the human. Finally, we studied, and then controlled, contingencies in the process until we were able to extract general principles and technologies that we could apply in a variety of domains. In short, we achieved versatility. These activities map directly into the stages of procedural knowledge in the development of a manufacturing service as postulated by Jaikumar and Bohn. Figure 29 traces our progress from high to low discretion and back again, and from increasing mechanization in an essentially static world to increasing intelligence in a more volatile, dynamic world.

We have seen in detail, for each of the six epochs, what the changes have meant for manufacturing management in the firearms industry. Is it possible to generalize these findings to other industries? As long as there are structural similarities in the manufacturing process technologies--metal fabrication, for instance--we would venture to say that the broad thrust of our argument holds true. There is a paradigmatic shift to a more dynamic, information intensive world, centered around the development of intellectual assets. Managing these intellectual assets, that is, attending to the man-machine cooperative system, is the new challenge.

TECHNOLOGICAL AND ECONOMIC FACTORS IN CIM APPLICATIONS

THE IMPACT OF ELECTRONICS AND INFORMATION TECHNOLOGY ON THE FUTURE TRENDS AND APPLICATIONS OF CIM TECHNOLOGIES

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1. INTRODUCTION

There is a lot of practical evidence resulting from the many case studies (see Ranta et.al., 1988; Jaikumar, 1986; Goldhar et.al., 1983, 1985; Meredith, 1987) which proves that the most critical issues of the application of CIM technologies are managerial and organizational aspects of the systems implementation. However, the basic technologies are not yet invariant and not at a mature stage of development. Thus it is reasonable to expect that technological factors can still considerably contribute to the technological and economic efficiency of different CIM technologies. We can also expect that many systems applications are simply dependent on economic efficiency and capital intensity of different manufacturing technologies. Thus many of the stated goals and targets of CIM and FMS technologies, such as flexibility, accuracy, processing speed, complexity of products and parts, are mainly dependent on the trade-off between the technological capabilities and the costs of technological solutions.

One of the main technological driving forces has been the application of information technologies, i.e. mainly basic electronics, computer technologies, and communication technologies, in both the products and the production of manufacturing industries. We can expect that this process will still be intensified when the possibilities of information technologies are fully utilized. This also means that the key carrier branches of technological change will be the manufacturing equipment industries, which utilize the dynamics of technological change both in their products and in their production, and which have forward linkages with other manufacturing industries providing them with systems and advanced tools. The motive branches of change will be electronics, the computer, communications and electric machinery industries, which provide tools and means for the manufacturing equipment industry. Thus the manufacturing equipment industry has backward linkages with information technologies and related industries. In the following the paper analyzes possible forms of future application and makes an assessment of different carrier technologies, i.e. electronics and information technologies, and their impacts on future manufacturing technologies.

2. COMPUTER INTEGRATED MANUFACTURING: BASIC DEFINITIONS AND TODAY'S APPLICATIONS

2.1 Production Automation -- as a Whole and in Part

No attempts will be made to give a complete definition of computer integrated manufacturing and all aspects of modern production automation. An illustrative definition is presented in Figure 1. Accordingly, CIM is integrating different technologies as well as different fields of engineering and knowledge.

We can differentiate four basic levels. The heart of production is, of course, the machine level. It has been one of the starting points of manufacturing automation and one of the first appliers of electronics and information technologies in

Technology base		Essential knowledge base
Planning methods	Applications in different industries	Customized needs, application know-how, project management methods, organization design, impact analysis
Production planning and control CAD/CAM CAPP	Planning and engineering Project deliveries	
	Systems - Flexible manufacturing units (FMU), flexible manufacturing cells (FMC) and systems (FMS) - Factory automation - Software systems - Production control systems	- System engineering - Manufacturing engineering - Software and computer technology - Information technology in general (especially communication)
	Machine automation - NC, robots, automatic storages, automatic vehicles, etc. - Special production machines	- Mechanical engineering - Electronics and software technology - "Mechatronics" - Control engineering
	Production interfaces - Sensors, transmitters, servo-mechanisms, switching devices, etc. - Special devices	- Physics - Mechanical engineering - Electronics - Special methods: signal processing, pattern recognition, image processing

Figure 1. The levels of production automation.

manufacturing. The most typical examples are CNC-machines, robots, automatic storage, transportation devices and special machines in different industrial sectors, such as cutting machines in the clothing industry. The automatic machines have two kinds of interfaces: one downward interface towards production with sensors, transmitting devices, servomechanisms and switching devices, and one upward interface towards the systems level and towards the planning process with different communication systems. E.g., a modern NC-tool or robot can have its own microprocessor control for each axis of the motion, custom-designed semiconductors in servomechanisms, as well as sensing and information processing devices to take care of the downward and upward interfaces and the all-over control of the machines. These are real mechatronic products, combining mechanical engineering, electrical engineering and electronics.

The systems level is the second level integrating single machines with the help of computers and communication technology. There are flexible cells (FMC), their combination in the form of flexible manufacturing systems (FMS), or even an integration of several FMS in the form of a factory-scale system. For such an integration, systems or single machines have to be able exchange data and information. Therefore a combination of communication technology with computer technology is important-- not only for the integration, but also for the upward interfaces to different planning systems. The second crucial issue is the mechanical integration with the help of transportation devices and storage systems. As a whole, the systems concept is at its emerging stage, because there are no ready-made or standard concepts for the software and the communication parts of the system; therefore software engineering is one of the key issues on the systems level.

The third level consists of different planning and design systems, including CAD, CAM and process planning (CAPP), as well as production planning and control. The planning level has been the second starting point for information technology applications in manufacturing and it has been far ahead of the systems level. E.g., different CAD and production control systems are well established and intensive users of computers. However, there have been problems with the integration of different planning technologies, such as CAD, CAM and CAPP, to produce directly from the design data bases the required tooling steps, routing instructions and NC-controls. The same is true for the downward interfaces with the manufacturing systems level. Thus, considering the whole CIM-concept, one of the key questions is again software engineering and communication technology and the integration of design and planning with manufacturing.

The fourth level, which is emerging parallel to the manufacturing systems, comprises application design and related engineering and project delivery activities. This can be regarded as a separate level or business activity, because there is a special need to combine customized requirements and technological possibilities and to specify applications as well as the systems architecture. The growing need for these activities is also due to the lack of common systems solutions and the novelty of systems technologies for small and medium-scale industries (see also Bullinger et al., 1985).

Apart from this vertical classification, the CIM technologies may also be classified horizontally according to the required processing steps. E.g., there exist different technologies for sheet metal processing, part tooling for prismatic and rotational parts and product assembly. To achieve all-over integration, different tooling steps have to be incorporated in addition to different functions.

The essential point is that there is no single, well-designed production automation technology, but it combines many different technical products and utilizes a high level of integration. It is also essential that software engineering plays a major role on the systems level and that organization innovations and marketing innovations (understanding special needs) are the key factors in a successful design of applications.

This integrated systems aspect of production automation makes it difficult to develop "a life-cycle model" for flexible manufacturing automation. The systems concept (CIM or FMS) is still at the emerging state, but it can utilize mature technologies as components, and clearly radical innovations and take-offs in the mature components (robots, NC-machines, such as laser cutting) will have a major role in future trends, if they become technically feasible.

The FMS or CIM systems can be considered as products and as product innovations. However, major difficulties arise for many industrial branches when FMS and CIM systems are regarded as production innovations. In practice, the successful application of FMS or CIM or of the concept of flexibility requires major organizational innovation. The FMS and CIM systems are always special, customized systems, usually designed to fulfill very special needs -- there are no unified, standard FMS or CIM technologies. For this reason application know-how (marketing innovation) is essential in the systems planning and the project output. Again we can conclude that flexible production automation has a highly integrating nature and that the future trends, and especially the diffusion of FMS and CIM technologies, will depend on many factors -- on many technical components, organizational factors and application design capabilities.

The integrating as well as the emerging nature of the FMS and CIM concept also reflects the fact that, as business activities, FMS and CIM are very diversified: there are specialized vendors for NC-machines, robots, AGV's, etc. In addition, there is a newly emerging line of business: systems integration and systems engineering, which is software-oriented, but which requires a thorough knowledge of a certain application area.

The lack of common standards also provides possibilities of going into business with specialized, interface- and communication-oriented software. Furthermore, there are considerable possibilities for small, high-tech firms, which are specialized in very narrow technological areas, such as special sensors, signal processing, image processing, etc.

Finally it should be noted that each industrial branch (metal products, electronics, clothing) requires its own special application knowledge which, in general, is not transferable from one branch to another.

2.2 Backward and Forward Linkages

In order to forecast the future applications of technologies, it is essential to know the routes of diffusion and the ways of how to utilize modern technologies. In this paper these routes are called forward and backward linkages. Figure 2 illustrates the basic way of thinking. The forward linkages present practical needs or the market pull, and then, of course, the backward linkages can be regarded as the technological push.

The first-order carrier branches consist of the machine-tool industry, the robot industry, and related industries. The development of these branches has been heavily based on information technologies; they also provide components for systems integration, which presents the second part of the first-order carrier branches. The systems integration is mainly based on extensive applications of computers and communication technologies. Important special issues are distributed processing and databases as well as local area networks. Therefore software engineering also plays a crucial role in this context. On the machine level the driving forces are, apart from computer technologies, the integration of mechanical engineering and electronics, and even of the basic component technologies, into the machine design. Also electrical engineering plays a special role because of its servos and drives.

The main application areas are here called the second-order carrier branches, because they are, apart from the machine-tool industry itself, the main users and appliers of the systems and the basic machine technologies. So far the main branches have been general machinery, the automobile and car industry and other transportation equipment industry, as well as the electronic and electric product industry. These branches will also be the main appliers in the future. However, depending on technological capabilities and economic efficiency, we can expect the diffusion of compact systems also to extend to small and medium-scale enterprises as well as to the so-called marginal branches, like wood product industries.

There are furthermore some special branches, like the clothing industry, which are extensive users of information technologies based on modern production technologies, but they are somewhat outside the mainstream of the development, because of special requirements and special machinery. The reasons might be difficulties in material handling, possibly necessitating special types of machines, or other technology-related reasons.

With regard to the backward linkages it is safe to expect that the manufacturing industries will not be the key industries

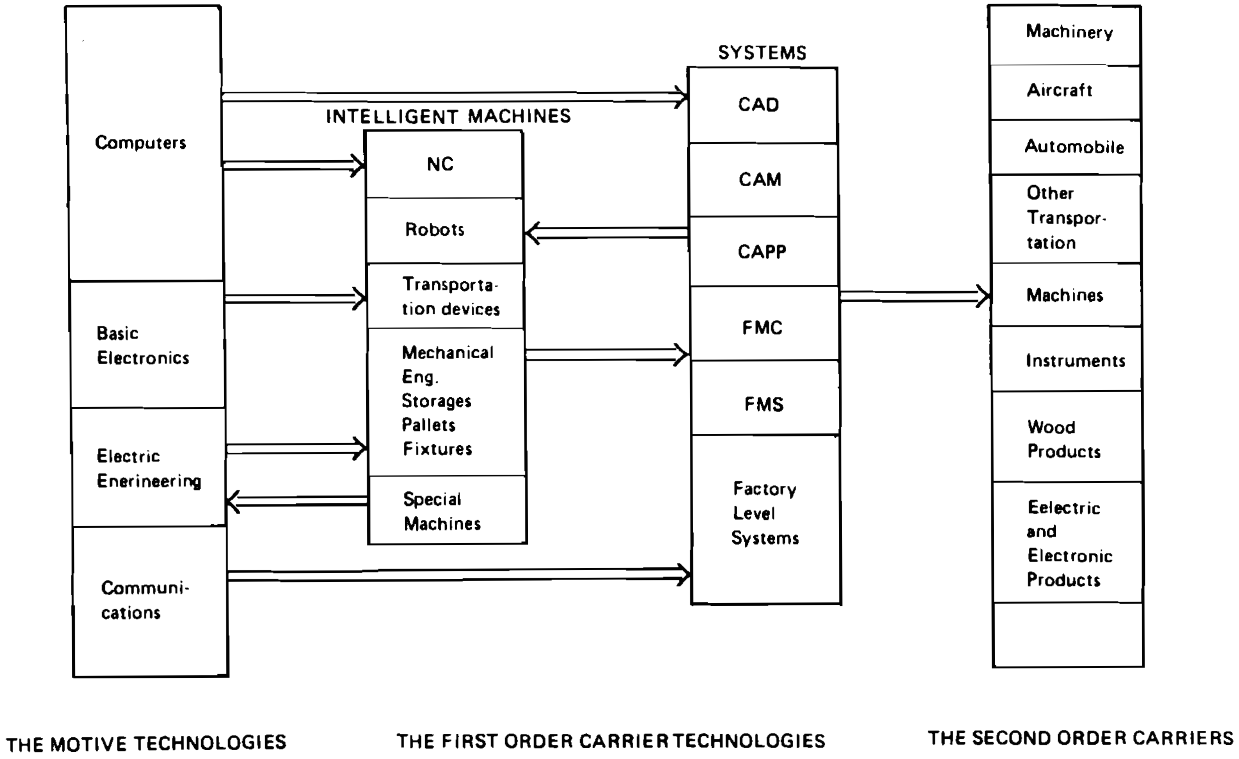

Figure 2. The motive and carrier technologies.

influencing the future trends of semiconductor and computer industries. In Japan and Europe this influence can, to some extent, exist. But in general we can regard the semiconductor and computer industry from the manufacturing viewpoint as an autonomous force, which will proceed in the near future according to its own laws, or which will partly be driven by the space, aircraft, telecommunication and military industry. Thus we can analyze the impacts resulting from the backward linkages to be a real technological push.

As mentioned before, the key element of change is the machine-tool and the related manufacturing systems industry. It has so far been the technological driving force, as it has provided the basic components for systems integration and as it has been the first user of FMS in its own production. In that way it has been the key element of the systems integration and has been moving from a component supplier and a systems applier to a systems vendor. Another important path to systems integration has been through electrical components and special controls. Usually this industry has provided special components and controls to the machine-tool industry or has even produced robots. It has also been an early user of the systems in its own production. It is quite a logical step to move from systems control to integration and related software products. The third main path has been from the computer and software industry to manufacturing software integration. This is, at the time being, the growing group, and there is a special need or a special market niche for that kind of activity, because the systems and related software products are still mainly customized products due to a lack of common standards and so far there is no common control structure for the systems and for their architectures.

It has been and still is common that the systems integration is carried out as an in-house activity directly by the final user of the systems in the application area. This is to a great extent due the customizing of the systems. At the present time there is also a common phenomenon that systems are supplied by a consortium of companies, which can be even international. Such forms of cooperation usually consist of a systems integrator and several component suppliers, where the systems integrator has the main responsibility. Such consortia seem to be quite sustainable forms of collaboration.

2.3 Technological Factors of CIM and FMS Applications

One common hypothesis has been that there is a shift from economies of scale to economies of scope in many industrial sectors. Thus the critical competitive factor lies in the ability to make product variations and to manufacture them in an economic way. In combination with product variations there are requirements for short delivery times, high quality products, small batch sizes and capital savings. Together, these requirements make it possible to respond to the customized needs and to compete in special market niches. An analysis of empirical data, as will be seen later, supports the above statement. One of the driving forces has actually been the attempt to realize economies of scope in terms of flexibility of product and delivery time, and, at the same time, to increase the product quality (Brödner, 1985; Bullinger, 1985; Talaysum et al., 1987).

If this is really the case, then the next natural question is: what are technological means and what are the main technological obstacles to achieve flexibility. These technological factors of flexibility are defined in more detail by Ranta and Vandel (1988) and Ranta and Alabian (1988).

Many of the basic factors of flexibility on the operational level are related to the current technology and its economic capabilities. From the empirical findings and case studies we can conclude that there exist main technological obstacles of flexibility. Pallets and fixtures are still expensive and they are main obstacles of machine and process flexibility. General-purpose -- but economic -- pallets and fixtures are still to be developed. The possibilities to make prismatic and rotational parts at the same manufacturing center are growing, but a real general-purpose machine and thus a remarkable increase of machine flexibility as well as process flexibility is still beyond our present economic capabilities. Production flexibility as well as structural flexibility is dependent on software issues. A modular systems software as well as a proper interface system can guarantee systems extendability in the future. An open communication system as well as the use of a common communication protocol will help to increase production flexibility. A modular software design and standardization of systems software can, in general, decrease tailoring and application design costs. Anyway, software engineering is a key issue when we try to guarantee the availability of systems and their high reliability. An increasing amount of functions will be controlled or realized by software.

The above problems are also reflected in the cost structure of the FMS systems. According to our empirical data (Sheinin et al., 1987, Tchijov et al., 1988a) the average investment costs of the systems are 3-5 million US $, and most of the systems are below that level, corresponding to 3-5 machining centers. The other parts of the systems are expensive, complicated, and typically consisting of over ten machining centers. The average cost break-down is typically 50-60% for the NC-tools, 15-25% for the auxiliary devices, such as robots, transportation and storage, 20-25% for the systems control -- both software and hardware -- and around 10% for training and planning. If the NC costs are split up, we can conclude that the basic machinery corresponds approximately one third, NC-programs to one third, and fixtures, tools, tool changers, etc. again to one third of the total NC-tool costs. Thus we see that the overall software costs corresponds to nearly 50% of the total costs of the systems. These figures are also found in other studies (Shah, 1987; Fix-Sterz et al., 1986).

If the empirical availability figures are studied, it can be concluded that the most critical issues are the interfaces of different software modules and the mechanical and electrical parts of the auxiliary devices. Also, the ability to make product changes and the costs of such changes depend more on the physical limitations and on the costs of the changes in the mechanical parts of the system than on software issues. Thus we can make a critical remark: one common way of thinking has been that the increasing share of software will lead to an increased flexibility because of the relatively easy changeability of the software functions. On the systems level this is basically true, but the flexibility potential created by the software can be considerably constrained by the mechanical part of the system, both as a cost factor and as a technical performance factor.

The application of FM systems basically falls into two broad categories, both of which present a different way of the substitution of conventional manufacturing technologies by CIM technologies. On the lower cost side of the applications there are compact systems, and on the upper cost side there are complex, large-scale systems. This phenomenon can be explained by technological factors.

There is also evidence in practice that the increased capacity of systems and the increased complexity will increase the systems costs/machining unit in a stepwise manner (Sheinin et al., 1987, Tchijov et al., 1988a). This is due to the need for more efficient machinery when a certain level of complexity is reached. Basically this due to the transportation and warehousing systems and systems control. In small size systems it is enough to have a compact type material handling system, like a conveyor, and simple systems control based on programmable logic. When the complexity increases, a more sophisticated material handling system is needed, like automated guided vehicles, and the systems control has to be based on computers, distributed data bases and integrating communication systems. These changes in systems complexity tend to change in a stepwise manner.

On the lower end of the applications modest benefits can be achieved by a compact system and by low investment costs. On the upper end there are possibilities for substantial savings, although the investment costs as well as the complexity of the system are high. The potential benefits usually justify the higher investments. The second factor, which generally conforms with the use of complex systems, consists in a real learning curve effect or economies of scale in software production. When the level which necessitates the changes in the basic systems architecture has been reached there are many possibilities to repeat (or simply copy) the basic software modules and use the same basic modules in different interfaces and in systems coordination and timing. The larger the scale of the system under design, the more immediate are the benefits of software repetitiveness.

However, we would like to make another critical remark. The medium-scale systems are critical from the economic point of view. It might happen that a sophisticated systems architecture based on distributed data bases and communication is needed, but the potential benefits are not high enough to justify the system investments and the system complexity is not high enough to draw the benefits from the economies of scale effects. This remark is also consistent with empirical data, which show that compact, small-scale systems and very complicated, large-scale systems have the shortest pay-back time. This also leads to the following conclusion: a critical technical issue for the future applications is the possibility of a module-type control structure and a transportation device, which allows for a soft extendability of the system without drastic architectural changes.

Thus, if there will be no real technical breakthroughs in realizing systems controls and all-over architectures, which guarantee module-based design of systems and an easy extendability, it is reasonable to expect that the basic application diffusion paths of the flexible manufacturing systems will be of the following two types: highly efficient and complex systems replacing rigid transfer lines, and, on the other hand, compact, small-scale systems replacing conventional semi-manual, NC-tool based production. The economy and applicability of the middle-range system will be highly dependent on systems control and communication software as well as on flexible transportation devices.

Moreover, it is worthwhile noting that the overwhelming majority of applications are tooling of either rotational or prismatic parts. Sheet metal processing is in a sense already mature, but lagging behind basic tooling. Assembly systems are rather few, but a growing area. Their technological factors are even more critical than in tooling.

3. IMPACTS OF MOTIVE TECHNOLOGIES: EXPECTED CAPABILITIES OF ELECTRONICS, COMPUTERS AND COMMUNICATION

One of the basic technological driving forces in flexible manufacturing systems and in CIM have been the possibilities created by electronics and computers (see Färber, 1986; Narita, 1987). It is safe to expect that this trend will also continue in the near future. Already today electronics and software systems are a critical part of the systems on all levels, i.e. from sensors and servos to systems control and architecture. There are many technical performance indexes such as speed of tooling, accuracy of the motion, accuracy of measurements and communication possibilities of system parts, which can still be improved by the application of basic technologies. In what follows are some of the most likely impacts on manufacturing automation are reviewed.

3.1 Basic electronics

One of the easiest forecasts has so far been the development of the transistor density of the microcircuit and of the costs of one bit on the memory circuits. The conventional wisdom, as it was seen in that year (1982), is presented by Figures 3a and 4a. It can be observed that the accuracy of the estimates is quite good, although a little too pessimistic. We already have commercial memory chips in the 1 Mbits range and first announcements regarding 4 and 16 Mbit memory chips (dram) have already been made. Of course, the market has so far been laid out for 256 kbits and 1 Mbits. For the static memory components the forecasts are quite accurate. Figures 3b and 4b show the actual new estimates (for data see Jurgen, 1988; Pickar et al., 1988).

It is reasonable to expect that these basic trends will continue, so that we will have even more efficient, more dense and cheaper circuits in the future. This development has several advantages with regard to manufacturing automation. The small size improves the possibilities to combine mechanical and electronic design -- or to make mechatronic devices, the higher density decreases mechanical connections, making systems more reliable and suitable for the so-called embedded systems, and the decreased power consumption also makes systems more reliable and makes it easier to develop embedded systems, which are important issues in industrial applications. Finally, the decreasing price, of course, makes new cost-effective applications available.

It is, of course, not only these quantitative numbers which matter, but the development also will include a lot of qualitative aspects, which are more essential for the industrial automation. These aspects will be emphasized below. But before starting on this subject, we will show some estimates resulting from expert panels.

According to the Scientific American expert panel, the following future seems to be possible in the next 10 years (Scientific American, 1987).

- The current trends of miniaturization will continue in the next 10-15 years, which will lead to an improvement of the component density by a factor of 20-40.
- This is made possible both by the decreasing line thickness and the lower operating voltage of circuits.
- The main transistor technology in use will be the so-called field effect transistors, most probably the CMOS-technology, providing a gate delay on the order of 0.2 ns and a chip density on the order of 16-20 million devices per chip, offering 256 Mbits memory chips and providing an operating speed of 30-60 MIPS in microprocessors or a fully single-chip computer in the speed range of 1-3 MIPS.
- Optical communication and optoelectronics circuits in general will be on the order of ten times cheaper than today and most likely [illegible] wide use.
- Advanced architectures will proceed and it is most likely that there will be commercially feasible parallel processing computers as well as other special-type architectures for signal processing, graphics, logic programming etc.

Figure 5 summarizes this promising future.

According to Electronic Design (January 7, 1988) the following future, which is very similar to that of the Scientific American, seems to be possible in the next 10-12 years.

- The device density as well as the processing power seem to be on the same order of as stated above.
- Optoelectronics and optical communication will be in general use in the future.

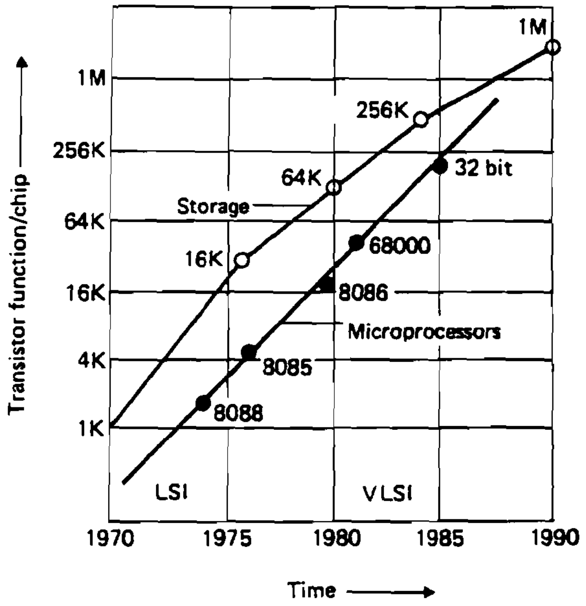

Figure 3a. The development of memory and microprocessor chips (Bursky, Electronic Design, 1983).

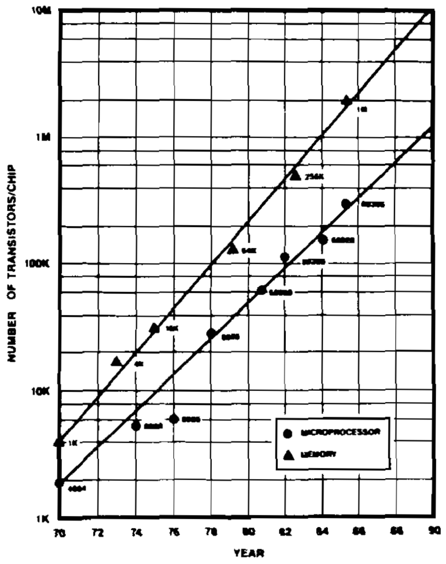

Figure 3b. The latest development trends (Pickar et al., 1986).

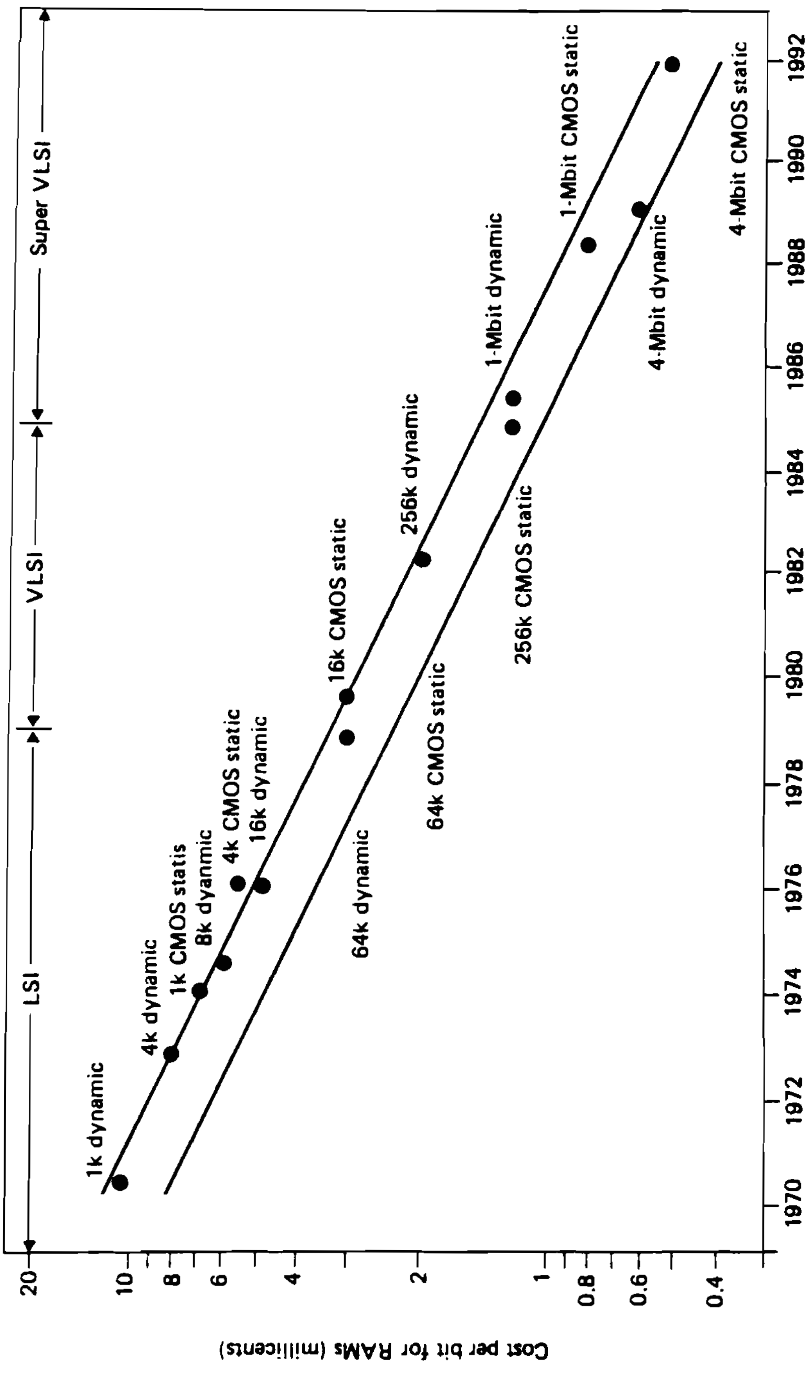

Figure 4a . Static and dynamic memory components (Bursky, Electronic Design, 1983).

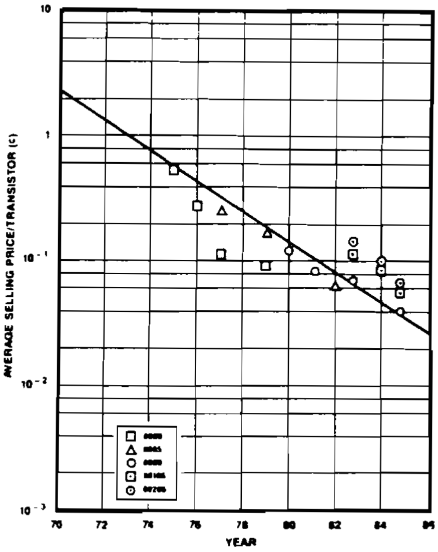

Figure 4b. The price impact of increasing density (Pickar et al., 1986).

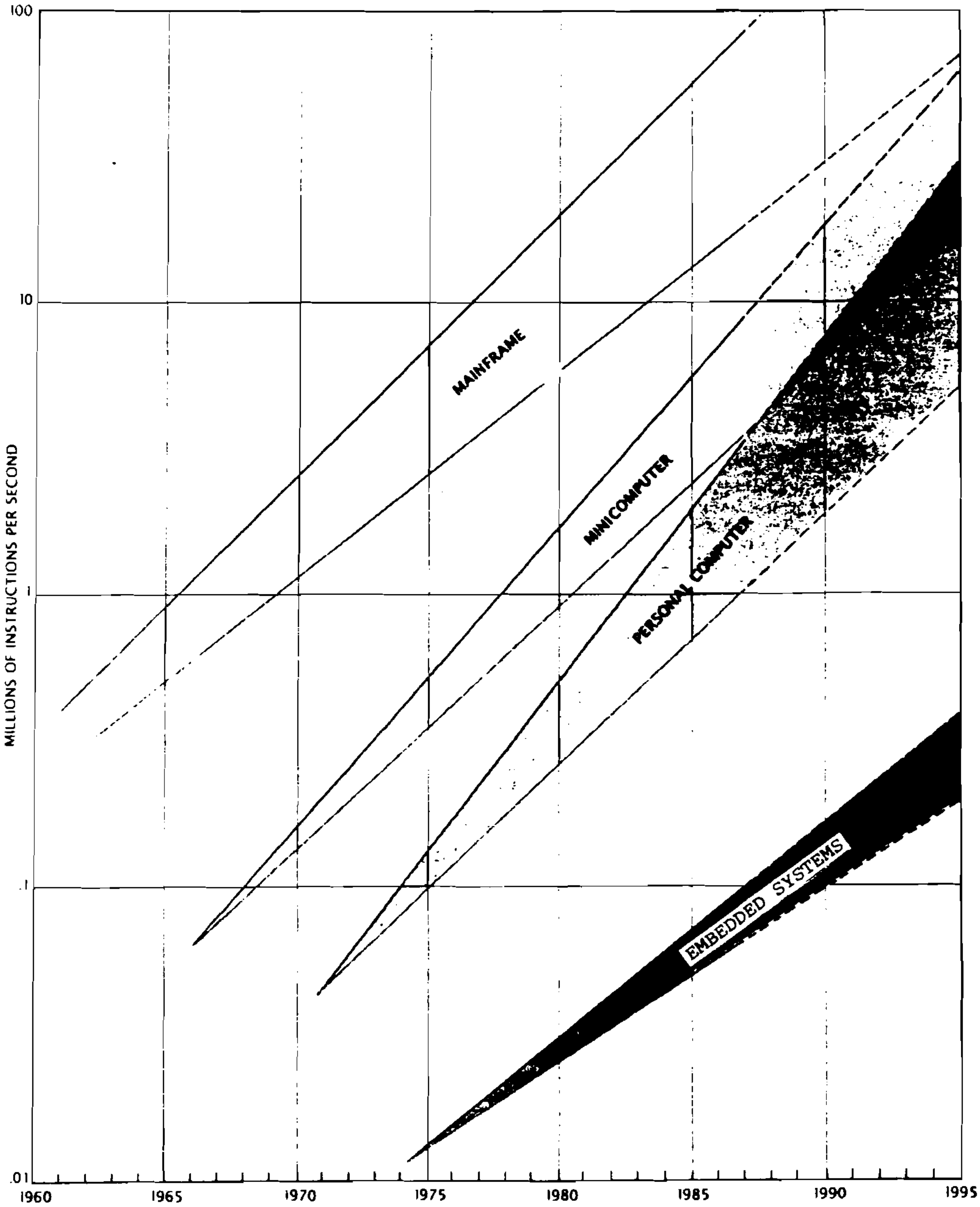

Figure 5. The evolution of efficiency of different computing categories (Sci. Americ., October 1987).

- Advanced architectures will evolve and will provide a cost-efficient way to increase computing power.

Figure 6 shows some of the future prospects.

The recent developments have been linear, so that it was easy to make forecasts. This also applies to the above forecasts: they are mainly extrapolations of the existing trends, which, of course, may appear to be valid. What really seems to be difficult is to forecast qualitative changes and their possible impacts, and to analyze obstacles, which may slow down the existing trends. In the following section some qualitative aspects will subject to discussion.

Basic silicon technologies

There have been continuous discussions on the future of silicon as a basic building material for microcircuits. For some 10-15 years there have been forecasts of the substitution of silicon technologies by new materials, such as GaAs (Gallium-Arsenide). However, this substitution never really occurred, which is due to the development of the silicon technologies -- they are by no means mature technologies.

The basic problem to be overcome in microcircuit design has been a triangle: demand for increased density, the necessity to have a low power consumption per transistor because of the increasing transistor density, and the demand for a high processing speed (small gate delay). The first requirement has been one of the basic driving forces and is obvious. To gain in efficiency, cost and reliability, there is a continuous demand for miniaturization and higher density. But just because of the higher density the power consumption as well as the waste heat production have increased -- therefore the second requirement is important. The third requirement is obvious from the efficiency point of view. Apart from this basic triangle, there is a need for easy manufacturing and design of circuits.

However, so far it has been nearly impossible to realize all these demands in the same design. Therefore it is common that the high density chips are based on technologies, which are not so efficient in terms of speed, and vice versa, the high processing speed chips also require more power.

The demand for low costs and reliability has been so high that there was a rapid substitution of the so-call bipolar transistor and low-delay technologies (such as ECL, TTL, etc.) by the less power consuming field-effect transistor technologies (NMOS, CMOS). Figure 7a shows the process as it was estimated in 1983. In practice, this substitution has been more rapid and we can expect MOS-technologies to represent 80% of all the circuits sold in 1990 (see Figure 7b). This is nearly exclusively due to the development of the manufacturing and design processes of the CMOS technologies. Therefore, the CMOS technologies will be the most highly used single transistor technology and it will gradually replace the NMOS and bipolar technologies. For the details (see Immonen, 1983; Ranta et al., 1985; Riezenman, 1984; Thompson et al., 1987; Chow et al., 1987; Pickar et al. 1986).

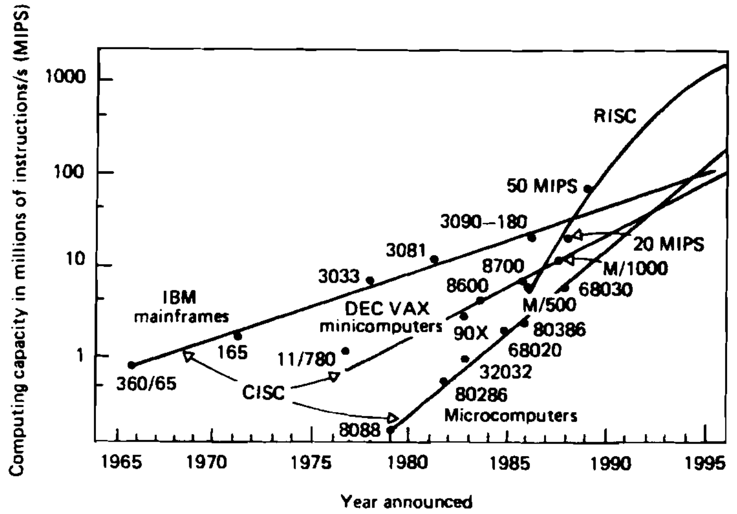

Figure 6. The efficiency of different computing architectures (Electronic Design, January 7, 1988).

Process	1982	1985	1990
bipolar	46.8	40.0	30.0
mos			
- pmos	6.1	2.6	0.4
- nmos	37.2	43.7	38.9
- cmos	9.9	13.7	30.7
mos, inclusive	53.2	60.0	70.0
Total	100.0	100.0	100.0

Figure 7a. World market shares of IC technologies, 1982 ... 1990 (Immonen, 1983).

Process	1982	1985	1990
bipolar	46.8	33	19
mos			
- pmos	6.1	3	1
- nmos	37.2	44	35
- cmos	9.9	20	45
Total mos	53.2	67	81

Figure 7b. The corrected forecasts of 1986 (Electronic Design, January 1986).

What is essential now, is that due to the development of design and manufacturing the CMOS technologies begin to be as efficient as the conventional low gate delay circuits, such as ECL and TL. This means that for the first time in history there are possibilities to combine the high density requirement with the high speed requirement on the same chip.

Therefore it is most likely that the cost-performance ratios of silicon technologies (U$/MIPS or U$/transistor) will still be greatly improved in the next 10 years. Therefore it is reasonable to wait for the cost-performance ratio of silicon technologies to become an order of 10-15 better than the GaAs technologies, or to reach even a higher ratio. Thus our future will mainly be a silicon (CMOS) future. This was also expected by the expert panel of the Scientific American. It is also reasonable to expect that the trends they forecast are most likely to occur.

From the manufacturing automation point of view this means increased possibilities to use so-called embedded circuits, more rapid and accurate controls of machines and more powerful work stations at the design end of the systems.

Semi-custom and custom-specific technologies

One of the advantages of CMOS technologies has been easy design (relatively speaking) and the possibility to integrate analog and digital functions on the same ship. These facts have made CMOS technologies a proper candidate for semi-custom and custom-specific circuits. The experience gained in manufacturing and design of CMOS-circuits has led to a rapid growth of the use of semi-custom or custom-specific circuits (see Bell 1986; Guterl, 1984).

In the beginning of 1980's the economic break-even point was about 10,000 chips a year for custom-specific and 5,000 chips a year or slightly less for semi-custom circuits. The forecasts for the substitution are presented in Figure 8a, as it was seen in the beginning of 1980's. In practice this process has been more rapid than was expected. Figure 8b shows the recent and corrected estimates. This substitution process partly also explains the rapid takeover of CMOS technologies explained in the previous section. For the data, see Seminconductor Int., 1987; Financial Times, 1987; Fey et al., 1987. An extensively good overview is given by Fey et al., 1987.

These trends indicate that the economic break-even point has come rapidly down to 1,000-2,000 chips a year at present. This development will make custom or semi-custom circuits reasonable alternatives for small-scale applications, which are typical in industrial automation.

There is sufficient reason to expect that these trends will continue in the future. This is partly due the more efficient manufacturing process and partly due to the new kind of software aids, called silicon compilers. These can utilize so-called cell or function libraries and automatically translate the functional

	1982	1985	1990
Port matrix	6.4	11.0	14.6
Custom	15.3	17.1	19.1
Standard	78.3	71.9	66.3
Total	100.0	100.0	100.0

Figure 8a. The shares of port matrix, custom and standard circuits in world markets 1982 ... 1990 (Immonen, 1983).

	1982	1985	1987	1992
Semi-custom	6.4	12	20	22
Custom	15.3	18	25	30
Standard	78.3	70	55	48
Total	100	100	100	100

Figure 8b. Corrected estimates for semi-custom and custom-specific circuits (Financial Times, September 1, 1987).

requirements to the chip layout and to the placement of algorithms and transistors. This approach makes the design and manufacturing more rapid and cheaper. We can call this approach, as opposed to the custom-specific design, a modular design approach (see Fey et al., 1987; Guterl, 1984; Kates, 1987).

The advantages of the semi or custom-specific design are apparent for specific demands for high reliability, small size or small final implementation space, high speed and high efficiency or for special types of signal processing. All of these are mostly features, which are typical of many industrial applications. Thus we can expect that custom design technologies will in the future be used in motion control, measurements, signal processing and interfacing. The benefits are increased accuracy, higher speed of tooling or motion and possibly new kinds of sensors, transmitters and actuators.

The advanced special technologies: GaAs, superconductivity and optoelectronics

As stated above, our future will be a silicon future at least in the time span of the next 10-15 years. The reasons for this development are explained in somewhat more detail in the following.

A usual candidate for the substitution of silicon has been gallium arsenide, which is again a strong candidate for this substitution. GaAs technologies have, of course, some advantages. The most important of them is the small gate delay, which makes the operating speed faster than that of silicon technologies. Moreover, the power consumption can, depending on the design, be lower than for silicon technologies.

However, if a specific function is implemented by means of GaAs, the cheapest realization will be at least by a factor of 10-20 more expensive than the silicon counterpart. In this case usually only the processing speed is improved, but the power consumption may be even worse than that of the silicon technologies. If both the power consumption and the speed are likely to be improved, then the cost difference will be even higher as compared to the silicon technologies (see Milutinovic, 1986; Frensley, 1987).

It can be forecasted that this basic situation will not change in the near future. This is partly due to the physical properties of GaAs (crystal structure and discolations) and it is partly due to a more difficult and complicated manufacturing process. Therefore it is a common way of thinking that the reject rate in GaAs processes will always be higher than in silicon technologies. As a result of these factors and the more expensive and rare raw material, GaAs chips will never reach the price level of silicon chips. Thus the cost-performance ratio will still be better for the silicon chips and there will be no rapid changes in this respect -- the development is more likely to be vice versa due to the rapid development of CMOS technologies. Thus we can conclude that there will be no general substitution of silicon technologies by the GaAs technologies (see Milutinovic, 1986; Nelson, 1985).

However, those kinds of signal processing tasks, in which the price is not a critical factor, are more likely to be the basic application areas of GaAs-technologies. Moreover, the insensitivity of GaAs to electromagnetic disturbances in combination with speed and power consumption make the most likely applications still in space and aerospace technology. Optoelectronics is also a new and growing area for GaAs-technologies. But there are no reasons for its rapid diffusion into manufacturing automation.

Superconductivity is, of course, due to the recent achievements in this field, another typical issue. There have, however, been too optimistic overtones. There is still a long way to go before practical applications. As many specialists have noted, high temperature alone does not open the way for practical application; the critical issues are the current density, which is not yet high enough for practical applications, the requirement of exceedingly high magnetic fields and the sustainability of the superconducting stage. Thus it is most likely that superconductivity will not play an important role in manufacturing automation in the near future.

The wide spectrum of the optical technologies has also presented candidates for various kinds of innovations in manufacturing automation. In practice there exists some potential, and expert panels are quite optimistic regarding the future of optical technologies (see Batchman et al., 1987; Giallorenzi, 1986).

In manufacturing automation the main application areas are communication, mass storage and sensing devices. From the technical point of view communication technologies are already in existence and there is a slow substitution process for the conventional systems. The starting point has been a point-to-point type of communication in mass transfer of data and signals. The local area network applications and industrial applications have so far been few. These applications are mainly used in those areas where there is a high risk of electromagnetic disturbances. This situation is primarily due to the high prices of connections, junctions and interfacing devices. An optical LAN is still on the order of ten times more expensive than its conventional counterpart.

However, it is reasonable to expect a slow cost decline of interfacing and connections. This means that optical communication can compete with the conventional communication systems when high speed, high capacity or very high reliability are needed.

The other possible application area is the field of sensing devices. This could be one approach to get reliable feedbacks, e.g. from the tooling process (Giallorenzi, 1986). There are no practical ways to make any concrete forecasts in this respect. However, the robotized arch welding is one example of that kind of development, where combined laser, optical sensors and fibers are applied together with image processing to the seam tracking problem.

The third and probably the most important issue of optics is laser cutting and tooling. If this technology will actually be commercially available, we can expect the whole range of manufacturing to change, and even the machine tool industry will then look completely different. However, for the time being there are no reasons to expect a rapid diffusion of laser tooling, but it can be this kind of qualitative change which causes discontinuity.

3.2 Computers, Software and Communication

Basic processors

In the beginning of Chapter 3 some general trends have already been presented. It is reasonable to believe that those main trends will actually occur. From the viewpoint of manufacturing automation the most interesting technologies are embedded systems, minicomputers and software engineering.

The efficiency of processing can not only be influenced by the basic component technologies, but it is also influenced by systems design and architectures (see Torrero, 1983; Fitzgerald et al., 1987). So far the systems have been classified according to price and efficiency (MIPS -- million instructions per second), as shown in Figure 9. But the most important differentiating or classifying principle is the semiconductor technology used to build up the system. This is also indicated in Figure 9 (see Gupta et al., 1984).

Conventionally the low price-level systems have been realized by the MOS-technologies. The low price has necessitated high component density to avoid expensive boards and mechanical connections. Therefore low power consumption has also been required. On the other hand, the high price-level systems are based, due to the required efficiency and MIPS-power, on the low gate-delay technologies, such as ECC and TTL and other bipolar technologies. Therefore, due to the higher power consumption, the component density has been lower and the functions are mainly integrated on the board level -- which makes the systems more expensive. Many functional properties of different categories (e.g. micros and minis) as such can be the same, like the word-length or the capacity of the main memory; the efficiency is gained mainly through different transistor technologies.

The essential event taking place at present is the development of the CMOS-technology to have a low gate delay in addition to a low power consumption. Therefore it is reasonable to expect CMOS-technologies to be the main transistor technology over the wide range of the individual categories. This means that the categories will be overlapping and the boundaries will still be reduced. On the other hand, it is likely that completely new kinds of special systems will appear among the classical systems categories (such as minisuper systems, signal processors, graphic processors, etc.). Therefore it is also likely that the future systems will be rather classified according to the purpose of use and not necessarily anymore

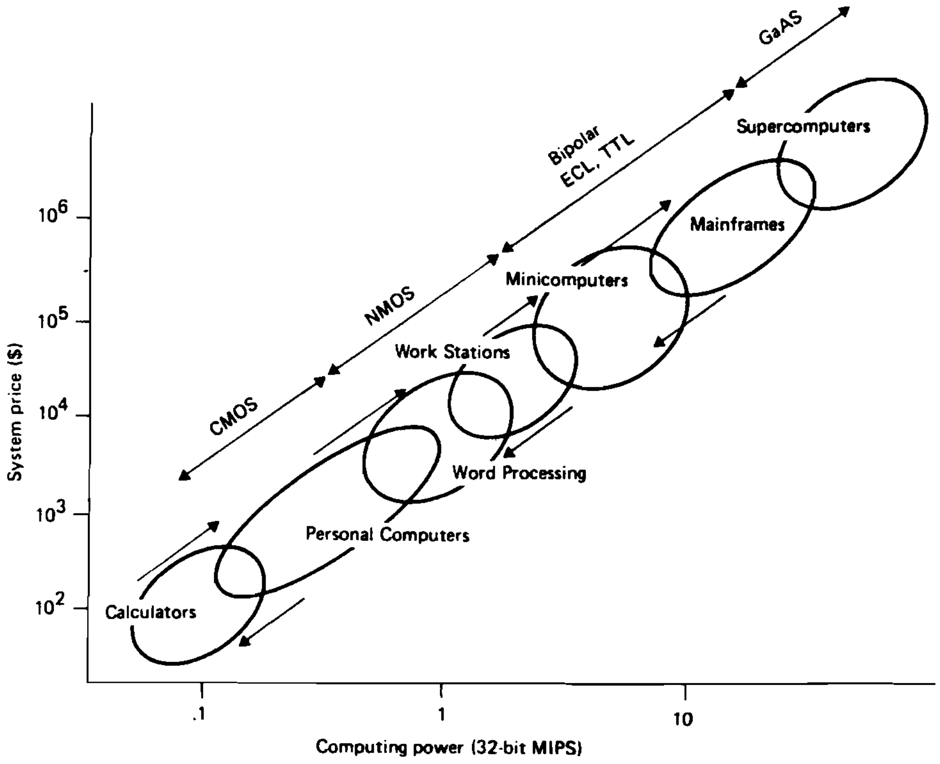

Figure 9. Price and computing power, by category (Gupta et al., 1984).

according to prices and MIPS. Figure 10 presents the dynamics of the change (see Bond, 1986; Martin, 1987; Pickar et al., 1986; Jurgen, 1988; Electronic Design, 1988).

The work stations and basic minis have their main impact on the design end of the CIM.

The special architectures and signal processors and the embedded systems in general affect mainly the machine level.

Special architectures and signal processing

The special architectures such as co-processing, reduced instruction sets (RISC), and task or application-oriented architectures, like graphic and signal processors can double or triple the performance of the normal systems. This is due to the optimization of the instruction set and the architecture for a specific task, so that unnecessary overheads can be avoided. Applying task-specific architectures for embedded systems and work stations, they easily reach the efficiency of minis, and this at a more moderate price. Especially signal processors, graphic processors and co-processor architectures can be valuable for machine automation. Moreover, it is reasonable to expect a declining price trend of specific architectures, which will mean a lower economic break-even point for many applications (see Rauch, 1987; Mitra et al., 1987; Wiley, 1987; Electronic Design, 1987). An extensive survey is given by Mitra et al., 1987.

Signal processing in general is usually thought to be that technology, which gives intelligence to machine automation applications and which will improve the efficiency of robots and machines. However, there is a wide range of signal processing applications; they are not only dependent on the basic hardware available, but the are also highly dependent on the methods to be used. Finally, the intelligence or the signal processing capabilities also have to solve a technological problem and provide a superior efficiency compared to the ordinary systems, and, in addition, their price has to be reasonable.

For example, the main obstacles to extensive applications of image processing and pattern recognition have partly been methodological and partly hardware issues, which made image processing rather expensive for standard industrial applications (see Kent et al., 1986).

Although there are a lot of successful examples of image processing in practice, it is reasonable to expect a rather slow diffusion of these technologies for manufacturing automation applications. In any case, image processing will not have a large-scale impact on the diffusion rate of CIM technologies in the near future.

This is basically due to the following methodological problems: in order to be efficient each application has to use specific recognition methods customized to that application. Therefore visual seam tracking, accurate positioning of a robot arm by a visual system, recognition of discrete parts -- they all use different methods for image processing. Also the hardware

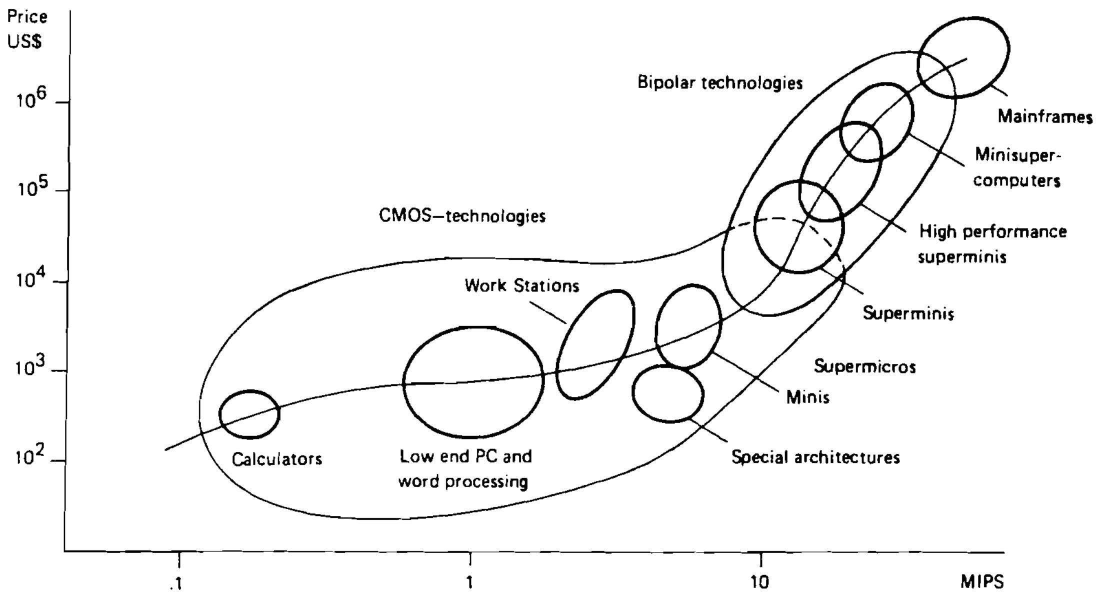

Figure 10. Changes in computing categories.

architecture of systems differs according to the used method and applications. In some cases there is a need for special-purpose processors and custom-specific circuits because of the required MIPS-efficiency, and on the other hand some applications can be based on ordinary processors. Therefore image processing will be a relatively expensive technology, because there are no standard commercial solutions available for every specific problem. And such generic solutions will not appear in the near future.

Therefore it is usually difficult to economically justify an image processing system. E.g., the visual seam tracking system for robotized arch welding has already been available for some years. It has a good technological performance and in some cases the quality improvement of welds can be remarkable. However, there has been a very slow diffusion and only few commercial applications, because in many welding applications there is no real need for a visual system and the system cannot be economically justified.

Anyway, there might be a slow diffusion of visual systems into manufacturing automation -- the benefits will be seen in the form of increased accuracy and increased tooling speed.

Apart from image processing, the other important, and even more important application area is diagnostic and measurement processing. These tasks can be realized by an embedded system and usually there is a need for signal processing and special architectures. Basically these systems can be pattern recognition systems of acoustic signals or other kinds of statistical (stochastic) analysis of signals. The results are again a more reliable operation of machines and a higher speed of tooling.

Still, there is a third application area for special architectures. That is graphics processing and utilization of graphic processors in work stations. They might be an improvement in the processing capabilities and also in the man-machine interface. These might, again, result in more cost-effective CAD/CAM systems and also improve the performance of those systems.

Software engineering, communication

Software engineering plays a critical role in manufacturing automation. Software is based on all levels of automation, starting from the machines up to the integration of different subsystems. It is an important cost factor, and it is also an important reliability and availability factor. Many previously described signal processing tasks are completely based on the software methods and algorithms. In manufacturing automation we will therefore experience all problems known from software engineering (see Hecht et al., 1986; Schatzberg, 1986; Boehm, 1987).

There are two main trends in software engineering which might have an impact on manufacturing. The first is high-level, problem-oriented languages, and the second is logic programming (AI-techniques). Both techniques can facilitate NC programming, robotics programming, and systems integration. A definition and requirement specification aid system will make the design of systems easier and may reduce the application barriers. But software is still a critical issue for the integration and diffusion of CIM (see Weisbin, 1987; Kusiak, 1987).

Communication systems are necessary for the integration of systems. As such there are no technological problems. Problems are rather related to the huge amount of customized software needed to integrate systems to communicate. The critical issue, therefore, is the problem of commonly accepted communication standards. If the development of MAP, e.g., will succeed, it will have strong cost impacts and it will certainly speed up the diffusion.

4. CIM TECHNOLOGIES

4.1 NC-machines and Machine Automation

NC-machines are key components of FMS and CIM for part manufacturing of metal and wood products. The NC-business has many indications of a mature industry (Horn et al., 1985; EEC, 1985): standard products, cost competition and new market balance, in which the winners seem to be efficient producers (with respect to costs and product quality). There has been a considerable change in market balance during the last ten years (Department ..., 1984; Automation Forum, 1987).

Behind these changes there have also been technological factors. Maybe the two important factors are the incorporation of electronics and improved cost efficiency as well as the development of new types of compact machines for small batch production.

Electronics and software engineering can be applied on many levels (see Figure 11). Usually the control of axis motion and the basic tooling process are now based on electronically controlled servo systems. Most advanced systems already utilize custom design circuits. The direct measurement of the tooling process has so far been a difficult task. The control is basically an open control or based on indirect measurement, such as power, torque, or stress. For diagnostic purposes advanced signal processing, like acoustic noise analysis, or other stochastic analyses, can be utilized. The impact of electronics has been an increased efficiency without any major cost increase -- or an improved cost-performance ratio (see also Wright, 1988).

The NC-controllers are nowadays usually realized by programmable controls or by a free programmable microprocessor system. So far it has been a common habit to obtain the basic machine and NC-control from separate sources. In this case a separate interface is needed to connect the NC controls and the servos. However, the trend is toward more integrated systems and, again, an improved cost-performance ratio. It is reasonable to expect that new software engineering tools and the foreseen development of processors will furthermore improve the cost-performance ratio.

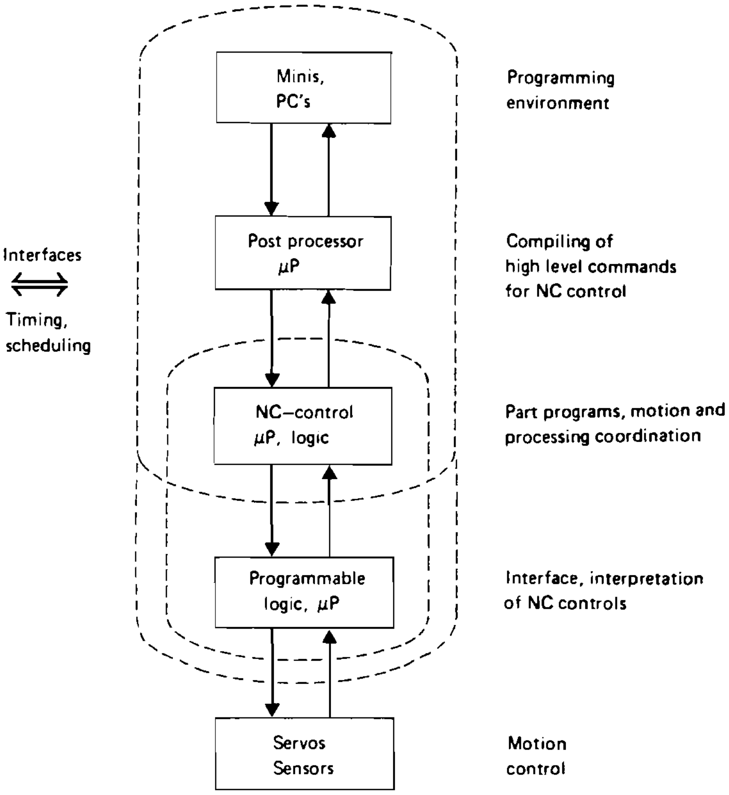

Figure 11. Levels of machine control.

There are many special tools and high-level languages to produce basic NC-programs. However, usually a separate micro- or minicomputer system is used for this purpose. Then a separate compiling system (post-processor) is needed to interface the programming system and the NC-controller. The recent trends indicate, however, that integrated systems will be increasingly available, which consist of the programming environment, NC-controls and all required interfaces. It is reasonable to expect this trend to become even stronger because of the advances of processing devices, particularly of special processors and work stations. This again will improve the cost-performance ratio and might also provide tools to facilitate flexibility (e.g. to produce new part programs).

All these changes have caused the NC-machines to become more diversified and markets to become segmented, according to capacity and basic tooling functions. Therefore there are also compact systems available for small batch production.

However, at the same time there are other interesting trends and signs: incorporation of electronics, software functions and the flexibility of production processes open a new potential for special-purpose machines, which, with their high performance, satisfy the needs of a special application. After many years there is now a growing class of small manufacturers who have built up a competitive power based on special segments and customized machines. Moreover, we can expect that the previously described trends in software engineering will facilitate the customizing process and open new possibilities for product development.

In any case, the big problem still is to integrate basic tooling functions, turning, drilling and milling, into a universal machining center. There are weak signals of a slow progress in this respect. Some machining centers can already do elementary turning functions or have a horizontal axis, and, similarly, some turning centers have a vertical axis to make drilling operations. Electronic and software development will yield completely new prospects in this respect -- it might help to create real flexibility in a cost-efficient manner.

On the systems level important aspects of NC-machines are: new measurement technologies, fixtures and pallets, tool and work piece changers. The development in all these aspects means an increasing level of flexibility and increasing performance measures of FM-systems. However, these mechanical auxiliary devices may be the key technological obstacles to creating operational flexibility and they will remain to be key cost factors. There are no rapid changes foreseen in this area (see Feldmann, 1985; Pfeifer et al., 1985).

It may be repeated that the machine level provides the basic framework for flexibility. Software functions can not help to provide any extra flexibility, if the machines are hard and expensive to change. Figure 12 shows some results of the Delphi studies of OTA (OTA, 1984). They are still quite relevant and

	Current (1984)	1985-86	1987-90	1991-2000	2001 and beyond
Hardware:					
1. Systems which can automatically and reliably remove a wide variety of metal chips produced in cutting[a]			▲	● ■	
Both hardware and software:					
2. Reliable, widely applicable adaptive control to optimize speed of metal removal	▲		●	■	
3. Tool wear sensors applicable to wide range of cutting tools	▲	●		■	
4. Systems for measurement of parts of a variety of shapes and sizes while the parts are being machined		▲	●	■	
Software:					
5. Controllers to accommodate ties to robots	▲	●		■	
6. Model-based machining in which the machine tool operates substantially automatically based on data about metal processes and the part to be produced		▲	●		■
7. Widely applicable 3-D verification of NC programs using CAD-based simulations ..		▲		●	■

[a] Systems currently exist for automatic removal of metal chips, but despite much interest and research, they are neither very reliable nor generically applicable (i.e., they can only be used for certain kinds of metals or cutting processes).

▲= solution in laboratories.

●= first commercial applications.

■= solution widely and easily available (requiring minimal custom engineering for each application).

Figure 12. NC machine tools: projections for solution of key problems (OTA, 1984).

give reasonable forecasts. Also other estimates seem to be quite analogous (see Wright, 1988; Department ..., 1984; Horn, 1985).

In terms of general trends we can conclude:

- there will be a slow trend towards universal machining centers or multipurpose CNC-machines capable of parallel tooling and of several standard tooling functions;
- special-purpose, multi-functional machines will become cost effective, providing an efficiency increase in the areas where one special machine can replace many standard, single-purpose machines;
- incorporating electronics and software engineering with the mechanical design will bring flexible and general-purpose fixtures into commercial use in a ten-year perspective, increasing the machine flexibility and decreasing the costs of flexibility;
- new programming environments and methods make it easier to implement new NC-programs and improve the cost-efficiency ratio of NC-machines;
- all these trends mean that the efficiency and flexibility of the basic machinery will increase without a considerable cost increase.

One radical innovation which could change the whole picture is laser processing. If the technical reliability of lasers increases, they could become an effective means of increasing flexibility (milling, drilling and turning by the same tool; no tool maintenance and drift; flexibility of software; applicability to different materials). This could be a real qualitative change from the viewpoints of both, production and the NC-machine business. In general we can claim that optics could, in a wide sense, be the technology which necessitates a new technological form in material processing and possibly also information processing.

4.2 Robotics

Robot manufacturing shows some of the same tendencies as the NC-machine industry: there are indications of a mature industry. The so-called standard robots are an area in which competition is highly cost-oriented. There have been considerable changes in the market balance: many companies have given up and there are only a few strong manufacturers left. At the same time new possibilities and potentials have been created in specialized robotics for very narrow applications by adding specific technical properties (speed, accuracy, interfaces, signal processing, image processing) with the help of electronics and software engineering. Specialized robots have also opened possibilities for small manufacturers.

Robotics is also analogous to machine automation with control hierarchy. Figure 11 is valid only with appropriate terminological changes. Basically all that has been said regarding the control technology is also valid (see, e.g., Knasel, 1987; Wright et al., 1988).

The effects of robots seem to have two major trends. First, there are many stand-alone applications of standard robots, such as point and arch welding, painting and other surface finishing tasks, etc. The diffusion of robots seems to depend mainly on the costs of standard robots compared to replaced labor (Tani, 1987a,b,c; Mori, 1987). Since their costs are decreasing and their efficiency is increasing, we can expect a steady diffusion of the standard applications. The second main application trend is the use of robots as a part of manufacturing systems (FMU, FMS, FMC assembly systems, etc.). The technical features and the performance of robots are essential for these applications. The capabilities of the robots can have a considerable influence on the flexibility and the techno-economic performance measures of FMU, FMS and FMC and also of assembly cells and systems. In particular reliability, accuracy, speed, flexible grippers and intelligent interfaces (tactile sensors, vision, other signal processing) play an important role. New achievements in these areas always mean new possibilities on the systems level and also increase the flexibility.

The advancement of sensors and grippers is especially critical for assembly systems. The flexibility of robots is critical both with respect to technological performance and cost efficiency of the systems. The second critical factor is speed and accuracy, which present slightly conflicting goals. On the systems level it is no longer the simple labor replacement, which matters, but there are more complicated performance requirements. However, it can be expected that the development will be rather slow and real generic and flexible grippers and reliable and cheap tactile sensors will be commercially available only after 1995 (see also Dario et al., 1985) at a reasonable price (10% of the robot price). The image processing problems were already shortly reviewed above; they show the same tendencies as tactile sensors and grippers. Again, the OTA forecasts seem to be relevant (see Figure 13) and in agreement with other forecasts (see Wright, 1988).

It has been commonly thought that the so-called intelligent robots will gradually substitute for the standard robots, such as playback and fixed-sequence robots. Basically this is not true. The intelligent robots are more likely to expand robot applications to completely new fields and create new markets. But because this process has been slower than commonly forecasted -- due to technological and economic reasons -- there were too many optimistic expectations for the market growth. This is one of the origins of the problems of robot manufacturers. The substitution process is more likely to happen between different generations of playback and fixed-sequence robots, because their cost-performance ratio has also improved and will improve even further. This presents basically the same fact as stated above concerning stand-alone robots. From the economic and technical point of view there are no reasons to buy an expensive visual system or flexible grippers, if a simple fixed sequence robot with simple grippers can perform the task reliably enough, and

	Current (1984)	1985-86	1987-90	1991-2000	2001 and beyond
Hardware:					
1. Lightweight, composite structures and new forms of drive mechanisms	▲	●	■		
Both hardware and software:					
2. Force sensors	▲ ●		■		
3. Versatile touch sensors		▲	●	■	
4. Coordinated multiple arms		▲	●	■	
5. Flexible, versatile grippers			▲	● ■	
Software:					
6. Precise path planning, simulation and control with CAD	▲		●	■	
7. 3-D vision in structured environments which have been planned to simplify the vision task	▲ ●		■		
8. 3-D vision in unstructured complex environments which have not been planned to simplify the vision task			▲	●	■
9. Robust mobility in unstructured environments			▲	●	■
10. Standards clarifying different versions of robot languages, and helping ensure a common language for similar applications			▲ ●	■	

▲ – solution in laboratories.
● – first commercial applications.
■ – solution widely and easily available (requiring minimal custom engineering for each application).

Figure 13. Robotics: projections for solution of key problems (OTA, 1984).

vice versa, there are tasks, which simple robots can not perform. There has been a lot of misbelief in this respect. As a product robots are diversified and markets are segmented.

The following trends might materialize in a ten-year perspective:

- grippers will no longer be technical and economic obstacles in assembly systems and because of the increased speed and accuracy of robots the general efficiency of assembly systems will be improved;
- robots will no longer be a practical limitation in tooling systems;
- a completely new set of applications, such as mobile robots, will be available.

4.3 Special Machines

In manufacturing areas such as the clothing industry, electronics and also the metal product industry (e.g. assembly tasks), there are many special machines. They are mainly dominated by the traditional producers. However, signs of diversification are clear. Especially in the clothing sector new possibilities are created by electronics, software engineering and robotics. New entries have occurred and will continue to occur -- the production technology will experience radical changes in the near future.

4.4 Integration Technologies

Software engineering or software systems play a key role in system integration. This has many performance consequences; in particular it has a strong impact on the reliability and availability of a system. On the other hand, the software systems can also improve the flexibility (see Savolainen, 1987; Boehm, 1987).

On the software side standards will play an important role. Today, customizing and integration of the systems are carried out with the help of software. Each system requires, in principle, basic software and communication software modules which must be developed separately for each system. This is nowadays a significant cost factor and is, in fact, also a major entry barrier for newcomers to the system integration business (FMS and CIM systems). It also increases the costs of the specific applications (see also Horn et al., 1985), and customizing is also a major source of software errors. The standard modules, both for communication and basic functions, which could be used in many applications, can considerably decrease the development costs of a system.

In general it is difficult to identify a life cycle model for software products. But we can say that the standardization of the basic software modules corresponds to the maturity stage of the product life cycle. Standardization usually means a cost decrease and thus opens possibilities for newcomers and specialized systems.

Thus, if e.g. the MAP development is to succeed, we can expect that in addition to the standardization it will open possibilities or potentials for cost-effective means to realize specialized systems architectures, or in other words, to increase the flexibility in the systems development process itself (as will usually happen at the mature stage). This means that:

- the economic barriers for new entries will decrease;
- the special-purpose systems or the subsystems can be economically realized, which means the creation of new business segments and increased diversification of the system products;
- the technology-oriented, specialized subsystems or systems (signal processing, image processing) can be economically realized as a part of the standard system; this again means new growing market segments;
- in a longer perspective all these trends reflect on the applications of FMS: economic barriers will slowly decrease, application areas will extend and the concept of flexibility will broaden with respect to part families (shapes and sizes).

The basic elements of the integration are manufacturing systems, such as FMC and FMS. As already indicated above, software can not help very much on the FMS level. The flexibility as well as the cost-performance ratio depend also on the fixtures and tool changers, apart from the software. Again, the OTA forecasts (Figure 14) are still relevant. However, the advancement of the factory level is completely dependent on software and communication issues. Even more critical is the software for the integration of CAD/CAM with the manufacturing level. There is still a long way to go for a complete integration, as Figures 15 and 16 show.

An optimistic forecast could be the following for the ten-year perspective:

- there exists a common standard for the systems architecture (communication, interfacing, etc.) which makes it possible to develop modular type automation systems for manufacturing (FMS) control;
- this modular approach makes it possible to decrease software costs of manufacturing systems, to extend systems, it makes it easier to develop systems and decreases the risk of software errors and software quality;
- design databases are integrated into manufacturing systems and the first, low-cost commercial transformation programs are available to generate NC-programs from the design databases;

	Current (1984)	1985-86	1987-90	1991-2000	2001 and beyond
Hardware:					
1. Generic fixtures for holding a variety of work-in-process parts		▲		● ■	
Both hardware and software:					
2. FMS for:[a]					
a) cylindrical parts production	▲●			■	
b) sheet metal parts production	▲●			■	
c) 3-D mechanical assembly	▲			● ■	
d) electronics assembly	▲●		■		
3. Materials handling systems which can handle a variety of parts in any sequence necessary	▲●		■		
Software:					
4. Automatic diagnosis of breakdowns in the FMS			▲	●	■
5. Standardization of software interfaces between computerized devices in an FMS			▲	●	■

[a] Almost all FMS currently running are used to machine prismatic parts, (e.g., engine blocks) which are those whose outer shape consists primarily of flat surfaces. The projections in this entry refer to FMS for quite different applications: a) machining of cylindrical parts, such as rotors and driveshafts (or "parts of rotation," in machining jargon, since they are generally made on lathes); b) stamping and bending of sheet metal parts, such as car body panels; c) assembly (as opposed to fabrication of individual parts) of three-dimensional products, such as motors; and d) assembly of electronic devices, such as circuit boards. While machines currently exist for automatic insertion of electronic parts into circuit boards, an electronics FMS would integrate the insertion devices with soldering and testing equipment.

▲= solution in laboratories.

●= first commercial applications.

■= solution widely and easily available (requiring minimal custom engineering for each application).

Figure 14. FMS: projections for solution of key problems (OTA, 1984).

	Current (1984)	1985-86	1987-90	1991-2000	2001 and beyond
Software:					
1. Well-understood, widely applicable techniques for scheduling and logistics of complex materials handling systems that would allow full factory integration ..			▲	●	■
2. Standard communication systems (networks)	▲	●		■	
3. Standardization of interfaces between wide range of computerized devices in an integrated factory................			▲	●	■
4. Data base management systems which could sort, maintain and update all data in a factory				▲ ●	■
5. Computerized factories which could run on a day-to-day basis with only a few humans in management, design functions					▲

▲ — solution in laboratories.
● — first commercial applications.
■ — solution widely and easily available (requiring minimal custom engineering for each application).

Figure 15. CIM: projections for solution of key problems (OTA, 1984).

	Current (1984)	1985-86	1987-90	1991-2000	2001 and beyond
Hardware:					
1. High-resolution, color display of designs, with rapid generation of images[a]	▲	●	■		
Both hardware and software:					
2. Low-cost, powerful microcomputer-based workstations for:[b]					
a) electronics design	▲	●	■		
b) mechanical design		▲	●	■	
3. Independent CAD workstations linked by network, with access to super-computer for powerful analysis and simulation	▲	●	■		
Software:					
4. Three-dimensional solid modeling systems, resulting in:[c]					
a) more realistic images	▲ ●		■		
b) enhanced ability to connect with manufacturing equipment	▲		●	■	
5. Comprehensive, powerful computer-aided engineering systems[d] for mechanical design			▲	●	■
6. Extensive design/manufacturing integration[e]		▲	●	■	

[a] While color displays are currently available, they tend to sacrifice either resolution (the fineness and clarity of the picture) or the speed with which the images can appear on the screen. New techniques for displays, such as the use of dedicated microprocessor chips (sometimes termed "silicon engines") to generate images, promise to improve this situation.

[b] Microcomputer-based workstations for CAD are now being marketed, but in the judgment of technical experts consulted by OTA, they are either not powerful enough and/or not inexpensive enough to be useful in a wide variety of applications.

[c] CAD experts report that many systems for 3-D solid modeling are available now, but they are not being used because of their large appetite for computer power, and because their capacity to link design data to manufacturing equipment is inadequate. Part (b) of this entry refers to this ability to store and manipulate design data about the physical characteristics of a part in such a way that it can be transmitted to manufacturing equipment with only minimal intermediate steps.

[d] This entry refers to modules powerful enough to allow extensive interactive testing, simulation and refinement of designs in a wide range of applications. Such systems are strongly product-dependent; while they may be *near* available for certain products now (e.g., integrated circuits, certain portions of aircraft and motor vehicles), they are much less advanced in other industries and applications.

[e] This entry denotes the "window from design to production" which would, for instance, allow designers to examine the production implications of design choices. These include the costs and necessary production processes, as well as the history of manufacturing similar items at the plant. Such comprehensive connections would allow much more substantial integration of CAD, CAM, and computer-based management.

▲ – solution in laboratories.

● – first commercial applications.

■ – solution widely and easily available (requiring minimal custom engineering for each application).

Figure 16. CAD: projections for solution of key problems (OTA, 1984).

- Figure 17 presents this situation.

On the manufacturing level mechanical integration is also critical. Transportation and storage systems are significant cost factors and they are, together with related interfaces, important performance factors, too. Now the changes of the systems architecture tend to cause discontinuities in the cost-performance ratio. If a modular type system, which is easy to expand as system requirements change, will be commercially available, it might have a great impact on the systems level. Now many systems are on based compact-type, standard architectures -- especially at the low cost end of applications -- which are difficult to change and to expand. This is a special risk factor of investments.

5. CONCLUSIONS

The growth of flexible manufacturing systems applications has been quite rapid and it is estimated to have reached about 500-600 applications by now. The simple estimate (the annual growth rate of 40% will continue) gives about 1800-2000 systems for the year 2000.

Another way of estimation can be put forward as follows; it is based on the shares of CNC total investment of all machine tool investments and the share of CNC's implemented in systems (the figures are valid for the Western industrialized countries; there are a lot of differences between individual countries).

	1985	1990	2000
CNC: % of all machine tool investments (new + replacement)	40	50	70
CNC implemented as a part of systems, % of all CNC investments	50	70	80

Taking into account Tchijov et al. (1988b), the age distribution of NC-machinery and the average replacement time, we can conclude that around 2005-2010 the strategic part and the main share of the production of manufacturing industries is produced by FMS- or FMC-type systems.

However, there are a lot of barriers to diffusion.

- Technological barriers influence the basic performance and efficiency of a system and therefore they are also important economic factors defining the cost-performance ratio of systems.

- Organizational barriers are related to training, work content, and task division of the user organization. They define the availability of systems and thus influence the life-cycle costs of the systems and can be a critical factor behind the profitability of the systems.

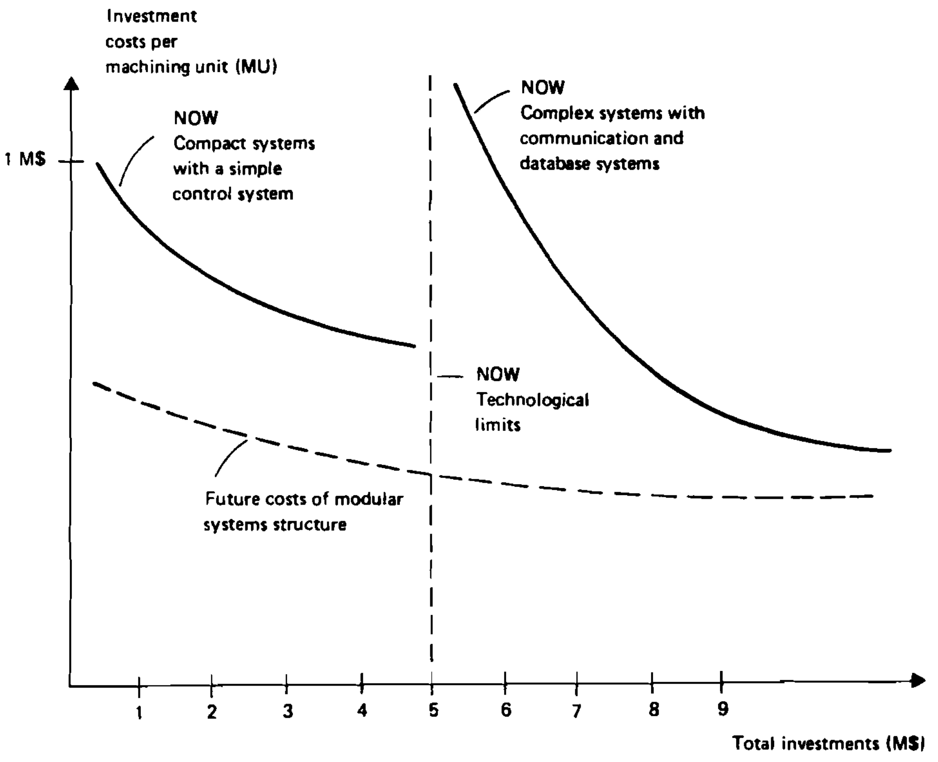

Figure 17. Effect of decreasing software costs, standards and systems modularity, see also chapter 2.3 for explanation.

- Managerial and design aspects define how the systems are implemented and which goals are the driving forces of the design, and how technological aspects and social aspects are integrated during design. They solve a lot of economic problems -- or can create even new problems, if the impact assessment is not good enough.

The technology analyses show that even the technological issues are not simple or straightforward. FMS-technologies, and even more so CIM-technologies, are not mature and there exist many alternative ways to go.

The above figures correspond to quite a rapid growth rate. However, it is a precondition for the above growth that there will be a remarkable technological development and achievements in all the key areas of CIM technologies. This development has to have an impact on cost factors, efficiency and performance factors of different building blocks of CIM technologies. Both on the machine and system levels, electronics and information technologies will still be key technological elements of development. It is reasonable to expect that in the ten-year perspective flexible grippers, speed and accuracy of robots will no longer be obstacles to assembly systems, there will be software and communication standards to help integrate basic building blocks, there will be modular systems control and interfacing systems, which make step by step development possible, relative software costs will decrease and the systems development will be easier. All this trends mean a gradual improvement of the efficiency (performance) - cost ratio in terms of speed, capacity, accuracy, complexity and flexibility of systems.

If these technological trends become reality to their full extent, new systems architectures will be realized, opening completely new possibilities to small and medium-scale industries. Therefore the growth of new applications will be even more rapid than illustrated above.

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APPENDIX

RESPONSES TO A SMALL DELPHI-STYLE QUESTIONNAIRE ON THE TECHNOLOGICAL TRENDS

14 EXPERTS FROM 9 COUNTRIES

QUESTIONNAIRE

1. The following tables from Chapter 4 present the OTA forecasts for key technologies of CIM. Can you please add your personal estimates using the same categories.

	Before 1987	1987-90	1991-2000	2001 and beyond
Hardware:				
1. Systems which can automatically and reliably remove a wide variety of metal chips produced in cutting[a]		▲ 1	2 3 ● ■	
Both hardware and software:				
2. Reliable, widely applicable adaptive control to optimize speed of metal removal	▲ 1	●	2 ■ 3	
3. Tool wear sensors applicable to wide range of cutting tools	▲ 1 ●	2	3 ■	
4. Systems for measurement of parts of a variety of shapes and sizes while the parts are being machined	▲	1 ●	2 ■	3
Software:				
5. Controllers to accommodate ties to robots	▲ 1 ● 2	3	■	
6. Model-based machining in which the machine tool operates substantially automatically based on data about metal processes and the part to be produced	▲	1 2 ●	3	■
7. Widely applicable 3-D verification of NC programs using CAD-based simulations	▲ 1		2 ● 3	■

[a] Systems currently exist for automatic removal of metal chips, but despite much interest and research, they are neither very reliable nor generically applicable (i.e., they can only be used for certain kinds of metals or cutting processes).

▲ = solution in laboratories.

● = first commercial applications.

■ = solution widely and easily available (requiring minimal custom engineering for each application).

NC machine tools: projections for solution of key problems (OTA, 1984) and Delphi results of IIASA CIM-projects.

1 = ▲

2 = ●

3 = ■

	Before 1987	1987-90	1991-2000	2001 and beyond
Hardware:				
1. Lightweight, composite structures and new forms of drive mechanisms	▲ 1 ●	■ 2	3	
Both hardware and software:				
2. Force sensors	▲ ● 1	2 ■	3	
3. Versatile touch sensors	▲ 1	● 2	■ 3	
4. Coordinated multiple arms	▲ 1	● 2	■ 3	
5. Flexible, versatile grippers		1 ▲	2 ● ■ 3	
Software:				
6. Precise path planning, simulation and control with CAD	▲	● 1	2 ■ 3	
7. 3-D vision in structured environments which have been planned to simplify the vision task	▲ ● 1	■ 2	3	
8. 3-D vision in unstructured complex environments which have not been planned to simplify the vision task		▲ 1	2 ●	3 ■
9. Robust mobility in unstructured environments		▲ 1	● 2	3 ■
10. Standards clarifying different versions of robot languages, and helping ensure a common language for similar applications		▲ ● 1	2 ■	3

▲ — solution in laboratories.
● — first commercial applications.
■ — solution widely and easily available (requiring minimal custom engineering for each application).

Robotics: projections for solution of key problems (OTA, 1984).

1 = ▲

2 = ●

3 = ■

	Before 1987	1987-90	1991-2000	2001 and beyond
Hardware:				
1. Generic fixtures for holding a variety of work-in-process parts	▲	1	● ■ 2	3
Both hardware and software:				
2. FMS for:[a]				
a) cylindrical parts production	▲ ● 1 2		3 ■	3
b) sheet metal parts production	▲ ● 1 2		3 ■	
c) 3-D mechanical assembly	▲ 1		2 ● ■	
d) electronics assembly	▲ ● 1 2	■	3	
3. Materials handling systems which can handle a variety of parts in any sequence necessary	▲ ● 1 2	■	3	
Software:				
4. Automatic diagnosis of breakdowns in the FMS		1 ▲	2 ●	3 ■
5. Standardization of software interfaces between computerized devices in an FMS		1 ▲	2 ● 3	■

[a] Almost all FMS currently running are used to machine prismatic parts, (e.g., engine blocks) which are those whose outer shape consists primarily of flat surfaces. The projections in this entry refer to FMS for quite different applications: a) machining of cylindrical parts, such as rotors and driveshafts (or "parts of rotation," in machining jargon, since they are generally made on lathes); b) stamping and bending of sheet metal parts, such as car body panels; c) assembly (as opposed to fabrication of individual parts) of three-dimensional products, such as motors; and d) assembly of electronic devices, such as circuit boards. While machines currently exist for automatic insertion of electronic parts into circuit boards, an electronics FMS would integrate the insertion devices with soldering and testing equipment.

▲ – solution in laboratories.

● – first commercial applications.

■ – solution widely and easily available (requiring minimal custom engineering for each application).

FMS: projections for solution of key problems (OTA, 1984).

1 = ▲

2 = ●

3 = ■

	Before 1987	1987-90	1991-2000	2001 and beyond
Software:				
1. Well-understood, widely applicable techniques for scheduling and logistics of complex materials handling systems that would allow full factory integration ..		▲ 1	2 ●	3 ■
2. Standard communication systems (networks)	▲ 1 ● 2		■ 3	
3. Standardization of interfaces between wide range of computerized devices in an integrated factory................		▲ 1	2 ● 3	■
4. Data base management systems which could sort, maintain and update all data in a factory			1 ▲● 2	3 ■
5. Computerized factories which could run on a day-to-day basis with only a few humans in management, design functions			1	▲

▲ = solution in laboratories.
● = first commercial applications.
■ = solution widely and easily available (requiring minimal custom engineering for each application).

CIM: projections for solution of key problems (OTA, 1984).

1 = ▲

2 = ●

3 = ■

	Before 1987	1987-90	1991-2000	2001 and beyond
Hardware:				
1. High-resolution, color display of designs, with rapid generation of images[a]	1 2	■	3	
Both hardware and software:				
2. Low-cost, powerful microcomputer-based workstations for:[b]				
a) electronics design	▲ ● 1	2 ■ 3		
b) mechanical design	▲ 1	● 2	3 ■	
3. Independent CAD workstations linked by network, with access to supercomputer for powerful analysis and simulation	▲ 1	■ 2	3	
Software:				
4. Three-dimensional solid modeling systems, resulting in:[c]				
a) more realistic images	▲ ● 1	■ 2	3	
b) enhanced ability to connect with manufacturing equipment	▲ 1	● 2	■ 3	
5. Comprehensive, powerful computer-aided engineering systems[d] for mechanical design		▲	●	■
6. Extensive design/manufacturing integration[e]	▲ 1	●	2 ■ 3	

[a] While color displays are currently available, they tend to sacrifice either resolution (the fineness and clarity of the picture) or the speed with which the images can appear on the screen. New techniques for displays, such as the use of dedicated microprocessor chips (sometimes termed "silicon engines") to generate images, promise to improve this situation.

[b] Microcomputer-based workstations for CAD are now being marketed, but in the judgment of technical experts consulted by OTA, they are either not powerful enough and/or not inexpensive enough to be useful in a wide variety of applications.

[c] CAD experts report that many systems for 3-D solid modeling are available now, but they are not being used because of their large appetite for computer power, and because their capacity to link design data to manufacturing equipment is inadequate. Part (b) of this entry refers to this ability to store and manipulate design data about the physical characteristics of a part in such a way that it can be transmitted to manufacturing equipment with only minimal intermediate steps.

[d] This entry refers to modules powerful enough to allow extensive interactive testing, simulation and refinement of designs in a wide range of applications. Such systems are strongly product-dependent; while they may be near available for certain products now (e.g., integrated circuits, certain portions of aircraft and motor vehicles), they are much less advanced in other industries and applications.

[e] This entry denotes the "window from design to production" which would, for instance, allow designers to examine the production implications of design choices. These include the costs and necessary production processes, as well as the history of manufacturing similar items at the plant. Such comprehensive connections would allow much more substantial integration of CAD, CAM, and computer-based management.

▲ = solution in laboratories.
● = first commercial applications.
■ = solution widely and easily available (requiring minimal custom engineering for each application).

CAD: projections for solution of key problems (OTA, 1984).

1 = ▲

2 = ●

3 = ■

2. What are your cost estimates

☐ majority

⬚ second best estimate

a) Flexible, versatile grippers for robots

below 5000 US$	1990	[✓ 1995]	2000	2000-
below 1000 US$	1990	1995	[✓ 2000]	2000-

b) Versatile touch sensors for robots

below 5000 US$	1990	[✓ 1995]	2000	2000-
below 1000 US$	1990	1995	[✓ 2000]	.2000-.

c) General-purpose 3D-vision for robots

below 20 000 US$	1990	.1995.	[✓ 2000]	2000-
below 10 000 US$	1990	1995	2000	[✓ 2000-]

d) On-line part measurement system for tooling

below 20 000 US$	.1990.	[✓ 1995]	2000	2000-
below 10 000 US$	1990	.1995.	[✓ 2000]	2000-
below 5 000 US$	1990	1995	.2000.	[✓ 2000-]

e) Generic fixtures for FMS-systems

below 20 000 US$	1990	[✓ 1995]	2000	2000-
below 10 000 US$	1990	1995	[✓ 2000]	.2000-.
below 5 000 US$	1990	1995	2000	[✓ 2000-]

3. A modular, standard-type and generic system for FMS and factory automation control will be commercially available

1990-1993 [✓ 1994-1996] .1997-1999. 2000-

4. A modular standard-type and generic warehousing and transportation system will be available for FMS and factory level integration

....
.1990-1993.   [✓ 1994-1996]   1997-1999   2000-
....

5. Estimate the relative importance of different technological factors in the development of factory automation. Rank the most important as "1", the second as "2", and so on.

a)	Software for control and integration	1.3	(max. 4, min. 1)
b)	Measurements in tooling	3.8	(max. 7, min. 2)
c)	Mechanical engineering, like pallets, fixtures	3.5	(max. 6, min. 2)
d)	Robot speed and accuracy	4.8	(max. 7, min. 1)
e)	Robot grippers	4.4	(max. 7, min. 2)
f)	Robot sensors	5.2	(max. 7, min. 4)
g)	Scheduling of transportation and warehousing	2.9	(max. 7, min. 1)

6. Estimate the relative cost shares in 1995 of total investments of FMS

a)	Software for systems control (very much depending on the given applications)	16.8%	(max. 25, min. 10)
b)	NC-software	6.7%	(max. 10, min. 3)
c)	Robot software	5.5%	(max. 10, min. 4)
d)	Basic machinery	33.7%	(max. 50, min. 20)
e)	Auxiliary devices, pallets, fixtures, tool changers	1[illegible]%	(max. 25. min. 5)
f)	Transportation and work piece handling	14.7%	(max. 20, min. 10)
g)	Software for communication	7.0%	(max. 15, min. 2)
h)	Others: specify (Planning, training, testing, quality control)	3.5%	(max. 10, min. 0)
	Σ	99.9%	(max. 165, min. 54)

7. Free comments:

Some Aspects of Reconfigurable Manufacturing Cells as Building Blocks of FMS

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Abstract

Cellular organization offers high flexibility in implementation and operation of manufacturing systems. The discrete part manufacturing has several special problems and demands, which can be solved by means of a special system development approach. A solution which meets the requirements is a more or less generalized cell control system to ensure that an FMS could be built up from different cells, having similar cell controllers.

INTRODUCTION

As a flexible manufacturing system is a great investment and it has a great production value it is of crucial importance to use all its elements with high efficiency.

Manufacturing cells have been proven to be the appropriate size building blocks to get sophisticated FMSs (see [1]). Generally a manufacturing cell is considered as a group of one or more machine-tools, robots, adjacent mechanical elements, tool and fixture supporting workstations and an internal transport system. The cell elements have their own local controllers (NC, CNC, PLC, etc.) and each cell has its separate controller. The cell controller functions are performed by a micro-, mini-, or supermini computer.

A manufacturing system may consist of different types of cells, such as manufacturing, warehouse, transportation, cleaning, measuring and dispatcher cells, etc. Each cell may have the same type of cell control computer, and similar control software. The cell controllers can be connected via a local area network (recently mainly MAP is suggested, however still rarely used).

THE ADVANTAGES OF CELLULAR ORGANIZATION

The cell controllers have only local supervision and scheduling functions, i.e. their authority remains inside the cell. This provides some advantages, such as :

- FMSs can be built up gradually from cells as all cells can work stand-alone as well. Only one or two cells must be installed at the beginning, and then the connection of additional ones can be done without threatening the work the rest of the system for longer time periods.

- The cell elements have to be connected only to the cell controllers, so cabling costs and noise sensitivity will be reduced.

- The data base can be distributed among cell controllers, and a flexible data structure can be provided for the whole FMS.

- New LANs and computer systems with distributed intelligence support the cellular construction even in harsh industrial environment.

- Dinamically reconfigurable cells improve the performance by better organization of the available equipment and by optimally sharing the resources.

Flexibility of manufacturing systems means the necessity of relatively fast reactions (reconfiguration) of the systems. In our concept this flexibility can be achieved by using easily reconfigurable cells as building blocks of an FMS.

System reconfiguration may be necessary in several situations, such as :

- A better adaptation to changing workload can be achieved during normal operation. This is done by the rearrangement of system elements, eventually by changing some of the cell element-cell control assignments.

- In the case of component break-downs the system has to operate excluding the defective element, and a minimum production loss is required.

- When new elements are introduced into the system, or old ones are removed.

FMS DESIGN - CELL DESIGN

A cell control system (FLEXCELL) was developed to be used in implementing and running manufacturing systems. It is believed that the given system has advantages from the designer's point of view as well. Design means the design of all cells which will work together to meet the requirements of the planned flexible manufacturing system.

When an FMS is designed, the first step is to choose the appropriate cell configurations containig the necessary manufacturing, transfer and other units. Based on the parts to be produced by the system, knowing all the technological plans and all the available equipment it is possible to configure the cells and the whole FMS. Because of the complexity of the task we restrict our first investigations to cell-size, 'small' FMS, i.e. we deal only with cell design problems, however it is never forgotten that the set of cells will work in an FMS.

Cell design has two separable, but not independent tasks, the cell configuration (hardware) and the cell control software design.

Our recent cell control software structure fulfils the following main requirements :

- In order to ensure the generality the main tasks were implemented independently of the specific features of the machines, processes and hardware-software resources.

- The control software runs on an enhanced professional personal computer and it is easily adaptable to other computers. The enhancement is achieved by adding an intelligent slave-processor module to ensure the necessary real-time, high prformance communication with the external world.

- The cells are easily reconfigurable, and the cell controllers meet the requirement of system level reconfiguration as well.

The software design of FLEXCELL was based on our SATT (System Analysis Technique and Technology) method, namely the decomposition to separated modules with exactly specified logical interfaces and with the definition of functional levels.

FUNCTIONS OF THE (FLEXCELL) CELL CONTROLLER

There are three functional levels (computer level, cell operation level and control & supervision functions) with the following main modules :

- operator interface
- communication
- data handling
- event logging
- task supervision
- configuration
- job coordination

- scheduling
- control of normal operation (command)
- test/diagnostics
- other cell specific functions

Functional modules of the cell control software

The functional modules of the cell control software can be separated into two large groups :

- Basic routines and programs which serve only as computational background :

    * The operational system PC-DOS 3.0 with its utilities
    * Programs to provide multitask services (starting sequence and priorities of the tasks can be changed, and there is a direct data transfer between tasks)
    * Data base management and library management
    * Communication routines (via interfaces)
    * Screen management and graphics, etc.

- Programs to control the cell functions, based on the elements of the previous group. The programs of this group are more interesting from the user's point of view, thus some details of some of them will be given.

It is common, that the main functional blocks are working as separate tasks within the system. Tasks are activated by means of predefined events, taking into consideration the connections between these events and the internal status of the cell.

a. Production scheduling

Scheduling means an appropriate assignmemnt of the activities which are in connection with distribution of production tasks among cell elements, taking into consideration the requirements of the 'external world'. (Crireria of the distribution may be the maximal load of machines, the minimal costs, minimal time delays, etc.)

If a break-down of any cell element occurs, a new distribution can be initiated without the assistance of the external world, without human intervention.

This helps in running a partly unattended operation, what is the ultimate goal of all production automation efforts.

The reconfiguration of the cell may be necessary in different cases, as it was mentioned earlier. The cell control software gives the necessary means to solve the task fast and effectively.

b. Working according to the task-list

The synchronouos operation of all cell elements is supported by the controller software, as the main task.

Information-flow between separate units is solved, together with on-line workpiece-, tool- and fixture management:

- Workpiece management : The cell controller takes care of all workpieces, to work on them with arbitrary sequence. It gives information on capacities, takes care of the transfers and deliveries of products of all production status and environment.

- Tool-management : Tools and tool-data are checked continuously, and automatic tool exchange, tool demand forecast, etc. can be achieved.

- Technological information management : Working sequences (e.g. NC programs) belonging to each workpiece ensures the fulfilment of the technological tasks of a cell. If any of the necessary information is not present the cell controller gives an indication, and the missing data can be found or delivered prior to the beginning of production.

The cell controller takes the workpieces along all working phases within the cell as it is defined in the task-list.

The transport tasks within the cell should be solved by the cell controller, even if problems occur, when a re-scheduling of transport requirements and a reassignment of means and tools are necessary.

Workpieces, tools and other objects necessary to the actual machining process are transported between the machine tools on the basis of technological plans. This is done by robots in most cases. If synchronization problems occur, puffer stores are defined automatically to ensure the continuous load of the machine-tools.

The technological information, which are necessary to run the machines are distributed as required. Overload is automatically resolved. There is a book-keeping of finished tasks and the cell controller may request new tasks from its environment to keep uniform load of the machines.

All information are stored on data files and can be reached and modified by the operator and by a higher level information system. This way several versions of part-programs can be put into libraries.

The operator is informed about all events of operation including failures, and he can send data and decisions to the controller. Both directions of information-flow is organized via an appropriate man-machine interface.

Production data of the cell elements are important for the higher level management to be informed about the instant and statistical situation of the production.

Measurement, collection and a pre-evaluation of production data can be done as the user wants. This can be important for the management to make decisions on special requests.

c. Diagnostics

Diagnostics is necessary when something is different from normal working behaviour of the system. Recently only those events can be evaluated, to which reaction strategies are known and predefined by the software. In this case certain signals arriving from the cell elements can initiate the necessary intervention of the controller.

Depending on the diagnostics information the cell controller may exclude defective elements from the cell model ensuring that all other elements continue normal, eventually reconfigured activity.

If the reasons of the break-down are known than the controller can suggest the service people what to do and how to do it.

The scope of events to be a subject of diagnostics should be defined for each cell individually by the user, and the eventual reactions should be defined, too. This is the main reason why the diagnostics programs are separated from the other parts of the system software.

d. Emergency situations

Emergency situation means when further activities may cause serious damages, e.g. cutting with a broken tool.

The control software initiates an activity to prevent damages, in most cases by stopping ('freezing') the defective element. These parts of the software are cell-dependent, and the user has to define his needs. To help him there is a frame system to handle the emergency situations, which should be given the special demands.

e. Diary

The diary of the cell contains all events of a cell including the identifiers of elements and exact dates. There are two levels of diaries in our cell concept : user level and cell software level. This latter one cannot be reached directly by the user, as the data of the cell software level diary are used internally, as e.g. as inputs of diagnostics, etc.

f. Cell configuration (set-up)

There are two kinds of configurations:

- basic configuration
- reconfiguration

Basic configuration means, that the appropriate data should be put into the state tables to define the cell. Even in the case of a working cell some further data may be inputted by the operator, however this may be automatically forbidden or changed by the diagnostics programs.

Reconfiguration takes place if something goes wrong in the cell operation, or when the diagnostics or emergency modules suggest modifications.

DESIGN OF CELL CONFIGURATION (and reconfiguration)

The cell cofiguration design has two separate steps, which can be done by iterations : The first is to get a pre- or basic configuration, which is an 'average' of several possible configurations, and the second is reconfiguration from this average according to the actual production (or other) task. To process the complex basic configuration task a good database of all parts, materials, technologies, available machines, robots, controllers, etc. is necessary together with a deep expertise of engineers (and economists). This expertise (or knowledge) can be transformed into a dedicated expert computer system.

Our planned expert system will be a hybrid one, as it will contain an embedded simulation program to model the operation sequences of all building blocks and of the whole cell. An optimal configuration will be chosen using the simulation results as well.

The cell reconfiguration demands arise from the production needs in the case of having only one cell, and from the reconfiguration demands of the whole FMS consisting of two or more cells. The process of reconfiguration of the machine side (hardware) is given above.

The software reconfiguration will be assisted based on the same hybrid expert system, only the data-base including design-rules, strategies, heuristics, etc. should be rewritten to have all the necessary knowledge. Thus the procedure will be based on the following:

The implementation of a general ('average') cell controller can be done by taking the above given modules, modifying some of them, and collecting the necessary operational set of them.

This procedure includes a rather small or no modification of the basic software (computer level), as the software elements of this level are the same in almost all applications. They depend on the type of the control computer, on the hardware configuration and on the operating system.

The modules of the control and supervision level are the most cell-specific ones, therefore they have to be modified when the general cell control software is adopted (configured) to an actual environment. The complexity of the command, scheduling or diagnostics module can be quite different in the case of e.g. a manufacturing cell and a warehouse cell. Some modules can be omitted in certain applications.

The modifications of the middle level (cell operation) modules depend on the cell requirements and on the local controllers.

Naturally the first version of our expert system will not perform the necessary coding to modify the software modules, as it will give advice only on what to do, and not on how to do.

CONCLUSION

The first applications of FEXCELL will be in a pilot plant at the Technical University, Budapest, where a CIM system is under implementation consisting of different cells :

- CAD cell
- preparatory cell
- sheet-metal cell
- forging cell
- welding and assembly cell
- AGV and storage cell
- manufacturing cell (milling machine, lathe, robot, etc.)

This last one is already working in an experimental setup.

This plant, which will work as a kind of FMS will give us experiences on the real advantages and possible weak points of our cell concept, and about its realization, the FLEXCELL system.

Further applications are forseen in machine-tool factories and in the vehicle industry, etc.

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SOFTWARE PRODUCTION FOR CIM - AN APPROACH TO STRATEGY ELABORATION

Prepared for IIASA Workshop on Technological Factors in the Diffusion of CIM (Prague, May 24 - 27, 1988)

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> "Software is the heart, mind and soul of any system." (H. Simon)
>
> "Those who will be able to conquer software will be able to conquer the world."
> (T. Sekimoto)

1. INTRODUCTION

Software engineering is a high technology that proved critical for the devolopment of modern productive forces. Uncontradictedly, this applies to computer-integrated manufacturing (CIM), too (ECE, 1987; Kochan, 1986; Ranta, 1988). The broad experience the GDR has been accumulating in flexible automation since the early 70s (for a comprehensive view on this experience see Haustein, 1987) as well as first steps in developing and introducing CIM-systems confirm the role of software engineering as a major limiting factor for a more rapid diffusion of these innovations (see Petermann at al., 1986). Therefore, the software bottleneck and all suggestions for alleviating it deserve special attention in research aiming at strategy elaboration for CIM systems.

The project "<u>Sof</u>t<u>w</u>are Strategies for <u>CIM</u>" (SOFTCIM) was initiated at the Institute for Theory, History and Organization of Science (ITHOS) to adress this perceived research problem. (For recent results of this project see Weber et al., 1987, Weber et. al., 1988, and Weber and Belitz, 1989.)

This paper

- reviews research at ITHOS on strategy elaboration in the field of software development for CIM to set a starting point for
- discussing approaches to and problems in the socio-economic evaluation of software innovations,
- introducing the concept of a simulation model for aiding strategy elaboration and
- pointing out directions for further investigations.

The objective of our project SOFTCIM is to develop a generic methodology for strategy elaboration and comprises

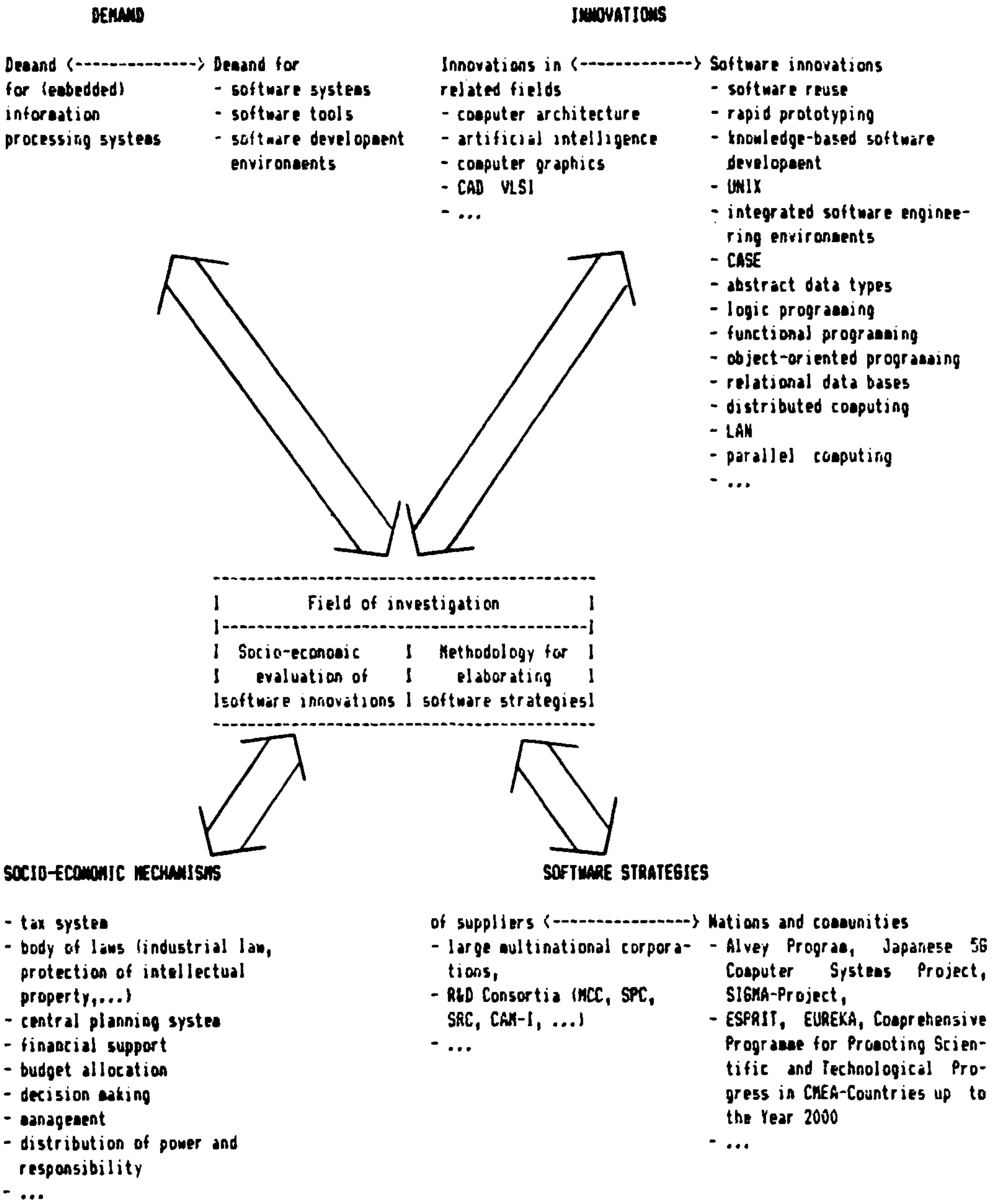
- the analysis and synthesis of socio-economic mechanisms for promoting software engineering as well as
- the provision of easy-to-use tools (including modeling) to support the design of alternative actions both for enterprises and the national economy as a whole.

Considerable effort is being devoted to analyses and evaluations of software innovations and software strategies pursued by leading corporations and international communities (Figure 1).

In a broader sense, we conceive the socio-economic evaluation of software technologies (innovations) as a multifaceted process of

- acquiring knowledge pertaining to the complex web of socio-economic conditions for innovations to evolve and of their implications,
- shaping (designing) these conditions.

Section 2 provides a brief overview of our simulation approach. Section 3 deals with economic evaluation of software technologies (innovations) as a cornerstone for strategy elaboration in our context. Section 4 adds the social dimension for evaluation. The paper reveals questions not solved yet.



DEMAND

Demand for (embedded) information processing systems <--------------> Demand for
- software systems
- software tools
- software development environments

INNOVATIONS

Innovations in related fields <-------------> Software innovations

Innovations in related fields:
- computer architecture
- artificial intelligence
- computer graphics
- CAD VLSI
- ...

Software innovations:
- software reuse
- rapid prototyping
- knowledge-based software development
- UNIX
- integrated software engineering environments
- CASE
- abstract data types
- logic programming
- functional programming
- object-oriented programming
- relational data bases
- distributed computing
- LAN
- parallel computing
- ...

Field of investigation	
Socio-economic evaluation of software innovations	Methodology for elaborating software strategies

SOCIO-ECONOMIC MECHANISMS

- tax system
- body of laws (industrial law, protection of intellectual property,...)
- central planning system
- financial support
- budget allocation
- decision making
- management
- distribution of power and responsibility
- ...

SOFTWARE STRATEGIES

of suppliers <----------------> Nations and communities

Suppliers:
- large multinational corporations,
- R&D Consortia (MCC, SPC, SRC, CAM-I, ...)
- ...

Nations and communities:
- Alvey Program, Japanese 5G Computer Systems Project, SIGMA-Project,
- ESPRIT, EUREKA, Comprehensive Programme for Promoting Scientific and Technological Progress in CMEA-Countries up to the Year 2000
- ...

Figure 1: Framework for elaborating software strategies

2. CONCEPT FOR A SIMULATION APPROACH (SOFTSIM) TO STRATEGY ELABORATION

2.1. MODEL STRUCTURE

This section describes briefly the concept of a simulation model called SOFTSIM that is being developed for supporting the elaboration of software strategies in the field of CIM. SOFTSIM is conceived for examining the behaviour of software suppliers under different scenarios. Our research is focused on the following questions:

- With respect to both quality and quantity, which potential for software engineering is required in a country like the GDR to keep up with the state of the art in flexible automation and CIM ?
- How can the gap between rapidly increasing demand for CIM-software and supply been reduced whithin a reasonable period of time, and how should we manage software innovations to meet this challenge ?

The structure of our simulation model SOFTSIM as well as major functions of its building blocks are illustrated in Figures 2 and 3.

```
         ------------------------------------------------
         I                                              I
---------V--------     ------------------     ----------I-------
I DEMAND for CIM I     I PRODUCTION of  I     I EFFICIENCY of  I
I components and I-----> CIM components I-----> CIM components I
I systems        I     I and systems    I     I and systems    I
------------------     -------^-------I-^-     ----I------------
  I  I                        I       I I          I
  I  I     ------------------ I     --V-I----------V--
  I  I     I  POTENTIAL     I--     I    Software    I
  I  ------> of software    I------->   TECHNOLOGY   I
  I        I production     <-------I                I
  I        ------------------       ---------^--------
  I                                          I
  --------------------------------------------
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Figure 2: Structure of the simulation model SOFTSIM

Block	Function
Demand	Project future demand for CIM software components/ systems
Potential	Model the dynamics of the software engineering potential and its activities (operations, actions, use)
Production	Development of CIM software components/systems and their application
Technology	Evaluation of software technologies (innovations)
Efficiency	Assessment and evaluation of economic and social implications brought about by development and application of CIM software components/systems

Figure 3: Blocks in the model SOFTSIM and their functions

2.2. OBJECTS IN MODEL SOFTSIM

Three classes of objects are represented in our model for simulating CIM software development:

* Units - enterprises supplying and/or exploiting CIM components/ systems,
* Projects - CIM software components and their assemblages,
* Technologies - software technologies available in units to develop, implement and to maintain projects.

Units

In our context, we define units as enterprises that develop, install, maintain, expand and/or exploit projects. Machine tool suppliers, R&D corporations, hardware and software vendors as well as enterprises in other industrial branches running projects count among this set.

Recently, scientists at the University of Michigan suggested a new conceptual framework for integrated manufacturing systems control software (Naylor and Volz, 1987). This framework is also suited as a metaphorical base for SOFTSIM. Naylor and Volz view an integrated manufacturing system as an assemblage of generic software/hardware components which represent a generalization of the software component concept. Some of the key concepts in Naylor's and Volz' framework are relevant to SOFTSIM as well:

- With recursively defined extended software components, plug compatable software can become a reality allowing different suppliers of manufacturing equipment to bid for contracts.
- Generic components can be considered as a further elaboration of software reuse and confirm our idea of a stock of reusable projects.

This component concept justifies focussing our modeling efforts on software production.

Units have a software potential (referred to as potential) at their disposal consisting of software personnel and tools for software development. The tools comprise hardware and software tools incorporating software innovations. This potential can be enlarged both by extensive and intensive methods. Enlarging the potential by extensive methods implies increasing the number of the software personnel. For this purpose units in our model are required to transfer certain payments to the government in order to take into consideration the shortage of qualified software engineers. Furthermore, a unit can engage "unemployed" software personnel of other enterprises. To rely on intensive methods for enlarging the potential means investing in software tools and software development environments. We assume that the availability of advanced software tools and software development environments, in other words, the change-over to higher levels of technology, leads to a considerable increase in software productivity at least in the next decade.

In our model units compete for contracts aspiring at maximum profits. According to regulations existing in the GDR, profits for software products are calculated as a certain percentage of costs. This practice does not correspond to the requirements of software engineering. For this reason, we shall implement ideas in SOFTSIM starting from the market potential of a given software product (see Haustein in Weber at al., 1987). It will be necessary to elaborate these ideas in more detail.

Our simulation approach takes an exploratory view. Most decisions on economic activities are delegated to the units. A posteriori, simulation data are analysed and compared with given objectives. If necessary, simulation will be repeated under different circumstances by adjusting control variables (see Figure 4). This exploratory approach renders possible the evaluation of strategies.

Economic activities of a unit U_i can be described using three groups of variables: Resources, results, and projects (see Figure 5).

For every time period, the economic activities of a given unit U_i are modeled in two steps:

Step 1 - Find an admissable allocation of contracts. Starting with the values of the parameters in the beginning of the time period an admissable allocation of all newly generated projects must be computed.

Step 2 - Improvement of the solution defined at step 1. The initial allocation of contracts for projects is being improved until an aspiration level of profits for the whole community of units is reached.

Thus, all parameters can be calculated for the end of the given time period.

Projects

By projects we mean software components or assemblages of such components (software systems) that are developed within a certain number of time periods and implemented afterwards for solving given manufacturing tasks of a unit U_i. A project is defined by its technical purpose. From this purpose, a system or project configuration with certain software/hardware components can be derived. For the sake of simplicity, our simulation approach limits the number of project classes. For a comprehensive view on software for industrial automation see a recent ECE study (ECE, 1987).

It is well known that CIM systems are being developed step by step. Projects in our model can pass through (as a maximum) three stages. With a certain probability an existing project can reach a higher degree of complexity.

The national economy as a whole maintains a stock of reusable projects. Every newly developed project is characterized by a certain degree of similarity with at least one of the projects in the stock. This degree of similarity is considered as a major input for a decision concerning project reuse. Finally, the idea of this stock leads to the generic software component concept introduced by Naylor and Volz (1987). Running projects require software maintenance over their whole life cycle, reducing this way the options for initiating new projects.

We use four groups of variables to model projects (relations between projects, relations between projects and units, technical and economic parameters, and life-cycle parameters; see Figure 6).

Units having a need for projects offer contracts to the other units and, on the other hand , bid for contracts according to their specialization. A project is awarded to a unit provided that

- the required number of software personnel is "unemployed" at the moment or can be made available,
- the unit has the best conditions among all competitors and works at lowest costs.

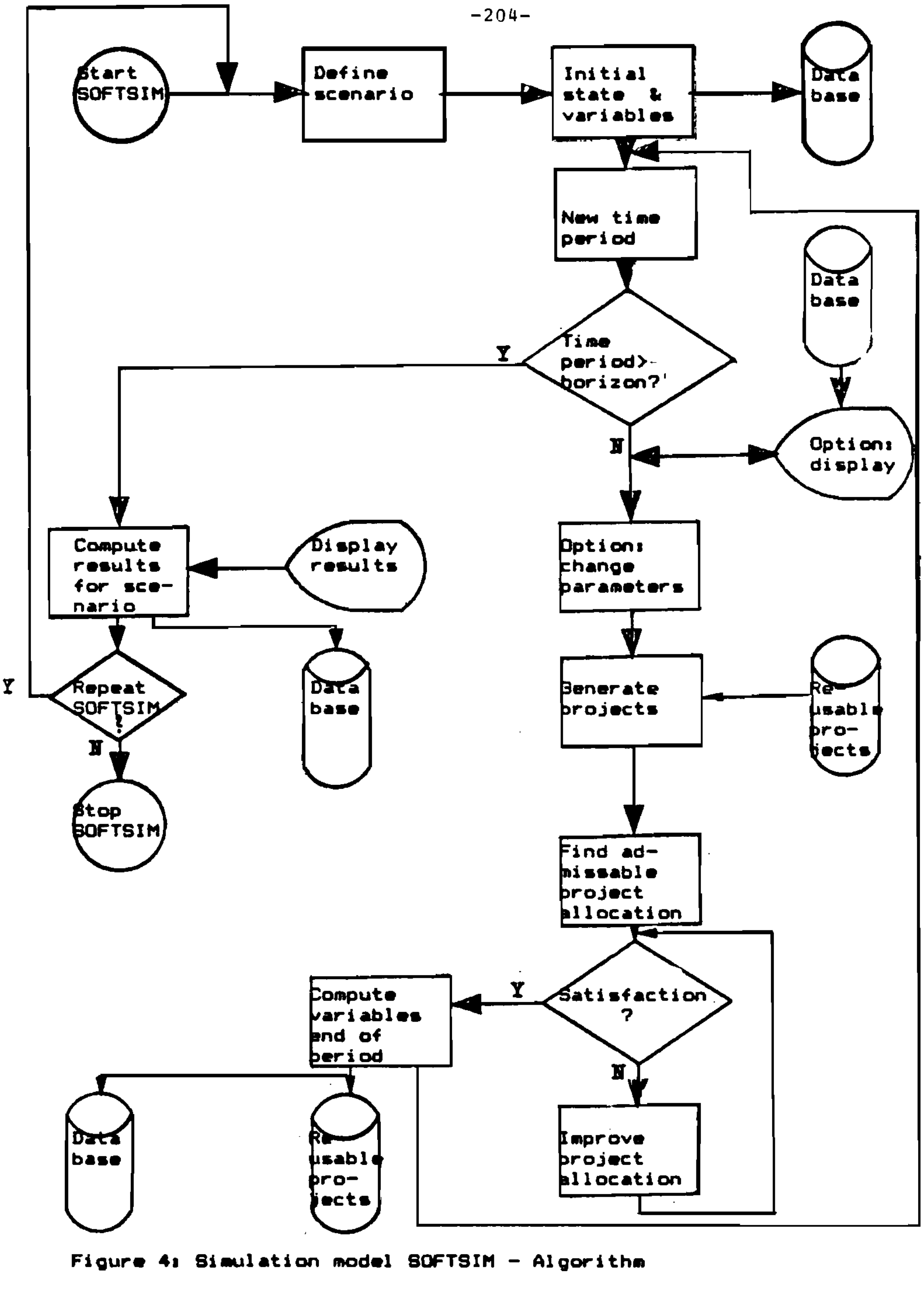

Figure 4: Simulation model SOFTSIM - Algorithm

Variable	Interpretation
t^{gen}_{i}	Time period of generation.
IL_{it}	Upper limit for investments of U_i in the beginning of time period t.
NSP_{it}	Number of software personnel at unit U_i in the beginning of t.
SST_{it}	Stock of software productivity tools at U_i in the beginning of t.
FA_{it}	Fixed assets in software production at U_i in the beginning of t.
SC_{it}	Software cost at U_i in time period t.
SO_{it}	Software output at U_i during t.
PR_{it}	Profit at U_i in t.
$SETP_{it}^{init}$	Projects, for which U_i has offered contracts in t.
$SETP_{it}^{real}$	Set of projects under development at U_i in t.

Figure 5: Variables for describing operations at unit U_i

Variable	Interpretation
P_{orig}	Project, in which P_j takes its roots.
P_{inter}	Intermediate project with a complexity higher than P_{orig} and lower than P_j.
P_{ref}	Project in the stock of reusable projects resembling P_j.
U_{init}	Unit that has initiated the project.
U_{real}	Unit that has been awarded the contract for project P_j.
CL_j	Class of projects P_j belongs to. By defining CL_j all major software/hardware components of P_j are determined.
DN_j	Degree of novelty.
CE_j	Cost estimate. Using CL_j and P_{ref} a cost estimate CE_j for developing the required software components can be derived.
t_j	Time period in which contracts for P_j have been offered.
t_{impl}	First year of the operation of P_j.
t_{stock}	Number of time periods P_j will remain in the stock of reusable projects.
t_{expl}	Time period in which P_j was or will be stopped.

Figure 6: Variables for describing project P_j

2.3. CONTROL VARIABLES IN SOFTSIM AND SCENARIOS

Software development for CIM systems is modeled in SOFTSIM using the following control parameters:

- software potential (existing potential and methods for enlarging it),
- specialization of units (specialization means differentiation of costs for developing projects),
- pace of advances in software technology (determines costs for reusing projects),
- variety of demand (number of project classes),
- dynamics of demand (number of contracts for projects from different project classes that occur within a given period of time).

Having implemented the approach outlined above we intend to study scenarios that deserve considerable interest for a country like the GDR, among them the following:

- "Small is beautiful" (development of many small-scale CIM systems),
- "Gigantomania" (development of few but complex CIM systems),
- "Intensification" (enlarging software potential by intensive methods; orientation towards software innovations),
- "Reuse" (reusing standardized software components is given preference).

This simulation concept is being elaborated in close cooperation both with a large machine tool supplier and the State Committee for Planning and will be implemented on personal computers. In most cases, consulting experts is the only way to obtain required information.

3. ECONOMIC EVALUATION OF SOFTWARE INNOVATIONS (TECHNOLOGIES)

3.1. PREMISES FOR EVALUATION

In the following, considerations will be made on the measurement and evaluation of software technologies (software innovations) that make more transparent the black box "Software TECHNOLOGY" (see Figure 2).

From the initial thesis for the development of the model concept SOFTSIM, according to which an improved equipment of software engineers with tools leads to a fundamental improvement of software quality as well as to a remarkable reduction of software costs (over the whole life cycle) the following questions can be derived:

- Which equipment of software engineers with tools is useful from an economic point of view? What strategies must be applied for the equipment of software engineers with tools and development environments?
- What an increase in the productivity of software development is necessary and possible? How much influence do software innovations have on software productivity and how can software innovations be evaluated in socioeconomic terms?
- What qualities must tools have in order to effectively solve certain problems of software production?

Trying to answer some of these questions we proceed from the following premises.

(1) Evaluation and socioeconomic mechanisms

The evaluation of software technologies and software innovations is integrated into the socioeconomic development mechanisms as a whole (see Figure 1), which characterize the development and formation of the software industry (see Weber and Belitz, 1989). That is why one cannot only ask for the essence, the criteria and methods of evaluation; the evaluation problem in the formation of strategies in a broader sense is the mechanisms (relationships of production) that anticipate the essence, criteria and methods and influence the essence of the object of evaluation.

(2) Objects of evaluation

Software tools support certain methods of software production that, on the other hand, are derived from software paradigms (methodologies, programming concepts):

Methodology -----> Methods -----> Software tools.

Software technology is dealing with all three levels mentioned. That is why the evaluation of software technologies is dividing into the evaluation of methodologies (software paradigms), methods and software tools. The evaluation of software tools has to take into consideration that tools are embedded in methods and software paradigms.

(3) Software quality versus software productivity?

New technologies and international competition call for developing high-quality software with a minimum of effort. This requires the quality of the software processes to be increased substantially relying on innovations.

(4) Strategic architecting of software development environments

Modern software development environments for a large software supplier have to be built step by step having an underlying strategic concept and must be tailored to the specific circumstances. Economic parameters do not reflect the existence of such an advanced and promising concept indicating, thus, limits to quantitative approaches as, for example, SOFTSIM.

The need for strategic architecting software development environments is also dictated by emerging revolutionary changes in software technology. Software is taking on the form of accumulated knowledge about processes, objects and relations. This development will have great consequences for its evaluation in socioeconomic terms.

(5) Acquisition of software technologies - an investment

Advanced software development necessitates substantial investment needing economic justification. Amortization should be put on a large number of products. For this reason, only large software suppliers are able to afford advanced development environments.

(6) Classification of software (technologies)

Software technologies differ fundamentally for

data processing <----> embedded real-time systems,
programming
in-the-small <----> programming in-the-large,
traditional
von-Neumann
architectures <----> parallel computers.

Therefore, the typical situation in units supplying CIM components/systems will be the coexistence of different software technologies.

(7) Coexistence of different technology levels within organizations supplying software

For the evolution of modern software development environments refer to Figure 7. We should consider five levels of software technology shown in Figure 8. They will be used in the block "TECHNOLOGY" of our model SOFTSIM. As a rule, suppliers of CIM components/systems will be characterized by the coexistence of different technological levels.

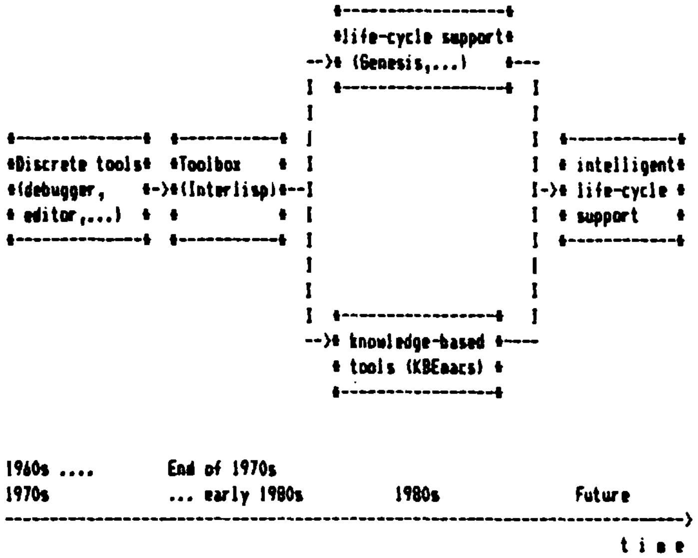

Figure 7: Evolution of modern software development environments
(Source: Ramamoorthy et al., 1987)

Level of technology	Characteristics
1	Discrete tools or groups of tools; no functional integration; no communication and sharing of data between different tools; no support for integrating tools.
2	Functional integration: tools fit together to make a toolkit; sharing of data between tools possible; toolkit may be available also on different computers but with only rudimentary sharing of data via data carrier or LAN.
3	Syntactic integration: tools can communicate via agreed interfaces or communication protocols (pipeline concept in UNIX or data base concept, for example).
4	Semantic integration: all tools form a complex system and are interrelated and compatible.
5	Intelligent life-cycle support.

Figure 8: Levels of software technology (see also Balzert, 1987)

(8) Level of software technology and qualification of software developers

It is nearly impossible to imagine advanced integrated software development environments without concepts or techniques such as relational data bases, data dictionaries or artificial intelligence. Their introduction requires highly qualified software engineers mastering them. Inadequate qualification of software engineers is regarded a major handicap for a more rapid distribution of efficient software technologies. For this reason, in the evaluation of software innovations we have to take into consideration the qualification of software engineers, too.

(9) Scientific prerequisites for qualified evaluation

Evaluating software technologies (innovations) was identified as a scientific problem in the mid 1970s, having attracted increasing attention ever since. Leading R&D organizations (Microelectronics and Computer Technology Corporation, Department of Defense Software Engineering Institute) initiated large-scale research efforts to shed light on this problem. The vast number of tools and development environments available on the market emphasize this need now. Curtis (1980) argued that further advances in software technology will require

- new results in measurement, and
- more experimental verification and test of new software techniques and methods

Thus, formalizing software development is the prerequisite for progress in evaluation of software technologies. This view is shared by Boehm (1984, p. 8): "Whatever the strengths of a software cost estimation technique, there is really no way we can expect the technique to compensate for our lack of definition or understanding of the software job to be done." (Boehm, 1984, p.8)

The formalization of software development and of production processes in CIM systems (see Naylor and Maletz, 1986; Naylor and Volz, 1987) will complement one another and are both challenges to basic research.

Beam et al. (1987) suggested a systems engineering concept for software productivity and characterized the state of the art in evaluating software technologies as follows (p. 169/170): "At this time, no comprehensive taxonomy of methods for software productivity exists, nor much other than folklore concerning how succesful or unsuccessful these methods habe been in specific operational software design contexts. ...

Generally, we do not believe that it will be possible to determine the cost and benefits, including risk elements, of particular approaches out of context. This suggests the strong need for the development of a robust set of task, functions, and methods taxonomies within meaningful operational settings. What is needed is not a set of abstract listings of methods, but rather a set of application-related taxonomies, developed to include methods and methods characteristics as well as tasks and functions, that will permit assessment of the benefits and costs of particular approaches." (Beam et al., 1987, p. 169f.)

For ongoing and future research efforts on software design aids Beam et al. (1987) developed a concept called the situation room for software productivity and suited as a theoretical framework for the evaluation of software technology (see Figure 9). Many investigations into new methods for raising software productivity revealed multifaceted and complex interrelations between them questioning the isolated evaluation of any particular method.

From these interrelations we shall conclude that the real problem is to determine those methods, concepts or tools which are appropriate for an existing or desirable socioeconomic environment and, as a whole, promise a maximum increase in productivity.

Starting from the mutual stimulating effects between software engineering, cognitive and computer sciences and governed by the basic nature of software engineering as a production and reproduction process of knowledge several research groups are elaborating knowledge support systems for raising software productivity, thus, paving the way for advances in evaluation, too.

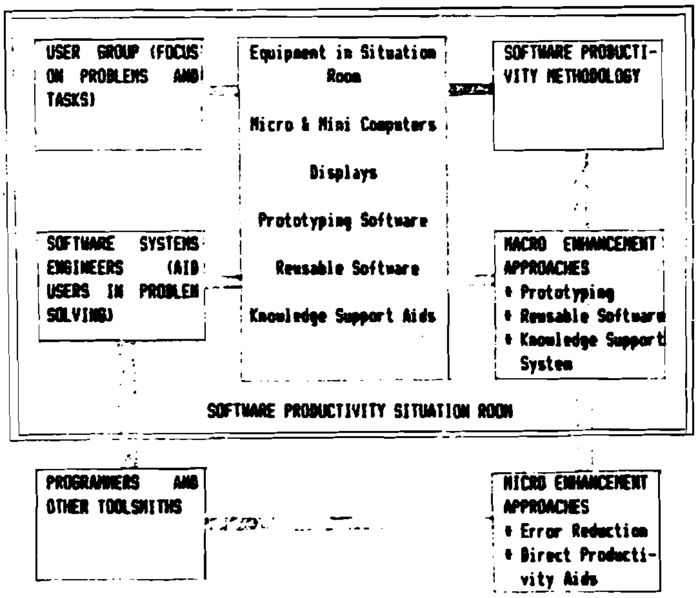

Figure 9: Conceptual diagram of structure and function of software productivity situation room (Source: Beam et al., 1987)

3.2. APPROACHES FOR EVALUATING SOFTWARE INNOVATIONS (TECHNOLOGIES)

Statistical basis

For measuring and evaluating software technologies and software innovations we can rely on

- software catalogs,
- scientific literature,
- software statistics and market reviews.

The software catalogs issued twice a year using *MENU™ - The International Software Database™ deserve particular attention (see TSC, 1985). Such catalogs make it possible

- to derive market and price trends for specific software categories,
- to assess the performances of software tools in different price ranges, and
- (to a certain degree) to analyse software innovations.

We began to compile data concerning software development tools and environments in a data base called SOFTBANK. This data base comprises the following parameters: name of a tool; supplier; field of application; product category; International Standard Program Number™; description of functions; year of market introduction; number of installations; currency unit; price(s); hardware (operating systems); terms of sale; source of information; phase(s) in the software life-cycle supported; software paradigm of the products; technological level; possible size of the products; real-time requirements.

The official software statistics of all industrialized countries is rather incomplete. Data on installations of software tools or environments and on productivity gains achieved are rare in the GDR literature (see, for example, Müller et al., 1988, Bräuer et al., 1988). Analyses of price structuring for software tools on international markets and of leading suppliers' price strategies reveal important trends in software development practices as well as the influence the supply of powerful hardware systems do have on them. With prices on tools and environments becoming more flexible the economic justification of investment decisions concerning software productivity systems is aggravating even more. Only recently, a data processing enterprise located in Dresden (VEB Datenverarbeitungszentrum Dresden, GDR) started to compile information on all software products developed in this country. On request this firm provides selected information that we use for elaborating the simulation model SOFTSIM.

International experience in evaluating productivity effects of software tools

Boehm's assessment of cost reduction in different phases of the software life-cycle that is due to an appropriate application of computer-aided tools (see Gönenc, 1985, p. 40) can serve as a general guide line of what is possible. This reduction amounted to 10% in design specification, 20% in the analysis phase, 60% in coding and in module test, and 80% in integration and system test. Provided that cost distribution among life-cycle phases is known one can assess the implications for the overall development and maintenance costs (see Boehm and Standish, 1983). An idea of medium-range or long-range cost reductions to be achieved by implementing the knowledge-based software paradigm is given in Figure 10.

Estimated productivity gains (%)

Activity	Current effort[1]	Automated effort[1]
Requirements analysis	3.0	3.0
Design	11.0	0.2-4.0
Programming	7.0	0.1-2.0
Integration and test	12.0	0.4-5.0
Corrective maintenance	18.0	0.3-3.0
Adaptive maintenance	14.0	0.5-3.0
Perfective maintenance	7.0	0.5
Update: misunderstanding	14.0	0
Update: new functionality	14.0	1.0-5.0
Total	100	6-25.3

[1] Measured as a percentage of total current effort.

Figure 10: Productivity gains by means of knowledge-based software development (Source: Rockmore, 1985)

According to C. Jones, using the most advanced software productivity system that will be available in the mid 1990s and will cost about 80 million US$ will affect software development in the following way (see Butler, 1987):

- less-than-10-percent cancellation rate (versus today's 25 percent rate),
- a one- to two-year development cycle (versus today's three- to 10-year cycle), and
- million-dollar budgets (versus today's multimillion-dollar budgets).

These quoted productivity gains could give the impression that measuring and evaluating software technologies does not raise any problems. Quite the reverse ! "Despite numerous approaches to quantification of software productivity ... there are not any generally recognized measures. ... The amount of the intellectual substance called 'software' cannot be measured remaining incomprehensible." (Sneed, 1988, p. 22) This overstated phrase outlines the inherent problems very clearly. To get a broader picture of the them we shall analyse three approaches for evaluation briefly.

1. The approach suggested by Schulz (1986) focuses on functional features, i.e. on the components of the utility value, but neglects their relations to economic reference numbers.
2. In the Software Engineering Laboratory of the NASA Goddard Space Flight Center, Card et al. (1987) (see also Card et al., 1986) tried to assess the influence selected technologies (methods, tools, or techniques) exert on software productivity. This approach relies on a software data base that has been maintained for more than a decade. The objects for evluation are rather heterogeneous some of them being aggregates. The investigations have shown that no single technology had an essential influence on productivity. The authors reached the following general conclusions:

- The effect of a given technology (innovation), but also the influence of non-technological factors depend, to a certain degree, on the pecularities both of the software development environment and the software products.
- The decisive way to an increase in software productivity is employing highly qualified and experienced staff.

3. Another approach was developed by Dworatschek and Höcker (1985). It aimed at "making more transparent the supply of software engineering methods" or, in other words, making easier the choice between alternatives. Some of the authors' considerations will be useful for our model SOFTSIM, too:
   - An evaluation by means of experiments does not provide general and directly applicable results (see also Boehm et al., 1984).
   - Determining productivity reference numbers for applied software engineering methods is hopeless because recording in quantitative or monetary terms is impossible. For this reason, Dworatschek and Höcker derived their approach from the so-called utility theory ("Nutzwertanalyse").
   - As "quantitative measurement of utility using cardinal scales does not turn out to be attainable" the authors recommended (and practised) ordinal scales and comparative measurement of utility (see Dworatschek and Höcker, 1985, p. 185).

   This microeconomic approach offers a relatively simple way for supporting the choice of software engineering methods. It shows clearly both possibilities and problems of evaluation in the field of software technology (renunciation of cardinal measurements) in enterprises that lack carefully maintained software data bases, highly qualified personnel and an arsenal of specific methods.

From the approaches analysed above we can draw some conclusions for our own efforts:

1. The predominant research efforts on socioeconomic evaluation of software technologies (innovations) have been done so far by multinational corporations such as TRW, IBM, ITT, but also by governmental organizations (NASA, DoD SEI). These corporations and organizations have software data bases at their disposal. The approaches towards evaluation are the result of long-term interdisciplinary work that was performed as a part of strategic programmes aimed at alleviating the software crisis: "... productivity improvement requires much more than the isolated application of new technologies and policies. To be successful, a productivity improvement program must address the entire spectrum of productivity issues. Key features of such a program are management commitment and an integrated approach. ...
   No single technology can guarantee large productivity gains in all cases. A successful programming project requires doing many things right; failure may result from doing only one thing wrong. The best approach for increasing programming productivity is the careful selection and implementation of complementary technologies and practices that address the entire programming life cycle." (Vosburgh et al., 1984)
   Comparing our research work on SOFTSIM with those strategic programmes we have to be content with more modest conditions. Aggregated approaches like SOFTSIM can serve as methodological guidelines for particular enterprises or bodies, but not substitute their own efforts.

2. **Software innovations** are not the only way for increasing software productivity, which depends on **socioeconomic mechanisms** and on a variety of other interrelated factors, among them technological, organizational, psychological, and ergonomic. Therefore, elaborating a methodology for software strategies should not be restricted to an investigation into measures and methods for the evaluation of productivity gains.
   Nevertheless, we have to grasp software innovations to be the general **breeding-ground.**
   The relations between the building blocks of our model SOFTSIM (see Figure 2) cannot be **reduced to simple cause-and-effect** chains.
3. As the implications of single technologies for productivity are hardly provable, any attempt to proceed this way seems to be on shaky grounds and neglects the **necessity of integrated approaches** for alleviating the software productivity dilemma.
   The idea of technology aggregates is taken up in form of five technological levels (see Figure 8) the economic parameters of which will have to be obtained by interviewing experts.
4. Existing approaches for evaluating software technologies are **tailored to specific environments** and focus on the micro level. Insufficient knowledge about actual software development, missing standards for measuring software products and software processes, the interconnection between software innovations, the fact that costs and benefits are tied to the context, but also the enormous expenditures for experiments give rise to the unsatisfactory state of the art.
5. Another result of our considerations is to draw attention to research problems not solved yet. As a rule, any significant progress requires mutual enrichment of computer, cognitive and industrial sciences, systems and software engineering, and CIM technologies.
6. Many trends to be observed in software engineering are being reflected in the cost structure of software products. It is not appropriate to overload SOFTSIM with minor technological details. Instead, **economic** and **social indicators** should be placed in the centre of our modeling effort (see also Figure 11).

	Present software development		Development of applications using 4G languages	Applications using 5G computers
	without <--------->	with development tools		
user participation	5	15	30	40
management (planning, control)	5	15	10	10
development costs (coding, test)	85	50	30	10
computer	5	20	30	40

Figure 11: Changes in net product in software development (%)
(Source: Computerwoche, 1985, May 10)

4. SOCIAL EVALUATION OF SOFTWARE INNOVATIONS (TECHNOLOGIES)

Social (socioeconomic) evaluation of software innovations can hardly be separated from hardware innovations or be restricted to flexible automation. The following reflections will indicate directions for further research and fix some points to start with:

1. Remarkable social effects of software innovations can be brought about only in a context of related innovations mutually strengthening each other. Social effects are dependent on mediating factors even more than economic ones.
2. Considering the military importance of software technologies and the danger of its criminal abuse the necessity of encouraging the consciousness of social responsibility becomes evident.
3. In many scientific disciplines, software mediates between new results and applications giving rise to the danger to put all social effects down exclusively to software.

The social (socioeconomic) evaluation of software innovations related to flexible automation in production and information processes requires the investigation of the following mutually dependent implications:

- working and living conditions and protection from misuse,
- content of work (taking decision support as an example),
- "personalization" and user comfort,
- requirements for qualification,
- human relations and place of human beings in working and decision making processes.

Here we have to restrict ourselves to selected implications.

Working and living conditions,
Protection from misuse

In our times computer systems are increasingly controling vital societal functions. Therefore, their malfunctions and breakdowns can have catastrophic results or, at least, cause big damage.

Many software innovations contribute to higher quality of software and hardware systems, make them more reliable and, thus, maintain industrial health and safety standards, support health protection as well as protection from misuse.

However, progress in software technology does not automatically lead to higher software reliability, the qualification of software specialists being a necessary catalyst. Mills (1986, p. 66) has shown that new software tools are double-edged: "An interactive debugger is an outstandig example of what is not needed - it encourages trial-and-error hacking rather than systematic design, and also hides marginal people barely qualified for precision programming." Another example is the programming language Ada attracting substantial interest of CIM-developers. But, on the other hand, Ada is criticized because of its low reliability in military systems.

A large number of innovations mediated by software products (language syntheses, language understanding, Braille printer, input devices for handicapped persons, ...) considerably improve the man/machine interface facilitating the integration of handicapped persons into production.

Job enrichment due to the introduction of CIM systems and a better integration of the production personnel's knowledge and experience into the organization of work in these systems are important aims of the ESPRIT software project "Human Centered CIM System". This will eventually lead to higher flexibility, faster reaction on defects and higher efficiency. Apart from technicians and software specialists, sociologists and industrial scientists will participate in this project demonstrating this way the increasing importance of socioeconomic criteria in the evaluation of software.

Content of work
(Decision support as an example)

Since the last decade the possibilities for supporting decision makers even in unstructured complex decision situations have been expanded remarkable (De et al., 1985). Investigating the contribution of artificial intelligence and other software innovations is a topic of large-scale research efforts.

At present time, knowledge-based decision supporting systems are being developed for management levels ranging from production control to strategic planning. When such systems are being implemented

(1) the contents of work
  - of managers (consultation with these systems)
  - of system engineers (new profession: knowledge engineer)
  - of clerks in management and planning departments (automation of many mental routine processes)

as well as

(2) the demand for qualification
  - of knowledge engineers
  - of clerks in management and planning departments (they need an idea of what the foundations of knowledge engineering are, otherwise knowledge-based decision support systems will remain a black-box)

will change accordingly.

The diffusion of knowledge based decision support systems will raise the experts' social status.

Radical changes in content of work can be observed for representatives of all professions and occupations faced with CIM systems including managers (DSS, CAO), planners, engineers, operators and skilled workers (MRP, CAD, CAM, CAT, CAQ), and software engineers (CASE). All these changes are closely related to a substantial improvement of man/machine interfaces.

"Personalization" and user-friendliness
(The example of CASE)

With the technological level in software production being raised (see Figure 8), the user-friendliness of software engineering environments is substantially increasing. This becomes evident in

- the way of working (interactive mode),
- the adaptability of the interface to changing requirements as well as to knowledge, abilities and skills of the personnel (novice programmers, occasional programmers, expert programmers),
- the availability of a help mode,
- fault-tolerance,
- the standardization of the interface to all tools,
- the availability of macros,
- the configurability of tools.

Tailoring software engineering environments and elements of flexible automation (personal robots) is supposed to stimulate the utilization of manpower's individual abilities and skills in automation systems, to encourage identification with the work environment and, at long last, to improve productivity. Besides advances in psychology, sociology and industrial science, progress in software technology is the decisive prerequisite for "personalizing" technical systems.

Software ergonomics is a new special field of computer science intending to close the gap between possibilities for problem-solving by machines and the needs and limits of human beings. In the literature, many cases of neglecting achievements of software ergonomics are documented (see Potosnak, 1987). The necessity to get end-users involved into the software development process will shape software technology significantly. Software ergonomics can contribute to counteract tendencies of dequalification often associated with the introduction of new information and communication technologies. Ergonomic man/machine interfaces require manifold knowledge and point directly towards artificial intelligence.

Requirements for qualification

With software innovations taking place systems engineers are increasingly faced with **great demands on formal training.** Software engineers being able to understand the intricacies of modern software technologies and the underlying concepts will use them best. At the same time the ability to communicate with representatives of other professions is becoming more important.

The tendency to endow CIM systems with more intelligence does not necessarily lead to an impoverishment of the contents of the operators' work.

Software is applied in training increasingly, too. This tendency can be clearly recognized in the qualification as operators of expensive CIM equipment, where simulation models have proved to be very useful.

Software innovations and social aspects of software management

The historical development of software technology indicates that every technological level brings about a corresponding division of labour. Managing software teams implies to care for the relations

- between users and software engineers,
- among software engineers,
- between managers and software engineers.

Some software innovations have a serious influence on these human relations. With software innovations such as 4GL and knowledge-based software engineering the users, for example, become increasingly involved in software development. This tendency finds its expression in the structure of the net product (see Figure 11). **Software innovations concern different groups** of the software personnel that had been forming in a phase of exaggerated division of labour.

The automation of many tasks in the software life-cycle involving a lot of labour causes the tendency of software teams to be reduced and of diminishing, thus, the need for management and coordination. During the last 20 years, however, the complexity of many software projects has been increasing faster than software productivity. Therefore, it was necessary to align large teams including sometimes hundreds of software engineers with common project goals.

In the literature (see Mills, 1986, p. 65) "cleanroom" software engineering served as an example for software innovations both **requiring and encouraging professionalism**, but also strengthening **team spirit and boosting morale**. In the mid 1970s software engineering was focussing on technological problems, whereas evaluation centred upon economic ones. But comprehension sharpened soon: "... concerns for the **social implications** of computer systems are part of the software engineer's practical methodology, rather than treated as a separate topic isolated from our day to day practice" (Boehm, 1979). Scacchi (1984, p. 58) went beyond this understanding paying attention to "how the **complex web** of **social arrangements** shapes the production and consumption of software systems, the local **software engineering practices**, the distributions of costs and benefits, the **appropriateness** of new **software technologies**, and the ease with which these can be managed."

Organizational structure of development teams, the state of the art, individual capabilities and skills of team members have to be conceived as **closely related**: "The focus of a few minds, the frequent walkthroughs, the major commitment of each individual's time, and the common goal shared by team members - all these factors head in the direction of a product of much higher quality than is likely to be produced by any other means. In short, **programming teams** should be the **cornerstone** of **software excellence**." (Ledgard, 1986, p. 68)

The well-documented differences between software engineering practices in the USA and Japan (Japanese software factory concept!) show that modern software management concepts are rooted in the system of national cultural traditions and social value judgements. It is obvious that the evaluation depends heavily on the sociocultural environment.

CONCLUSIONS:

With respect to the efforts for modeling software strategies we argue that:

1. The **economic evaluation** of prerequisites and implications related to software innovations with particular importance to CIM systems is intricate due to the **lack of measurements** in monetary terms. Including the **social dimension** creates even more difficulties for those who are involved in strategy elaboration. The recognition of the relations between socio-economic conditions and implications is still **vague** and does not **serve** as a sound basis for quantification.
2. As a creative process, **strategy elaboration** in the field of **software** production for CIM systems can be supported by means of modeling **some of its aspects**. It is in the nature of strategy elaboration that it **cannot be formalized completely** (see also Danilov-Danilyan, 1986).

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FLEXIBLE MANUFACTURING SYSTEMS (FMS): CURRENT DIFFUSION AND MAIN ADVANTAGES

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1. INTRODUCTION

During the last two years we have collected information from national and international publications [2, 3, 10, 24, 25, 27, 31, 32, 33], special experts' estimates, prepared within the collaboration with IIASA's Computer Integrated Manufacturing (CIM) Project [9, 17, 26], as well as information from occasional publications with descriptions of some specific systems [1, 15]. The preliminary analysis was published in [28].

As a result, our FMS data base includes more than 400 cases, but only 394 are under consideration, because there are no appropriate data on the other cases, except for their names or identification (user, vendor, country). Unfortunately, we practically do not have any adequate detailed information from the USSR (only several cases), Hungary and the NIC. We also suspect that in some cases a duplication takes place due to the use of different sources with unsatisfactory identification. For example, in spite of the exclusion of FMC from consideration, possibly some of them might be mentioned among the British or French cases.

Now we have almost complete information up to 1985 and approximately 50% of the data for 1986 and 1987.[1] The collected data bank for FMS is now the biggest in the world and consists of much more cases than [5, 7, 10, 12, 16, 20, 27, 32] and other international collections.

It is true that the increase of the number of cases was accompanied by a rather restricted spectrum of the factors. For the purpose of a further analysis we concentrated mainly on economic features of the systems, but not on technical features.

DATA BANK DESCRIPTION

As we originally based our work on the FMS data base published in [28], we had to use the same variables (or factors) in adding new information. This is why we followed the original bank structure with some modifications. The following data were collected for each FMS.

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[1] The estimated number of FMS in use is between 350 [27] and 550 [4] for the year 1985. According to our latest estimates these were about 500 FMS installed in the world by the end of 1986.

I. System Identification:

1. "Country" - name of country where FMS is allocated.
2. "Company" - name of user.
3. "Vendor" - name of main producer.
4. "Year" - year of installation.

II. Application:

5. "Industry" - industry of application (1 - final metal products + non-electrical machinery + transportation equipment; 2 - electrical machinery and electronics + instruments).
6. "Applic" - application area (machining, assembling, manufacturing, metal forming)

III. Technical Complexity:

7. "MC" - number of machining centers.
8. "NCMT" - total number of numerically controlled machine tools (including MC).
9. "Robots" - number of robots
10. "Trans" - type of transportation system (1 - conventional conveyor or crane; 2 - automated guided vehicles or computer-controlled carts).
11. "Storage" - type of storage system (1 - automated storage and retrieval system; 2 - computer-controlled warehousing system).
12. "Inspec" - type of inspection (1 - manual or automated measuring and final inspection; 2 - automated maintenance and monitoring system).

IV. Economic and Operation Data:

13. "Oprate" - operation rate (number of shifts a day).
14. "Unmanop" - number of shifts of unmanned operation.
15. "Bsize" - average batch size.
16. "Prodvar" - product variation or part family (number of products produced by FMS).

17. "$ Invest" - investment cost in million US $ (converted according to the exchange rate for the year of installation).
18. "PB time" - pay-back time (years).

V. <u>Relative Advantages</u>:

Reduction of, by a factor of:
19. "Leadt" - lead time.
20. "SUT" - set-up time.
21. "IPT" - in-process time.
22. "WIP" - Work-in-progress.
23. "Mtime" - machining time.
24. "Invent" - inventory.
25. "Pers" - personnel.
26. "Flsp" - floor space.

Increase in, by a factor of:
27. "Product" - productivity.
28. "Prodcap" - production capacity.

Of course, complete data on all variables do not exist in all the cases. For example, there are a lot of empty spaces in the columns of "relative advantages". Nevertheless, a high enough quantity of such data was collected to use statistical approaches for their analysis.

3. FIRST ADOPTERS AND FURTHER DIFFUSION

The first case of a FMS installation, registered in our data bank, was the Sundstrand Aviation (Rockford) system, installed in 1965[2] [27] for pump parts and aircraft speed drive housing production. In 1969/1970 another US company, Ingersoll Rand, installed its first FMS, and the Heildelberger Druckmaschinenfabrik did the same for printing press precision parts production.

Before 1976 eight Japanese companies (Fuji Xerox - 1972, Hitachi Seiki - 1972, Toyoda - 1972, Yammer Diesel - 1972, Toyota - 1973, Yamatake Honeywell - 1974, Fanuc - 1974, Kawasaki Heavy

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[2] An alternative estimate is 1967 [10].

Industry - 1975) had installed FMS mainly for car engine and machine tool parts production. There were four US first adopters, which used FMS mainly for cast iron truck/tractor parts production. Among the Eastern countries the GDR was one of the first adopters, according to the rather limited information we have got in the data bank. The FMS installed in 1972-1973 (7 October, Fritz Hekert, Herman Mateen and Werkzeugmaschinenkombinat) were used for machine tool parts production.

A wider diffusion of FMS began after the 1974-1975 recession in Western countries and the annual number of installations was growing up to 60 in 1985 (see Figure 1). The incomplete preliminary data for 1987 do not demonstrate a change in this tendency, because the coverage of the inventory for these years does not exceed 50% of real installations.

The geographical distribution of FMS, installed up to 1987, is demonstrated in Figure 2. The main users of this technology are the USA and Japan. In reality there are more FMS installed in the Japanese industry than in the US industry, but in our data bank not all Japanese cases are represented (73 systems). We also think that more British cases are taken into consideration than actually exist. This is due to the use of several different sources, sometimes without clear system identification. Some companies provided data without their names or vendors. This is why the share of the UK is considered to be overestimated.

Generally speaking, it is possible to define a group of main FMS users (approximately 50-100 FMS installed).

There is Japan, the USA, the USSR (not shown in the bank), the UK, the FRG and France in this group. The second group includes countries with approximately 10-20 FMS in use: the CSSR, Finland, the GDR, Italy, Sweden. Finally, there are several newcomers -- countries which adopted FMS for the first time at the beginning of the 1980's.

4. APPLICATION

As in the cases of the first adopters, the majority of FMS in the world are used in a few metalworking industries: transportation equipment, non-electrical and electrical machinery. Among the approximately 300 FMS identified according to 3-digit industries of application, 50% were used in

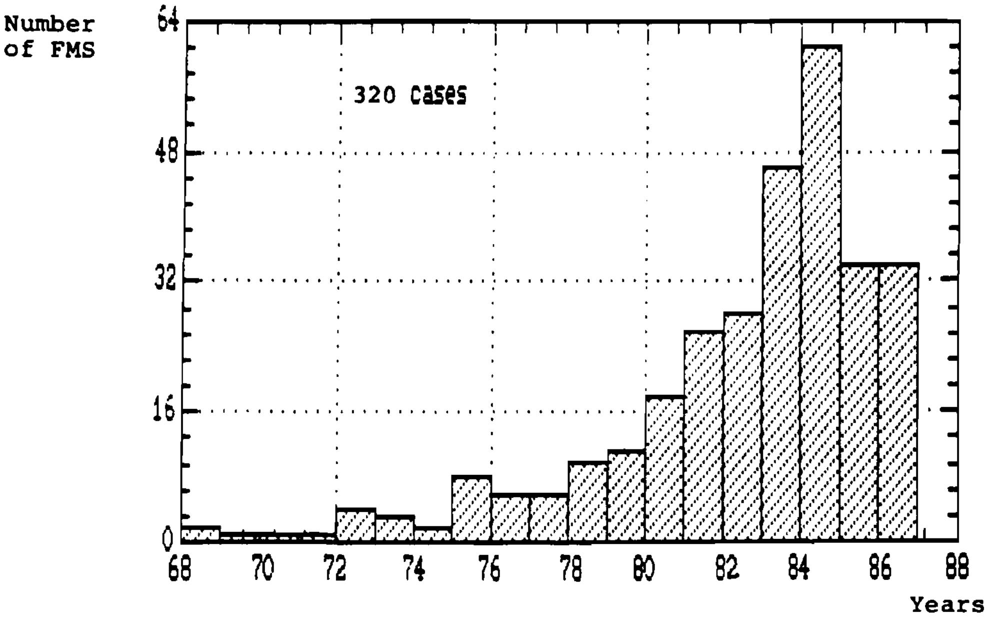


Figure 1. Number of FMS installations over time

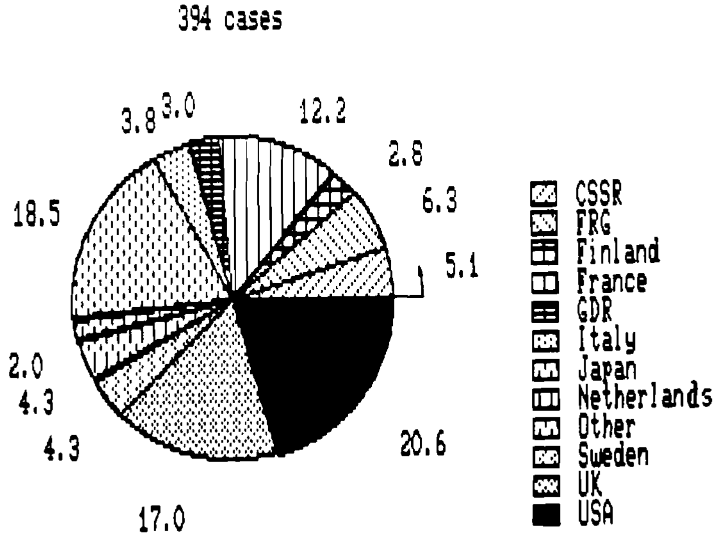


Figure 2. Percentage distribution of FMS installed by countries.

transportation equipment production, mainly for iron cast parts such as cylinder blocks, differential and gear boxes, as well as for steel parts (valves, crank shafts).

The second main user in this industry is the high-tech aerospace industry where FMS are used for precision production of rotational and prismatic parts (fixtures, control systems, jet parts). There are also several FMS in locomotive production and ship building.

Another FMS user is non-electrical machinery where 30% of the systems are allocated. They are used for machine-tools production (rotational parts and cast iron boxes), agricultural and construction machinery, etc.

The specific features of FMS use in these two 3-digit industries are as follows:

- rather big cast iron, steel, aluminum parts with rotation or prismatic forms;
- many surfaces to be developed;
- limited product variation (flexibility);
- limited batch size;
- high precision in some cases.

The third 3-digit industry, electrical machinery (including electronics) owns 15% of the FMS installed. They are mainly used in electronics: electronic components, fixtures for electronic goods production, consumer electronics.

There are some exceptions to the use of FMS in this industry. These FMS are applied for electrical machine parts production, such as rotors, fixtures, etc. These systems are similar to the ones used in non-electrical machinery, but their share in the total number of FMS in the industry is very low.

Finally, 6% of all FMS are used in the precision instruments industry. The main fields of their application are electrical control devices, optics, etc.

There are some common features of the use of FMS in these two industries, namely:

- micro and mini-parts;
- high accuracy of assembling;
- high precision of electronic components;
- big batch size;

- high flexibility.

Though such a division is conditional (sometimes FMS are used for precision mini-parts production in non-electrical machinery, and vice versa, or big rotors and other rotational parts for electrical machines are produced by FMS in electrical machinery) we have, for further analysis, clustered all FMS described in our data bank into two parts: heavy machinery (non-electrical machinery and transportation equipment) and precision production (electrical machinery and electronics as well as instruments).

Among the 375 identified cases, 83% were defined as FMS for machining, 12% for manufacturing, only 5% for assembling, and less than 1% for metal forming.

5. TECHNICAL COMPLEXITY

The technical production complexity of a FMS can be described by a number of machining centers (MC) or a total number of NC-machine tools (NCMT) and by a number of robots used in the system. The complexity, connected with transportation / communication within an FMS, storage, quality control / inspection depends on the types of the respective systems.

Normally a FMS includes one or more multi-functional MC. A most typical configuration (see Figure 3) has 2-4 centers. It applies to 56% of the 272 systems with MC. Another group of FMS has 5-8 machining centers each. Its share is 28%. One can observe that there are 28 systems with more than 8 MC, and only 15 systems have one center supplemented by other NC-machines.

Such systems, as, e.g. Mazda (1987), Fanuc (1981) and Yamazaki (1983) (all in Japan) include 21, 23 and 27 machining centers, respectively. The technically most complicated FMS for car engine assembling, installed by Fiat Auto in Termoli, includes 72 automatic stations for complete cylinder-block assembly.

Some FMS are based on MC use only, but in other cases the centers which usually substitute for drilling, milling and boring machines are accompanied by NC turning, grinding and other machines. The distribution of the FMS by the total number of NC machine tools (including MC) is shown in Figure 3.

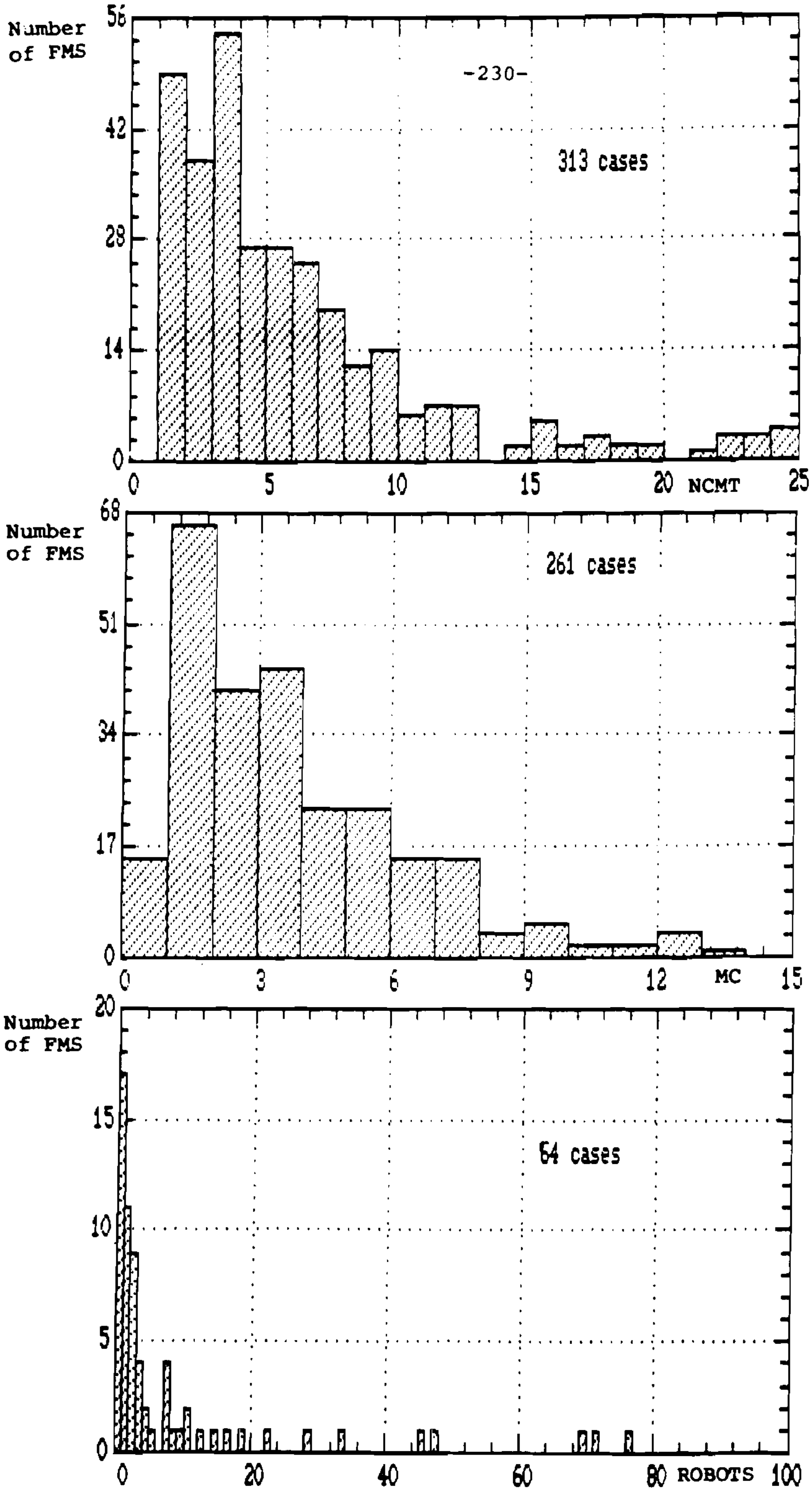


Figure 3. Distribution of FMS by their technical complexity. Number of FMS over numerically controlled machine tools (NCMT), machining centers (MC), and robots, respectively.

The first group (41% of the total) includes rather primitive systems with 2-4 NCMT. The second group (40%) includes sophisticated FMS with 5-10 NC machine tools. The residual 19% represent very heterogenous systems with more NCMT, up to the case of 38 CNC-machines installed at the Yamazaki plant. Totally, five FMS (or 1.6%) use more than 25 NCMT.

According to the collected data the use of industrial robots (IR) was shown only in 64 cases and 17 FMS included 1 robot. Twenty systems use 2 or 3 industrial robots, four systems use 4 or 8 robots. There are several FMS with 13 and more IR. Three companies (Casio, Toshiba -- both in Japan --, and IBM in the USA) have FMS with 70, 72, 77 industrial robots, respectively. All of them are used for electronics production.

The main conclusion that can be drawn from these data is that the majority of FMS in use are relatively simple from the viewpoint of production-technical complexity.

Approximately 30% of the 181 FMS, where there is information on transportation systems, use a traditional conveyor or crane connection between the working places, NC-machines, production and storage areas. The other 70% have automated guided vehicles or computer-controlled carts.

Data on storage systems were reported only in 42 cases. 37 (or 82%) FMS used an automated storage and retrieval system and only in 5 cases a computer-controlled warehousing system was installed.

The same situation is encountered for information on inspection systems -- we could collect only 33 cases with such data. In 25 cases a manual or automated measuring and/or final inspection was reported. In 8 cases (4 of them were shown in Finnish FMS) there was an automated maintenance and monitoring system.

The data on these three supplemented systems show that only the transportation system is sufficiently developed, the storage and inspection systems are rarely sophisticated.

6. ECONOMIC AND OPERATION DATA

About one half of the cases on our data bank consists of information on the cost of a system, usually in national currencies. These data have been recalculated into US dollars according to the exchange rates of the years of installation. As shown in Figure 4, the FMS price does not exceed 50 million dollars, and the majority of the FMS (97%) cost less than 20 million dollars.

Looking at more detailed data, it will be found that 15% of the FMS cost 1 million dollars and less, 24% from 1 to 2 million, and 16% from 2 to 3 million dollars. This means that more than 50% FMS cost no more than 3 million dollars.

Among the observed cases one can find several FMS with very high investments. Approximately one tenth of the US systems cost 18-25 million dollars, the Messerschmidt FMS investment also reached 50 million and the total investments in the Italian FIAT automated assembly plant for the FIRE engine were about 300 million dollars.

The international comparison shows that European FMS are usually relatively cheap, especially in the Scandinavian and East European countries.

In spite of the high price of FMS in comparison with conventional equipment, the pay-back time was reported in 44 cases as relatively short (from 2 to 4 years in the majority of the cases). A seven-year peak appeared when a set of Czechoslovak data was taken into consideration (see Figure 5).

This distribution can be treated as close to normal, but we suspect that in reality the observed maximum of the normal distribution curve (4 years) may be slightly shifted. There are two reasons explaining this shift. The looser's propensity to report on their failures is very low, and, furthermore, the majority of the FMS have not yet passed through a pay-back period, and its advance estimation is not very reliable.

The FMS flexibility, illustrated in Figure 6, is expressed by a number of products produced by each system. In spite of a very wide spectrum of the data, the majority of the cases are within a concentrated, narrow area -- 30 products and less.

One third of the FMS produced no more than 10 products, in 14% of the cases they produced from 11 to 20, and in 10% from 21 to 30 products.

There are several highly flexible systems in the data bank. For example, the British Aerospace FMS produces 2000 variants of small aircraft structural parts by batches of 5 to 10 units each.

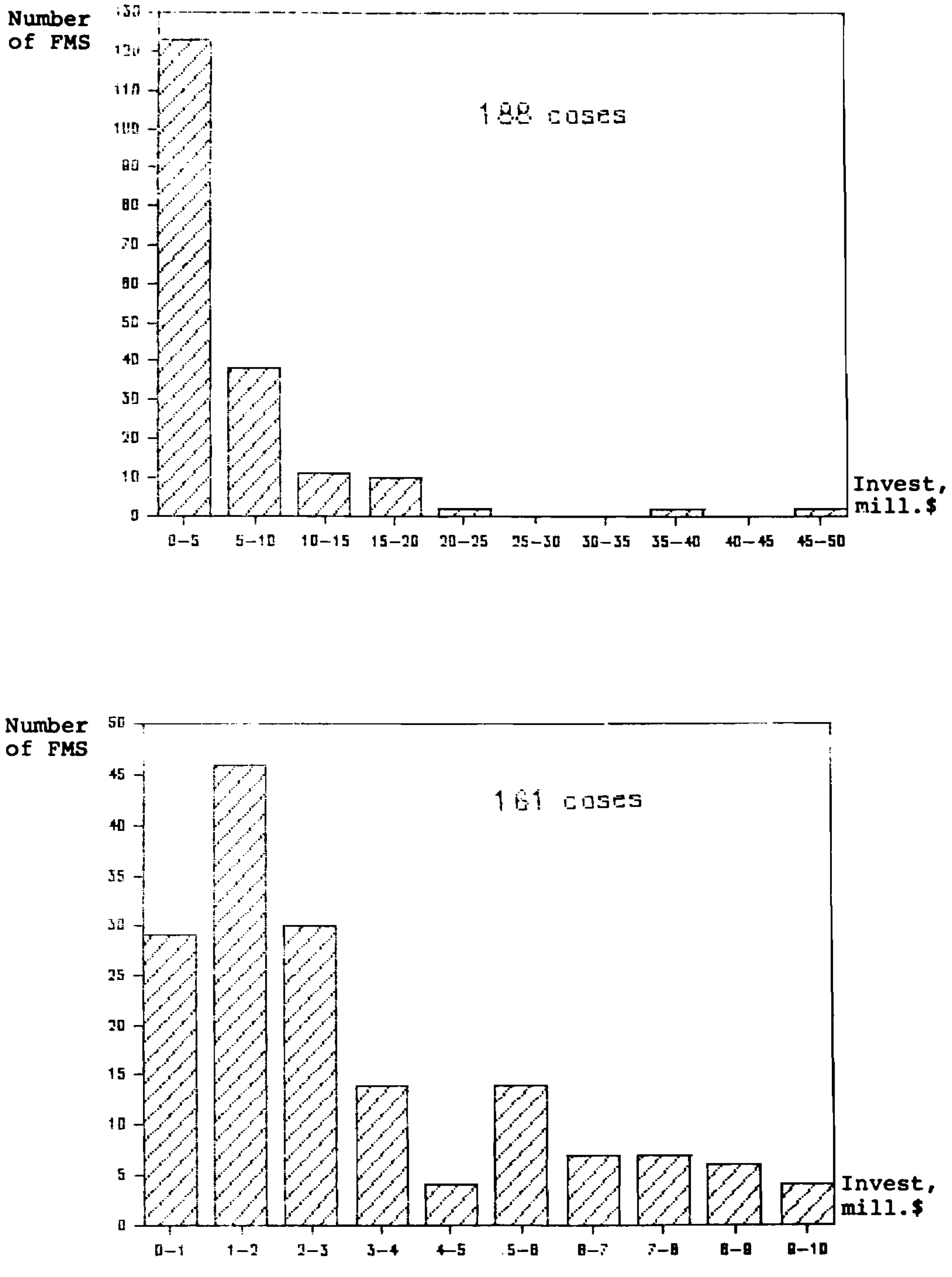


Figure 4. FMS distribution over investment cost.

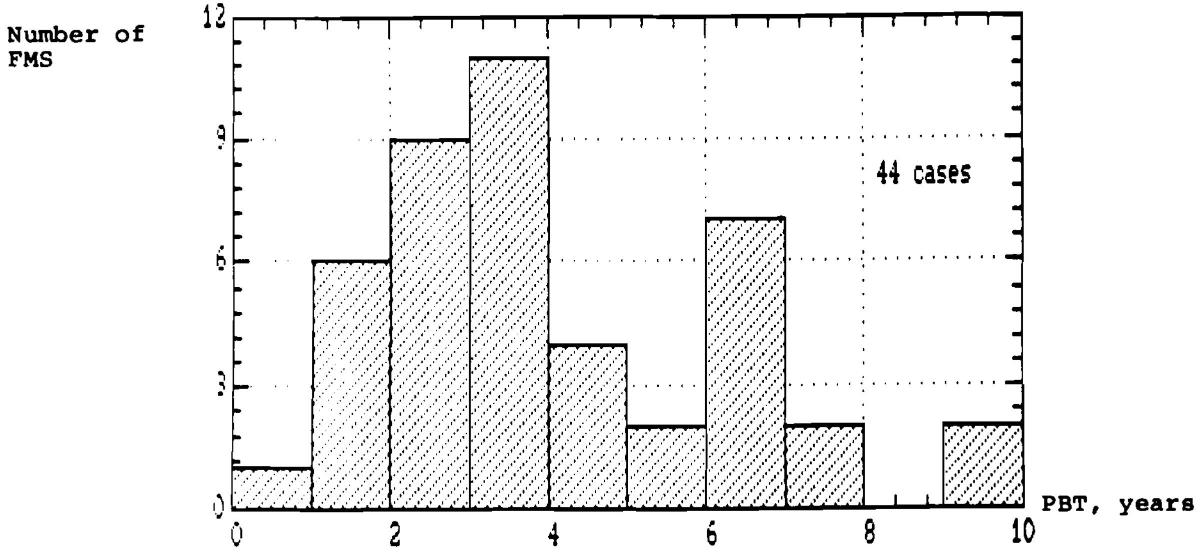
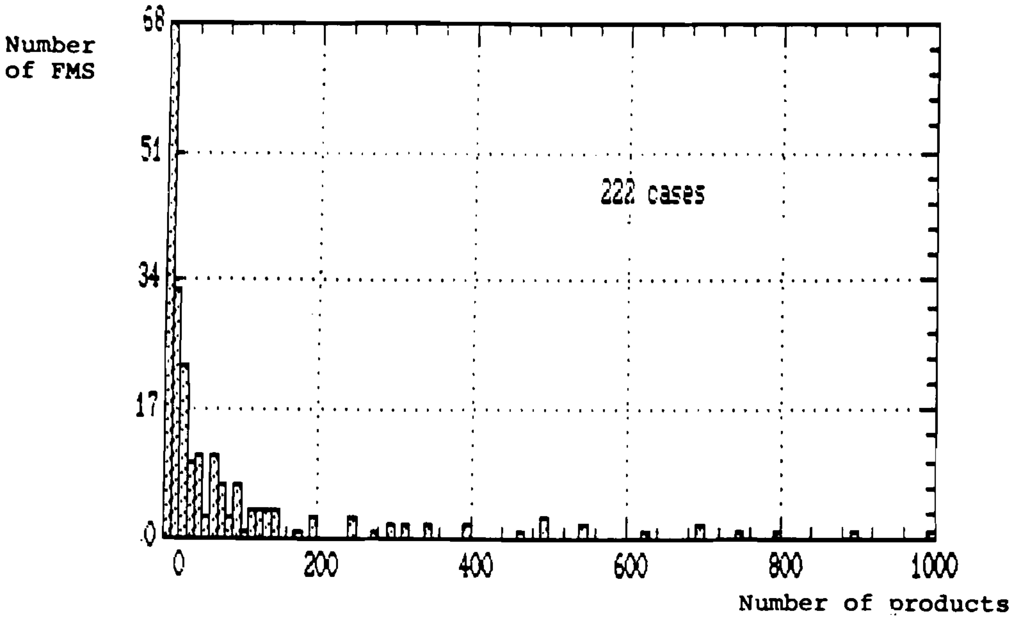


Figure 5. FMS distribution over pay-back time.



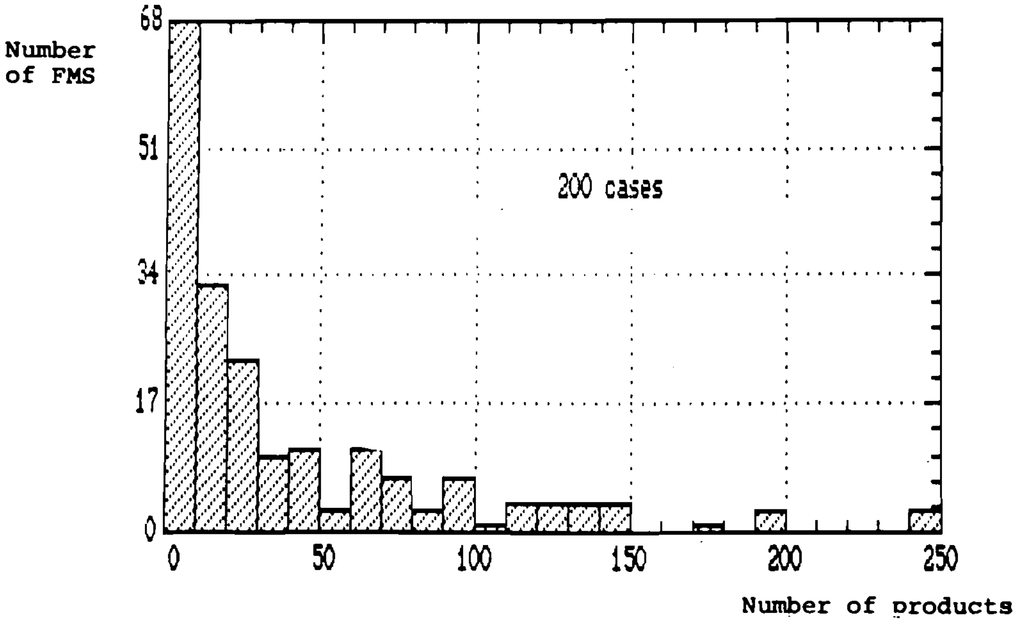


Figure 6. FMS flexibility (FMS distribution over number of products).

One Toshiba FMS produces 3000 variants of switch boxes and another small components with 1-20 units a batch. Still another FMS of the same company has a flexibility of 4000 milling cutter bodies with batch sizes from 2 to 20.

The leaders in flexibility are two Czechoslovak systems producing 5000 variants of parts with a maximum batch size of 300, and 40 on the average in one case, and 2000 (maximum)/260 (average) in another.

The batch-size distribution (see Figure 7) shows that in the majority of the cases (60%) the size ranges from 1 to 50 parts in each batch. Nine FMS out of 89 cases produce 51-100 parts, six produce 101-299 parts, and eight produce 200-500 parts. Maximal batches for certain parts reach sometimes 5000 units and the average is 2000 units. Almost all of such cases were reported by Czechoslovak and GDR FMS. This does not mean mass production by nature, but production of rather simple parts.

As is shown in Figure 8, the operation rate of FMS is much higher than that of conventional equipment. More than 60% of them are in use during 3 shifts a day, and 5 or 6 days a week. Sunday shifts and sometimes 2 shifts on Saturdays are usually used for servicing. 11% of the systems work between 2 and 3 shifts a day (usually 2.5) and 22% during 2 shifts. The third shift is normally used for servicing or setting up of a system.

Only 6% of 115 FMS are used less than during 2 shifts a day (1-1.5), which means either unsatisfactory performance of such systems, a lack of demand for their products, or a low capacity utilization rate.

In spite of the very high average operation rate, only 44 cases with unmanned operation were reported. Among them 12 FMS could work automatically during 0.5, and 29 during 1 shift a day. Two systems operated without human interference during 2 shifts and one (Niigata Internal Combustion Engine Plant) was used 21 hours a day in the unmanned regime (with a total operation rate of 3 shifts a day).

7. RELATIVE ADVANTAGES OF FMS

The total production time can be divided into several subperiods, namely:

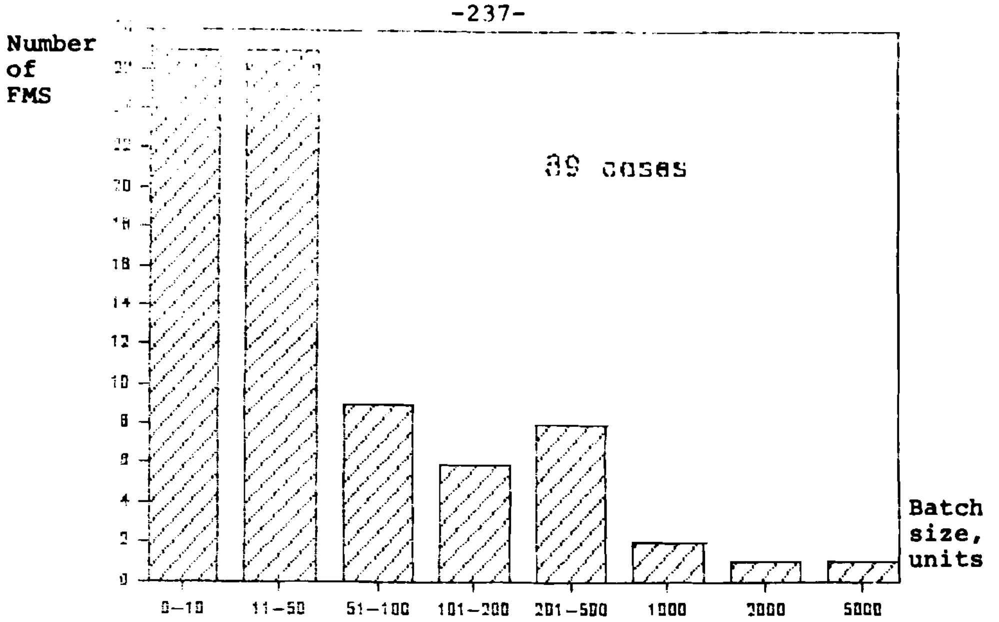


Figure 7. FMS distribution over batch size.

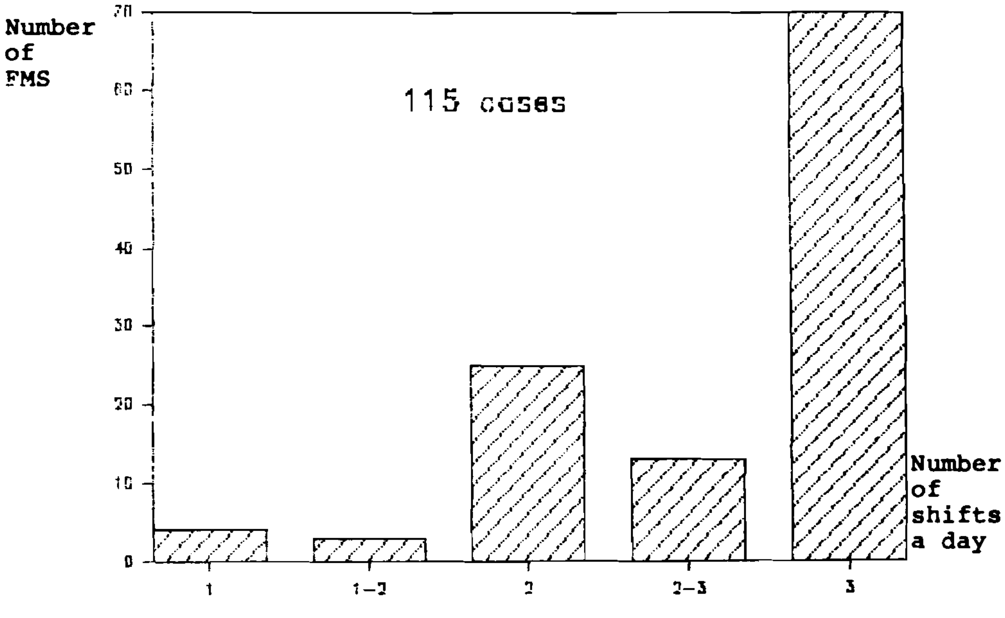


Figure 8. FMS distribution over operation rate.

- set-up time, which is necessary for setting up equipment to prepare a system for a new part production;
- in-process time, which is spent for part production from a first operation up to final operation;
- machining time, in which equipment is used for the part production;
- lead time is the period from the order to the delivery to a customer.

Unfortunately a very limited number of data bank cases (26-45) consists of the information on time reduction, but the number is still sufficient to estimate the most typical reductions in comparison with conventional technologies. The set-up time reduction has been reported for 26 FMS, 19 of them were Czechoslovakian FMS (see Figure 9). In two Canadian cases there was no SUT reduction. One Japanese and one Dutch FMS reduced this time by a factor of 4, a US company reported a reduction by a factor of 6, and for the Remington FMS this reduction was shown to be 12. The most typical SUT decrease was between 1 and 2 (less than 50%).

In-process time (see Figure 10) was 50% and less in 20 FMS (two third of 33 reported cases) as compared to conventional technologies. Among these 20 FMS, fifteen systems are installed in the CSSR industry. Four FMS demonstrated a reduction equal to 2-3. The other cases show different results. The maximum cycle-time reduction (24) was reported for the General Electric FMS, manufacturing motor frames and gear boxes for locomotives. The machining time reduction was shown only in 26 cases (see Figure 11) and was not so high -- in 22 cases it did not exceed 1/3. For two FMS this reduction reached 2.5-2.7, and the Anderson Strathclyde FMS (UK), producing parts for mining machinery, demonstrated a machining time decrease by a factor of 10.

In 45 cases we have collected data on lead-time reduction, which is one of the most important indicators of FMS flexibility. In 17 cases the LT decrease was 50% or less, among them 13 FMS belonged to the CSSR industry. The next 19 cases had a LT reduction by factors of 3-5 and there were several systems with a higher reduction (see Figure 12). The most exotic case was the Westinghouse sheet-metal FMS for punching, marking and shearing

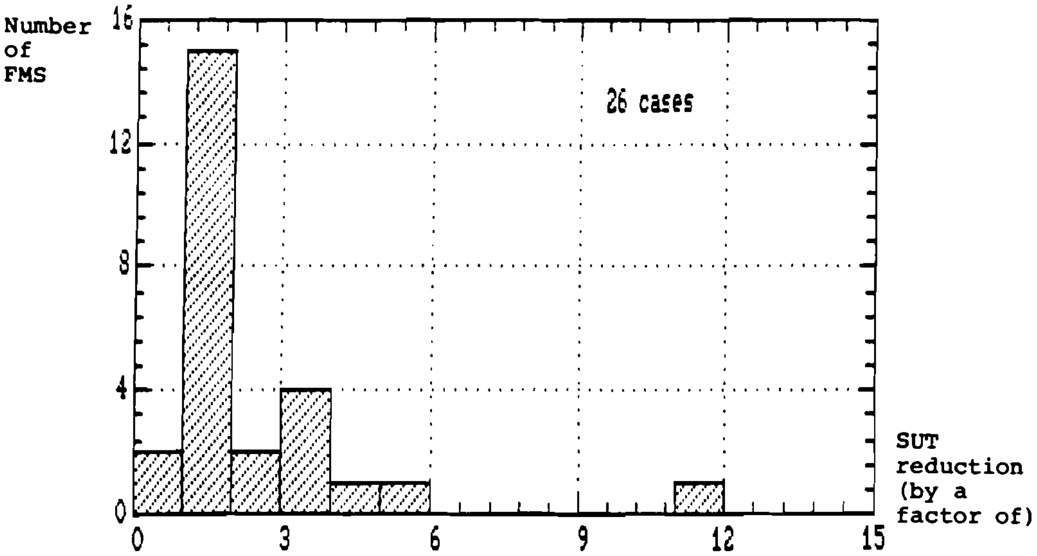


Figure 9. FMS distirubtion over set-up time reduction.

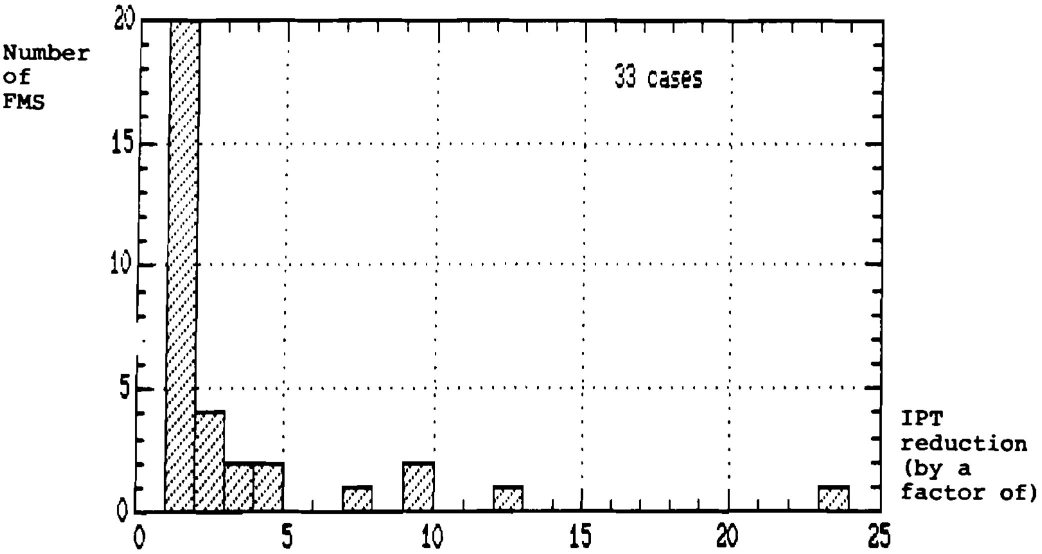


Figure 10. FMS distribution over in-process time reduction.

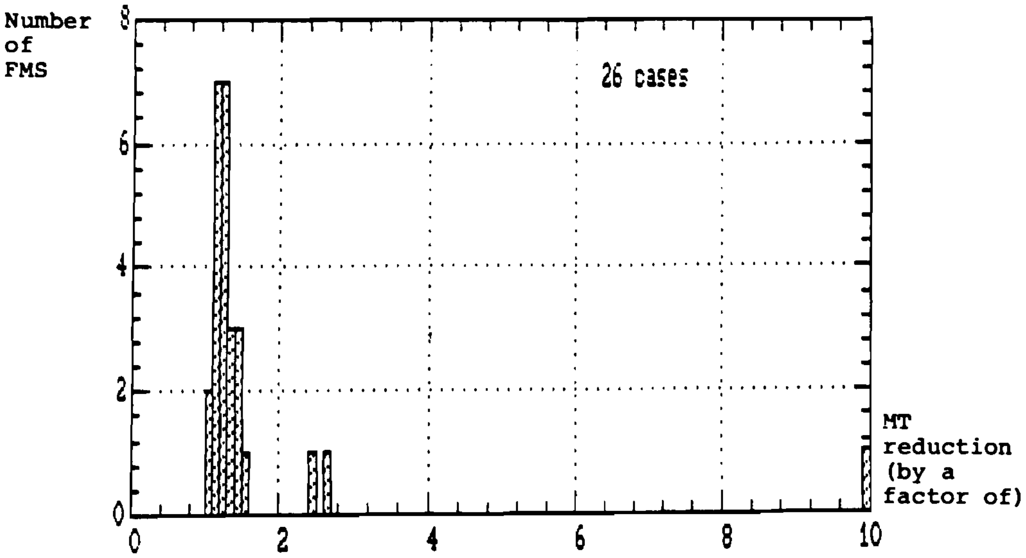


Figure 11. FMS distribution over machining time reduction.

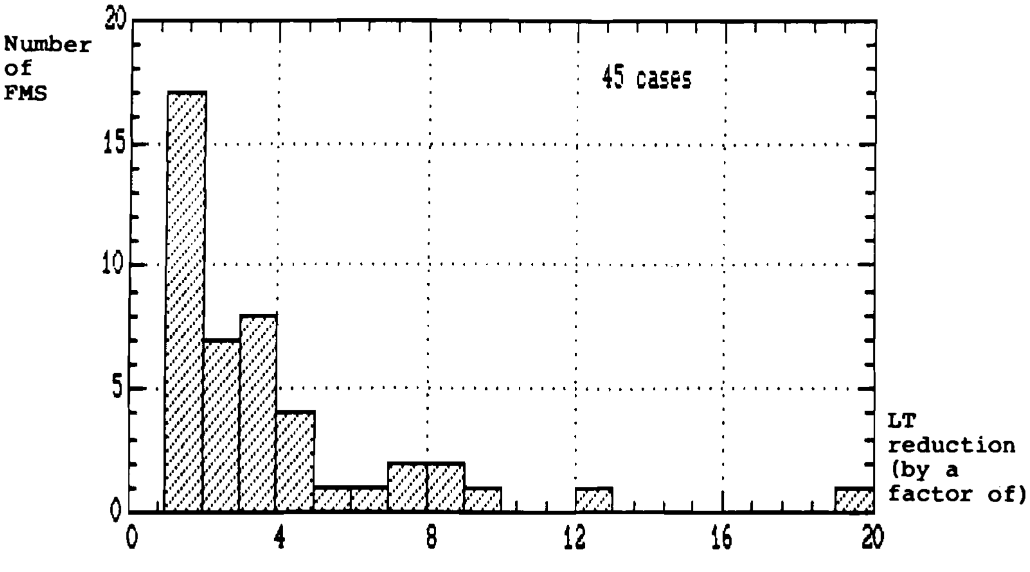


Figure 12. FMS distribution over lead time reduction.

of panels, where the lead-time reduced from 2-3 weeks to 30 minutes.

The time reduction, when using an FMS, influences the logistic elements of production at a high rate. We analyzed two types of such elements -- work-in-progress and inventory changes, which, in their turn, play an important role in the total production cost formation.

Almost all cases of WIP reduction in our data bank were reported by three countries: the CSSR, Finland and the UK. But in the first group (see Figure 13), where the reduction did not exceed 50%, the Czechoslovak share was very high -- 12 out of 17 cases.

In 7 Finnish FMS the WIP was cut by a factor of 4 on the average, and Valmet's system recorded the maximum reduction by a factor of 10, which was also recorded in the case of the British FMS, installed by Victor Product for manufacturing connectors. On the average the reduction in 14 British FMS was by a factor of 4.

Inventory reduction was reported only in 23 cases (see Figure 14) and the distribution is as follows (mainly for Finnish and British systems). The average reduction was 75%, or by a factor of 4, which was typical for 40% of the cases. The highest decrease (90%) was reported by a Finnish company -- Palomex. Almost in all observed cases inventories were reduced by factors of 2-5 in comparison with conventional technologies.

Exact estimates of the personnel reduction can only be made under the condition that there is a strict comparison between conventional and flexible production technologies. This means that the results illustrated by Figure 15 are very approximate.

The average decrease in personnel for 20 Czechoslovak FMS was only 36%. At the same time the number of persons was reduced by a factor of 3 (or 67%) for 7 Finnish and 8 Dutch systems, and by a factor of 6 (or 83%) for 16 Japanese systems. The majority of the cases show a reduction by factors of 2-4, but the Swedish company AB SKF reported that after the FMS installation for ball-bearing production two operators substituted for 200 workers at the old manned line, at a higher production.

A productivity increase of no more than by a factor of 2 was the most typical for 33 FMS (see Figure 16), where these data

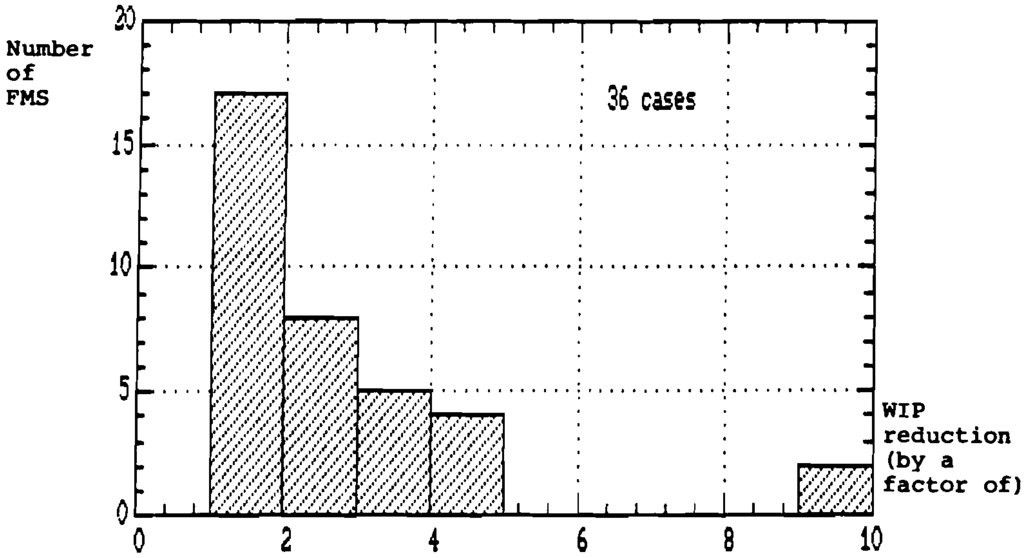


Figure 13. FMS distribution over work-in-progress reduction.

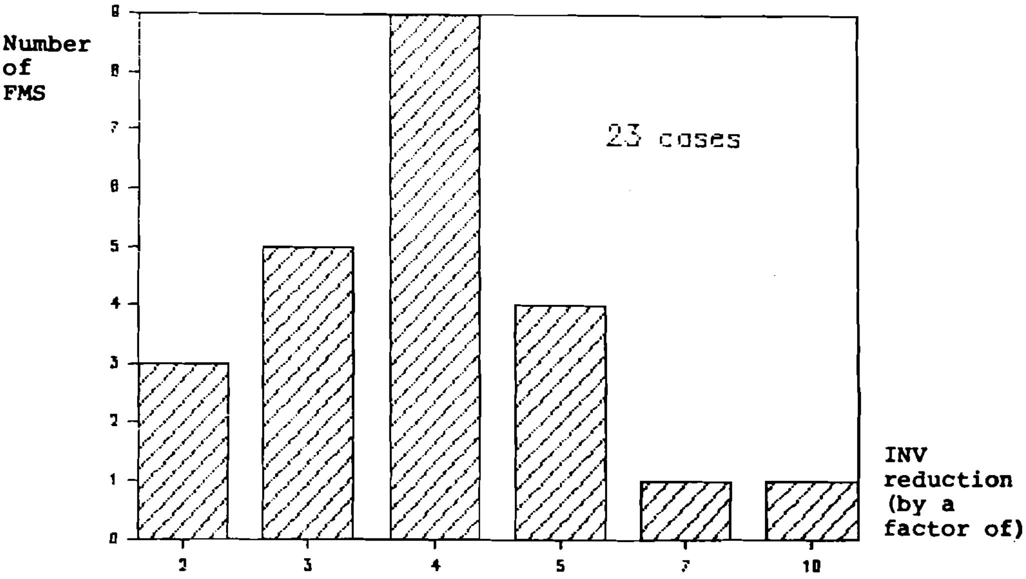


Figure 14. FMS distribution over inventory reduction.

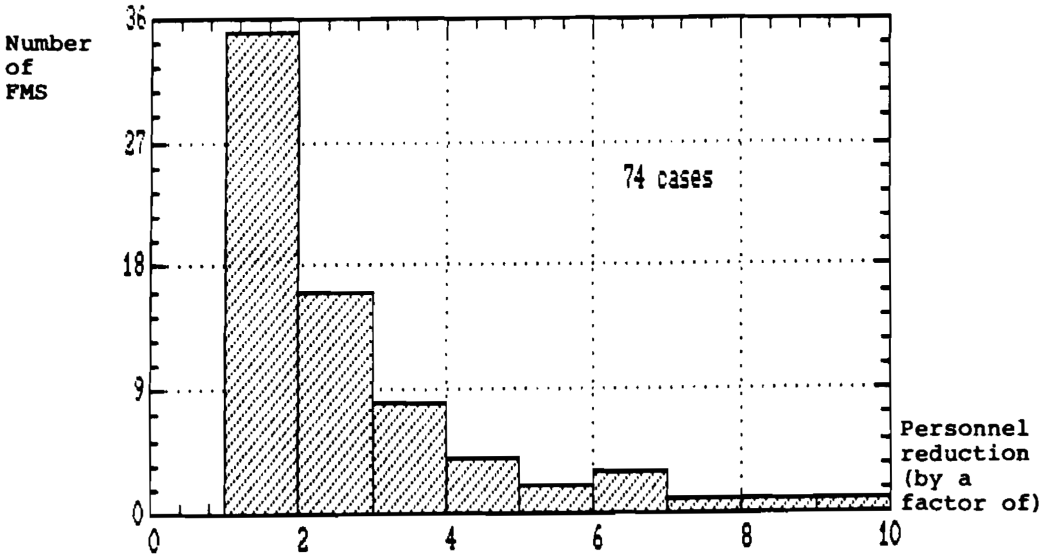


Figure 15. FMS distribution over personnel reduction.

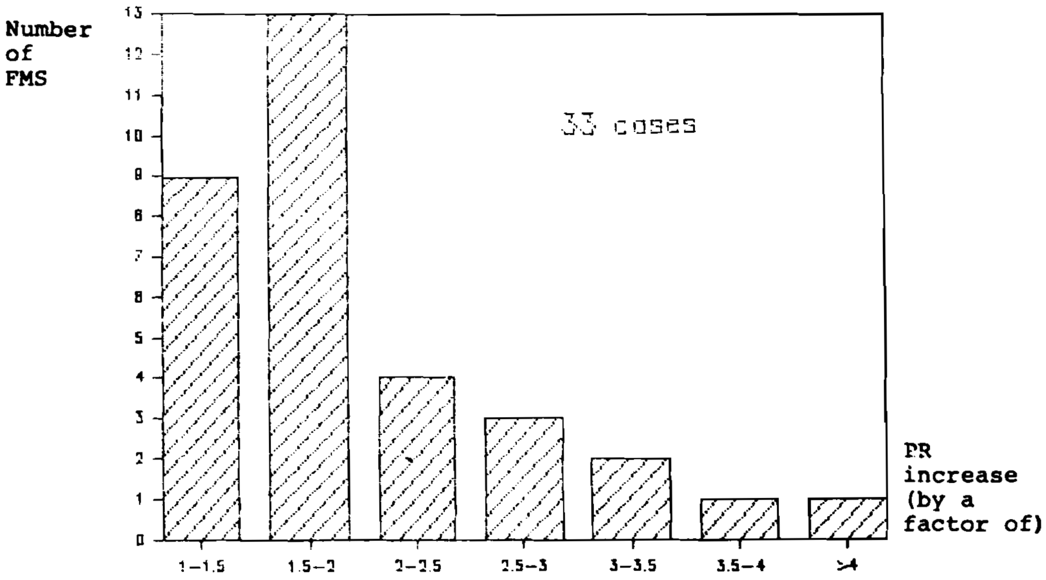


Figure 16. FMS distribution over increase in productivity.

were reported. There are some exceptions showing a higher productivity growth in the GDR, Finland and the CSSR. The highest achievement was 5.6. The production capacity increased by 50% on the average.

The composition of the different FMS advantages mentioned above is to lead to the product unit cost reduction (UCR). But only in 11 cases (5 for the USA, 2 for the FRG and the CSSR, and 1 for the UK and Finland) were the quantitative data on UCR reported. The average value was 2, but in 6 cases the unit cost reduction was between 1.1 and 1.4. The highest reduction, equal to 5, was reported for the Borg Warner FMS (USA), which was installed by Coman for machining of crankshafts, heads, and compressors. The exclusion of the case pushes the average figure to a value of 1.7.

According to this analysis FMS usually demonstrate strong advantages in comparison to conventional technologies. Exclusively high achievements can be explained, as a rule, by specific types of production (small parts, metal-forming processes, etc.). But we think that only successful appliers reported these data. This is why the real advantages are usually less impressive.

8. CONCLUSIONS

The portrait of a "typical FMS" is as follows:

- It is used in transportation equipment or general machinery production, mainly for prismatic cast-iron parts or rotational steel parts.
- Such an FMS includes 2-4 machining centers or 2-10 numerically controlled machine tools (including centers), 1-3 industrial robots.
- The supplementary systems are AGV or computer-controlled carts for transportation, automated storage and retrieval systems and automated measuring inspection systems.
- The cost of such a system is 1-3 million US dollars and its pay-back time is 2-4 years.
- The FMS flexibility is 30 and less products produced at a batch-size of no more than 50 units.
- The operation rate is very high -- 3 shifts a day, but usually no more than 1 shift in unmanned regime.

- Set-up, machining, in-process and lead time are reduced by factors of 2, 1.3, 2 and 2-4, respectively.
- The average reductions of work-in-progress and inventories are by factors of 2-3 and 4, respectively.
- The personnel reduction and productivity increase are between 1.2 and 2.0.

The current diffusion of FMS in the metalworking industries is mainly based on the introduction of these typical systems, which have already passed the main part of their learning curve, and a sufficient experience has been accumulated by producers and users in dealing with the systems.

Among the new directions of FMS implementation, which will increase the diffusion rate in the future, the following can be mentioned:

- New adopters by countries and industries, as for example NIC, electronics, furniture, textile, chemical industries.
- New areas of application -- assembling.
- New technological components within FMS: laser measurement and cutting, electronic beam and plasma cutting, etc.
- Sophisticated transportation, inspection within FMS and control systems outside FMS.

Among the collected data one can see examples of advanced FMS having much higher costs, flexibility, and technical complexity. Their future diffusion will depend on the decision of some technical and managerial problems.

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FLEXIBLE MANUFACTURING SYSTEMS (FMS)
MAIN ECONOMIC FEATURES

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I. INTRODUCTION

The correlation estimates and analyses for the main FMS features are presented in this Working Paper, on the basis of a 400 FMS World Data Bank described in [2],

All the variables from the Bank were aggregated into several groups:

1. FMS cost;
2. Flexibility (number of product variants and batch sizes);
3. Time reduction (lead time, set-up time, in-process time);
4. Logistic features (work-in-progress and inventories reduction);
5. Personnel reduction and productivity growth;
6. Technical complexity;
7. Pay-back time.

All relative advantages (in comparison with conventional technologies) were measured by factors of their reduction or growth. Therefore, a variable change leading to a lower relative advantage does not mean that the FMS is less effective than a conventional technology. It only means a lower advantage.

The reliability of any figure in the Bank is affected by the difficulties of measuring or due to possible misinterpretation. But the use of a relatively big number of observations for each variable leads to higher reliability of a general estimate or conclusion.

On the other hand, even if we have a lot of observations, the specific national or technical features dominate sometimes in such a sample. The only way to overcome such an obstacle is to purify the data from the special peculiarities by the use of the clustering approach.

Naturally, some results provided in this Working Paper are statistically not sufficiently confirmed and the collection of data and their purification will be continued. The following FMS-specific advantages have to be taken into consideration:

1. Higher flexibility (smaller batch size, higher product variation, shorter lead-time);
2. Lower production cost (labor reduction; operational capital cost reduction, including inventory reduction, work-in-progress reduction, energy saving, etc.; fixed capital

reduction, including a lower number of machine-tools, floor space saving, cheaper warehouse systems, etc.);

3. Higher product quality (production of new goods with higher quality, lower rejection rate for conventional products).

On the other hand, an economic analysis must include the comparison of the advantages with negative FMS features such as:

- higher investments in equipment and labor force (for retraining and education);
- higher technical complexity and consequently higher sensitivity to technical reliability of the sophisticated machines and supporting systems;
- high costs during the pioneering implementation period and while following the "learning curve";
- new social problems and obstacles.

The following analysis includes the majority of the factors, but not all of them. Quality and reliability problems are out of consideration. Social aspects are considered in [3]. The results have to be interpreted only in the sense of statistical correlation, casual relations are mentioned in some cases.

2. COST-EFFECT ANALYSIS

There is only one column in the Bank reflecting FMS "cost" data, i.e. investments measured in US dollars. On the other hand, there are several sets of "effect" data. It is possible to divide these data into the following groups:

1. Time reduction (lead time, set-up time, in-process time and machining time);
2. Logistic figures (inventory and work-in-progress reduction);
3. Operational data and pay-back time;
4. Personnel reduction and productivity growth.

A direct correlation between the cost and the effects usually showed indefinite clouds of points, or rather contradictory tendencies. This necessitated the use of the clustering approach to obtain a reasonable correlation. Several variables were used for clustering: investments, industries of application (machinery and transportation equipment versus electronics and instruments), types of FMS (machining, metal-forming, assembling, etc.) and in some cases countries, when we were not quite sure of the reliability of the investment or exchange rate data.

E.g., the FMS distribution over the investment costs shown in Figure 1 demonstrates that the total FMS population can be divided into two large groups: "cheap" systems costing less than four million dollars, and "expensive" ones costing more than four million dollars.

More detailed clustering is not reasonable because of the lack of statistical data on some "effect" variables for small groups of the FMS.

All data on investments were recalculated into US dollars, according to the official overall exchange rates for the years of FMS installation. All "effect" data were measured in relative terms (by the factor of increase or decrease).

A. Lead-time reduction over investments

Because of the unapproximated cloud of points for all data (see Figure 2), we clustered this relationship in two ways: by cost and by two industrial groups.

For all the cases of "cheap" FMS (where investments were between 0 and 4 million dollars), a certain negative slope was observed (see Figure 3). The corresponding approximation function is as follows:

$$LTR = 6.0 - 1.01 \text{ Invest}$$

where: Invest - investments (million dollars)
LTR - lead-time reduction

However, the statistical reliability of the approximation (dashed line) was not very high. The T-statistics of the slope coefficient did not exceed 1.3, R^2 was here, as well as in other cases, usually between 0.6 and 0.8.

On the contrary, for the "expensive" FMS one can observe a rather strong positive correlation between investments and lead-time reduction (see Figure 4). The linear approximation function is as follows:

$$LTR = -0.6 + 0.46 \text{ Invest}$$

The same estimation made for FMS installed in the machinery and transportation equipment industries (the majority of all cases) demonstrates the same two tendencies (see Figure 5).

The main conclusion is as follows. For "cheap" FMS the cost does not affect the lead-time reduction, but for "expensive" systems with investments exceeding 4 million dollars a high cost leads to a higher reduction of lead-time.

B. Set-up time reduction over investments

The relation between set-up time reduction (SUTR) and investments is very similar to the relation between lead-time reduction and investments described above. The analysis of the total set of the data (see Figure 6) shows that there are two clusters in the relationships.

For cheap FMS a weak relationship (negative slope) is demonstrated. At the same time, for FMS which cost more than 3-4 million dollars, a strong positive correlation is observed (see Figure 7). But the average values of SUTR are the same for these two clusters.

The approximation regression function for Figure 7 is:

$$SUTR = -1.0 + 0.52 \; Invest$$

C. In-process and machining time reduction over investments

The investment data were clustered into the same two groups (less or more than 4 million dollars) after we had analyzed the dependence of in-process time reduction (IPTR). Again, for cheap FMS (see Figure 8), the costs of a system did not influence IPTR, and also for expensive FMS a positive slope was identified (see Figure 9).

The approximation equation for Figure 9 is as follows:

$$IPTR = -5.0 + 1.15 \; Invest$$

Finally we could not identify any correlation between machining time reduction (MTR) and FMS costs. All the data were randomly spread around the average MTR value equal to 1.3 (see Figure 10). The latter result seems to be rather reasonable as the relative increase of machining time of an FMS only depends on a higher operation rate, but not on investments.

D. Logistic impact of FMS costs

The lack of observations with regard to inventory reductions (INVR) did not permit to cluster the investments data, but the total correlation, shown in Figure 11, is rather vague. For cheap FMS a certain negative slope is observable, but four available observations of expensive systems are not enough for a statistical identification.

As in the case of some time reduction variables, the dependence of the work-in-progress reduction (WIPR) on FMS investments also has a V-shaped form. Clustering of this relation on FMS costs demonstrates a statistically weak negative slope for cheap FMS (see Figure 12), and a positive correlation between these two variables for expensive systems (see Figure 13). The cost correlation can be approximated by the following regression equation:

$$WIPR = -0.73 + 0.34 \; Invest$$

E. Operational data and pay-back time

According to the data for 115 FMS, 72% of them are working during 3 shifts a day, 24% during 2 shifts a day and 4% only in one shift per day. Investment clustering (with a limit of 4 million dollars) shows that the operation rate for expensive systems is higher than for cheap ones. 74% of the expensive FMS are working during 3 shifts per day and 26% during 2 shifts. Among the cheap FMS, 53% are used during 3 shifts a day, 42% during 2 shifts and 5% only in one shift a day. The average operation rate for expensive FMS is 2.7 and for cheap systems it is 2.5 shifts a day.

It seems that, in spite of the more complicated management and work schedule arrangement, expensive systems are used more intensively to reduce their pay-back time.

Pay-back time (PBT) is one of the most important figures for FMS efficiency assessment. Its dependence on the cost of an FMS is positive (higher investments lead to a longer pay-back time), see Figure 14. But the approximation function looks exponential, with an upper boundary equal to 8-9 years.

F. Personnel reduction and productivity growth

There was no statistically strong correlation between personnel reduction (PER) and FMS costs observed for cheap systems, although a certain negative slope in approximation tendency does probably exist (see Figure 15). On the other hand, as in many cases mentioned above there is a positive correlation between these two variables for expensive FMS (see Figure 16).

The linear approximation has the following form:

$$PER = 0.61 + 0.18 \text{ Invest}$$

The same dependency applies to productivity growth (PRG): a negative correlation between PRG and FMS costs for cheap systems and a positive correlation, but with a lower absolute value of the coefficient, for expensive systems (see Figures 17, 18, 19).

The proposed cost-effect analysis leads us to the following general conclusions:

- The most effective systems are the cheapest ones (around 1 million dollars).
- Medium-class FMS which cost 3-4 million dollars are the least effective.
- Only very large investments provide the same FMS efficiency as the cheapest systems have.

The most typical approximation of the cost-effect correlation is shown in Figure 20, but the statistical reliability of the first part of the approximation is not very high.

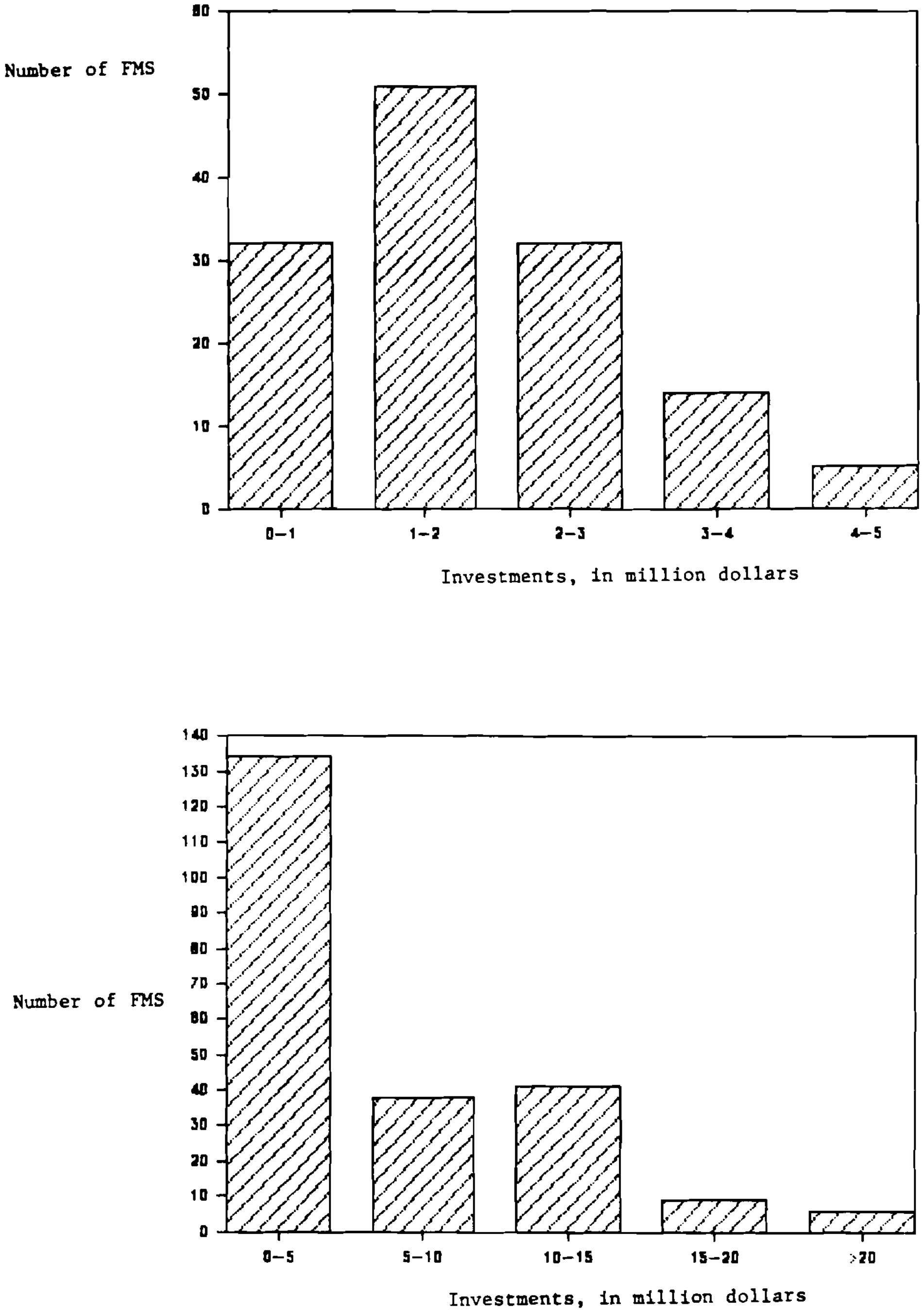


Figure 1: FMS distribution over investments

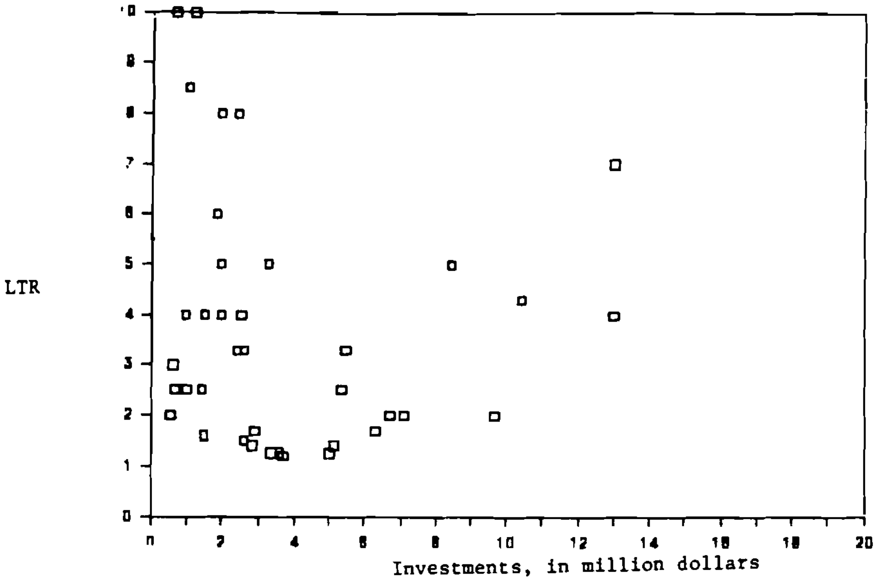


Figure 2. Lead-time reduction (LTR) over FMS cost.

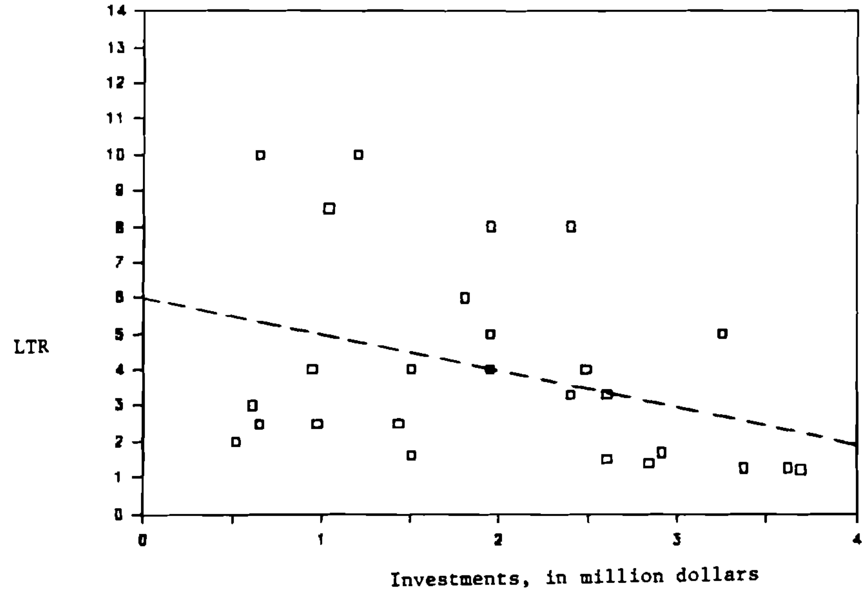


Figure 3. Lead-time reduction (LTR) over FMS cost.

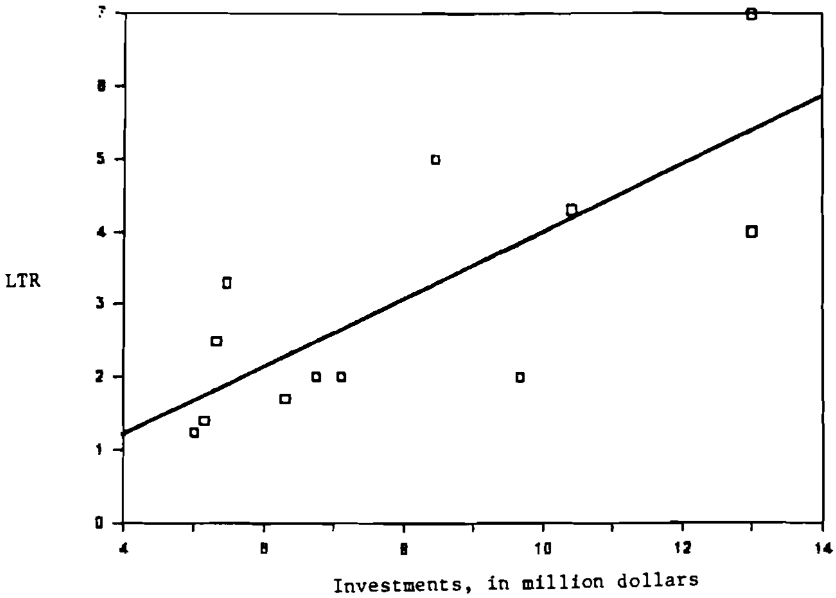


Figure 4. Lead-time reduction (LTR) over FMS cost.

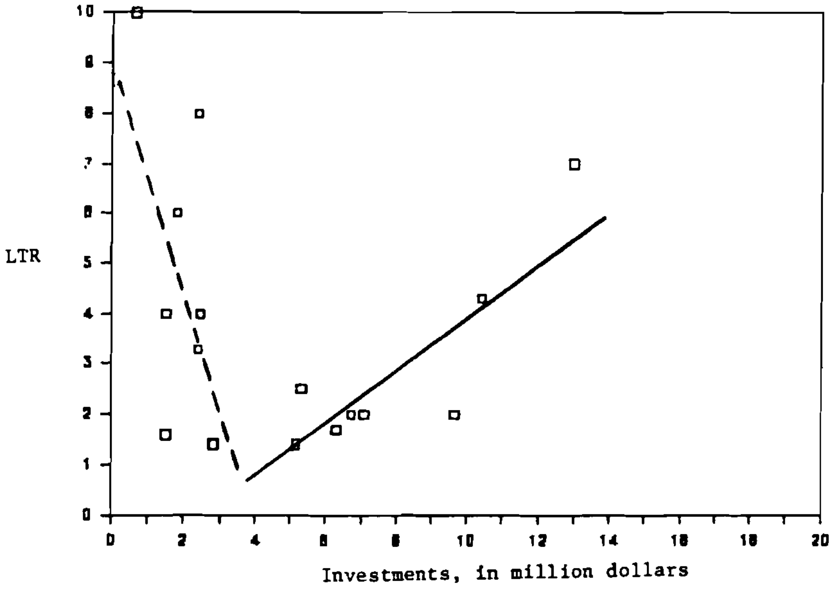


Figure 5. Lead-time reduction (LTR) over FMS cost for machinery and transportation equipment industries.

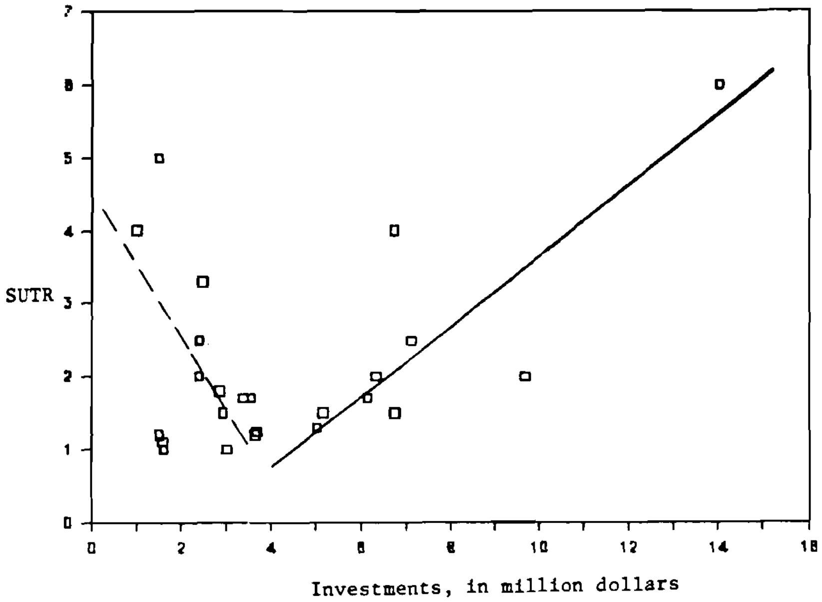


Figure 6. Set-up time reduction (SUTR) over FMS cost.

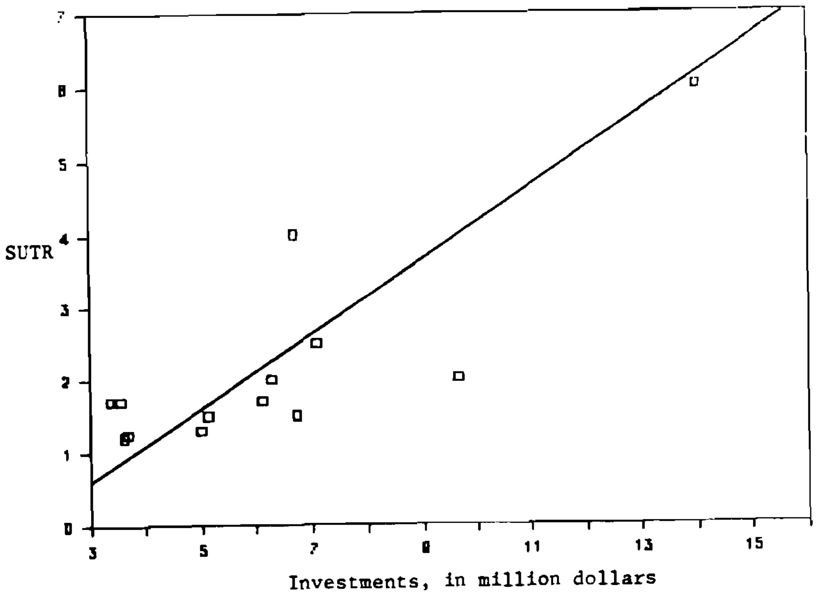


Figure 7. Set-up time reduction (SUTR) over FMS cost.

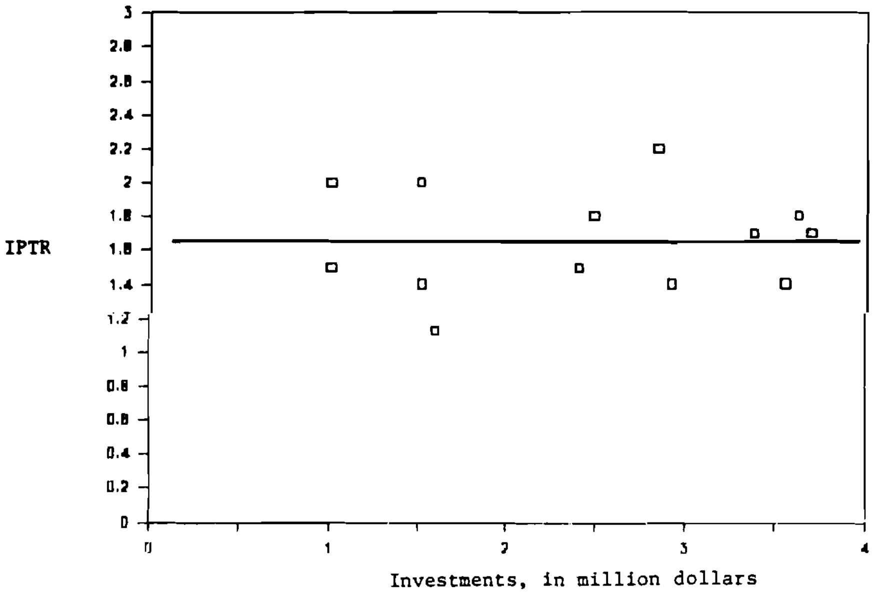


Figure 8. In-process time reduction (IPTR) over FMS cost.

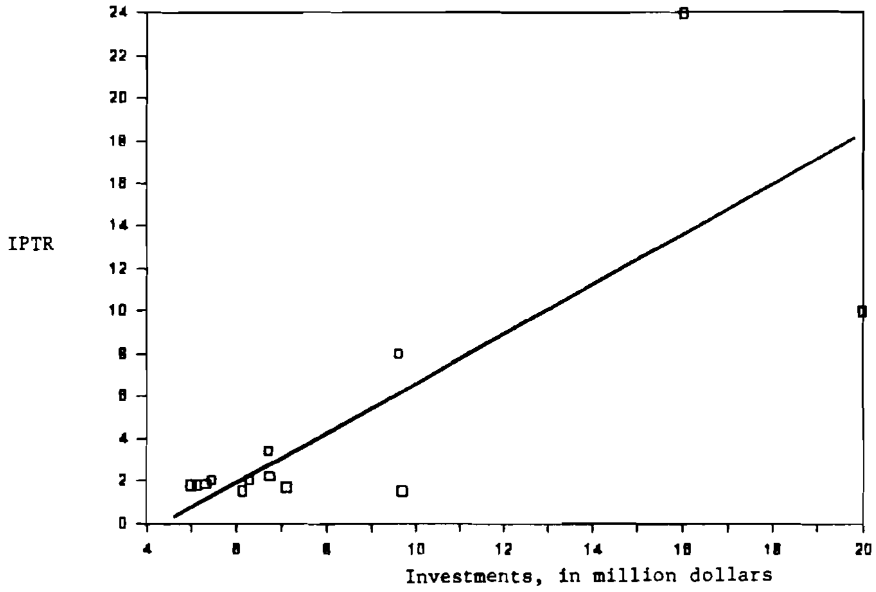


Figure 9. In-process time reduction (IPTR) over FMS cost.

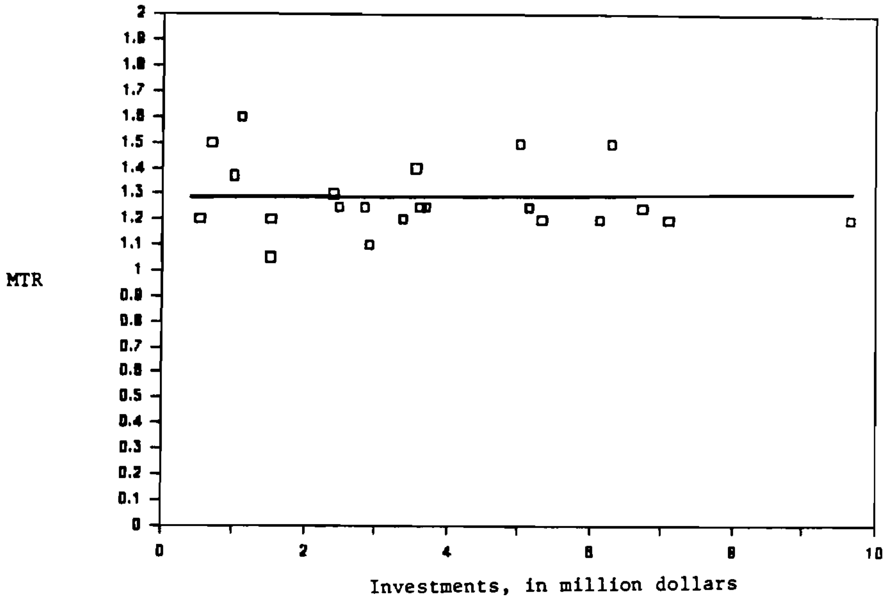


Figure 10. Machining time reduction (MTR) over FMS cost.

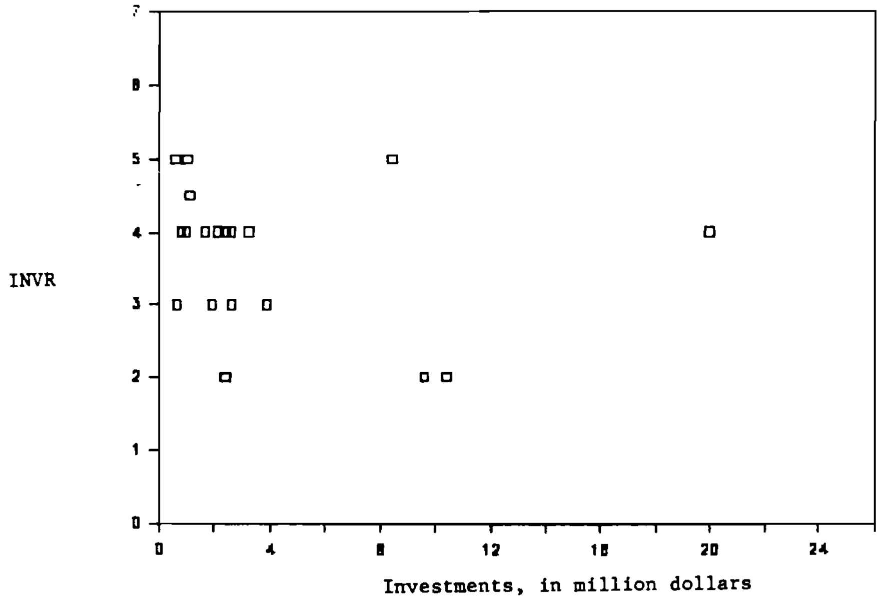


Figure 11. Inventories reduction (INVR) over FMS cost.

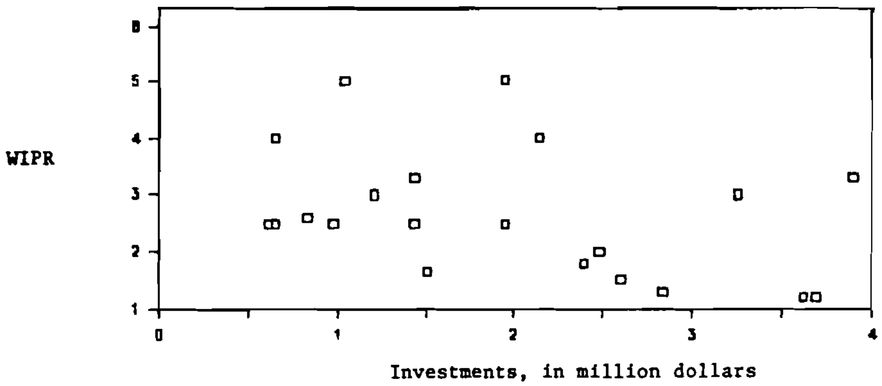


Figure 12. Work-in-progress reduction (WIPR) over FMS cost.

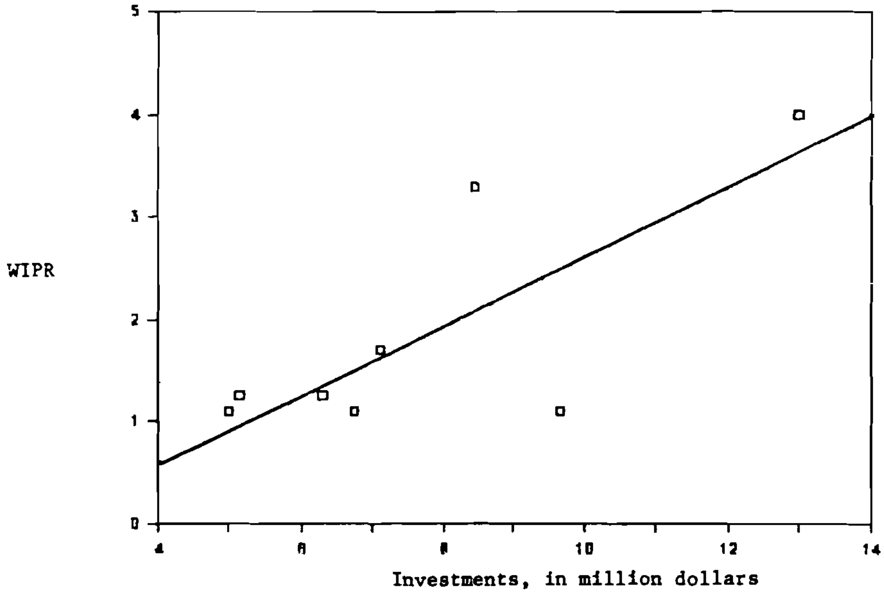


Figure 13. Work-in-progress reduction (WIPR) over FMS cost.

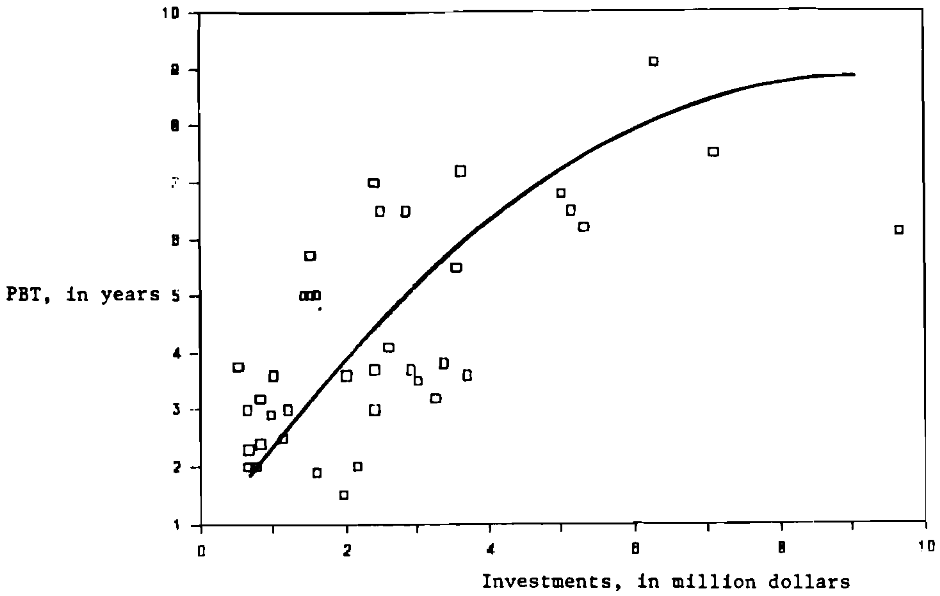


Figure 14. Pay-back time (PBT) over FMS cost.

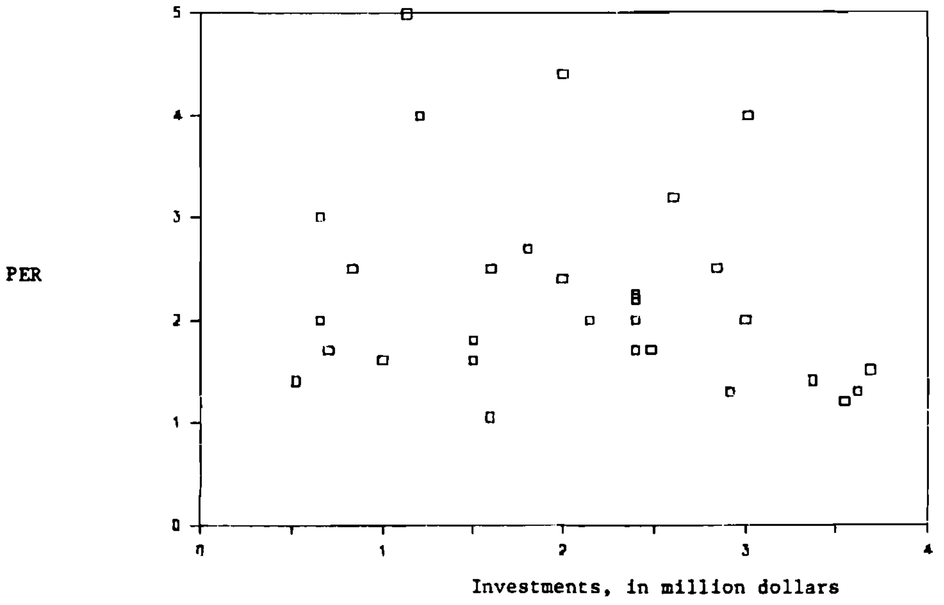


Figure 15. Personnel reduction (PER) over FMS cost.

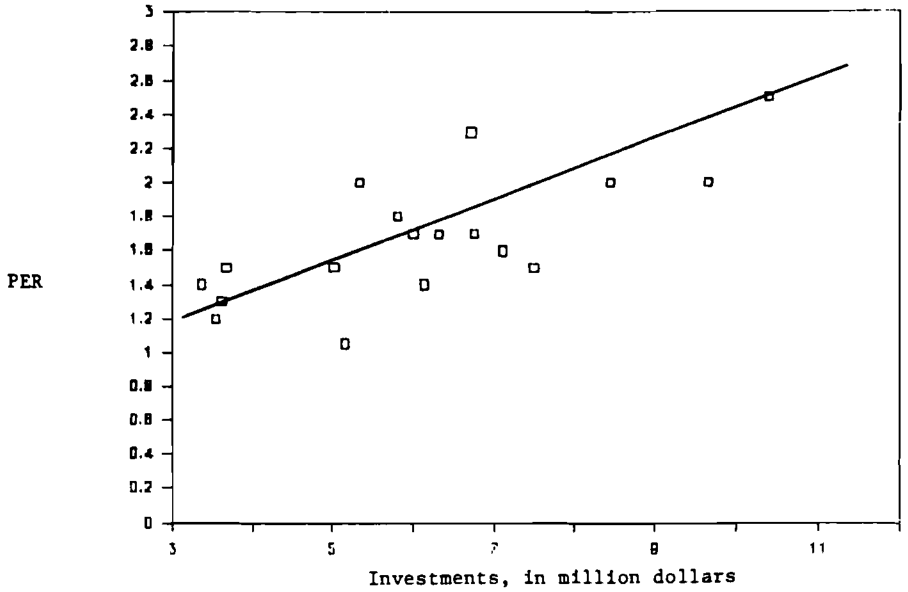


Figure 16. Personnel reduction (PER) over FMS cost.

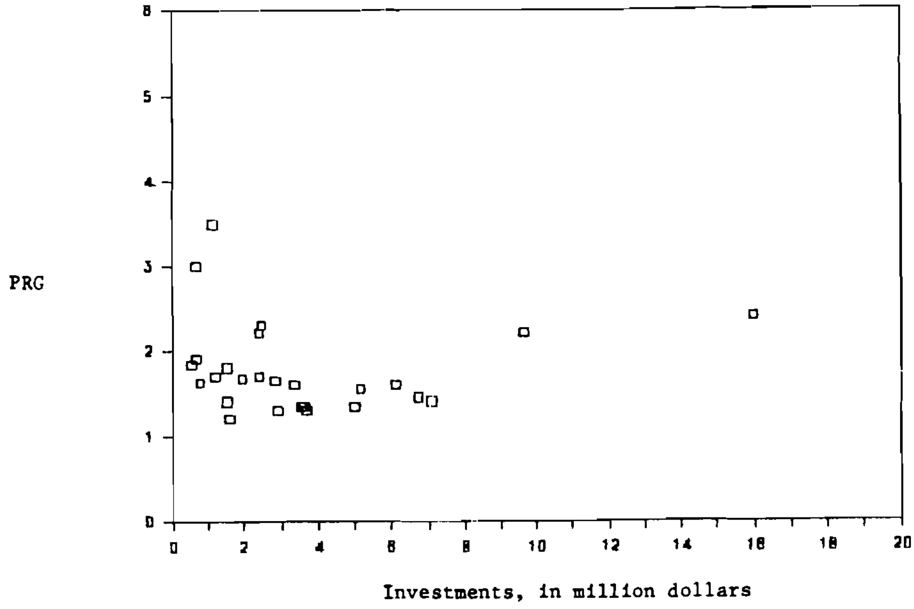


Figure 17. Productivity growth (PRG) over FMS cost.

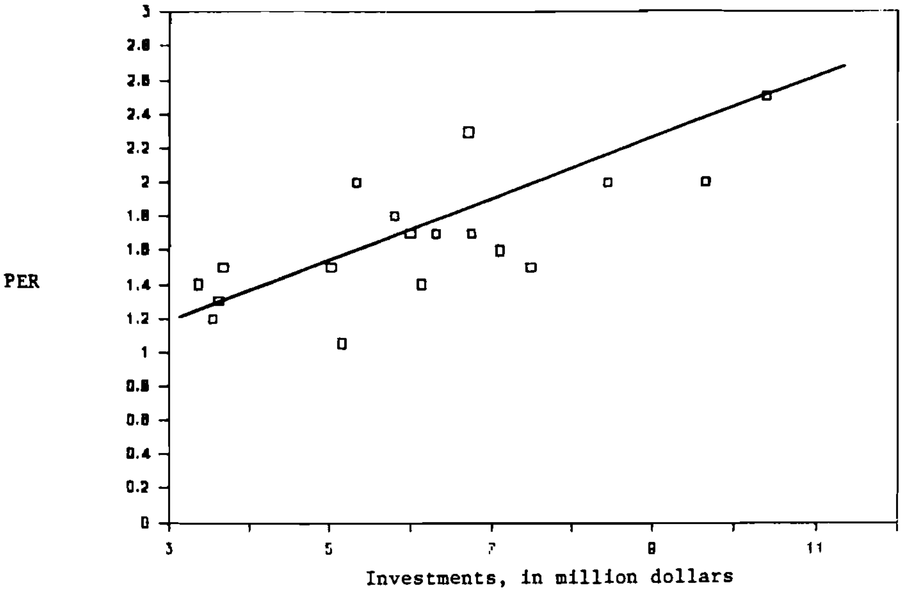


Figure 16. Personnel reduction (PER) over FMS cost.

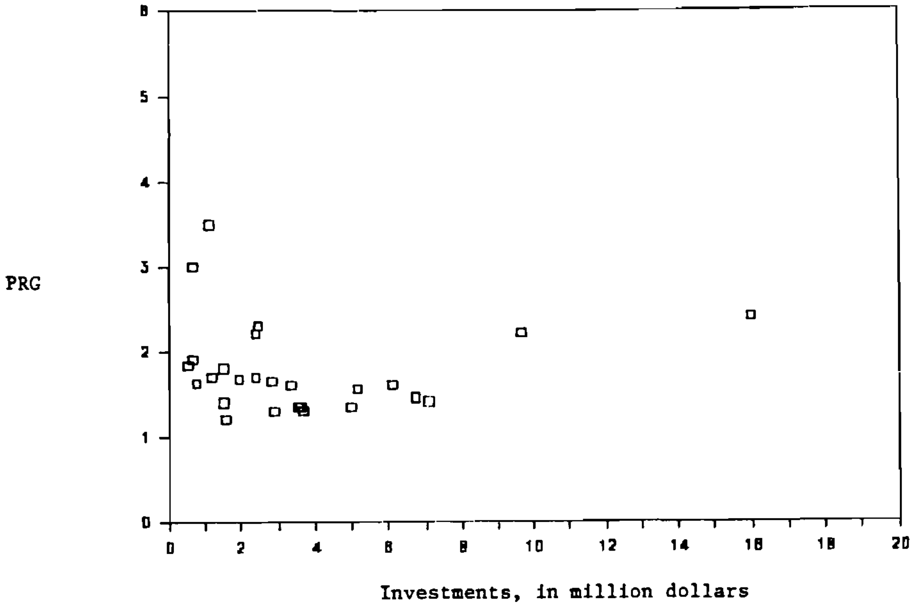


Figure 17. Productivity growth (PRG) over FMS cost.

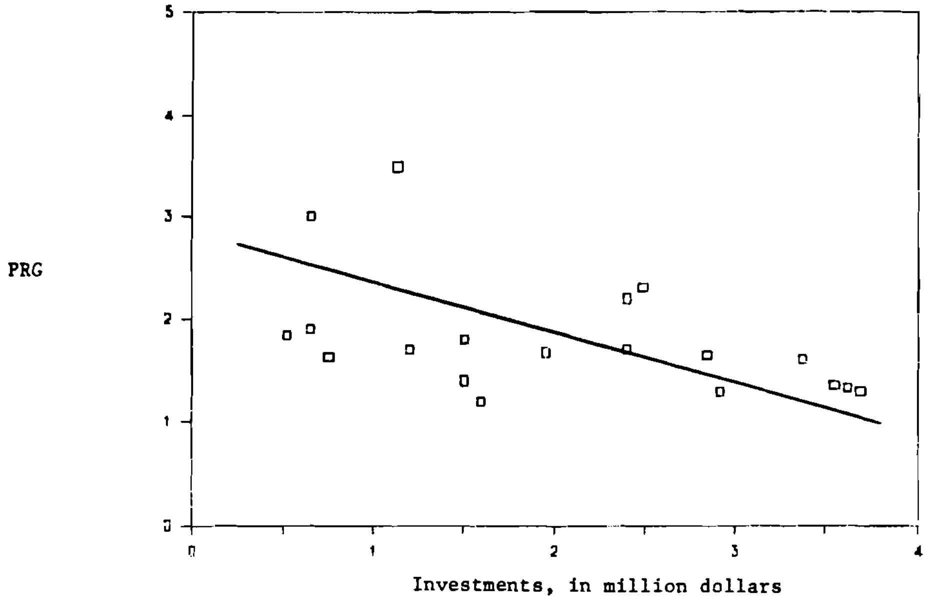


Figure 18. Productivity growth (PRG) over FMS cost.

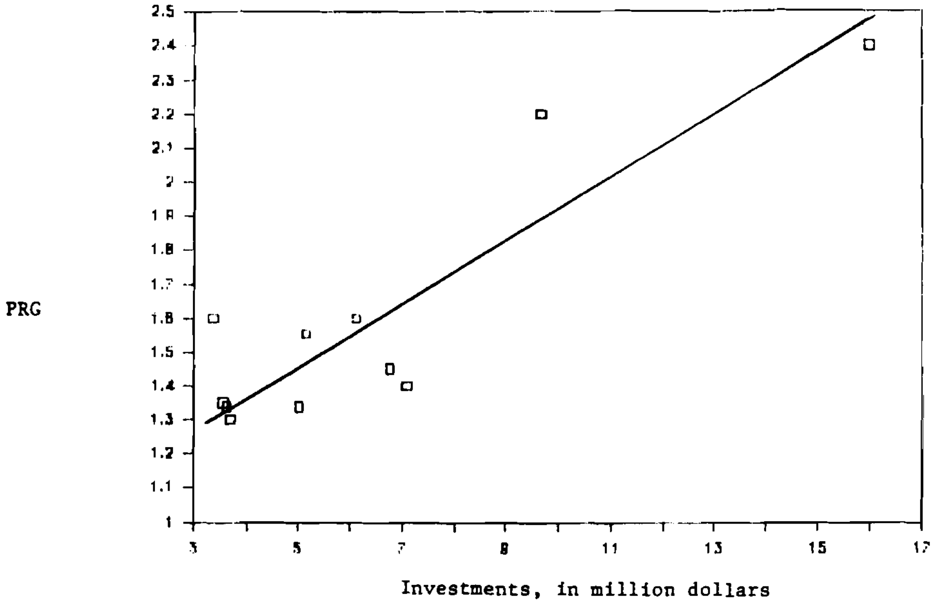


Figure 19. Productivity growth (PRG) over FMS cost.

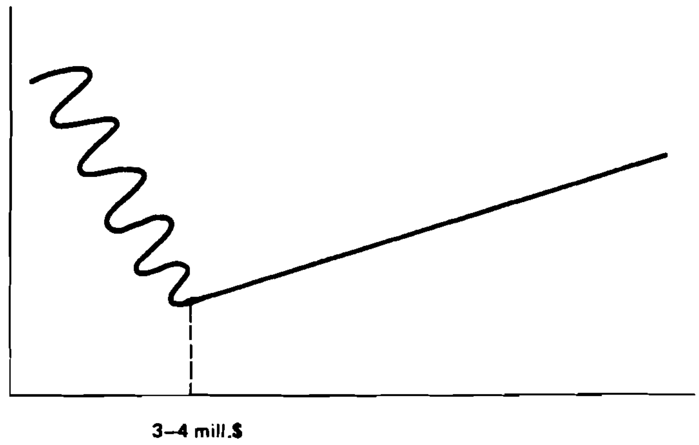


Figure 20. Typical cost–effect relation.

3. FACTORS AFFECTING LEAD-TIME REDUCTION

The flexibility of an FMS as well as the reduction of production costs through the application of an FMS can be reflected by a lead-time reduction (LTR). Lead-time covers all operations from order to delivery of a part to a customer. It includes set-up time, production time, distribution time, etc.

A shorter lead time means a faster reaction of a production system to changing demand. On the other hand, a shorter lead-time also means lower production costs, overhead expenses, and capital and labor saving.

The analysis of the interdependencies between LTR and other features of FMS allows us to define the main factors affecting this important indicator.

Among the different reductions in the production stages collected in the FMS data bank only set-up time reduction (SUTR) was significantly correlated with LTR (see Figure 21). The linear approximation is as follows:

$$LTR = 0.5 + 0.73\ SUTR$$

This means that a higher set-up time reduction usually leads to a higher lead-time reduction, but higher reductions of in-process time or machining time are not followed by a proportional reduction of lead time.

A rather strong hyperbolic type of relation between batch size and LTR is observable in Figure 22. Such a relation seems to be economically reasonable. When different parts are produced by small batches with frequent replacement, the use of conventional technologies leads to a longer set-up time and lead-time as a whole.

This is true only for FMS with a relatively small batch size-production -- from 0 to 100 or 200 units in one batch (78% of all FMS). For systems with a large batch-size production (1-5 thousand units per batch), which are encountered in some GDR machinery systems as well as in electronics production, we could not find any statistically reliable relation between these two variables.

The number of product variants (PV) produced by an FMS also affects the lead-time reduction (see Figure 23). But the results we had obtained for FMS with PV equal to 0.2-2 thousand variants demonstrated no reliable tendencies. Moreover, the average LTR for FMS with high PV was lower that for systems with low PV. This means that in cases of low variability of products (85% of the total FMS number have PV of no more than 200 units) the variability increase leads to a higher lead-time reduction. An additional increase beyond 200 units does not affect the LTR.

The data presented in Figures 24 and 25 show a negative influence of the number of machining centers (MC) or NC-machine tools, including MC (NCMT), on the lead-time reduction. The possible reason for these results is as follows:

> A higher number of MC or NCMT is usually connected with an increased technical complexity of the developed parts. The latter factor restricts lead-time reduction at an average level (by a factor of 4).

The lack of observations concerning inventory reductions (INVR) does not permit to reveal any statistically reliable tendency for the LTR - INVR relation (see Figure 26). There are only 14 cases in the data bank, where both variables are represented.

But for the case of a work-in-progress reduction (WIPR) there are a lot of data, and one can observe a fairly strong positive correlation between the WIPR and the lead-time reduction (see Figure 27). The linear approximation is as follows:

$$LTR = -0.86 + 1.85\ WIPR$$

and the correlation coefficient exceeds 0.9. This does not mean a casual influence, because both variables can be driven by an external reason.

The operation rate also influences the lead-time reduction. In the FMS which are used during 2 shifts per day there was an average LTR by a factor of 2.6, and in the systems which are used during 3 shifts a day the corresponding figure was 4.4.

It is possible to conclude that higher set-up time reduction, flexibility (higher product variation and lower batch size), and work-in-progress reduction will usually provide a higher lead-time reduction. On the other hand, technically more complex systems with a higher number of machining centers and NC-machine tools usually have a lower lead-time reduction.

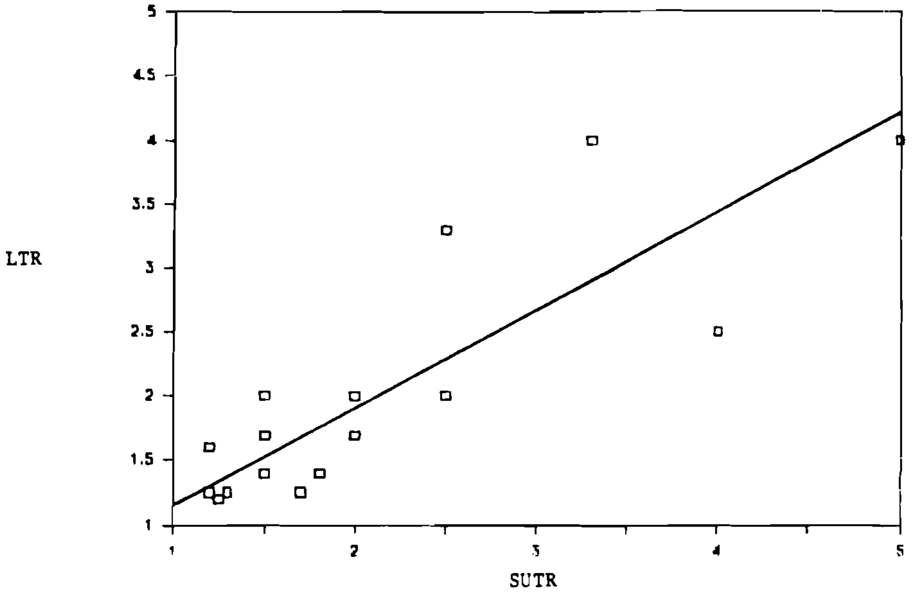


Figure 21. Lead-time reduction (LTR) over set-up-time reduction (SUTR).

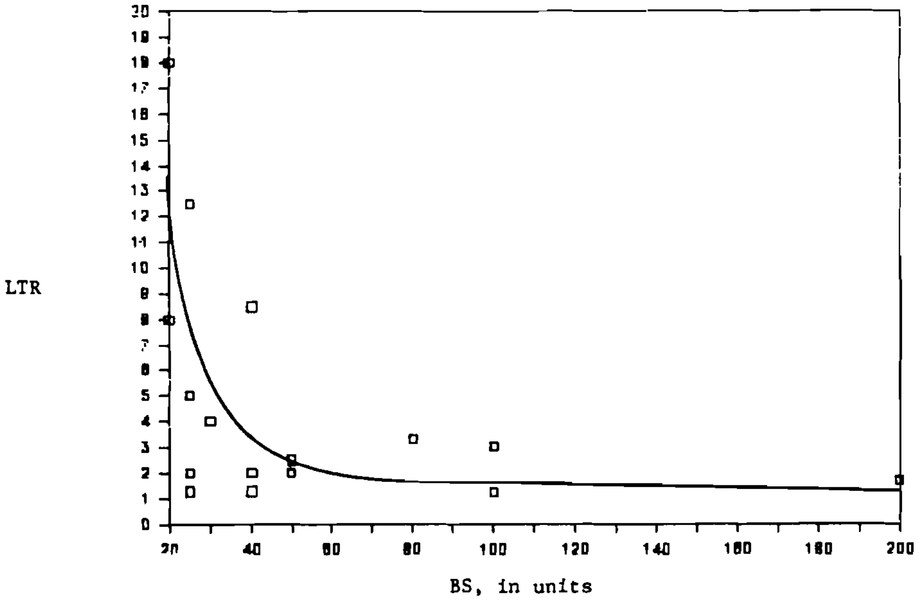
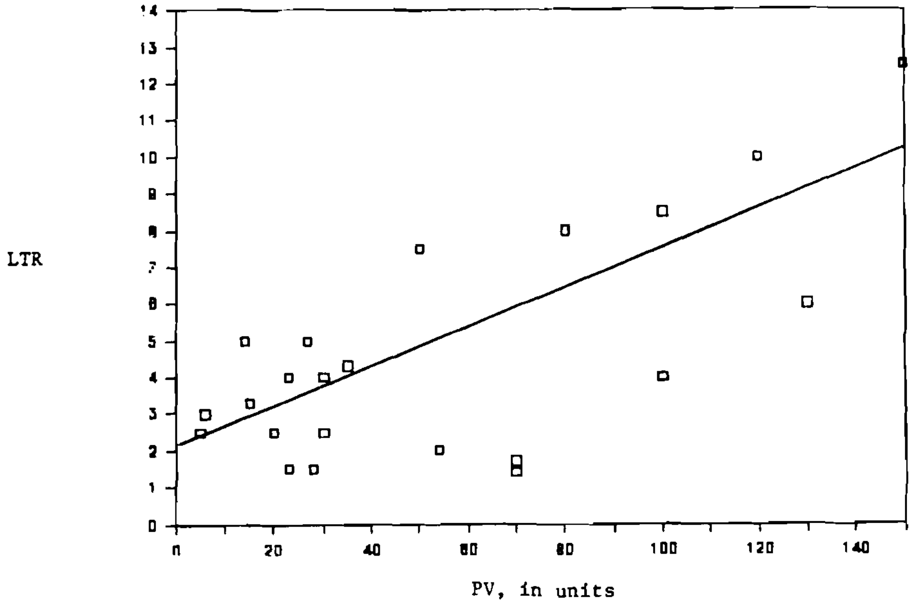


Figure 22. Lead-time reduction (LTR) over batch size (BS).



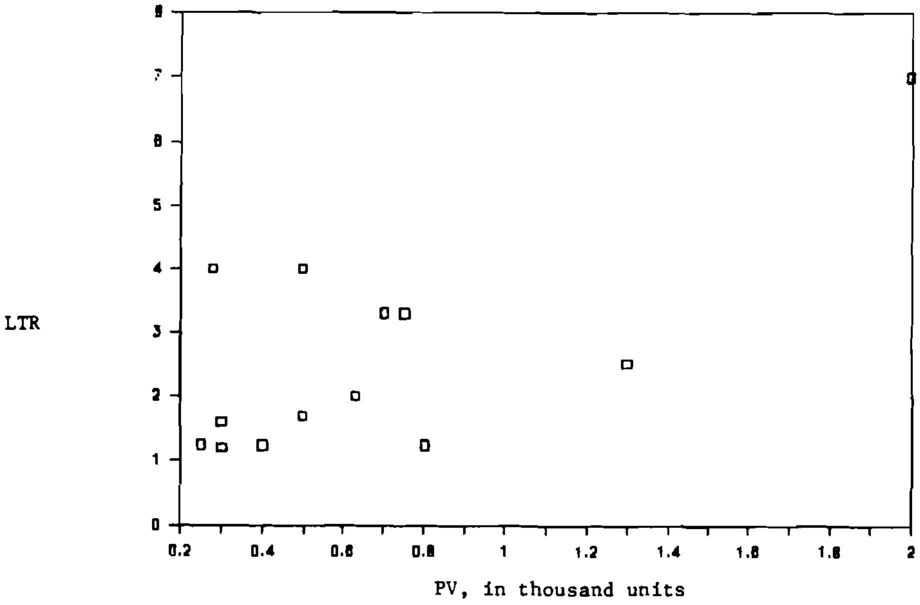


Figure 23. Lead-time reduction (LTR) over product variants (PV).

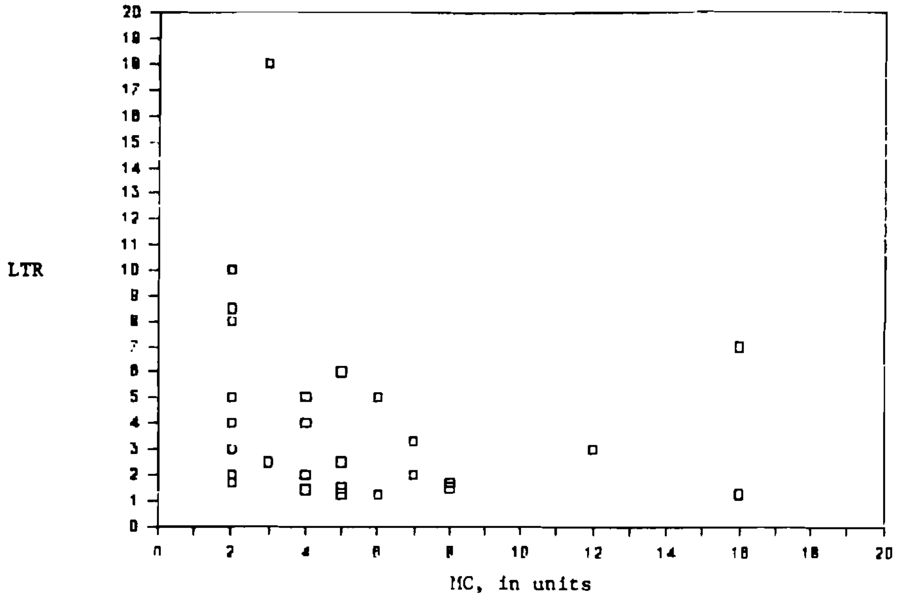


Figure 24. Lead-time reduction (LTR) over number of machining centers (MC).

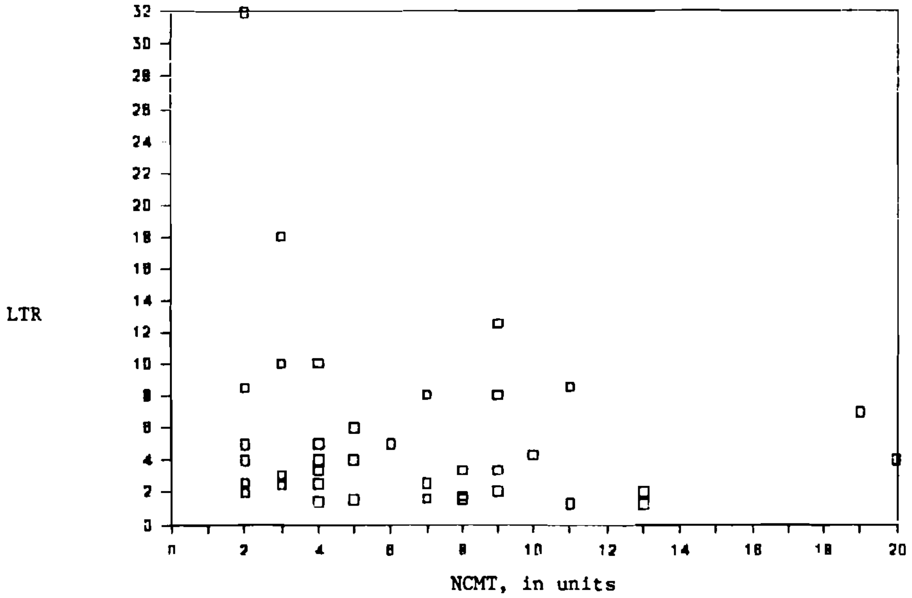


Figure 25. Lead-time reduction (LTR) over number of NC machine tools (NCMT).

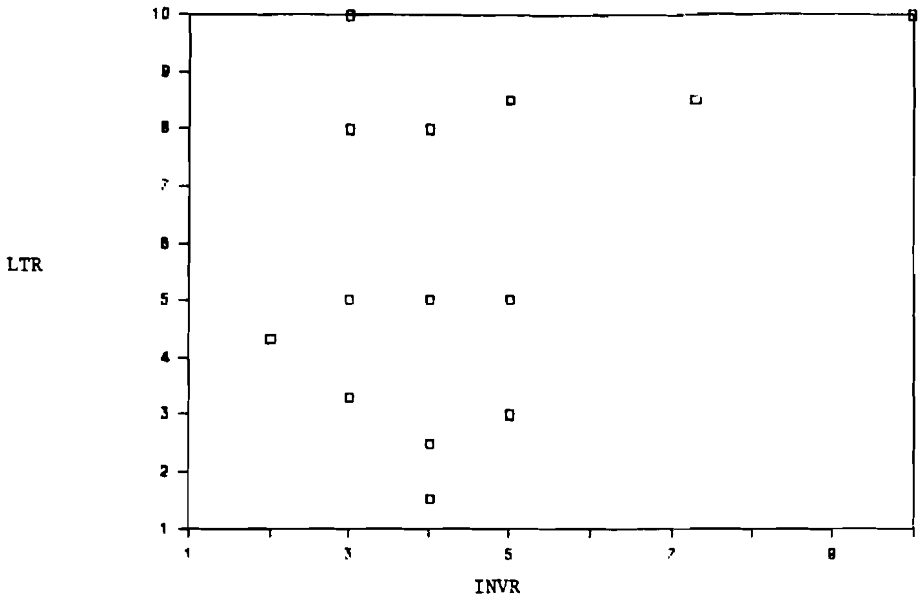


Figure 26. Lead-time reduction (LTR) over inventories reduction (INVR).

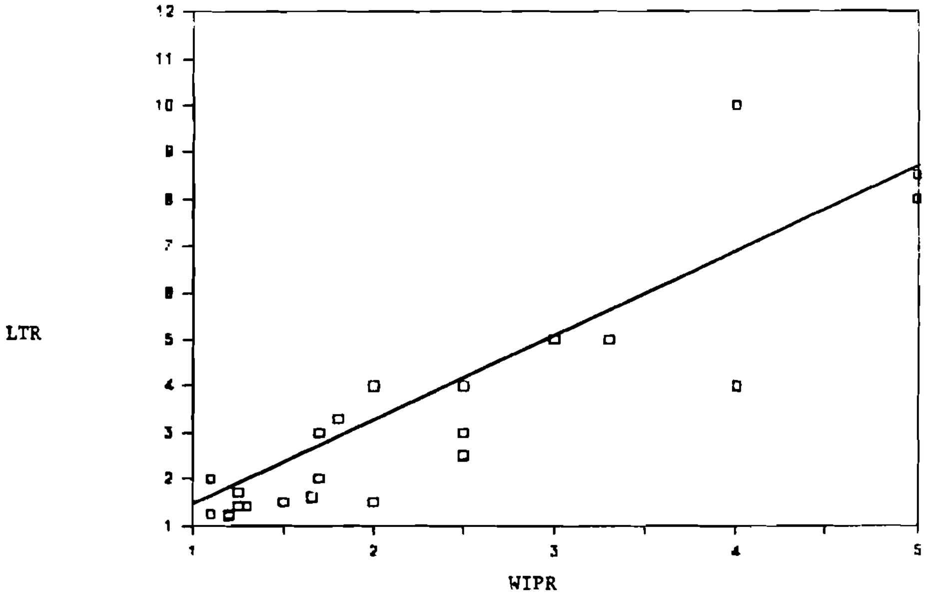


Figure 27. Lead-time reduction (LTR) over work-in-progress reduction (WIPR).

4. FLEXIBILITY OF FMS

There are two principal variables in the data bank reflecting FMS production flexibility: the number of product variants (or the part family) and the batch size. Naturally, these have to be interconnected in the following way: a higher product variation usually means a smaller batch size and vice versa.

In general some negative relation is observable, but it is difficult to retrieve any approximation which would be statistically significant. This is why we tried the clustering approach, dividing the product variation (PV) into the following five subsets:

- from 0 to 14
- from 15 to 40
- from 41 to 80
- from 81 to 150
- from 151 to 1000 variants.

These empirical boundaries are rather flexible because, for example, there was no observation between 40 and 50, 80 and 100, 150 and 300. For each of the clusters the correlation between the batch size (BS) and the product variation was approximated by hyperbolic-type curves (see Figure 28). This means that the function holds true for different types of production, but not for all FMS in use.

The influence of FMS flexibility (measured as PV and BS) on systems features was assessed by taking the clustering approach into consideration.

The set-up time reduction is affected by the product variation in two ways. When the PV changes from 0 to 200-300 variants, the set-up time reduction goes down, but afterwards a positive correlation is observed (see Figure 29).

Almost the same approximation curve was obtained for the correlation between inventory reduction and product variation (see Figure 30), but it was estimated in the PV interval from 0 to 200, and the turning point was between 30 and 50 product variants. The increase of product variations from 0 to 200-300 leads to a drastic decrease of work-in-progress reduction, but afterwards the approximation line is horizontal (see Figure 31).

The same turning point appears in the correlation between productivity growth and product variation (see Figure 32). When the PV increases from 0 to 200, the productivity growth drops to a factor of 1.4, and afterwards increases again up to a factor of 3 for those systems producing 1.3-1.5 thousand product variants.

Our analysis of the impact of batch size covered only really flexible FMS, where the BS did not exceed 300 units per batch. For the impact on set-up time reduction, in-process-time reduction and productivity growth we found that there were negative correlations between the three variables and the batch size until the latter factor exceeded 40-50 units (see Figures 33, 34 and 36, respectively). After this point we found no impact any more.

Practically, there is no batch size influence on machining time reduction, which fluctuates from 1.1 to 1.6, independently of batch size (see Figure 35). The growth of production capacity dropped from 2.0-2.3 to 1.2, while the batch size increased from 1 to 100 (see Figure 37).

After the exclusion of three Czechoslovak FMS with unusually long pay-back times we found that a batch size increase of up to 300 was connected with a certain growth of FMS pay-back time (3-4 years on the average), see Figure 38.

Generally speaking, it is possible to postulate that the efficiency of FMS producing less than 100 product variants is the highest. The next peak, which is lower than the first one, is reached only for "superflexible" systems with product variants of more than one thousand. An increase in batch size usually corresponds to a deterioration of the relative advantages of FMS.

But here it is necessary to take one important aspect into consideration. We have collected the average data on PV and BS for real modes of production, but not on the potential flexibility of the systems, which is reported to be much higher. This means that these two indicators (PV and BS) are usually chosen under real production conditions and have to be treated as exogenous for FMS use. Thus the optimal flexibility depends more on production conditions than on FMS potential features. If an FMS has to respond to irregular orders, BS and PV will be dictated by a customer. But if it is used for regular production, the BS and the number of set-ups are chosen by the enterprise decision makers to provide an optimal pattern (for example to minimize work-in-progress and to reduce unit cost).

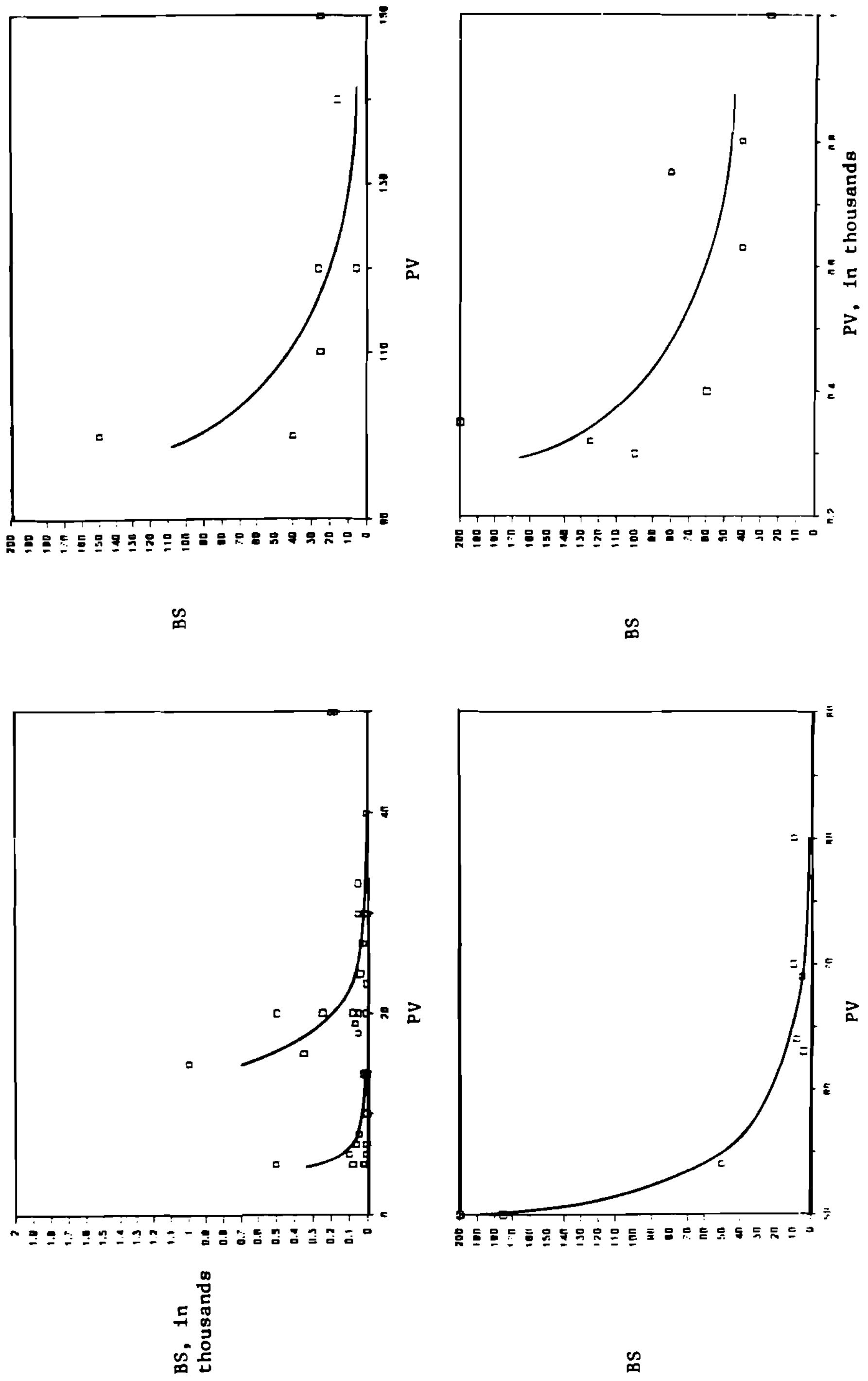


Figure 28: Batch size (BS) over product variation (PV), all in units.

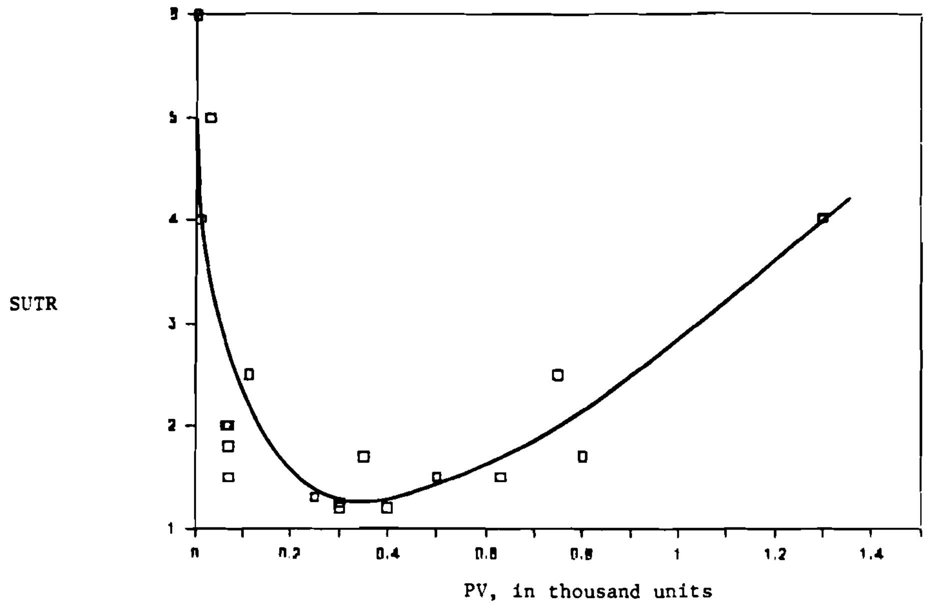


Figure 29: Set-up time reduction (SUTR) over product variations (PV)

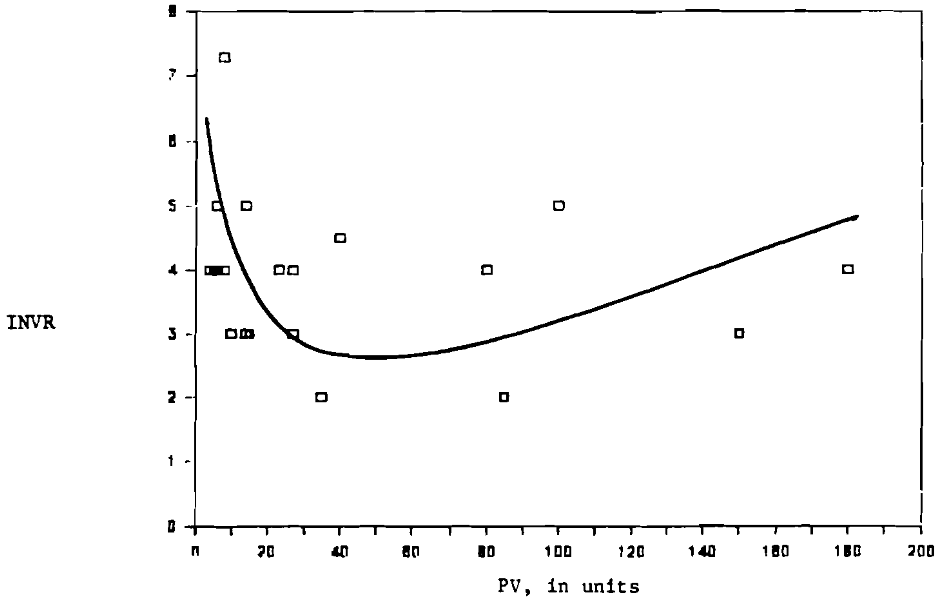


Figure 30: Inventories reduction (INVR) over product variation (PV)

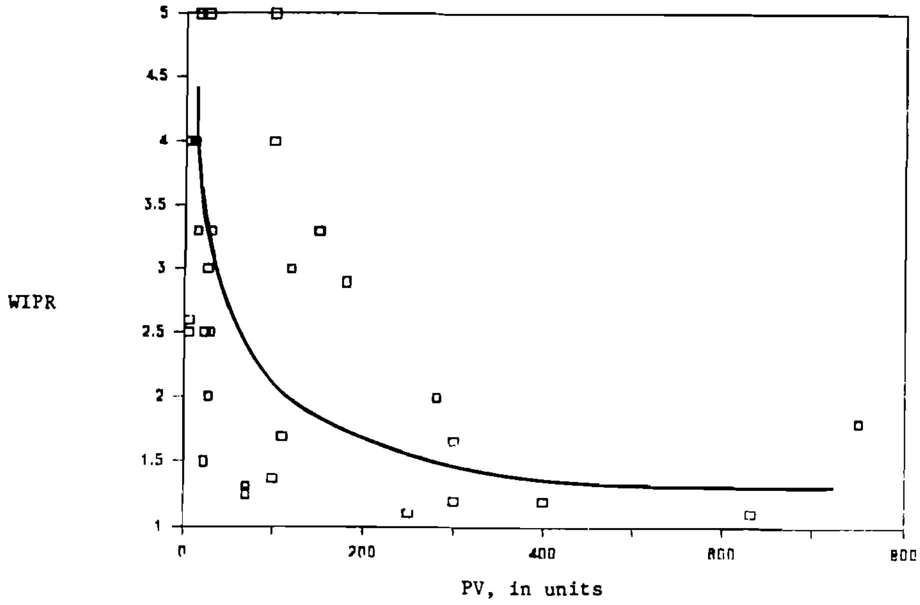


Figure 31: Work-in-progress reduction (WIPR) over product variation

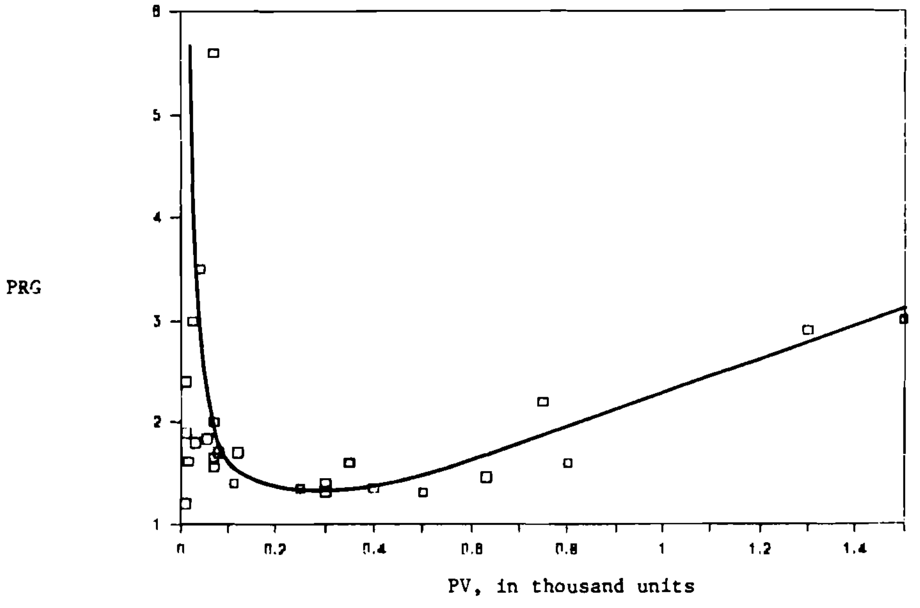


Figure 32: Productivity growth (PRG) over product variation

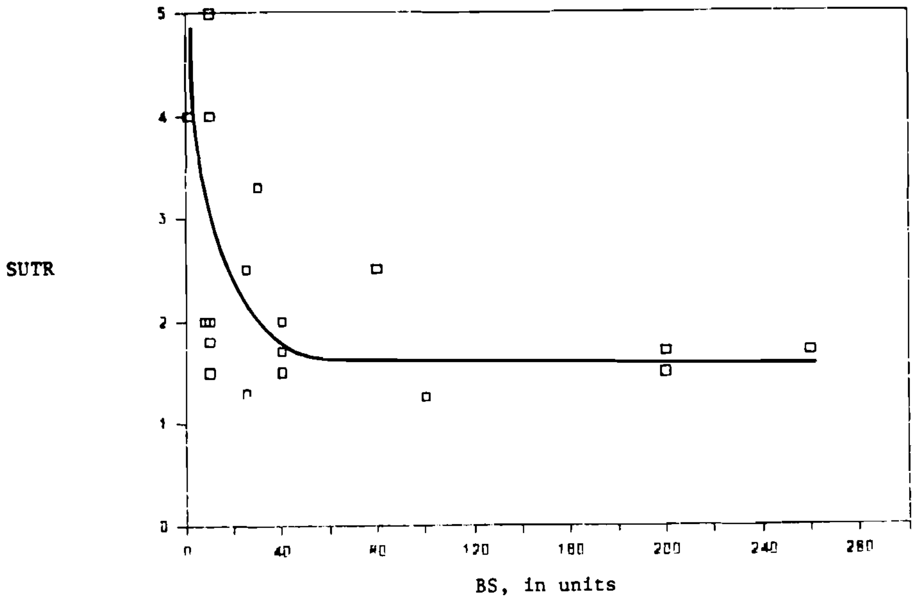


Figure 33: Set-up time reduction (SUTR) over batch size (BS).

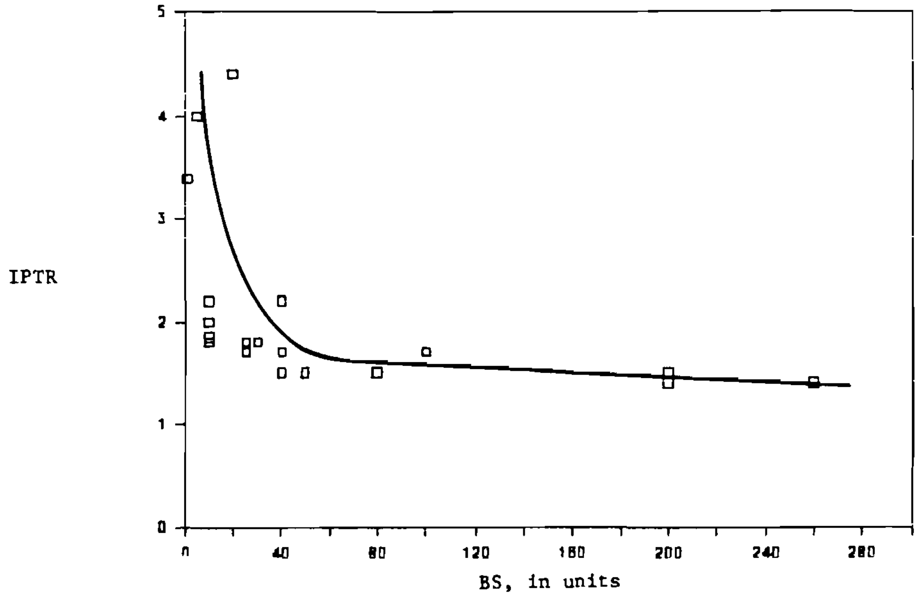


Figure 34: In-process-time reduction (IPTR) over batch size (BS)

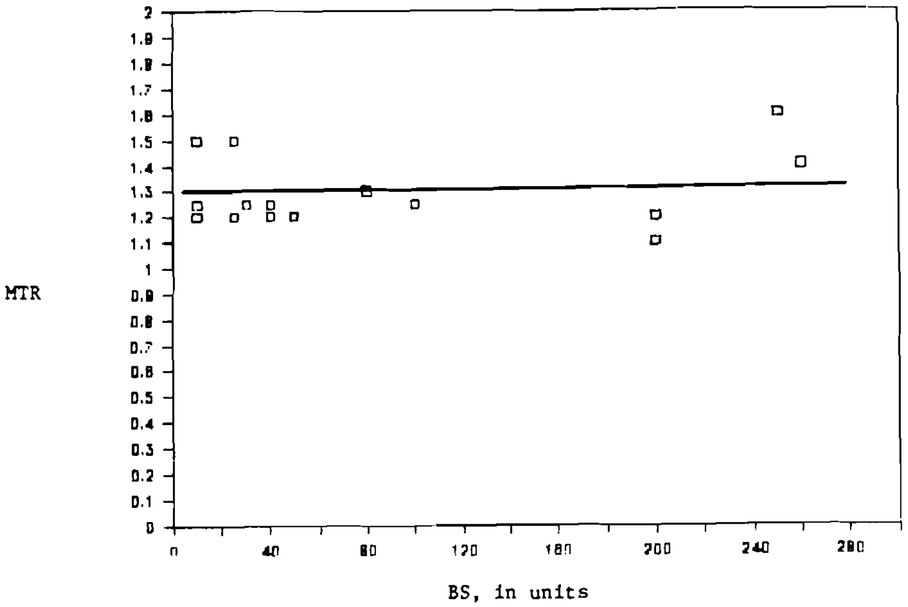


Figure 35: Machining time reduction (MTR) over Batch size (BS)

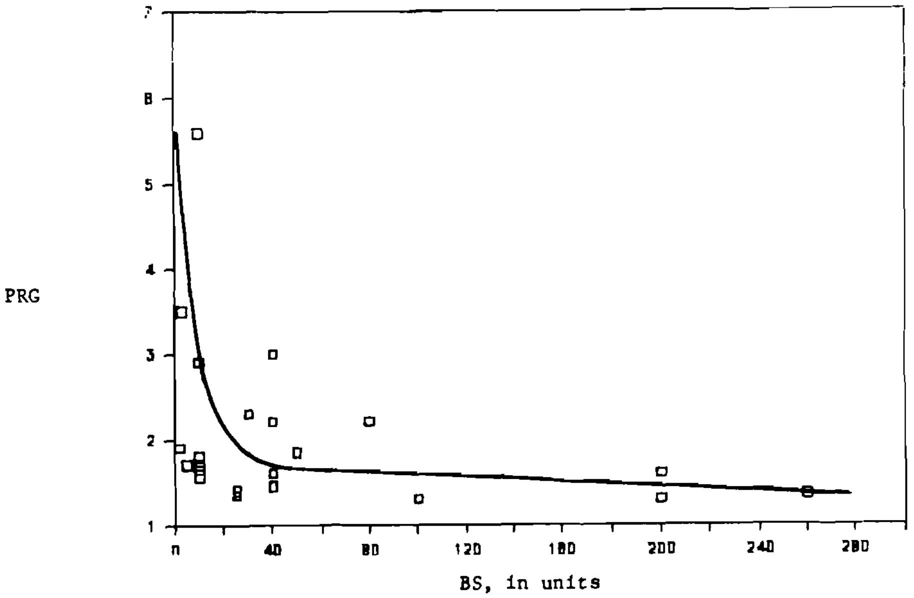


Figure 36: Productivity growth (PRG) over batch size (BS)

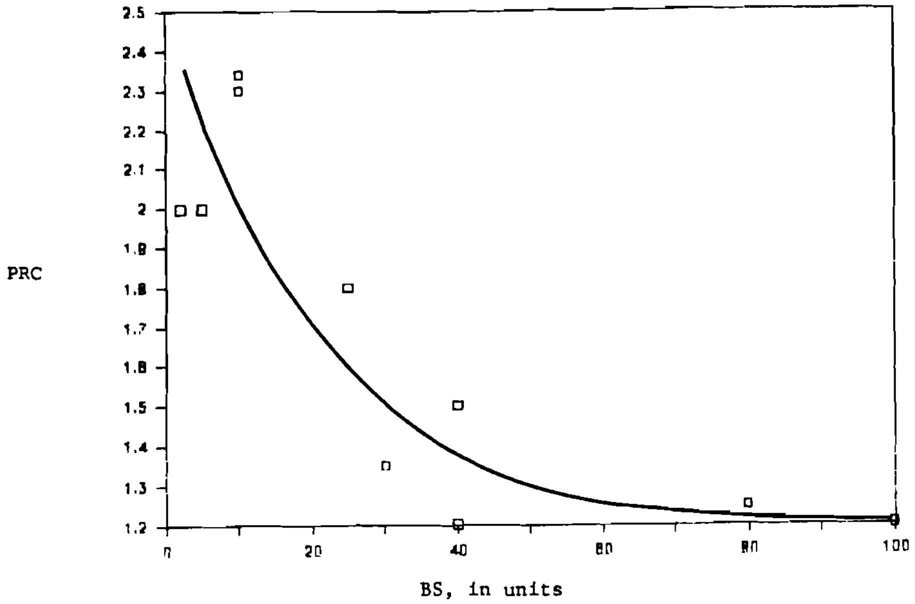


Figure 37. Production capacity (PRC) over batch size (BS)

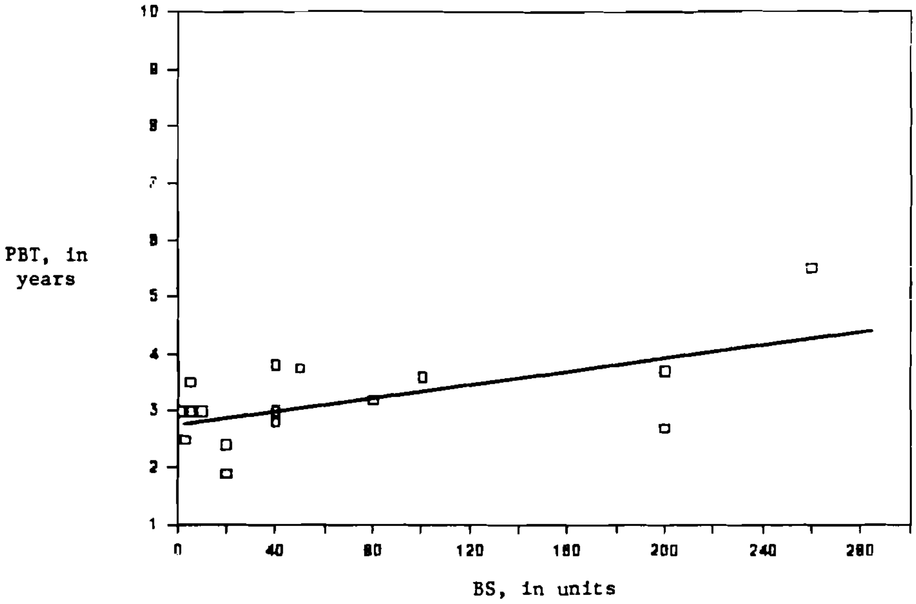


Figure 38: Pay-back time (PBT) over batch size (BS)

5. TECHNICAL COMPLEXITY OF FMS

There is no universal criterion of the technical complexity of FMS. Several indicators of the complexity have been collected in our data bank. Among them are: the number of machining centers (MC), the number of NC-machine tools (NC), the number of robots (ROB), and the types of transportation (TR), storage (ST and inspection (INS) systems in the FMS. The last three variables were indicated as dichotomic: (1) for simple systems and (2) for sophisticated ones [2].

The attempts to find statistically reliable, separate correlations between these indicators and other FMS features were usually a failure. This is why a combined indicator of the technical complexity was elaborated. The first accepted hypothesis is a that higher complexity is connected with higher FMS costs. The second one is that if there is no information on IR, the number of robots is zero. The third hypothesis is that in case of missing data on TR, ST and INS these were considered to be 1.0 (i.e. simple systems). Finally, several "extra" FMS used outside the typical types of production and industries were excluded from consideration.

The following linear regression equation was estimated for 315 FMS where data on MC and NC were available:

$$\text{Invest} = a \cdot MC + b \cdot NC + c \cdot ROB + d \cdot TR + e \cdot ST + f \cdot INS + g \cdot DUMUS$$

where

Invest - investments in million US dollar;
DUMUS - dummy variable = 1.0 for the US cases and 0 for other systems;
a,b,c,d,e,f,g - regression coefficients.

Coefficients "e" and "f" were statistically insignificant because only few FMS had sophisticated storage and inspection systems. DUMUS were used to purify the relationship from the extremely high costs of the US FMS. The other coefficients were used to construct the technical complexity indicator (TC) as follows:

$$TC = 0.7\ MC + 0.35\ NC + 0.3\ ROB + 0.3\ TR$$

The relative weights of the independent variables approximately correspond to their cost shares, but -- due to the procedure described above -- the technical complexity does not coincide with FMS costs. The FMS distribution over TC is shown in Figure 39.

This distribution shows that 58% of the cases in the FMS sample set can be treated as rather simple systems with a TC of less than four. 36% of the FMS are in a middle range and their technical complexity is between 4 and 10. And only less than 6%, or 18 systems, belong to a technically complex type with a TC of more than 10. This corresponds to the results of the FMS distribution analysis in [2]. According to this analysis (we should like to remind the reader), a most typical FMS includes 2-4 machining centers, or 2-7 NC-machine tools (including MC), and 60% of 64 FMS, where the use of robots was reported, have 1-3 industrial robots.

The technical complexity influence on FMS specific features and relative advantages is rather contradictory and it is sometimes affected by national or production conditions.

For the analysis of the impact of the TC on FMS pay-back time we had to exclude several Czechoslovak FMS with relatively high PBT from consideration. As a result (see Figure 40) a certain weak, negative relation was observable. At the same time one can find a positive correlation between these two factors for technically simple FMS with a TC of more than 4 (dashed lines). But the lack of data and the character of the point distribution decrease the reliability of such conclusions.

The lead-time reduction increases proportionally to the increase of technical complexity until the latter crosses the "magic" line of TC = 4 and decreases thereafter (see Figure 41). The lead-time reduction for most complex FMS ranges from a factor of 1.2 to 2.0.

A certain negative slope in the correlation between the set-up time reduction and the technical complexity of FMS is shown in Figure 42. Unfortunately, for lack of observations this case cannot be clustered into simple and complex sub-sets.

The point distribution in Figure 43 can be approximated by a combined curve, where a proportional growth in personnel reduction takes place for simple FMS, a sharp decline for middle-class FMS and a rather stable level of the reduction (by factors of 1.2 - 2.0) for 7 technically complex systems. With an increasing FMS complexity the productivity growth declines steadily to the level of 1.2 (see Figure 44).

The FMS flexibility indicators -- number of product variables and average batch size -- also depend on the system's technical complexity (see Figures 45 and 46). The huge cloud of points for product variation makes any statistical approximation unreliable, but one can observe a definite tendency of the product variation to decrease when the technical complexity increases.

The only exception to this tendency applies to FMS with a TC higher than 7.5. For 8 such systems proportional growth of flexibility is observable.

The batch size dependence on the TC can be approximated by a curve (see Figure 46) which is very similar to the lead-time and personnel reduction curves. The average batch size grows from less than 10 units a batch for FMS with a TC of less than 2 up to 50-70 units for systems with a TC = 4 and declines to approximately 20-30 for more complex systems. This means that there is no strong technical complexity influence on FMS flexibility.

We could not find any TC impact on such an important logistic indicator as inventory reduction either. The reduction values fluctuate independently around 3.5, changing from 2 to 5, see Figure 47. Another logistic indicator -- work-in-progress reduction -- demonstrates a negative technical complexity impact. The average reduction goes down from 3 for simple FMS to 2 for medium-type systems and to 1.2 for the most complex systems, see Figure 48.

The analysis of the technical complexity impact on FMS advantages shows that now there is no considerable and statistically identifiable influence of this factor on such figures as pay-back time, set-up time reduction, or inventory reduction. In some cases more complex systems had fewer advantages (in comparison with conventional technologies) than simple systems. This applies to productivity growth, flexibility measured by the number of product variants and work-in-progress reduction.

For such important FMS characteristics as lead-time reduction and personnel reduction it is possible to conclude that the most effective systems have a rather moderate technical complexity (from 2 to 4). The most complex FMS usually reduce lead time and personnel only by factors of 1.2-2.0.

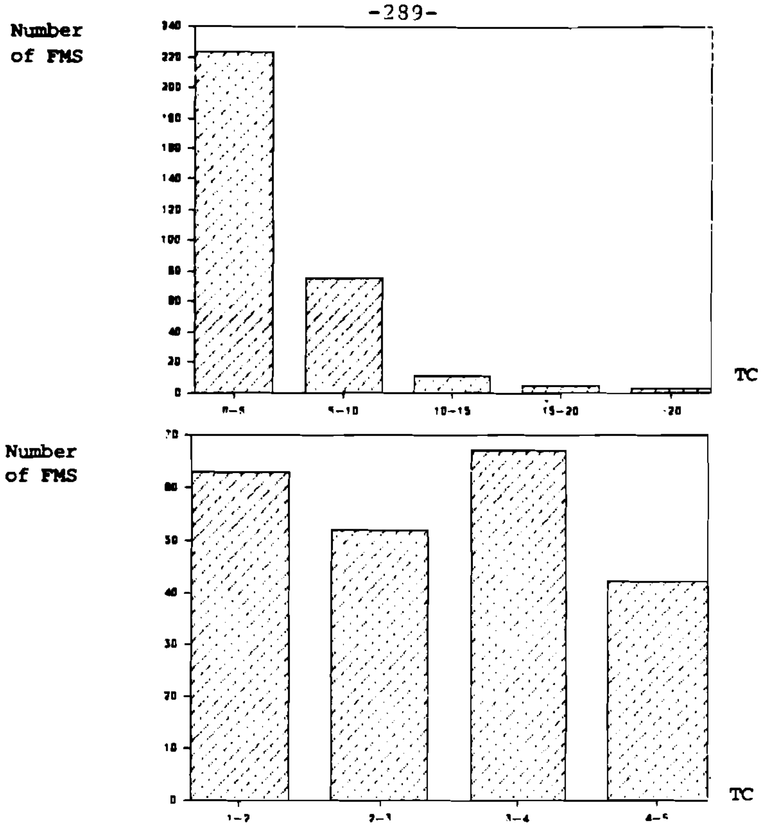


Figure 39. FMS distribution over technical complexity (TC).

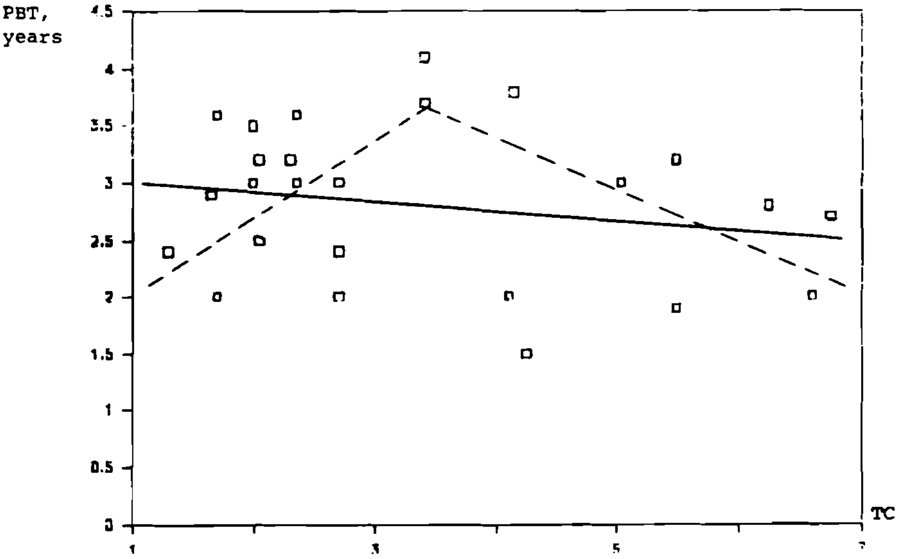


Figure 40. Pay-back time (PBT) over technical complexity (TC).

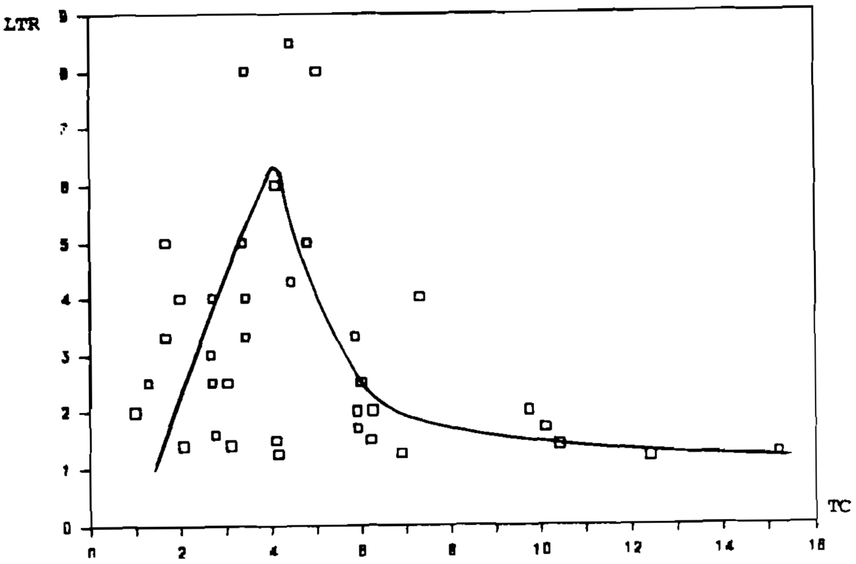


Figure 41. Lead-time reduction (LTR) over technical complexity (TC).

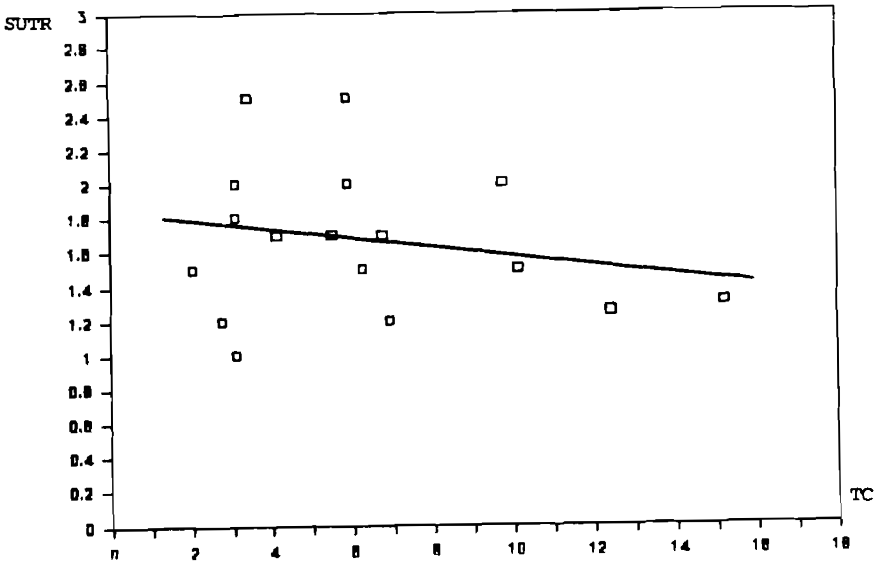


Figure 42. Set-up-time reduction (SUTR) over technical complexity (TC).

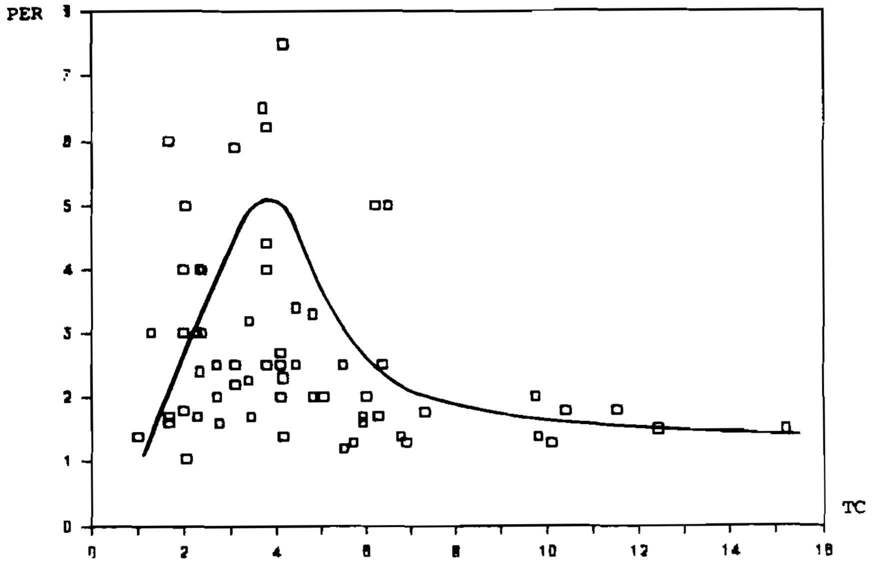


Figure 43. Personnel reduction (PER) over technical complexity (TC).

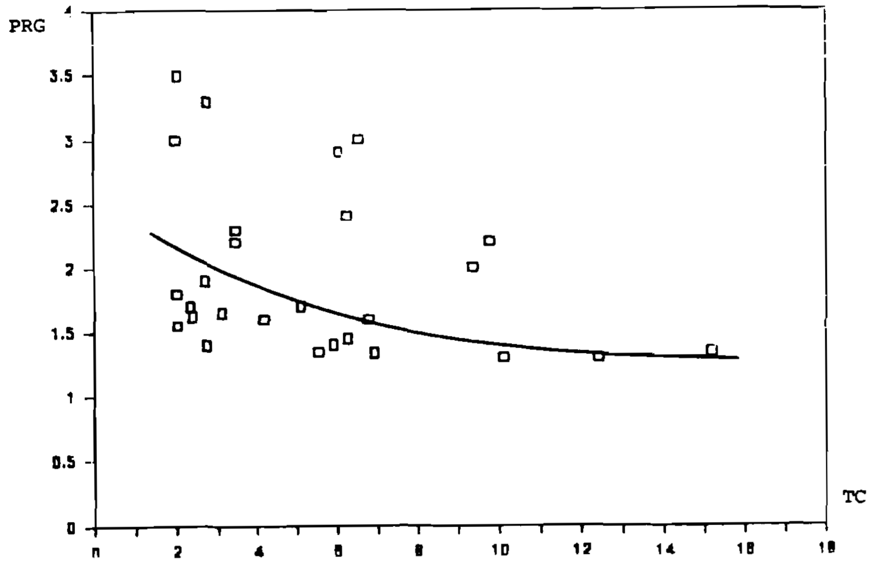


Figure 44. Productivity growth (PRG) over technical complexity (TC).

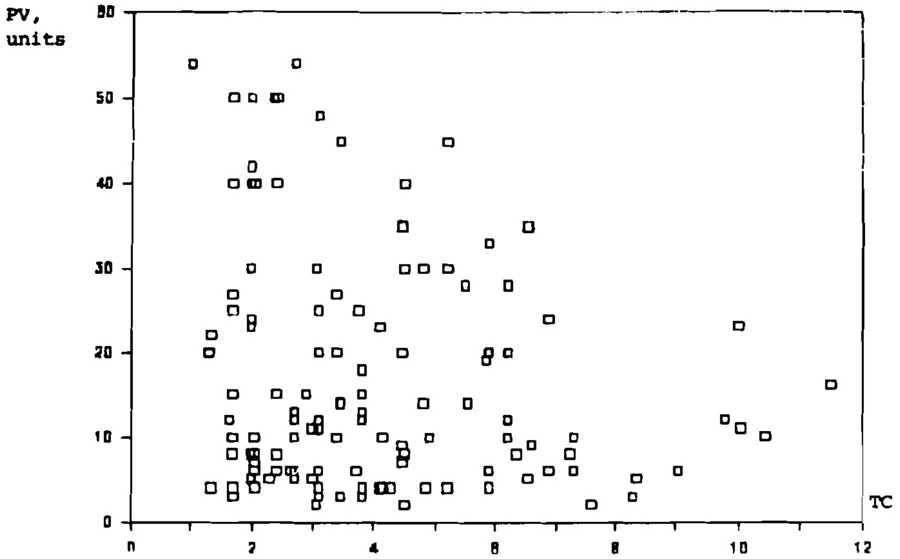


Figure 45. Product variation (PV) over technical complexity (TC).

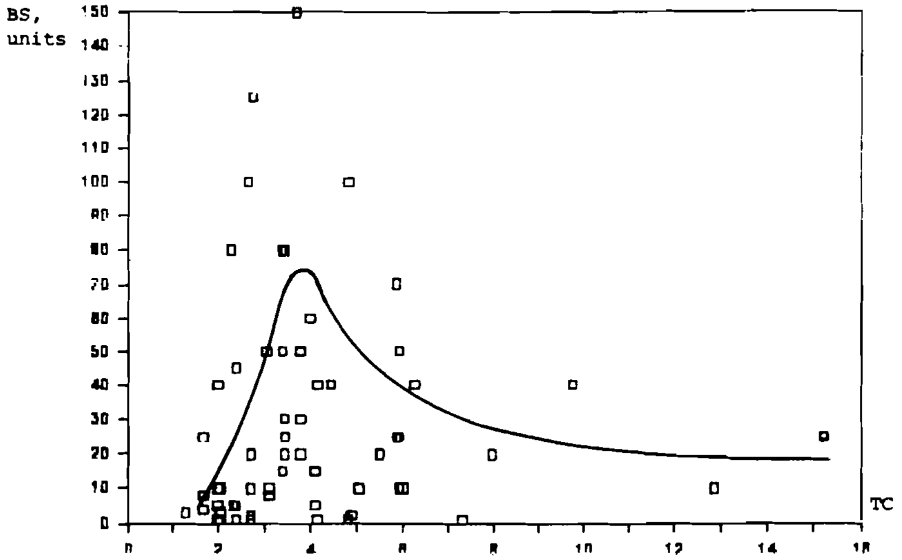


Figure 46. Batch size (BS) over technical complexity (TC).

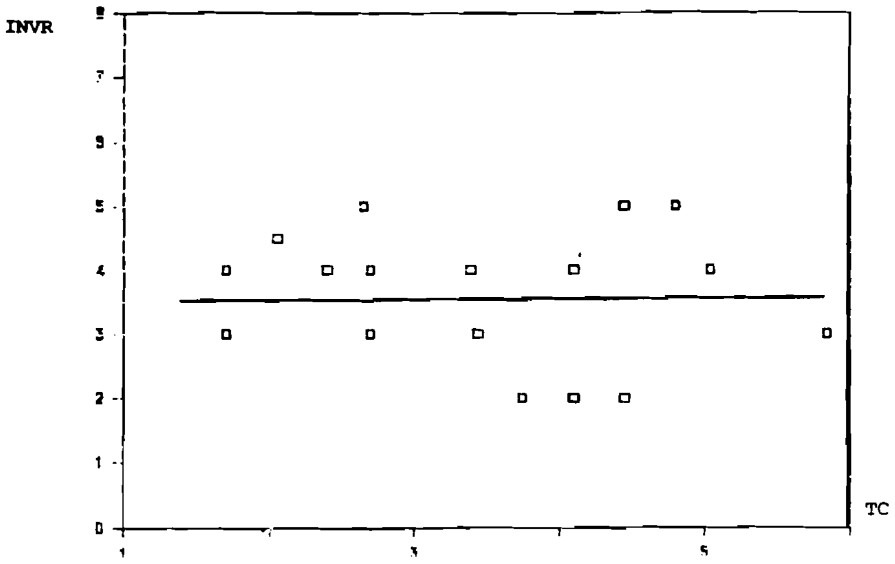


Figure 47. Inventory reduction (INVR) over technical complexity (TC).

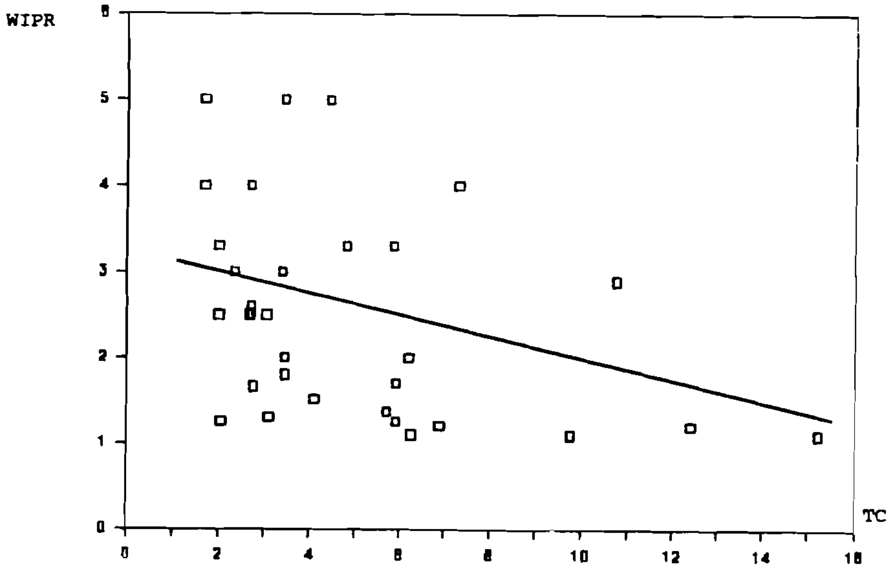


Figure 48. Work-in-progress reduction (WIPR) over technical complexity (TC).

6. FACTORS AFFECTING PERSONNEL REDUCTION AND PRODUCTIVITY GROWTH

These two indicators are closely interconnected because in the majority of those FMS, where they were reported, productivity growth was treated as a labor productivity increase. In some other cases it was treated as total factor of productivity growth, or there was no information on the calculation method. The personnel reduction was usually calculated as direct and indirect reduction.

For these reasons personnel reduction is slightly higher than productivity growth, but their correlation can be approximated by a straight line (see Figure 49):

$$PRG = 0.8 + 0.5\ PER$$

The next figures were estimated in pairs for the relative advantages of different FMS as factors affecting productivity growth and personnel reduction.

The lead time reduction (see Figures 50 and 51) certainly influences productivity and personnel in the following way: a higher LTR leads to a higher PRG and PER. The slopes of the approximation lines are 0.25 - 0.27.

A higher set-up time reduction also corresponds to a higher productivity growth and personnel reduction (see Figures 52 and 53), but in the latter case a very high growth of the personnel reduction is observed until the SUTR reaches 2.0 and the SUTR impact becomes stable after that point.

For the case of in-process-time reduction one can see the opposite situation. The approximation curve is a straight line for the personnel reduction and looks like an exponential curve with a saturation level of PRG = 1.75 (see Figures 54 and 55).

There are two straight lines approximating the influence of work-in-progress reduction on productivity growth (see Figure 56). The upper ray is fitted by Czechoslovak FMS and the lower one by Finnish systems. For lack of observations it is impossible to retrieve any statistically reliable curve, and the general conclusion is that a higher WIPR leads to a higher PRG.

Almost the same bifurcation takes place in the case of the impact of work-in-progress on personnel reduction (see Figure

57). An inventory reduction has an extremely unfavorable effect on personnel reduction (see Figure 58), but seven observations available are not enough to draw any sustainable conclusion.

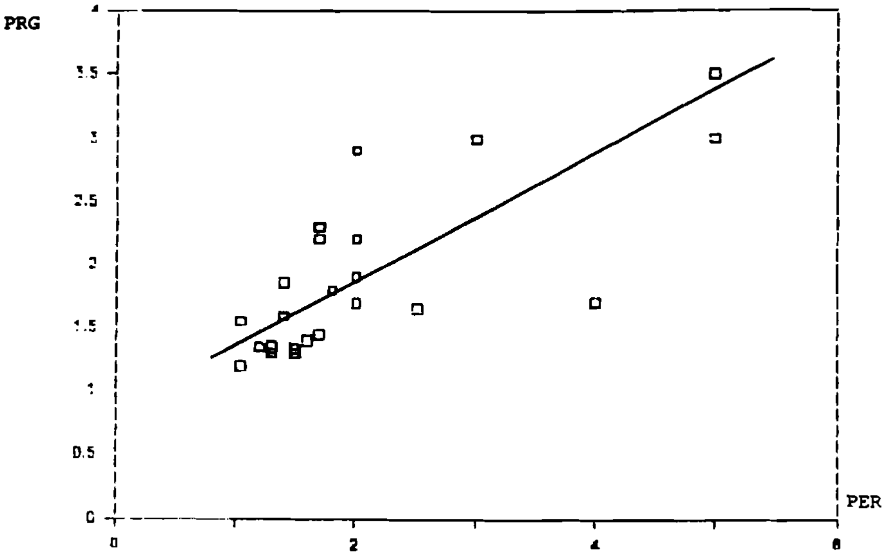


Figure 49. Productivity growth (PRG) over personnel reduction (PER).

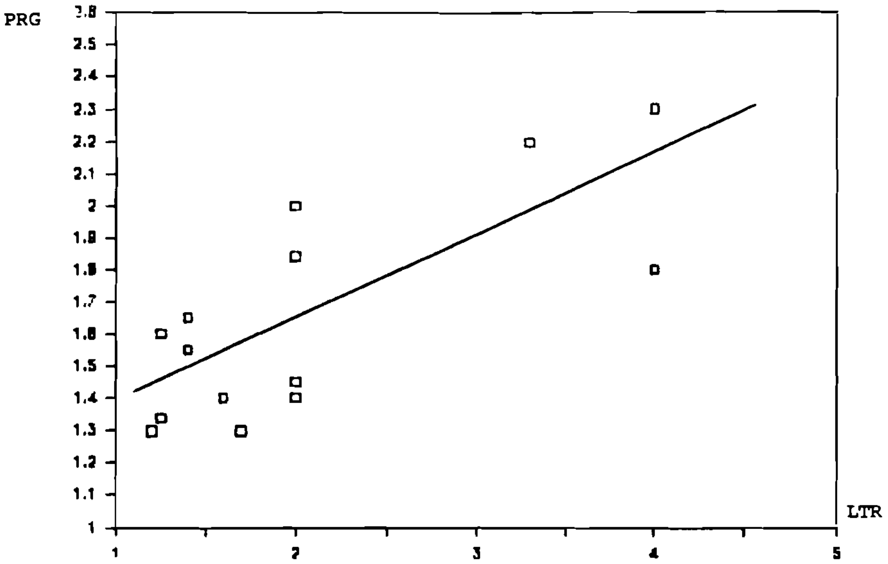


Figure 50. Productivity growth (PRG) over lead-time reduction (LTR).

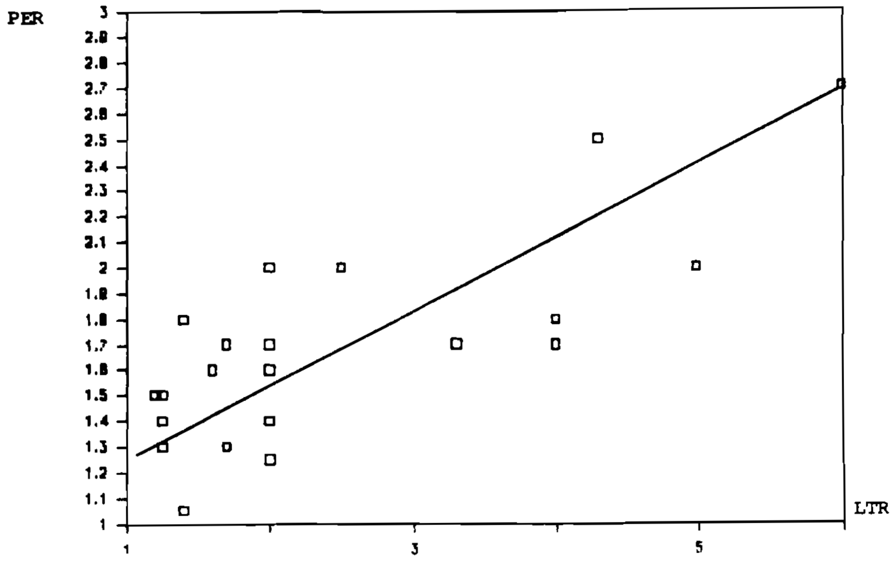


Figure 51. Personnel reduction (PER) over lead-time reduction (LTR).

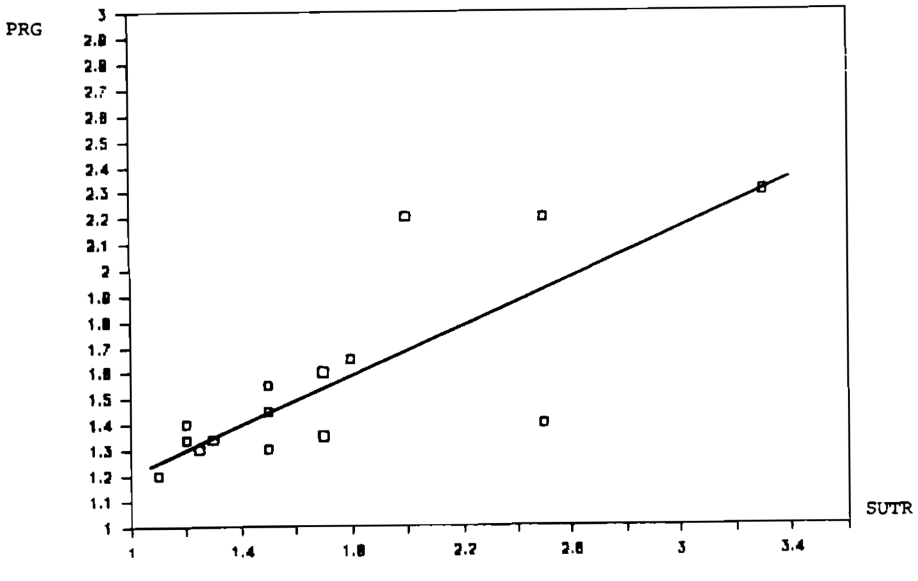


Figure 52. Productivity growth (PRG) over set-up-time reduction (SUTR).

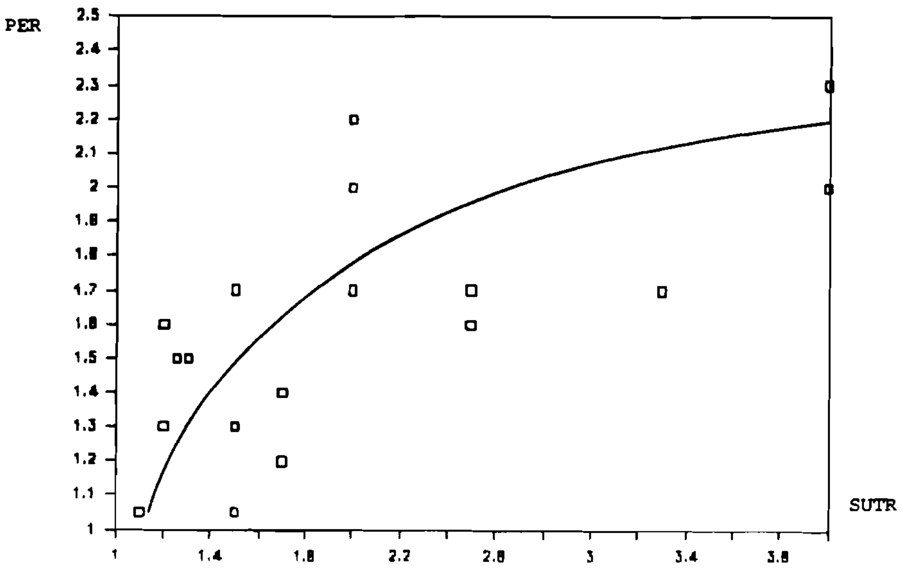


Figure 53. Personnel reduction (PER) over set-up-time reduction (SUTR)

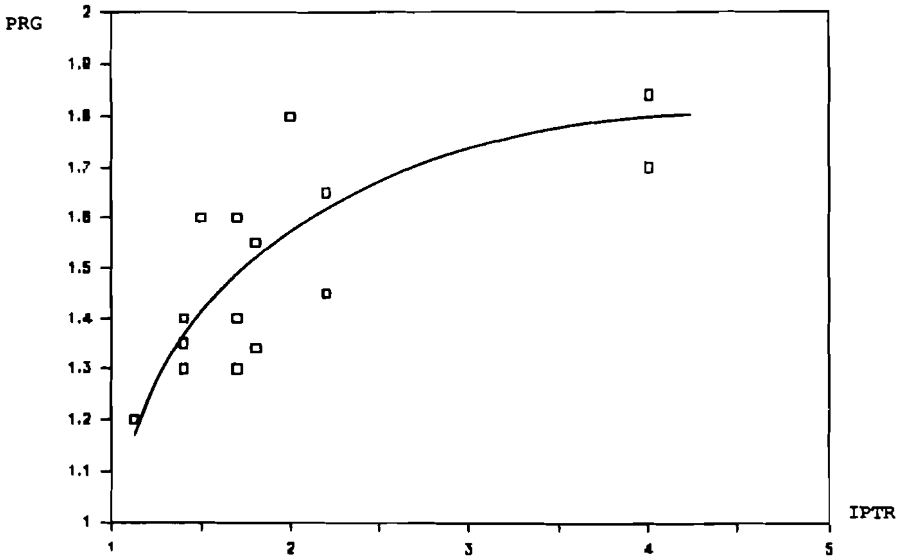


Figure 54. Productivity growth (PRG) over in-process-time reduction (IPTR)

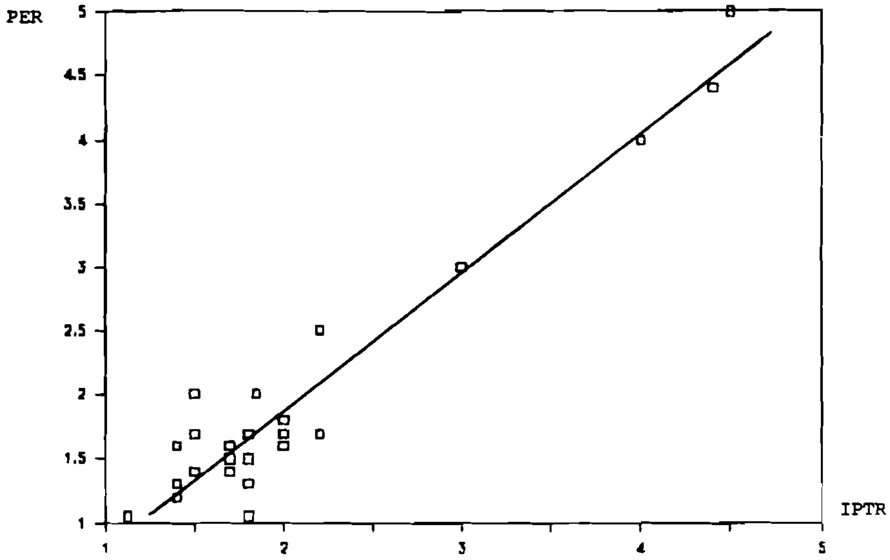


Figure 55. Personnel reduction (PER) over in-process-time reduction (IPTR).

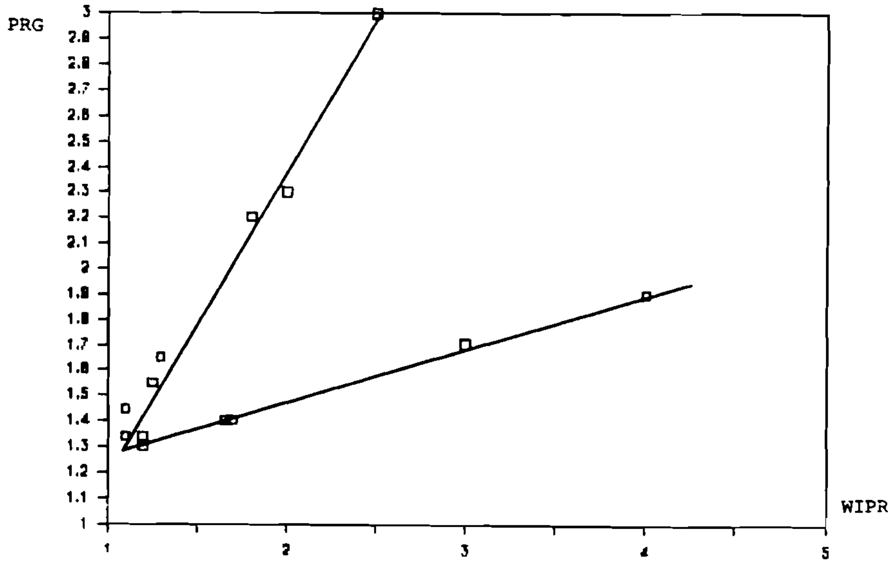


Figure 56. Productivity growth (PRG) over work-in-progress reduction (WIPR).

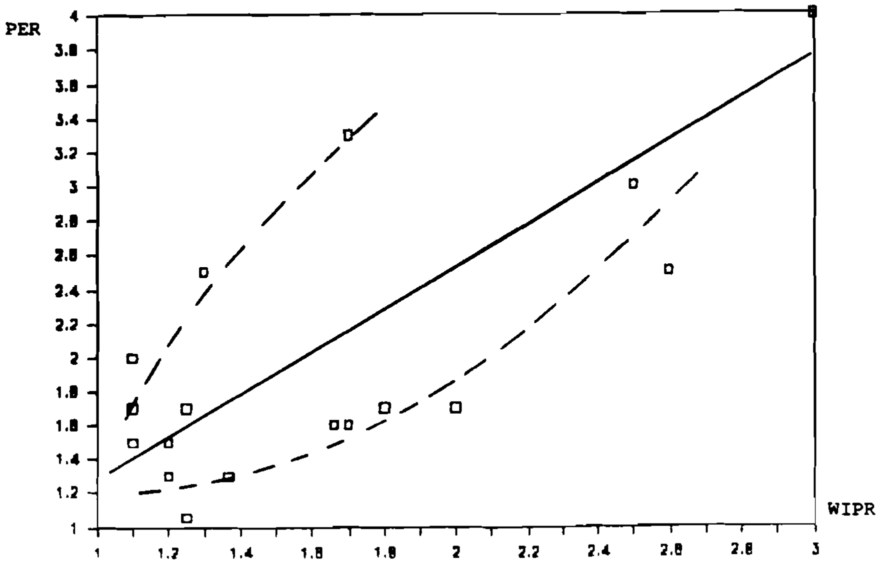


Figure 57. Personnel reduction (PER) over work-in-progress reduction (WIPR).

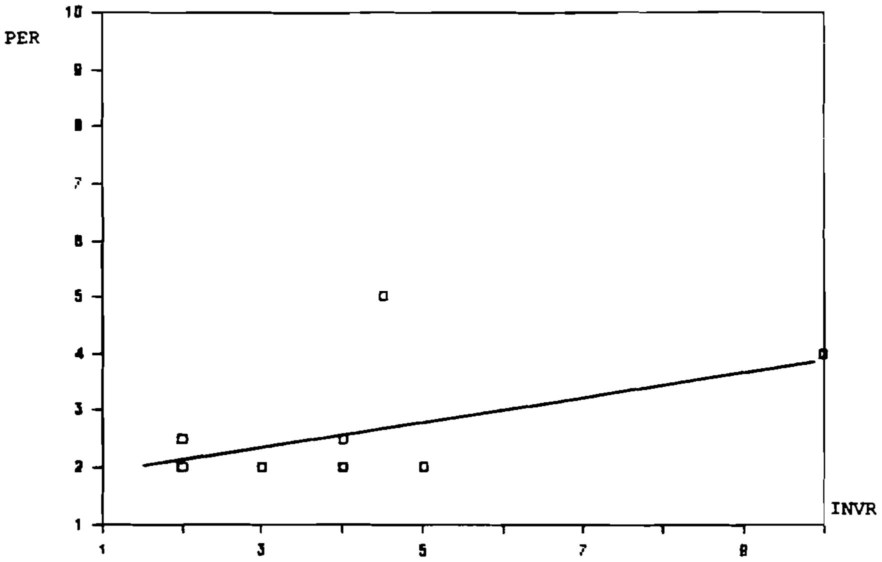


Figure 58. Personnel reduction (PER) over inventory reduction (INVR).

7. FACTORS AFFECTING FMS PAY-BACK TIME

The pay-back time is a crucial indicator of such an expensive technology as FMS in its competition with conventional technologies based on traditional machine-tools or stand-alone machines. This is why the analysis of factors affecting FMS pay-back time is very important.

We have already found in previous paragraphs that for relatively cheap FMS (less than 4 million dollars) higher system costs lead to a longer pay-back time. But an increase of the costs above this critical level or higher technical complexity of FMS do not influence the pay-back time.

As the share of the Czechoslovak FMS in the data on relative advantages (such as time, work-in-progress, personnel reduction, etc.) was considerably high, we sometimes had to exclude several CSSR cases with an extremely long pay-back time from consideration. The difference in the pay-back time data is due to different national standards. For example, seven years is considered to be an acceptable pay-back time in Czechoslovakia, whereas four years PBT is a normal upper limit for this indicator in Japan.

A higher lead-time reduction provides for a shorter pay-back time (see Figure 59). But the form of the approximation curve depends on a sample set. When we took nine Czechoslovak FMS with a PBT of more than 5 years into consideration, the curve would look like a hyperbolic curve, otherwise the relation could be approximated by a straight line with a moderate slope.

The impact of the in-process-time reduction on the bay-back time is definitely negative even if systems with a PBT of more than 5 years are excluded (see Figure 60).

The influence of personnel reduction and productivity growth on pay-back time is also negative (see Figures 61 and 62, respectively). As in the previous case, taking FMS with a high PBT into consideration provides a hyperbolic approximation curve, but their exclusion provides a straight line approximation.

The FMS flexibility measured in number of product variants has a positive influence on pay-back time (higher flexibility leads to longer PBT) until the number reaches 150-200, and there is no influence after this point (see Figure 63). An increase of batch size leads to higher pay-back time, but this impact is not very strong and disappears rather soon (see Figure 64).

The growth of work-in-progress reduction makes the pay-back time shorter, but the slope of the approximation curve depends on the choice of a sample set of observations (see Figure 65). If some CSSR cases with the longest PBT are excluded, the slope of the approximation curve can be reduced.

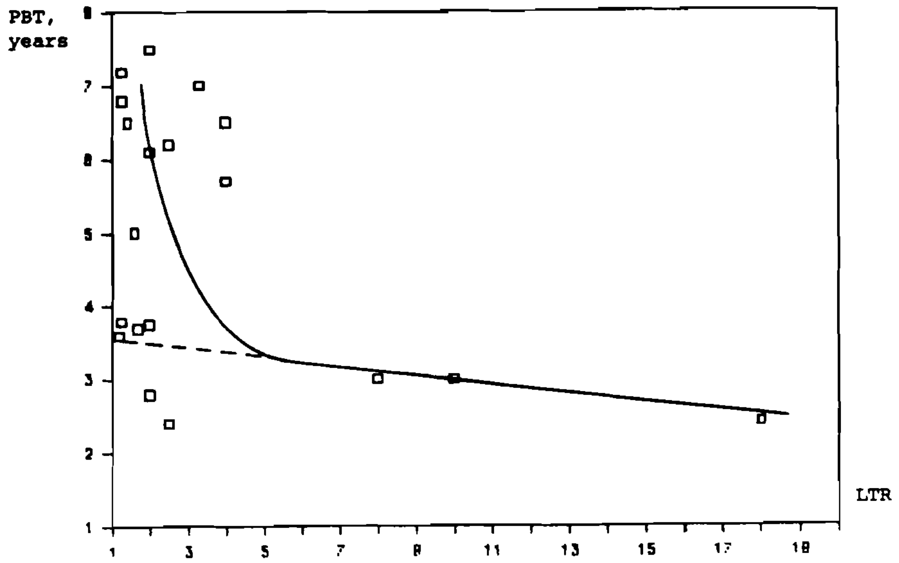


Figure 59. Pay-back time (PBT) over lead-time reduction (LTR).

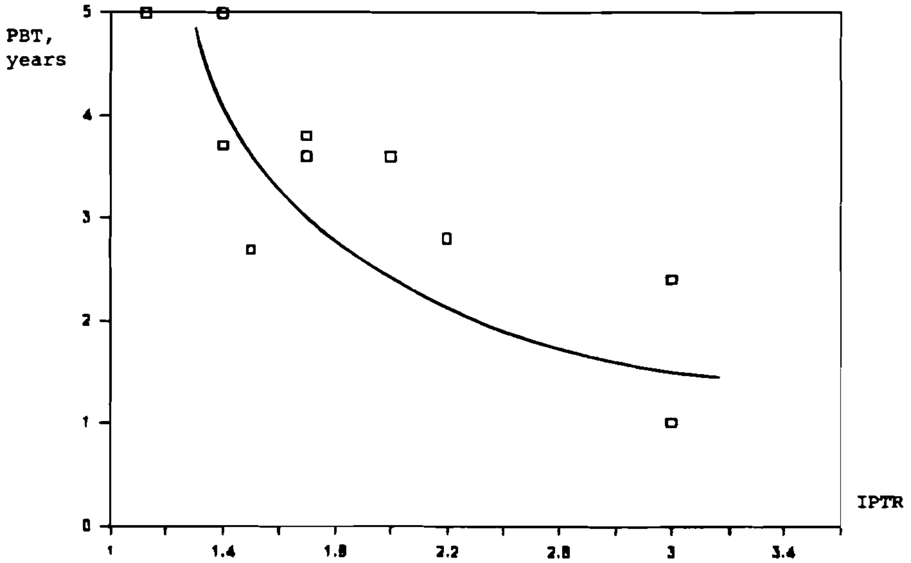


Figure 60. Pay-back time (PBT) over in-process-time reduction (IPTR)

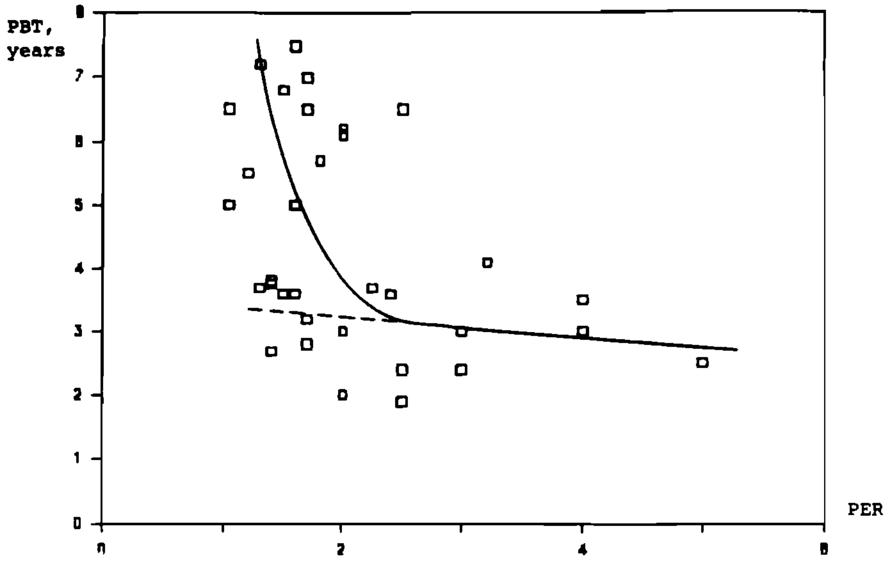


Figure 61. Pay-back time (PBT) over personnel reduction (PER)

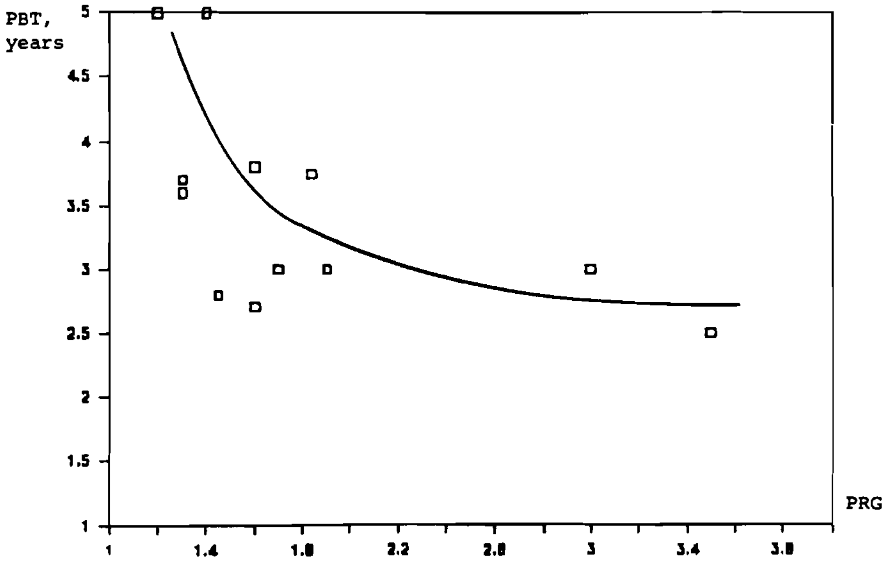


Figure 62. Pay-back time (PBT) over productivity growth (PRG)

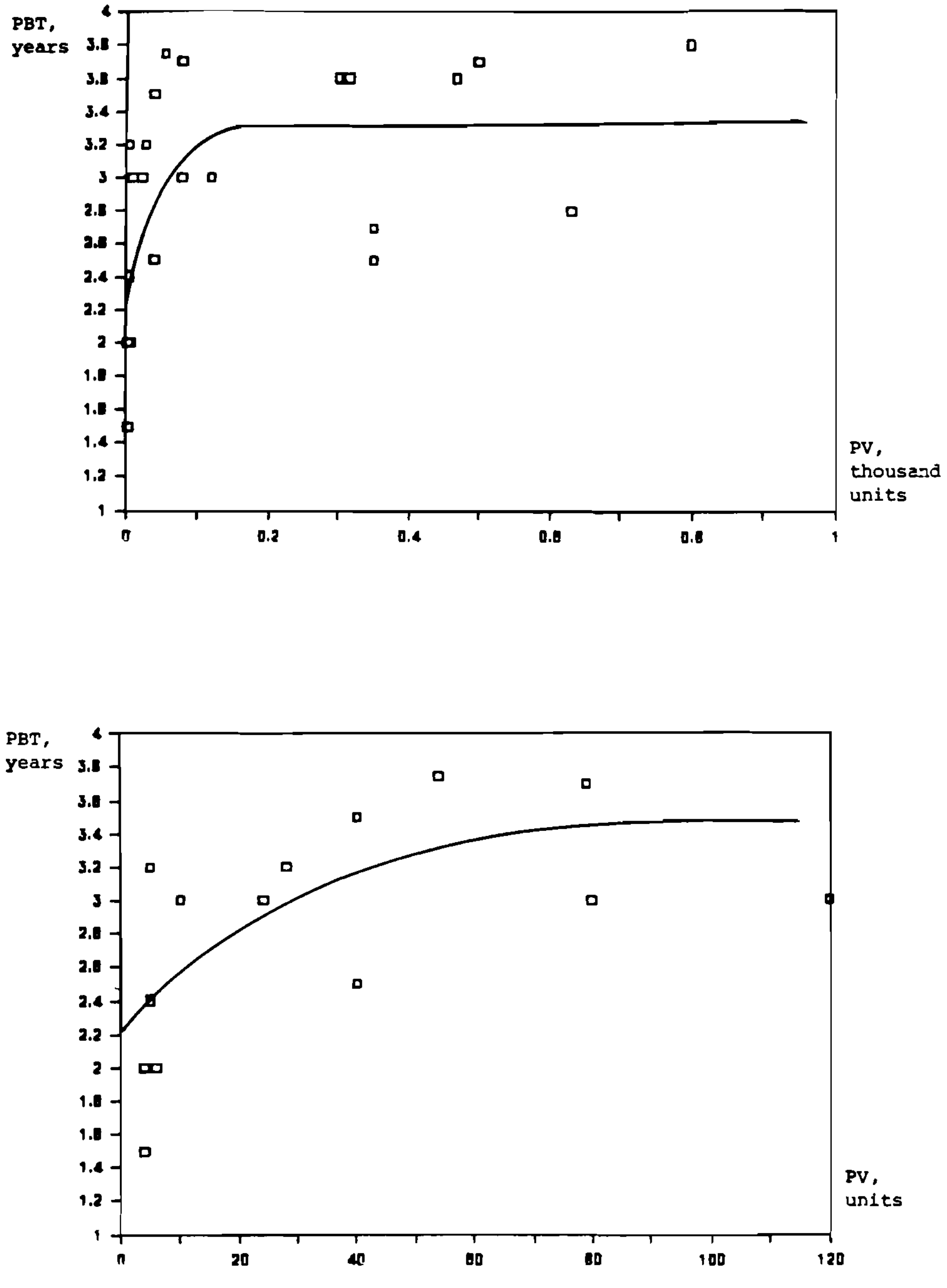


Figure 63. Pay-back time (PBT) over number of product variants (PV).

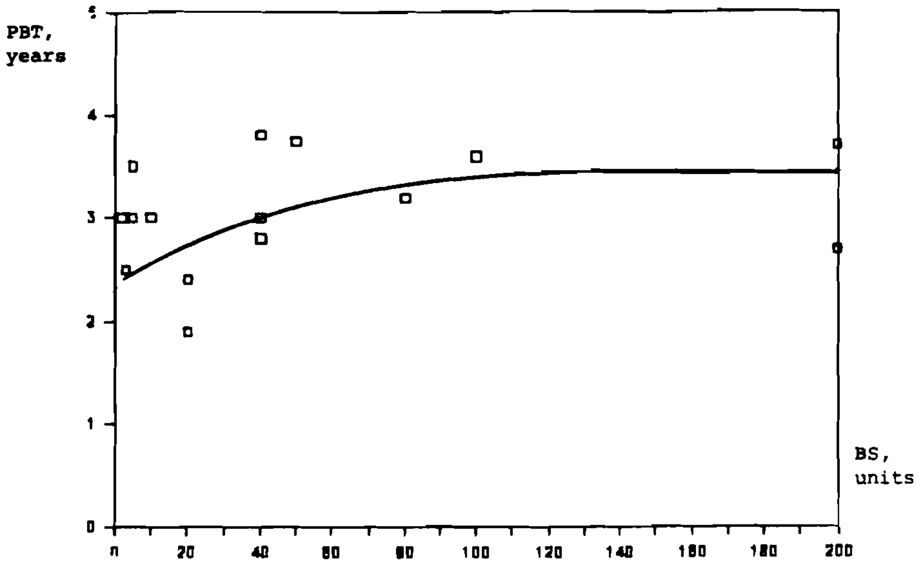


Figure 64. Pay-back time (PBT) over batch size (BS).

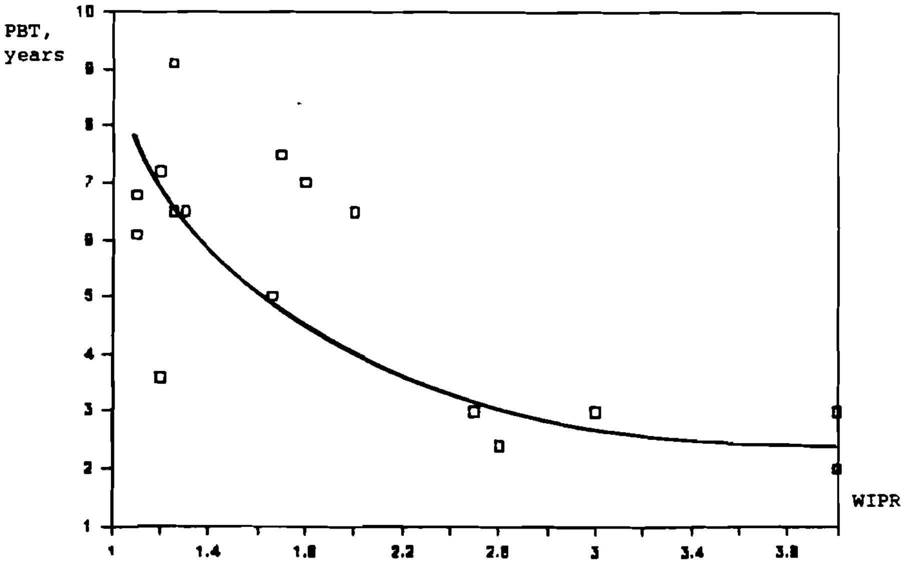


Figure 65. Pay-back time (PBT) over work-in-progress reduction (WIPR).

8. GENERALIZATION OF RESULTS AND DISCUSSION

All the results described in the previous paragraphs were collected in matrix form and are shown in Table 1. The influencing factors are shown by rows and the factors being influenced are given by columns. Some rows are clustered into two parts according to the following clustering factors: batch size, investments, technical complexity, number of product variants.

There are a few empty cells in the table which are either not interesting from the economic viewpoint (for example, in-process-time reduction over personnel reduction) or they are statistically not identifiable due to the a cloud of points (such as product variation over investments) or due to the lack of data (some cases of inventory reduction).

The forms of interdependencies are not shown in the table, only the correlation signs are reflected. The majority of the results correspond to theoretical ideas. But there are some contradictions as, for example, the opposite impacts of investments and technical complexity increase on the lead-time reduction. Some observed results are not explainable from a theoretical viewpoint: e.g., the negative influence of the growth of product variation on inventory and work-in-progress reduction.

The division of the interrelationships of FMS features into two parts, which is observable in many figures, can also be explained by two types of substituted production modes. FMS substitute custom production as hard automated lines when the production needs flexibility. This is why the relative advantages may be different for these two types of substitution.

Naturally, the graphical interpolations could sometimes be discussed and additional clustered data are necessary to clarify some relationships.

Some principally new conclusions can be derived from the clustering of the rows. First of all, there are two main types of FMS according to their cost and technical complexity. The interdependencies between the relative advantages of FMS and these two factors sometimes depend on whether we deal with cheap and simple or expensive and sophisticated systems. In these cases the approximation curve is V-shaped or a converted V-shaped curve.

The same situation is observed when influence of product variation is analyzed. An FMS with less than 200 product variants sometimes has interdependencies between variation and other system peculiarities which are opposite to the interdependencies of an FMS producing more than 200 product variants.

This means that there are several subgenerations of FMS within their total population and the specific features of these subgenerations are sometimes different. In some cases such differences appear due to different national policies and environments. This is why the next part of the FMS analysis will deal with a comparative cross-country study.

But, in any case, the demonstrated results can be useful for the development of an FMS diffusion model, and specifically for the quantitative estimation of its parameters.

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2. Tchijov I., Sheinin, R. Flexible Manufacturing Systems (FMS): Diffusion and Advantages. Part 1. IIASA WP-88-29.
3. Tchijov, I. CIM Application: Some Socio-Economic Aspects (Labor, Training and Institutional Factors). IIASA WP-88-30.

	Cluster	PBT*	PV	BS	LTR	SUTR	IRTR	PER	PRG	INVR**	WIPR
1. Investments, mill.$ (Invest)	>4 <4	0 +			+	+	+ 0	+ –	+ –	– –	+ –
2. Product variants (PV)	>200 <200	0 +	■	– –	0 +	+ –			+ –	– –	–
3. Batch size (BS)	>280 <280	0 +		■	–	–	–		–		
4. Lead time reduction (LTR)		–			■			+	+		
5. Set-up time reduction (SUTR)					+	■		+	+		
6. In-process time red. (IPTR)		–					■	+	+		
7. Personnel reduction (PER)		–						■	–		
8. Productivity growth (PRG)		–							■		
9. Work-in-progress red. (WIPR)		–			+			+	+		■
10. Technical complex. (TC)	<4 >4	0	–	– +	– +	0		– +	–	0	–

Table 1. The matrix of correlation between the main FMS features, "+"-positive, "–"-negative, "0"-no correlation.
*Pay-back time **Inventories reduction

ECONOMICS AND SUCCESS FACTORS OF FLEXIBLE MANUFACTURING SYSTEMS: THE CLASSICAL THEORY REVISITED

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ECONOMICS AND SUCCESS FACTORS OF FLEXIBLE MANUFACTURING SYSTEMS: THE CLASSICAL THEORY REVISITED

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1. INTRODUCTION.

The Computer Integrated Manufacturing Project of IIASA has made a major survey of flexible manufacturing systems in the world. The project estimates that there are now (in summer 1988) around 700--800 systems world-wide, which have at least two CNC-machines or machining centers, automated material handling devices and equipment, as well as a systems level central control to coordinate and to operate the systems as a whole. The growth rate of the new installations has, in the recent years, been around 30%. If this growth rate continues, there will be several thousand systems in the world by the year 2000; and even though a saturation of the diffusion process as well as many application barriers are expected, it is safe to say that there will be 2500-3500 systems in use at the end of the century or a 15 percent annual growth rate of the FMS population in 1986-2000, see Fig.1.

The future patterns for the traditional applications of FMS (electrical and non-electrical machinery, transportation equipment, instruments and electronics production) in industrialized countries are relatively clear now. But the potential impact of new areas (such as furniture, food, clothing) as well as new potential countries in the total FMS population are rather indefinite yet. This is why the forecast is mainly based on the extrapolation of the current tendencies and may be underestimated.

In any case, it can be concluded that the strategic and the major part of the production of the metal-working industries in the industrialized countries will be produced by FMS or other cell-like systems. Therefore it is also important to understand

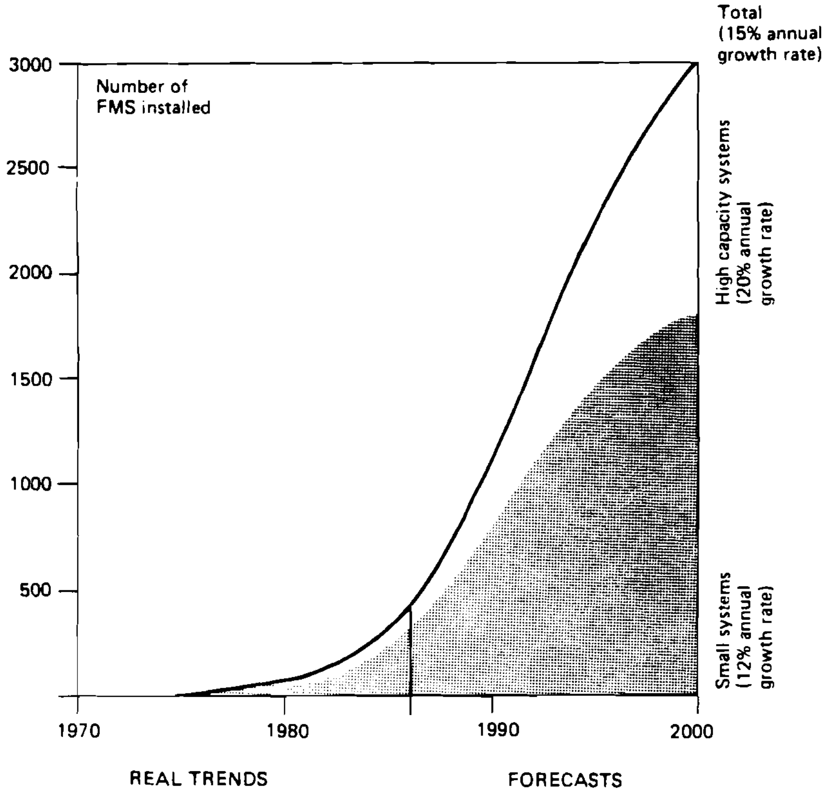


Figure 1. Trends and forecasts of FMS diffusion.

the basic driving forces and different economic and technological barriers behind the FMS applications.

IIASA has identified about 600 systems, which is by far more than other surveys (see [Edberg et al., 1988; Darrow, 1987; ECE, 1986]) have indicated. Over 400 systems have so far been described by technological and economic (cost and benefit) indicators in a database system. All basic analyses and conclusions presented below are based on this second edition of the database. The third edition, consisting of about 600 systems described and having an increased level of data reliability and completeness, will be available in the spring of 1989.

The database makes it possible to have different clusters and to look for regular patterns in applications as well as for different techno-economic success factors. These clustering approaches reveal quite many characteristics and features conflicting with the conventional wisdom of FMS. Also, some of the clusters and key analyses are as such conflicting.

In order to find an explanation for these peculiar and conflicting features it is necessary to look in more detail at different application patterns of flexible manufacturing systems. Thus the basic starting hypothesis to explain the complex economy of flexible manufacturing systems as well as the empirical findings is the following: It is evident that there are two kinds of highly beneficial systems: relative simple and compact systems, replacing semi-manual, traditional production, and highly efficient and high-capacity systems, replacing fixed automation and transfer lines.

Thus there are two factors explaining the conflicting data: the substitution process itself, or the starting point for the investment of flexible manufacturing systems, and the technological features of the systems implementation. Of course these two features are interconnected: different manufacturing environments require different implementation technologies. Also, it is natural that the goals of systems implementation and the achieved relative benefits are dependent on the way of substitution of the conventional systems.

Of course, we can also find simpler "sub-explanations" for our findings. It is furthermore quite clear that the systems properties are dependent on the industry sector and the application area in question. It is rather difficult to compare the machine tool industry and the electronic industry which each other, or to compare tooling and assembly systems. In any case, inside one industrial sector we can find again those two basic categories of systems applications. It is also worthwhile noting that the overwhelming majority of systems, i.e. 80%, is in metal-product and metalworking industry (general machinery, transportation equipment, such as trucks and automobile industry). Also, the overwhelming majority, again 80%, can be found in part tooling; only 15% of the applications are sheet metal systems and 5% are assembly systems.

Of course, relative benefits and systems properties show also country-specific features -- or geographical differences.

However, inside one country we can again find similar subclasses. Thus it is the implementation strategy and the specific technological realization which explains the regular patterns -- not the country-specific indicators as such. Similar conclusions also result from recent studies of the automobile industry [Krafcik, 1988].

In the following the basic technological and implementation characteristics are first explained together with their related substitution processes. These also explain the two fundamental clusters of the systems. Afterwards the basic economic impact and benefit data will be explained and some contradictory relative benefit figures will be demonstrated with the help of the substitution process and the technological properties of the systems. Finally some typical implementation strategies will be analyzed. The more comprehensive statistical and economic data can be found in earlier IIASA publications (see [Tchijov et al., 1988a,b; Tchijov, 1988; Ranta, 1988a,b; and Ranta et al., 1988a,b]).

2. SUBSTITUTION PROCESS, IMPLEMENTATION TECHNOLOGY AND ECONOMIC BENEFITS

Fig. 1 shows the estimated growth rate of the cumulative number of implemented systems. So far the growth has been rather high, as indicated already earlier.

To analyze the cost efficiency, we have to correlate costs and different efficiency indicators. The total investment costs are indicated in the database. On the other hand, there are several sets of "effect" data. It is possible to divide these data into the following groups:

1. Time reduction (lead time, set-up time, in-process time and machining time);
2. Logistic figures (inventory and work-in-progress reduction);
3. Operational data and pay-back time;
4. Personnel reduction and productivity growth.

A direct correlation between the cost and the effects usually showed indefinite clouds of points, or rather contradictory tendencies. This necessitated the use of the clustering approach to obtain a reasonable correlation. Several variables were used for clustering: investments, industries of application (machinery and transportation equipment versus electronics and instruments), types of FMS (machining, metalforming, assembling, etc.) and in some cases countries, when we were not quite sure of the reliability of the investment or exchange rate data.

The FMS distribution over the investment costs shown in Fig. 2 demonstrates that the total FMS population can be divided into two large groups: "cheap" systems costing less than four million dollars, and "expensive" ones costing more than four million dollars.

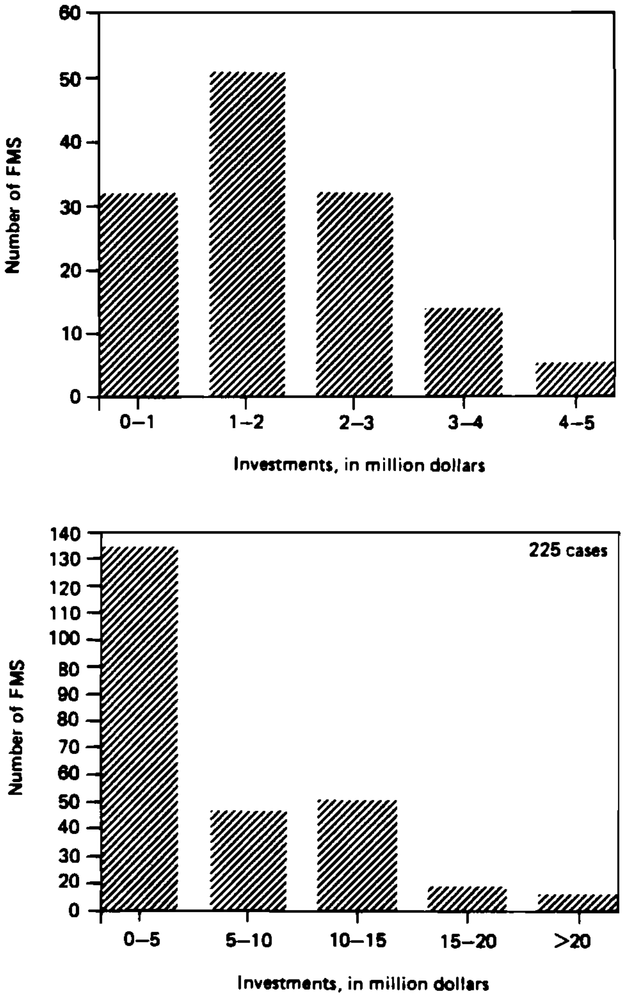


Figure 2. FMS distribution over investments.

The distribution presented by Fig. 2 reflects, of course, the technical complexity of the systems in terms of the number of CNC-tools and the control systems architecture. Fig. 3, which shows the distribution of the systems over the number of installed CNC-tools, indicates that the correlation exists. However, the number of CNC tools alone does not explain the investment cost distribution, we also have to look at the systems architecture and software costs for the explanation.

A typical compact, "cheap" system (see [Ranta et al., 1988b; Shah, 1987]) consists of 2-4 CNC-tool or machining centers, conveyor or/and automatic storage and retrieval system and two robots for material handling and has a programmable controller for systems control. Usually the costs of the system are 3M$ and the cost break-down is approximately the following: CNC-machines 50-55%, material handling and robots 15-20 %, control, communication and other systems level software 20-25 %, planning and training 10%. It is also typical that the systems architecture of the compact system is closed so that it is hard to extend and to add new features without major new investments. This can also be a major economic risk of investment.

A typical large-scale, "expensive" system consists (see [Shah, 1987; Bose, 1988]) of 15-30 CNC-tools, automated guided vehicles and an automated storage and retrieval system for material handling, a local area network and distributed microcomputer based cell and machine control systems and usually two VAX-type computers for coordination, scheduling and database management. It usually has a backup computer system to secure the availability of the system and advanced algorithms and a software system for the coordination of the system. The average costs are 10-15 M$ and the cost break-down is approximately the following: CNC-machines 35-40%, transportation and material handling 15%, control and communication and other system software 25-30%, and planning and training 15-20%. Is also typical that the systems architecture is open and systems can be extended in a step-wise manner and new features can be added without a major new design effort.

Thus we can see also that the expanding systems structure will typically lead to an increasing software complexity and a complicated control architecture.

We can call those systems, which are between these two basic categories, mid-range systems. Typically the investment costs are between 4-8 MU$ and the system consists of 5-10 CNC-machines, and most likely also of automated guided vehicles for transportation. The all-over control is based on super-minicomputers and the system may even have a local area network for coordination and communication. The systems are relative expensive, the total cost per CNC-tool rate is quite high, but their efficiency lies only in the mid-range.

All these three basic categories also show different cost-efficiency figures, which will be explained in more detail in the following.

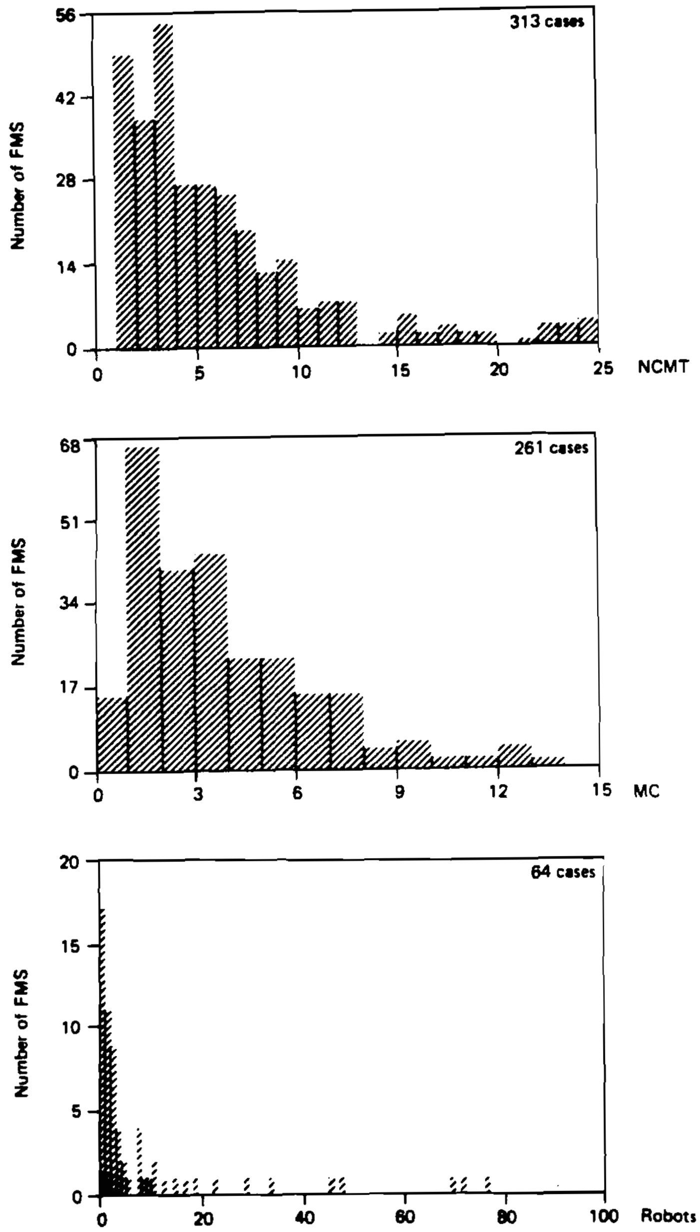


Figure 3. Distribution of FMS by their technical complexity. Number of FMS over numerically controlled machine tools (NCMT), machining centers (MC), and robots, respectively.

Fig. 4 shows the lead time reduction over the investment costs, and Figs. 5 and 6 represent the set-up time reduction and the productivity growth, respectively.

These figures clearly demonstrate a typical V-shaped form of the relative benefit measures. Thus it seems that

- the compact and small-scale systems have the best cost-efficiency ratio;
- the medium-range systems are inefficient from the viewpoint of their economic justification;
- only relatively large investments and relatively complex systems provide the same efficiency as the compact systems.

Fig. 7 idealistically demonstrates this fact.

Why these figures? The answer will be found if we look more carefully at the technical implementation features and the substitution process. Of course we can have two explanations for these figures. One could be that medium-size, conventional systems already show a good performance and therefore it is difficult to get high relative benefits. The other explanation is the FMS technology itself. We use these explanations in the following.

Fig. 7 can be interpreted so that the increased capacity of systems and the increased complexity will increase the systems costs/machining unit in a step-wise manner. This is due to the need for more efficient machinery when a certain level of complexity is reached. In small size systems it is enough to have a compact type material handling system, like a conveyor, and simple systems control based on programmable logic. When the complexity increases, a more sophisticated material handling system is needed, like automated guided vehicles, and the systems control has to be based on computers, distributed data bases and integrating communication systems. These changes in systems complexity tend to change in a step-wise manner.

On the lower end of the applications modest benefits can be achieved by a compact system and by low investment costs. On the upper end there are possibilities for substantial savings and benefits, although the investment costs as well as the complexity of the system are high. The potential benefits usually justify the higher investments. The second factor, which generally conforms with the use of complex systems, consists in a real learning curve effect or economies of scale in software production. When the level which necessitates the changes in the basic systems architecture has been reached, there are many possibilities to repeat (or simply copy) the basic software modules and use the same basic modules in different interfaces and in systems coordination and timing. The larger the scale of the system under design, the more immediate are the benefits of software repetitiveness.

Fig. 8 explains the situation.

The medium-scale systems are critical from the economic point of view. It might happen that a sophisticated systems

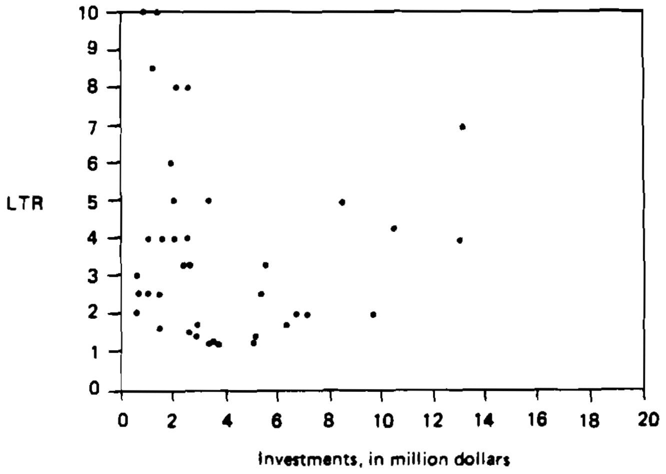


Figure 4a. Lead-time reduction (LTR) over FMS cost.

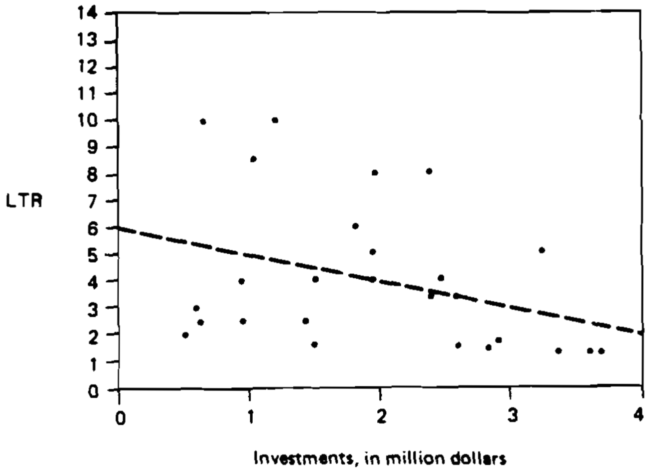


Figure 4b. Lead-time reduction (LTR) over FMS cost.

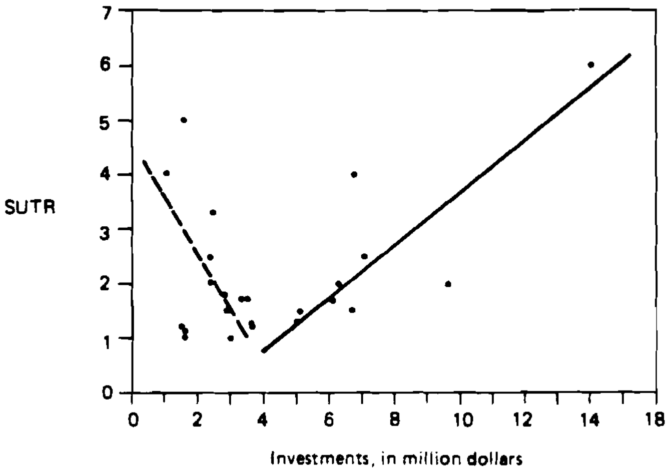


Figure 5. Set-up time reduction (SUTR) over FMS cost.

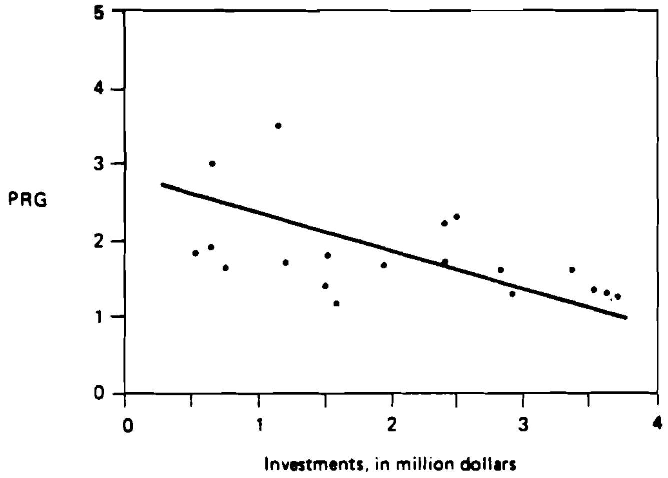


Figure 6a. Productivity growth (PRG) over FMS cost.

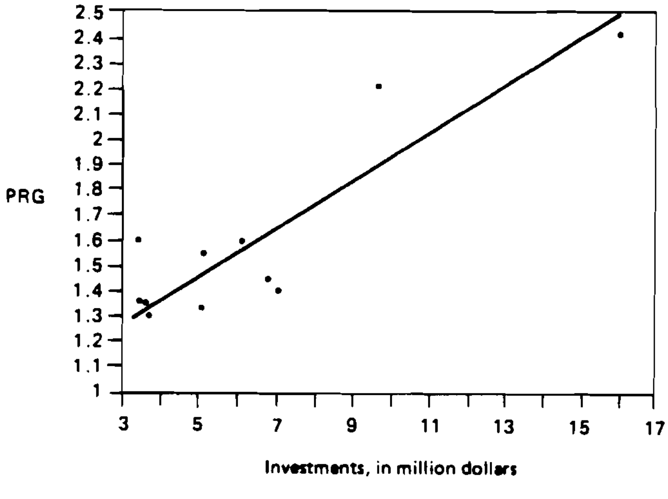
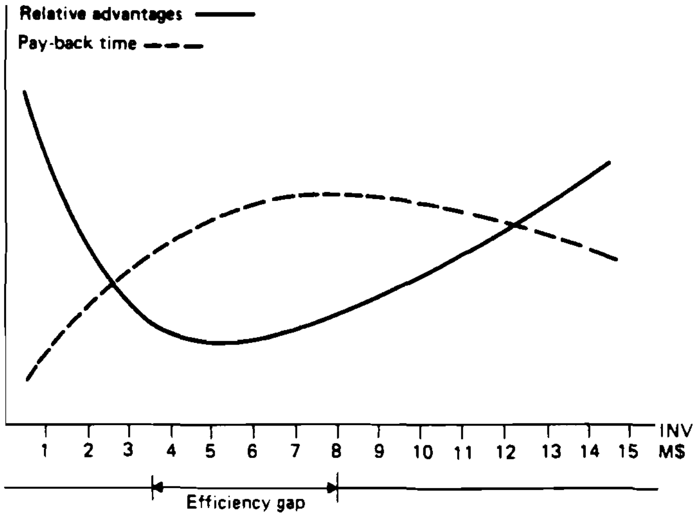


Figure 6b. Productivity growth (PRG) over FMS Cost.



– Total costs	3M$	– Total cost	10–15 M$
– CNC	50–55%	– CNC	35–40%
– Material handling	15–20%	– Transport + mat. handl.	15%
– Cont, commun. software	20–25%	– Cont. commun. software	25–30%
– Planning + training	10%	– Planning + training	15–20%

Figure 7. Efficiency and investment costs of FMS.

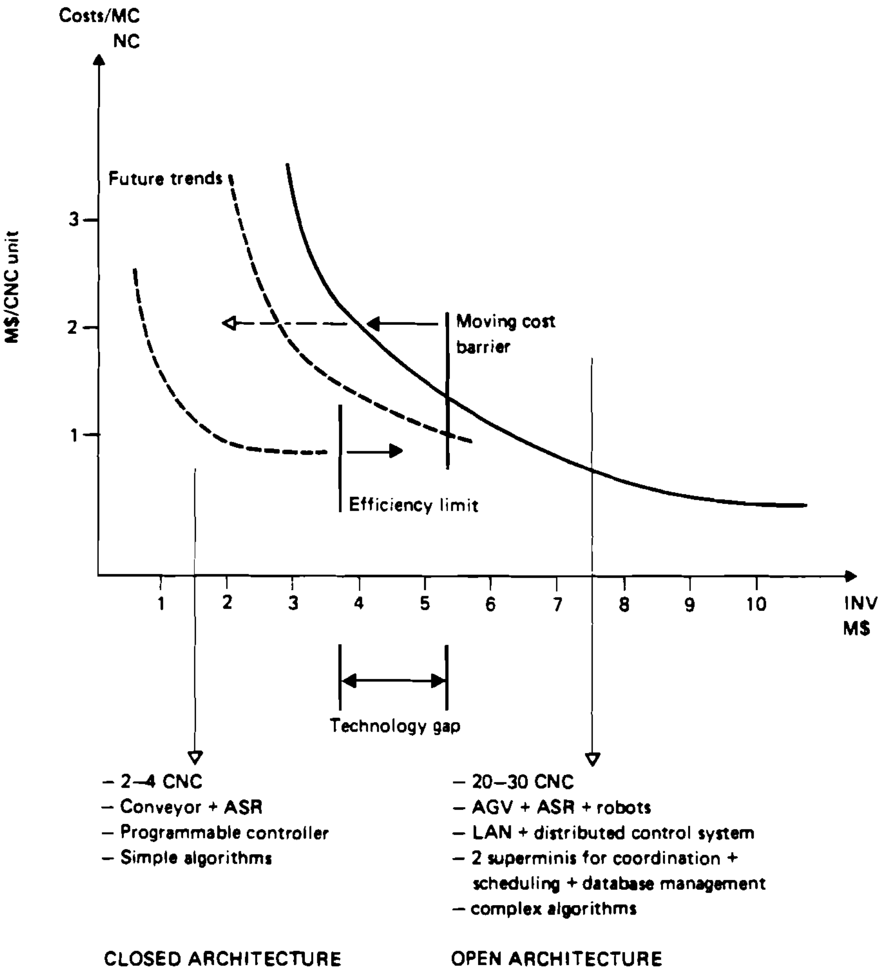


Figure 8. Technological factors of relative costs of FMS.

architecture based on distributed data bases and communication is needed, but the potential benefits are not high enough to justify the system investments and the system complexity is not high enough to draw the benefits from the economies of scale effects. This remark is also consistent with empirical data above, which show that compact, small-scale systems and very complicated, large-scale systems clearly have a shorter pay-back time than medium-scale systems. This also leads to the following conclusion: a critical technical issue for the future applications is the possibility of a module-type control structure and a transportation device, which allows for a soft extendability of the system without drastic architectural changes.

This problem can also be called a complexity dilemma. The higher number of CNC machines combined with a large part family usually results in such a complexity of systems coordination (e.g., routing, scheduling, tool management) that high software and planning costs can not be avoided. The only way to get the relative costs down is a modular systems structure and standardized software modules. The benefits of standard systems structures are already clearly visible in compact systems. It is a common practice that the same basic system layout and architecture is usable in many applications, providing learning curve advantages for different applications.

Thus, if there will be no real technical breakthroughs in realizing systems controls and all-over architectures, which guarantee module-based design of systems and an easy extendability, it is reasonable to expect that the basic application diffusion paths of the flexible manufacturing systems will be of the following two types: highly efficient, high-capacity, complex systems replacing rigid transfer lines, and, on the other hand, compact, small-scale systems replacing conventional semi-manual, NC-tool based production. The economy and applicability of the middle-range system will be highly dependent on systems control and communication software as well as on flexible transportation devices.

Thus the precondition for the rapid growth rate in the future is that there will be a remarkable technological development and achievements in all the key areas of FMS technologies. This development has to have an impact on cost factors, efficiency and performance factors of different building blocks of FMS technologies. Both on the machine and system levels, electronics and information technologies will still be key technological elements of development. It is reasonable to expect that in the ten-year perspective flexible grippers, speed and accuracy of robots will no longer be obstacles to assembly systems, there will be software and communication standards to help integrate basic building blocks, there will be modular systems control and interfacing systems, which make step by step development possible, relative software costs will decrease and the systems development will be easier. All this trends mean a gradual improvement of the efficiency (performance) - cost ratio in terms of speed, capacity, accuracy, complexity and flexibility of systems (see [Ranta, 1988a]).

If these technological trends become reality to their full extent, new systems architectures will be realized, opening completely new possibilities to cope with different systems efficiencies. Therefore the growth of new applications will be even more rapid than illustrated above.

If this optimistic scenario becomes reality we can estimate the cost to be as shown in Fig. 9. We can also expect that the diversity of the types of applications will be higher than in the two basic categories presented above.

Because of the two basic FMS categories it is natural that these technological factors also have an impact on the way systems are implemented and new FM-systems substitute conventional-type manufacturing. Thus it is obvious that there are two basic implementation strategies of flexible manufacturing systems: highly efficient systems replacing transfer lines and fixed automation, or highly flexible, compact systems replacing semi-manual small-batch production. Fig. 10 illustrates the situation.

The starting point for the first implementation strategy is usually a fixed automation or transfer line in a mass production of a big company. The main goal is to increase flexibility, save capital and decrease the lead times as well as to cope with the changing environment and demand in the future. As the FMS is replacing the highly automated lines, labor savings play only a minor role in this case.

A typical example of the strategy is a company which is producing engines and has three fixed automation lines to manufacture 5-8 different types of cylinder heads and has an annual volume of 20 000 pieces. The company replaces those fixed automation lines by a FMS having the same annual capacity, but producing all those different cylinder heads and having the theoretical flexibility potential of about 100 different heads and even some other parts. The system thus provides a considerable potential to meet the future changing markets and demands. The achieved benefits might be a decrease of the lead time from 4 weeks to one week, a work-in-progress reduction of 70%, more rapid customizing of engines, and fewer but more expensive machines with a clearly increased software share. At first sight the system might seem to be inflexible: the part family is only 8. But it is flexible enough to cover the needs of the company and also to decrease the potential risks of changing demands. Thus the flexibility potential is used to cope with long-term changes, such as yearly product (model) changes, or to rapidly introduce new products without changes in production. The question is, therefore, a question of product and production flexibilities. The small part family helps to manage the systems complexity and related software issues in spite of the high number of CNC-machines.

The starting point of the second implementation strategy is usually semi-automatic or even manual production in small or medium-scale companies. The systems usually used are compact and cost-efficient systems. There are two subcategories of this phenomenon. The first one is a simple capacity increase and

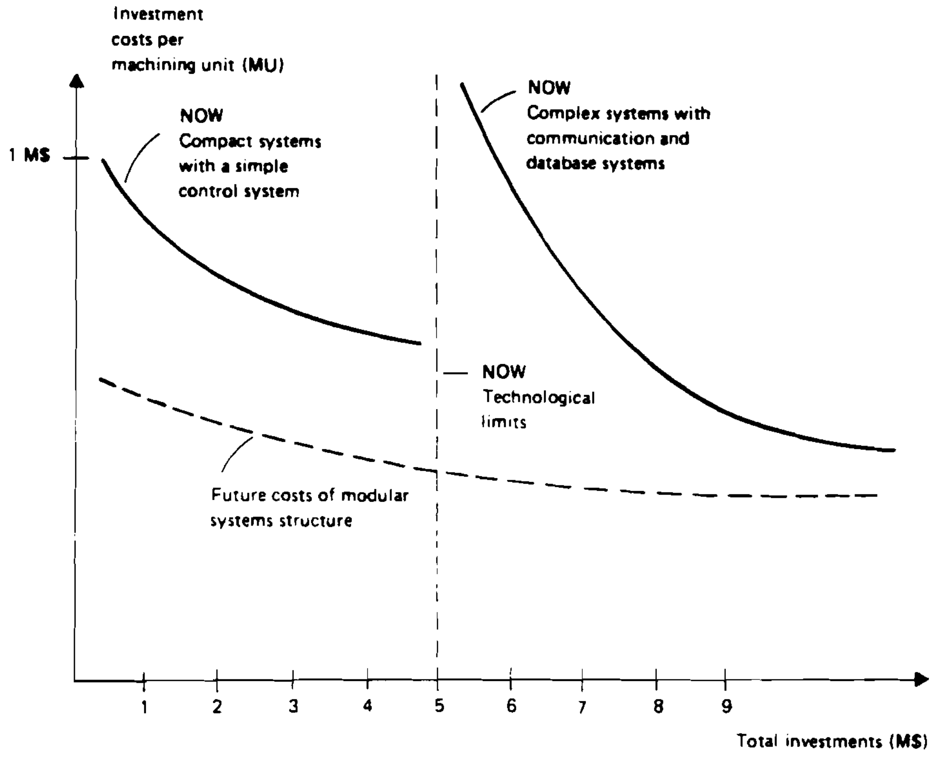


Figure 9. Effect of decreasing software costs, standards and systems modularity.

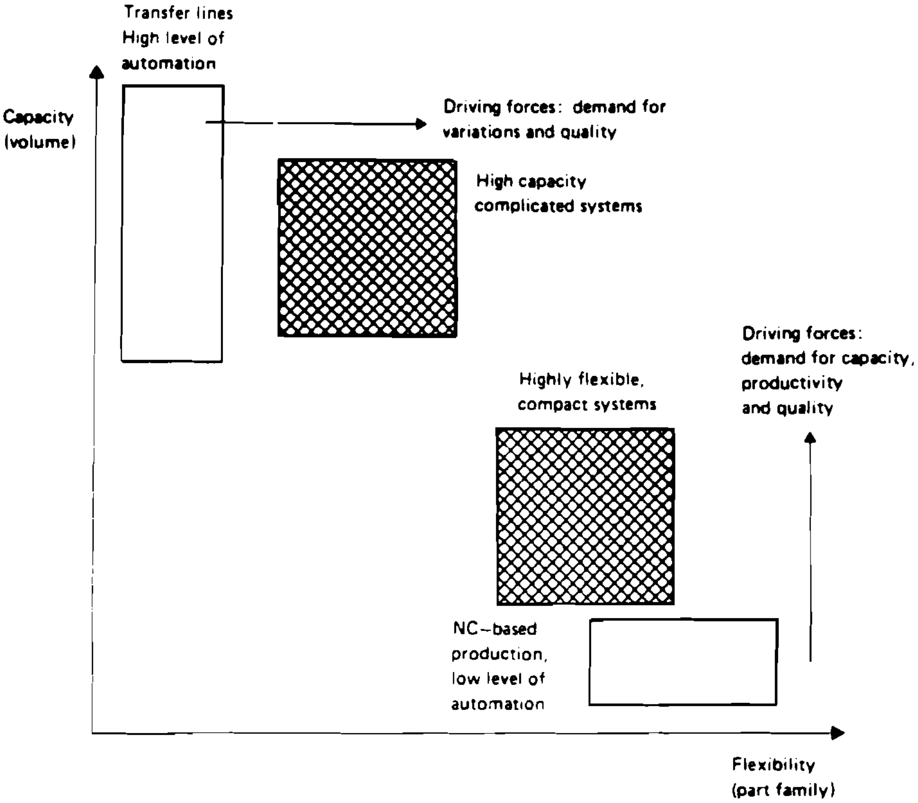


Figure 10. Substitution of manufacturing systems.

quality improvement strategy, while sustaining the already existing flexibility. This strategy is also an implicit labor-saving strategy, because a FMS can offer a considerable increase of production capacity without requiring new labor force or building new shop-floor space. The second subcategory is used for capital savings, e.g. to decrease work in progress and to decrease delivery times. This corresponds to a situation where the design flexibility is already in existence and the basic strategy is extended and enforced through modernization of the manufacturing system to guarantee rapid customizing and introduction of new products on the shop floor level. As it is also evaluated as a capacity extension, among other alternatives, and not as a machine investment, usually also a broader evaluation of investments than ROI, based on the expected cash flows, is used. The compact architecture of the system -- a small number of CNC -- makes it possible in this case to manage the systems complexity in spite of a large part family, i.e. a high number of product variants.

The achieved benefits of the second strategy are usually manyfold: quite high relative labor savings, decreased work in progress, increased production capacity and decreased lead times. Thus FMS, FMC and FMU are then used to improve customizing and decrease again the total delivery times on the shop-floor level. However, because of compact systems and closed architecture of FMS, there might be some risks to meet future demands. Basically this is the economic risk of the strategy.

What was stated above is, to some extent, conflicting with the conventional theory of FMS, which usually dictates that the proper use of FMS is that of a middle-range system between highly efficient transfer lines and semi-manual, highly flexible production providing medium-scale flexibility and medium-scale efficiency. According to empirical studies above, this does not seem to be true, but those medium-scale systems are the most critical systems in economic terms. The technical and economic reasons for this fact have already been explained above. In order to be beneficial, these systems have to provide all those possible benefits usually associated with FMS: high relative labor savings, high reduction of work in progress, fixed capital savings, high reduction of delivery and lead times and increased market share.

The implementation of these systems to meet the planned goals is risky due to their high complexity. The rather high number of CNC-machines and the rather large part family makes the system coordination -- scheduling and tool management -- rather complex and the systems software difficult to implement.

Finally it is worthwhile noting that nearly all the expensive systems are tooling applications, the assembly systems as well as the sheet metal systems are generally cheaper and most of them are usually compact systems. This is quite understandable from the technological point of view because the sheet metal systems are relatively simple and the assembly systems so far implemented are rather compact and dedicated due to the technological and economic constraints. Also, most of the expensive, high-capacity systems are in the metal-working industry.

3. FACTORS BEHIND THE RELATIVE BENEFITS

Above we have put down two strong hypotheses explaining the differences in the empirical data on application and system cost patterns. It is reasonable to expect that these factors will also be seen as explanatory factors for different relative benefits and for independences between different indicators. E.g., it can be expected that there are relationships in the statistical data between increase of production capacity, productivity growth, labor reduction, batch size, lead-time reduction, technical complexity and investment costs.

In order to support the analyses, a special indicator describing the technical complexity of FMS has been formed. Of course, it is difficult to obtain a universal measure for complexity, reflecting the mechanical part of the systems, the software and control structure as well as the layout of the system. However, in the database there exist several indicators, which can be used to measure complexity.

Among them are: the number of machining centers (MC), the number of NC-machine tools (NC), the number of robots (ROB), and the types of transportation (TR), storage (ST and inspection (INS) systems in the FMS. The last three variables were indicated as dichotomic: (1) for simple systems and (2) for sophisticated ones [Tchijov et al., 1988b].

The attempts to find statistically reliable, separate correlations between these indicators and other FMS features were usually a failure. This is why a combined indicator of the technical complexity was elaborated. The first accepted hypothesis is a that higher complexity is connected with higher FMS costs. The second one is that if there is no information on IR, the number of robots is zero. The third hypothesis is that in case of missing data on TR, ST and INS these were considered to be 1.0 (i.e. simple systems). Finally, several "extra" FMS costs in the USA were excluded from consideration by the use of a dummy variable.

The following linear regression equation was estimated for 315 FMS where data on MC and NC were available:

$$\text{Invest} = a \cdot MC + b \cdot NC + c \cdot ROB + d \cdot TR + e \cdot ST + f \cdot INS + g \cdot DUMUS$$

where

Invest - investments in million US dollar;
DUMUS - dummy variable = 1.0 for the US cases and 0 for other systems;
a, b, c, d, e, f, g - regression coefficients.

Coefficients "e" and "f" were statistically insignificant because only few FMS had sophisticated storage and inspection systems. DUMUS were used to purify the relationship from the extremely high costs of the US FMS. The other coefficients were used to construct the technical complexity indicator (TC) as follows:

$$TC = 0.7\ MC + 0.35\ NC + 0.3\ ROB + 0.3\ TR$$

The relative weights of the independent variables approximately correspond to their cost shares, but -- due to the procedure described above -- the technical complexity does not coincide with FMS costs. The FMS distribution over TC is shown in Fig. 11.

This distribution shows that 58% of the cases in the FMS sample set can be treated as rather simple systems with a TC of less than four. 36% of the FMS are in a middle range and their technical complexity is between 4 and 10. And only less than 6%, or 18 systems, belong to a technically complex type with a TC of more than 10. According to this analysis (we should like to remind the reader again), a most typical FMS includes 2-4 machining centers, or 2-7 NC-machine tools (including MC), and 60% of 64 FMS, where the use of robots was reported, have 1-3 industrial robots.

How the technical complexity influences FMS specific features and relative advantages is rather contradictory and it is sometimes affected by national or production conditions, although the question is more a technological and implementation question.

Increase of productivity and production capacity are two possible indicators, on which the above explained two main substitution paths have an impact. Thus the relative capacity increase can be expected to be higher in the case of compact systems than in the case of complex systems. It can also be expected that the labor reduction will only partly explain the productivity increase.

Fig. 12 shows the relative increase of capacity over the investment costs and the number of CNC-machines in the system. It can clearly be seen that there is tendency that the increase of the capacity will be higher in the case of small and compact systems. This gives some evidence to the hypothesized driving forces of the substitution.

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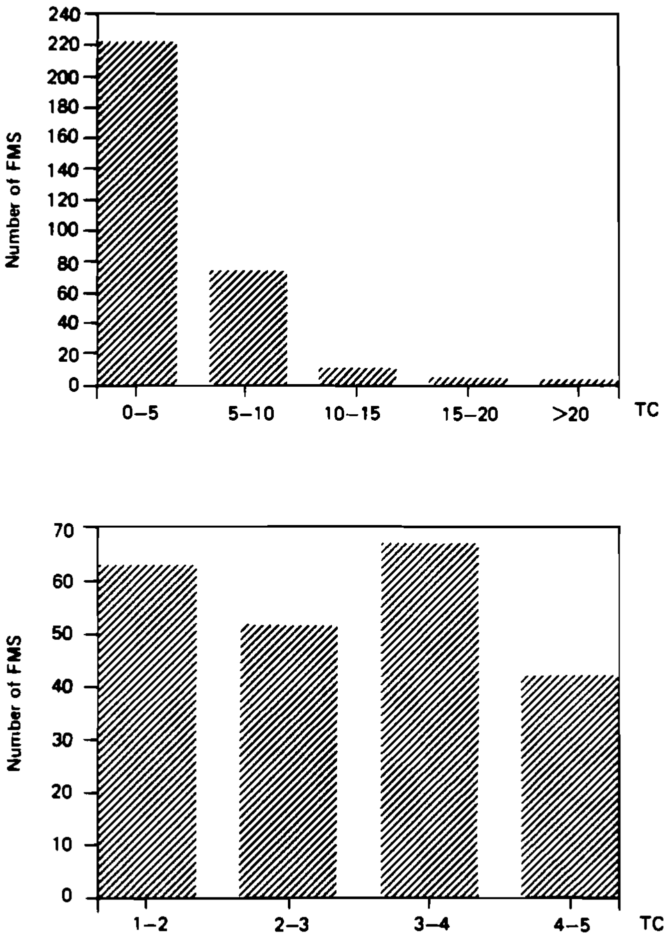

Figure 11. FMS distribution over technical complexity (TC).

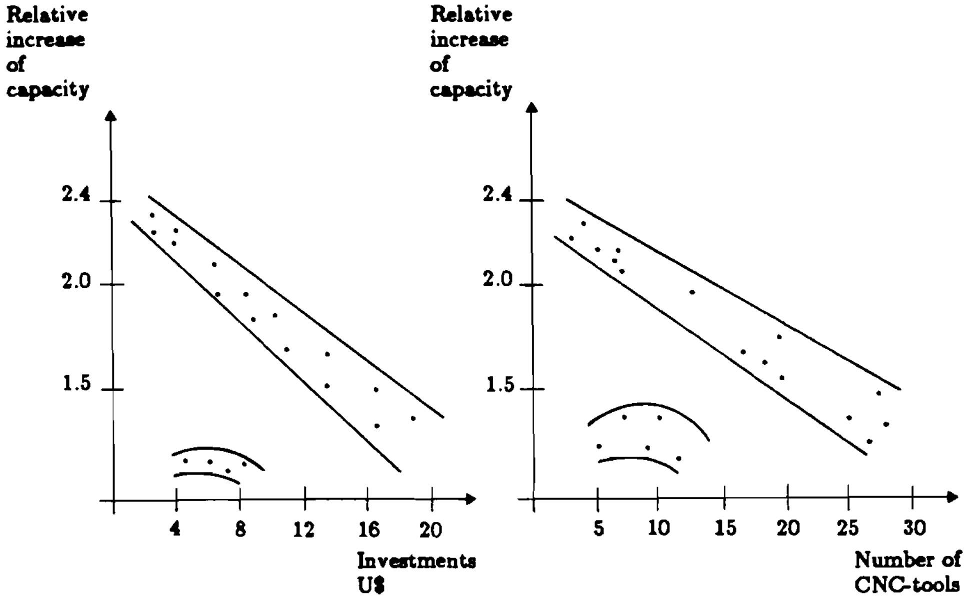

Figure 12. Increase of production capacity over investment costs and number of NC machines.

It is, of course, interesting to try to explain the factors behind capacity increase. Fig. 13 shows the relative capacity increase over labor reduction and productivity growth. The only conclusion we can make is that the capacity increase is not necessarily explained by productivity growth. On the other hand, those few cases, for which data on the operation rate (the number of shifts in use) and unmanned operation are available, show a general tendency: the higher the operation rate, the higher seems to be the capacity increase, and the higher the number of unmanned shifts, the higher is the capacity increase. This fact might indicate that the utilization rate could be a critical factor behind capacity increase. The same tendency also exists between productivity and operation rate, as well as between productivity and the number of unmanned shifts. Thus, apart from the technological innovations, the organizational innovations play a critical role in guaranteeing a high utilization rate. It is also understandable that the transformation from the semi-manual and functional production to the automated and cellular production has more potential for capacity increase or for improvement of the utilization rate than the transformation from highly automated transfer lines.

The above conclusion can be even more strongly supported. Fig. 14 shows pay-back time over operation rate and number of unmanned shifts. It can be concluded that the operation rate alone does not explain the high benefits. It is necessary to combine the use of unmanned shifts with a high operation rate to achieve economic benefits.

The productivity growth is highly correlated (nearly a linear dependence) with labor reduction, lead-time reduction and set-up time reduction. This is illustrated by Fig. 15 (see [Tchijov et al., 1988b]. This proves that the management of time or the unit time productivity is more critical than the classical variable costs. This is understandable due the high fixed capital costs (see [Jaikumar, 1988; Ranta et al., 1988c; Stalk 1988]). Also, the better the lead-time reduction, the shorter the payback time. It is well understandable why FMS can be a successful strategy for capacity increase in a small batch production.

However, there are some very interesting relationships. Productivity growth over batch size and technological complexity is presented by Fig. 16.

Fig. 16a shows that a small batch size will result in a high relative increase of productivity. At first sight this seems to be contradictory to conventional theory. The figure is, however, due the fact that one of the driving forces behind productivity growth was lead time reduction or efficient time management. Fig. 16a is also in agreement with Fig. 16c, which shows that a small batch size seems to result in a high lead time reduction. Fig. 16b also shows that the compact systems (low technological complexity) tend to have a higher productivity increase than highly complex systems.

How can this be explained? One explanation as such is the management of time as a critical success factor. The second

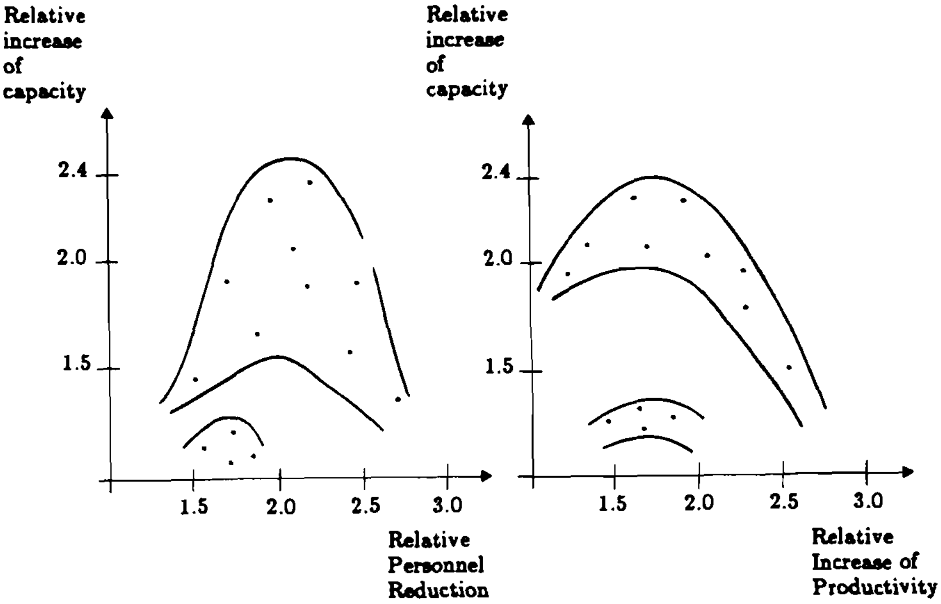

Figure 13. Increase of production capacity over personnel reduction and relative increase of productivity.

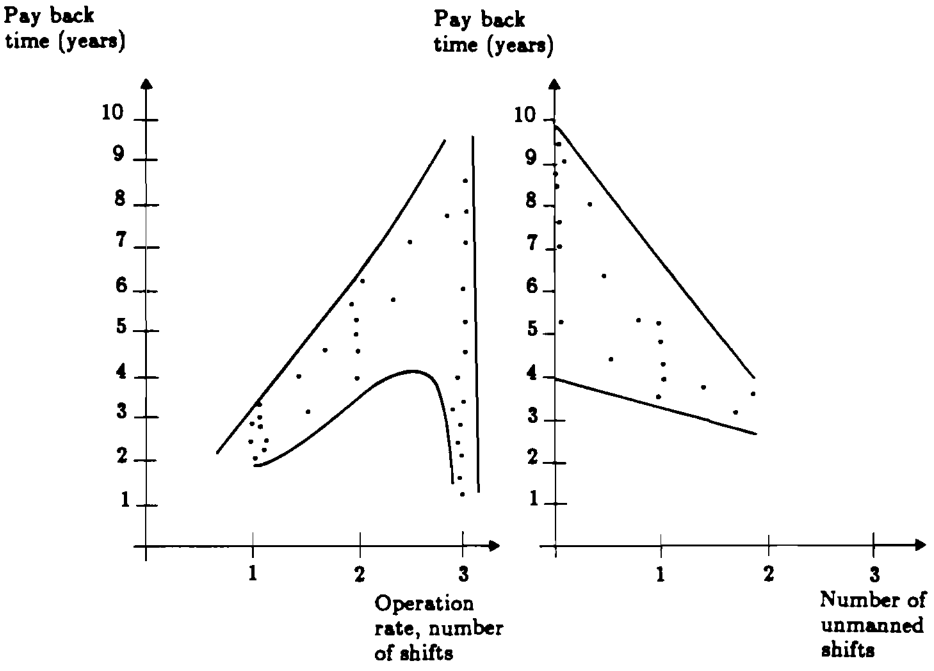

Figure 14. Pay-back time over mode of operation.

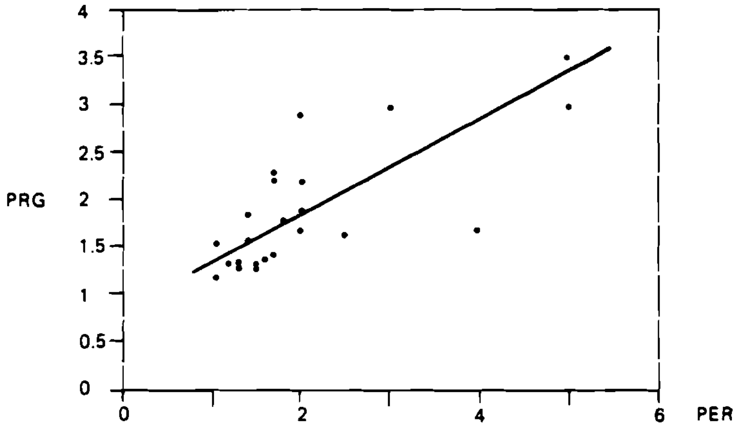

Figure 15a. Productivity growth (PRG) over personnel reduction (PER).

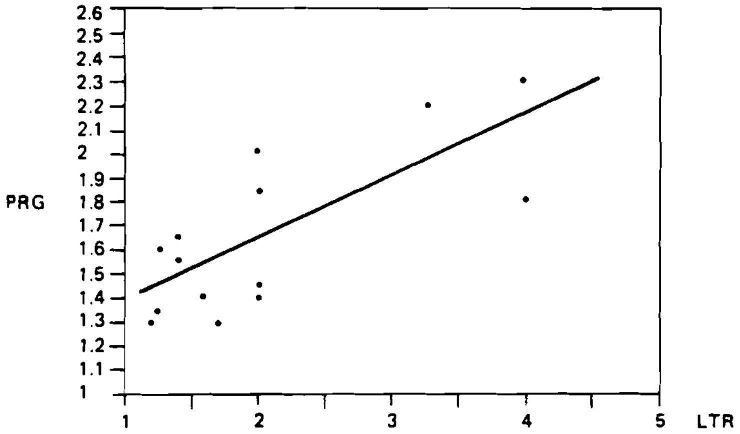

Figure 15b. Productivity growth (PRG) over lead-time reduction (LTR).

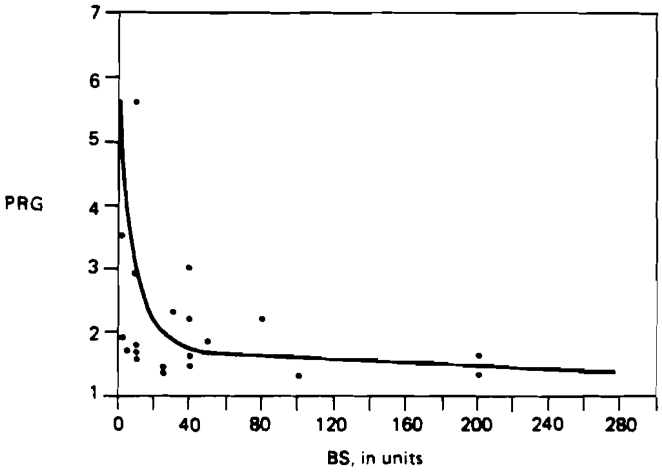

Figure 16a. Productivity growth (PRG) over batch size (BS).

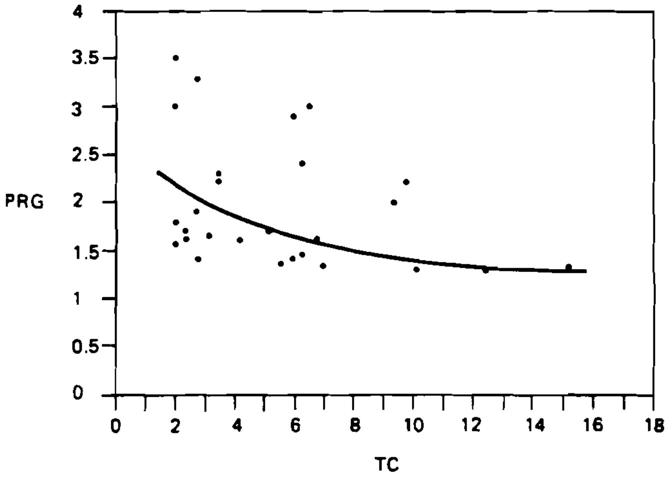

Figure 16b. Productivity growth (PRG) over technical complexity (TC).

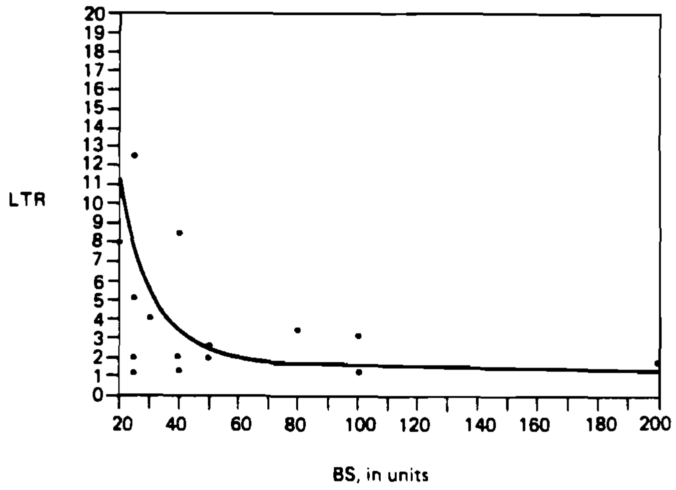

Figure 16c. Lead-time reduction (LTR) over batch size (BS).

explanation is that the compact systems are used to replace semi-manual production in order to increase the production capacity and to reduce the lead times of the production. The complex systems, on the other hand, are used to replace high capacity transfer lines in order to provide flexibility and capital savings. Therefore, since a small batch size is connected to small-scale compact systems, a small batch size is usually also connected to productivity growth and lead-time reduction. Some further evidence is given in Fig. 17. In terms of batch sizes the figure seems to be contradictory to what was said above. However, the small and compact systems seem to keep their flexibility and complex systems are looking for flexibility. An interesting case are, however. the mid-range systems. They seem to be medium-capacity and medium-flexible systems. Furthermore, the large batch sizes are typical of these mid-range systems. This is also in an agreement with above presented cost-efficiency figures and pay-back time figures.

Thus we can conclude that the critical factors for benefits are:

- the management of fixed costs and time and the guarantee of a high utilization rate;
- a careful selection of the goals and implementation strategies depending on the situation to be changed or replaced, as well as an assessment of the goals and their implementation together with the cost efficiency of different technological alternatives and possibilities.

4. A FRAMEWORK FOR IMPLEMENTATION STRATEGIES

Facing the fact that there seem to be two classes of beneficial systems, it is worthwhile classifying some typical implementation strategies which are successful and also associate different benefits with different strategies.

We can call the basic dilemma a capacity productivity increase problem and a complexity management problem. This fact has already been presented elsewhere (see [Ranta, 1988b; Ranta et al., 1988b]), and it has also been demonstrated quite clearly by Jaikumar [1988] in his case study. We can now start with the Table 1, which is a general presentation of two extreme cases.

It can thus be seen that if the system can be designed in such a way that capital is released or that the number of machines is decreased, then there is no need to increase the volume of production. This can typically occur in a situation when an investment for renewal is made and this is again a typical situation occurring in bigger companies. Also, when there is a need to increase production capacity, modern production technology offers very efficient ways to do so without necessitating investment in new building and factory space. This is usually applied as one economic approach of small and medium-scale companies, as discussed above.

In other cases a remarkable increase of production capacity

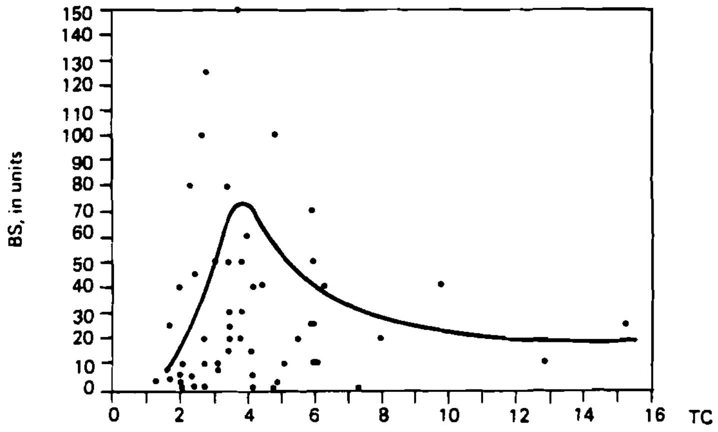

Figure 17. Batch size (BS) over technical complexity (TC).

Table 1. Economic impact of advanced production automation.

	Conventional	NC functional	FMS
Case 1. Constant production capacity			
Number of machines	N	$\frac{1}{3}N$	$\frac{1}{9}N$
Production capacity	C	C	C
Price	A	$\frac{1}{2}A$ + extended design	$\frac{2}{9}A$ + extended design + extended software
Case 2. Constant number of production units			
Number of machines	N	N	N
Production capacity	C	$3C$	$(9\text{–}15)\cdot C$
Price	A	$2\cdot A$ + extended design	$2\cdot A$ + extended design + extended software

will result, thus necessitating a guaranteed high demand for the company's products in order to justify the investment.

In a medium-size production it can be extremely difficult to meet the above requirements because of the relatively high basic investments and the already very extensive design process.

Using the above extreme cases as a starting point, we can draft several alternative implementation strategies. Fig. 18 and Table 2 give an overview of such possible candidates.

Strategies A and B correspond those two substitution patterns already described above. Strategy A can be called the capacity increasing strategy. Table 2 shows the necessary conditions for the successful implementation of the strategy: the capacity can be increased without increasing labor costs and with a relatively slight increase of fixed capital. Thus the benefits result from the increase of both, the capital and the labor productivity. Also a clear reduction of lead times and work-in-progress should be a result of a successful implementation. However, these are only preconditions or prerequisites for achieving benefits. The system has to be designed in such a way that it can meet these goals or fulfill the necessary conditions. Typically, this kind of manufacturing environment is a small batch production, where the transformation of a semi-manual process to an FMS-like process satisfies the boundary conditions of the implementation strategy. To be successful, however, the implementation process also has to meet sufficient conditions. These sufficient conditions are described in Table 2 by the columns "costs" and "risks".

Usually the renewal process as well as an expanding capacity can be realized without any extra shop floor or new factory buildings. The modest increase of fixed capital is due to more efficient machinery and increased software costs, although the FMS can be regarded as a compact system. Usually the software part of the system will also be a risk element, because software quality and reliability are critical for the system utilization rate, and because the realization as well as the maintenance require knowledge, skills and a way of thinking, which is different from the conventional system. Thus the management of the implementation is a critical factor. It is critical as a systems cost factor and as a factor of the utilization rate (see [Meredith, 1987a,b,c]).

It is also evident that, because of the multi-system nature of the manufacturing process and because of increased fixed costs, the management of time will be a critical factor, i.e., it is necessary to guarantee a high utilization rate of the manufacturing process. Therefore the <u>knowledge</u> and skills of the operators and their capability to cope with complexity to make prognoses and diagnoses and to develop the system further are more essential than in the case of conventional manufacturing systems. Thus the whole management of change, including training and organizational issues, is critical for the success of the project. This is, of course, a fact, which has been emphasized in many reports (see [Ettlie, 1988; Jaikumar, 1986, 1988; Maly, 1988; Martin et al., 1987; Ranta, 1988b; Tchijov, 1988]).

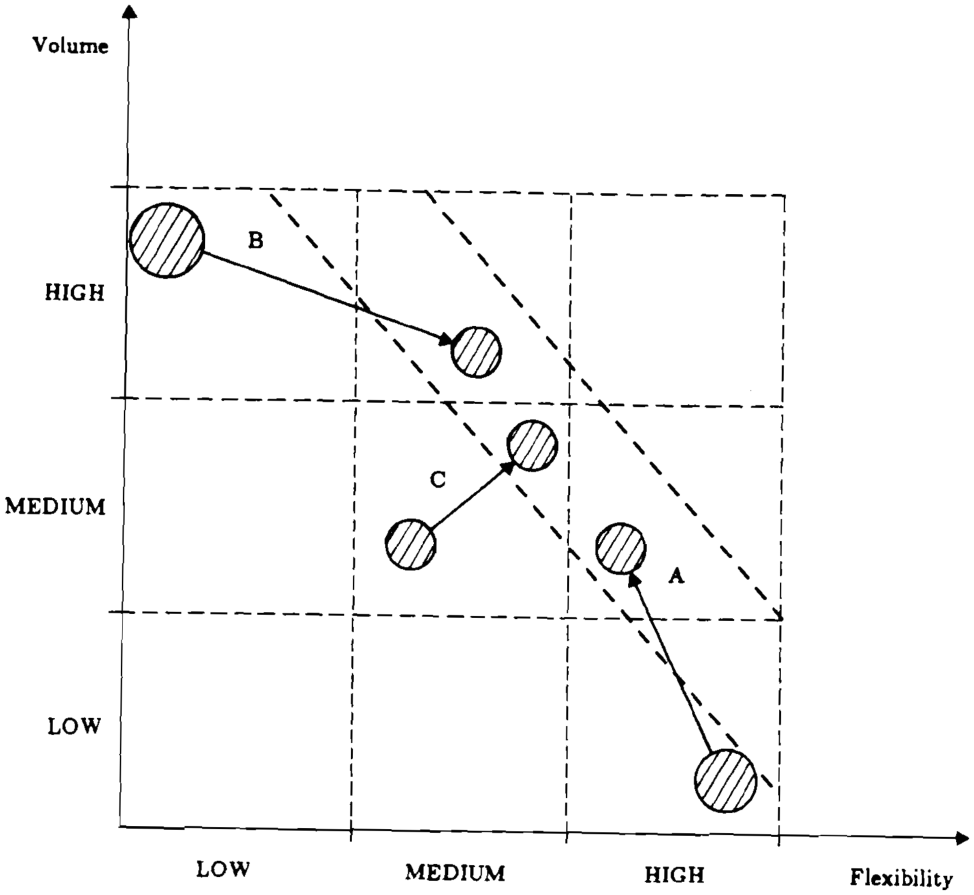

Figure 18. Capacity-flexibility problem of different strategies.

Table 2. Implementation strategies and associated benefits

	Starting point	*New system*	*Technology*	*Benefits*	*Costs*	*Risks*
Strategy A	–Small scale ⇒ semimanual batch production –Capacity C, number of machines N –Amount of fixed Capital K –Labor L	–FMS, automated high flexibility –Capacity 5 · C, number of machines N –Fixed capital 2 · K –Labor L	Compact control structure – Closed Architecture	–Capacity increase – capital productivity 5/2 × –Labor productivity 5 × –Decreased lead times and WIP –Improved quality	–Increased software costs –Increased training costs –More expensive machinery	–Software management –Management of change –Closed layout –Excess capacity
Strategy B	–High capacity ⇒ dedicated automation, mass production –Number of machines N –Amount of fixed Capital K –Labor L –Capacity C	–FMS, High capacity medium flexibility –Capacity C –Number of machines N/3 –Labor L –Fixed capital 0.7 · K	Advanced, complex control – Open architecture	–Flexibility increase –Capital productivity 1.4 × –Potential for future changes –Lead time and WIP reduction	–High software costs –High planning costs	–Systems complexity –Skills of personnel –Low utilization rate and high fixed costs
Strategy C	–Conventional, ⇒ functional medium scale production –Capacity C, number of machines N, amount of Fixed capital K Labor L	–FMS, medium capacity –Capacity 1.2 · C –Machines N/5 –Fixed capital 0.7 · K –Labor L/3	Complex control structure – Closed or open	–Capital productivity 1.75 × –Labor productivity 3.5 × –Quality improvements –Lead time and WIP reduction	–Software costs high –Partly more efficient machinery –High planning and training costs	–Management of change –Systems complexity –Skills of personnel

Table 2. Implementation strategies and associated benefits

	Starting point	*New system*	*Technology*	*Benefits*	*Costs*	*Risks*
Strategy A	-Small scale ⇒ semimanual batch production -Capacity C, number of machines N -Amount of fixed Capital K -Labor L	-FMS, automated high flexibility -Capacity 5 · C, number of machines N -Fixed capital 2 · K -Labor L	Compact control structure - Closed Architecture	-Capacity increase - capital productivity 5/2 × -Labor productivity 5 × -Decreased lead times and WIP -Improved quality	-Increased software costs -Increased training costs -More expensive machinery	-Software management -Management of change -Closed layout -Excess capacity
Strategy B	-High capacity ⇒ dedicated automation, mass production -Number of machines N -Amount of fixed Capital K -Labor L -Capacity C	-FMS, High capacity medium flexibility -Capacity C -Number of machines N/3 -Labor L -Fixed capital 0.7 · K	Advanced, complex control - Open architecture	-Flexibility increase -Capital productivity 1.4 × -Potential for future changes -Lead time and WIP reduction	-High software costs -High planning costs	-Systems complexity -Skills of personnel -Low utilization rate and high fixed costs
Strategy C	-Conventional, ⇒ functional medium scale production -Capacity C, number of machines N, amount of Fixed capital K Labor L	-FMS, medium capacity -Capacity 1.2 · C -Machines N/5 -Fixed capital 0.7 · K -Labor L/3	Complex control structure - Closed or open	-Capital productivity 1.75 × -Labor productivity 3.5 × -Quality improvements -Lead time and WIP reduction	-Software costs high -Partly more efficient machinery -High planning and training costs	-Management of change -Systems complexity -Skills of personnel

An interesting fact is the increased capacity as such. As noted above, if this has been a goal in itself, e.g., because of the growing demand, the necessary conditions can usually be met. However, there is always the possibility of excess capacity, which, to some extent, can be an economic risk. In any case, a company has to have a strong marketing capability to avoid overcapacity. As noted by Jaikumar [1988], if there are stable markets and a stable demand for the respective products, then there will be an imbalance between supply and demand, followed by a technological renewal process and a considerable productivity increase. Then only the most efficient producers will survive.

Usually the systems architecture corresponds to a compact system. Thus the system is, to some extent, closed, and it may be difficult to extend or change it. This can be an economic risk in a changing environment.

Strategy B can be called flexibility increase and future potential strategy. The economic benefits result from the increased capital productivity and the potential to make new product variations, which are usually associated with decreased lead times and work-in-progress. All these can lead to the acquisition of new market segments, due to the ability to customize products. These boundary conditions are usually met when a transfer line is changed to an FMS-type production without losing its high capacity. Usually the technological solution is a high-capacity solution, with a sophisticated architecture and a complex control and software system. Thus the major risks come from the complex system structure itself, which is managing the software production and managing rather complicated all-over planning. Because of the high price of the system, the utilization rate is even more critical than it was in the case of Strategy A. Thus, all that was said above on training and knowledge of operators is even more evident for case B.

The third potential strategy is case C, a strategy which can be called modernization strategy. Usually the starting point is a conventional, functional layout, including the problems of lead times and work-in-progress. In this case the main benefits result from different sources: considerable lead time and work-in-progress reduction, quality improvements and a rather high increase of both, labor and capital productivity. The old system as well the new system -- to some extent -- is a medium-capacity and a medium-flexibility system. This means that the system design has to meet numerous goals just to guarantee enough benefits, as described above.

In some cases a compact systems architecture is not enough, but a rather complex control and software structure is necessary. This may be a source of techno-economic risk; it does, however, put more emphasis on planning and designing for benefits. Other sources of risk are associated with the costs and the complexity of design. The change will be rather big. The management of this change is challenging, because a completely new way of thinking is needed in manufacturing. This necessitates again a special concern with regard to training and organizational

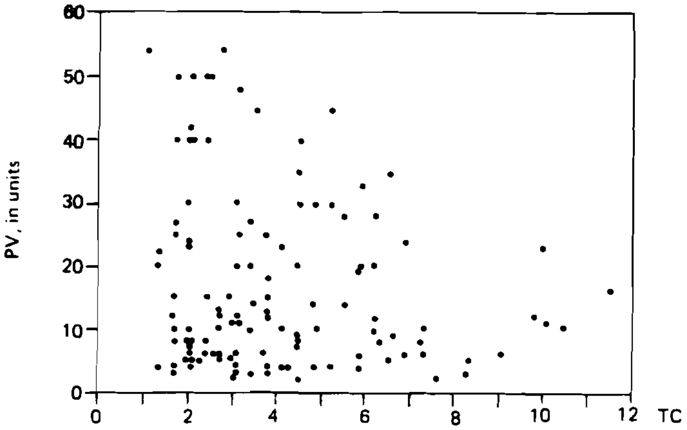

Figure 19. Product variation (PV) over technical complexity (TC).

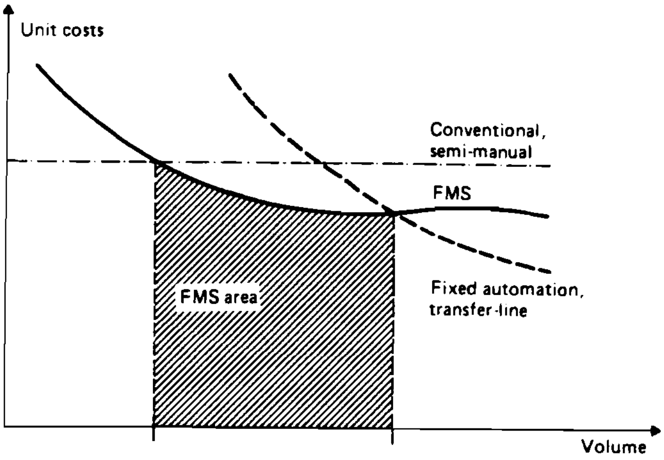

Figure 20a. Unit costs according to the conventional theory.

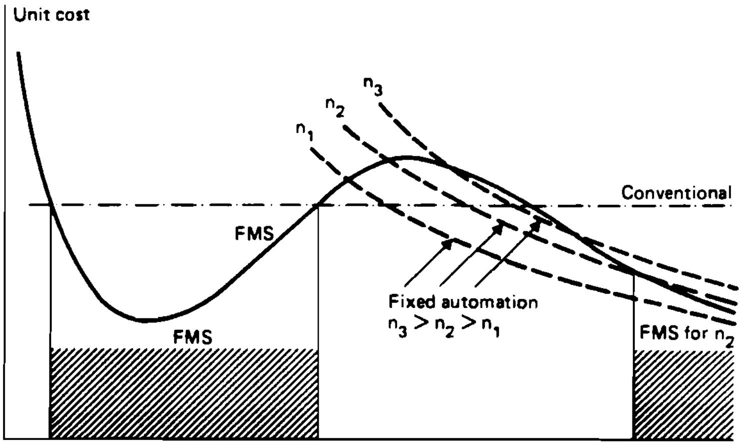

Figure 20b. Unit costs according to the revised theory (n-number of products).

which are associated with a capacity increasing strategy and lead time reduction. In between these two systems there is a modernization and work-in-progress reduction strategy, which can result in a complex or a compact system, depending on the starting point.

The basic typology can be explained by technological and economic factors. Because of technological limitations there are two kinds of systems realization technologies, which also represent different economic barriers, benefits and planning issues. A successful implementation is usually associated with a high utilization rate of the systems: the management of manufacturing time is critical for the success. This is understandable in view of the increasing share of fixed capital, and it also causes the design, as well as the training and capabilities of the personnel to be critical factors.

Based on the above facts, different implementation strategies can be proposed, where benefits, systems properties and costs will meet. The implementation strategies can also explain some contradictory results obtained from the statistical data.

It can be foreseen that the technological factor will still be critical in the near future. If, due to the standardization efforts, a modular type of systems software as well as a mechanical integration technology becomes available, it is possible to achieve step-wise implementation strategies and a wider range of beneficial systems. Then, of course, the diffusion of FM-systems can be wider than proposed above.

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BASES FOR FLEXIBILITY IN A SMALL COUNTRY
Some issues of the Finnish TES-programme

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Keywords: FMS, Production flexibility, Advanced manufacturing technology, Investment justification, Regional development

Abstract: Some results of the Finnish TES-program are presented. The general features of FMS-investment are discussed and the importance of production flexibility and its connection to the flexibility of the company are covered. The penetration of FMS-technology in Finland based on case studies is presented together with a presentation of the features of typical Finnish FM systems. The economical background of the Finnish FMS investments and some estimates for the future are given. The possibilities of flexible function and new technology for the Finnish clothing industry to change the recent declining trends are discussed. Some attempts to introduce flexibility and new technology into small and medium sized companies in two different regions are described.

1. PREFACE

Finland is a small country with about 5 million inhabitants. It is one of the youngest industrialized countries in Western Europe. The industrialization started late and industry exceeded agriculture and forestry as late as in the early 1960s, if the share of GNP is used as measure. For more detailed information see e.g. /6/ and /12/.

Until the late 1970s the forest industry has been the major industrial sector and still in 1986 this sector covered 37% of the Finnish export. The metal and mechanical engineering has, however, become the most important sector during the last years.

The trade with the Soviet Union and other CMEA countries was in the 1980s over 20% of the whole trade. The export has mainly consisted of machinery and other processed products, when the import has been energy and other raw materials (e.g. oil). Recently there have been difficulties to maintain the high level of the trade due to low oil prices.

According to /6/ the technological potential of Finland can be compared to other small OECD-countries like Norway, Denmark and Austria. Finland does not, however, belong to the same group as Switzerland, Sweden and Holland.

Although the development has been quite positive, there are structural problems combined both with the declining trade with the CMEA-countries and with maturation in certain sectors.

The Finnish TES-programme is connected to these estimations. It is dealing with the structural change in industry and the possibilities of technology and flexibility to meet the new demands. In this paper some of the themes of the national programme are discussed and some preliminary results are presented.

One of the aims of the programme is to develop models for investments in flexible production equipment. As apart of this work the meaning of different types of flexibility and their economical impacts are studied. In chapter 2 these general items are discussed.

The installed Finnish FM-systems are usually small and the main reason for the investment is the need of increased capacity. In chapter 3 some common features of the installations are presented.

The mentioned recent trends have had a great impact on the Finnish clothing industry. In the programme the possibilities of new technology has been studied. The work in this sector contains many manual phases. Moreover seasonal and other changes in the demand means that a flexible function is necessary. In chapter 4 some results from the study of the clothing industry are given.

For many small companies the changing surrounding induces difficulties. In chapter 5 some attempts to introduce new technology and especially flexibility into small and medium-sized companies are described. The companies are within two different regions with different industrial traditions, which has an influence on the possibilities for technological development.

2. SPECIAL FEATURES OF FMS-INVESTMENT

According to ECE /3/ FMS investments can be considered as pilot, showroom or rationalization investments. In a normal case the main motive is rationalization. If we compare FMS investments to other investments in the metalworking industry the following special features may occur.

- The impact of the investment reflects in a large area of the company. FMS causes changes in other departments. Benefits are gained in many cost centers but costs are calculated in one point.

- Costs are much more easily estimated than benefits.

- FMS installations require large organizational changes.

- The properties of the system will be developing along time after the actual installation.

- Training and retraining will increase 'knowledge capital' which is useful also later.

- Strategic advantages are difficult to evaluate.

2.1 Reasons to invest in FMS technology

The main reasons to invest in FM-technology are:

- need to increase productivity
- need to improve controllability of production
- customers need for a short delivery time
- desire to do more variations in the same system
- need to increase capacity
- lack of skilled workers
- desire to maintain large nominal flexibility
- desire to be low cost high quality producer

The most significant single reason is different for different companies and also in different countries. The increased capacity might be vital for a small but growing company. Need for productivity might be as important for a big as a small company. Especially in Finland one driving force is lack of trained machinists. The volume of the metalworking industry is increasing continuously and its needs more trained employees than is now available.

The production flexibility is also vital for both small and big companies. Without flexibility it is not possible for small companies to invest in automation. The main question is which kind of flexibility does the company need. This problem later will be discussed later.

The investment justification is totally different if the company is growing and needs more capacity than if it is declining. Companies also stress different matters if they have brilliant new products which they are starting to produce than if they are in the mature area where the competition is roughest.

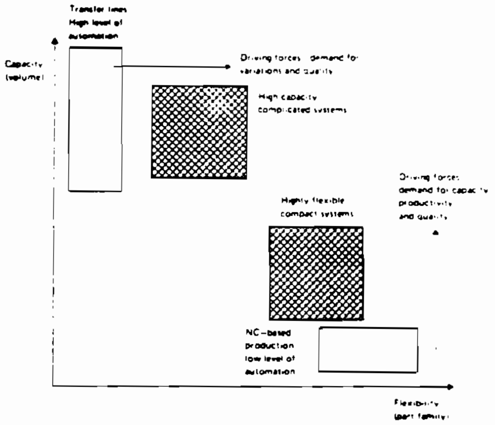

Figure 1. Companies can have different goals for flexibility. Either they need better productivity without loosing much nominal flexibility or they **want** more flexibility without **loosing** much productivity./1/

2.2 Cost and benefits of FMS

As said before it is much easier to estimate the coming costs of large production system than to take into consideration all the benefits. The easy way is to consider only those benefits which are clear and quite easy to quantify (direct and indirect benefits). But then there is a big risk to make a wrong investment decision. The list of costs and benefits are gathered from various sources and they are presented in source /8/.

2.2.1 Costs /8/5/10/4/

We can divide the costs of FMS into investment costs and operational costs. The investment cost is the sum of the elements in table 1.

BASIC INVESTMENT	OTHER INVESTMENT COSTS
Machine tools Robots Warehouse Transportation System control, HW+SW Special tools -pallets, fixtures, grippers, measurement	Project planning and development Installation Starting up -cost Training Changes in products Changes in other departments Adapting new prod. methodology

Table 1. Investment cost elements /8/.

Of course the main part of the investment is on the basic investment side. The other listed costs vary very much depending on the company's knowledge and complexity of the system.

The training costs might be very high. They depend on the workers basic education and their experience of CNC-machines and personnel strategy of the company. If the company is going to use multiskilled operators the training costs would be quite remarkable.

Starting up costs are connected to project planning and also to training costs. If the operators are well trained there would be less troubles in the starting up phase /10/4/.

When investing in FMS-technology there is most certainly a need of all kind of mental efforts which causes costs. Needed efforts are eg.: changing peoples attitude, adoption of new production philosophy, need to increase knowhow in the company in general. These costs are almost impossible to analyze but their nature is like investment. The company can use improved knowhow also in future investments.

Operational costs

The main difference in operational costs compared to stand alone NC or manual machines is that the capital costs are getting a greater share of the operational costs. Cost accounting based on direct labour cost and overhead costs is not any more accurate enough. Instead it is necessary to account the capital costs as a main part of the product costs.

2.2.2 Benefits

Even if it is not possible to evaluate the strategic benefits it is necessary to try to list them so that decision makers can take them into consideration in a non quantified way.

Data gathered from various sources shows that benefits of FMS-investment can be listed as below /8/.

DIRECT SAVINGS/BENEFITS	INDIRECT SAVINGS/BENEFITS
Direct labour savings	Indirect labour savings
Increase of productivity	Warehouse cost savings
Save of floorspace	W-I-P reduction
Save of material	Management cost reduction
Save of energy	Increase of market share
	Material savings cause of quality

BENEFITS WHICH ARE DIFFICULT TO QUANTIFY
Increased flexibility *)
More capacity
Better quality
Easier management of production
Impulse to innovations
Changes in working conditions
Solving the problem of lack of workers
Decrease of organizational errors

*) The production flexibility will be described later.

Table 2. Structure of the benefits of FMS /8/.

2.3 Strategy connected to FMS

2.3.1 Marketing investment

Particularly for small companies capacity increase is very meaningful. Their production capacity is intentionally or unintentionally increasing when they are investing in FMS. To achieve a high rate of utilization marketing must be taken care at early stage of planning and installation.

FMS is also somehow considered as a investment for marketing purposes. If the company invests in FMS only to fulfil the present needs it will not use the opportunity to achieve those benefits which are related to large product flexibility. If the company starts to use FMS in the most flexible way to give the best possible service to various customers it can achieve competitive advantages. Manufacturing is becoming more and more like a service function so it needs very close relations with R&D, marketing and production /15/.

2.3.2 Production flexibility/2/9/11/

The most important feature in production flexibility is that there are many different kind of flexibility. It is not so important to define strictly the different kinds of flexibility (because it can be specified in various ways) but to understand the differences and that companies have various needs and means to fulfill the needs. It must be noticed that there are different subareas in production flexibility and different ways to create flexibility.

Flexibility is always connected to <u>time</u>, <u>easiness of making changes</u>, and <u>cost</u>.

The opportunity to produce various parts and products in the same production system (<u>nominal flexibility</u>) is one of the most important reasons to invest in FMS. The other features of flexibility are how easily new parts can be introduced to the system (<u>new product flexibility</u>) and how secure the system is for future changes (<u>strategical flexibility</u>).

For a company it is necessary to share these three basic features of production flexibility in a more detailed way. The basic idea of production flexibility and its connection to the company's flexibility is shown in figure 2.

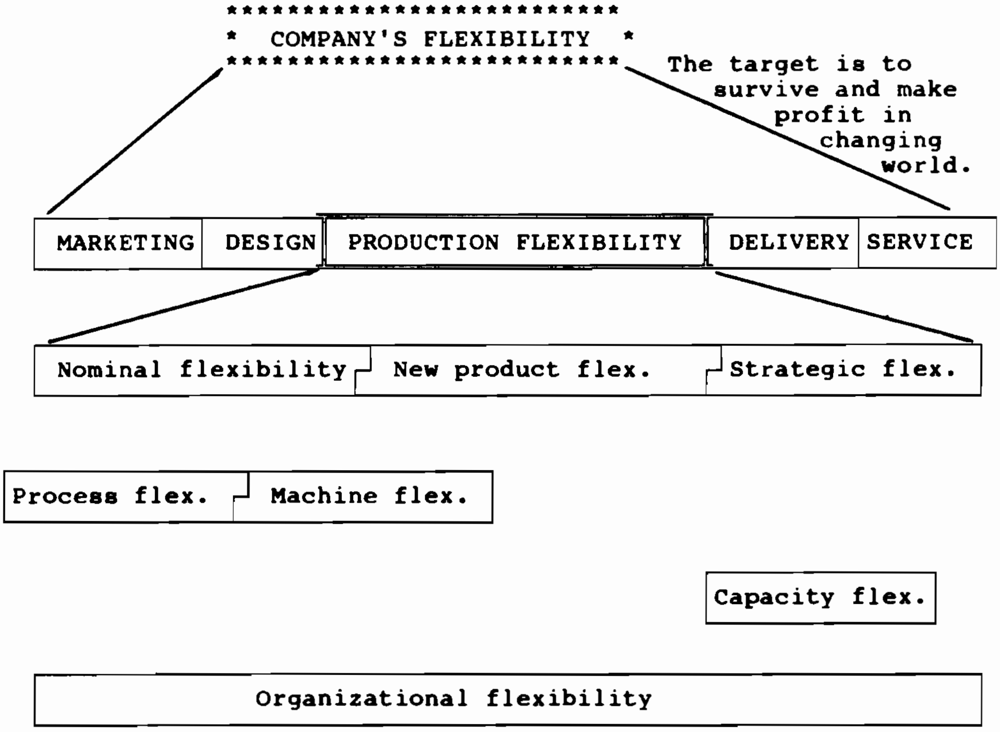

Figure 2. The structure of production flexibility and its connections to company's flexibility/9/.

The picture is trying to show that different companies can achieve flexibility in different ways. Some companies can shorten the delivery time mainly by investing in advanced design systems like CAD and CAE. Other companies may get most benefits by concentrating on flexible capacity. The most flexible companies will be flexible in many or all different branches of flexibility.

It would also be worth noticing that there can not be much flexibility without <u>organizational flexibility</u>. If the company will have ability to react to changing markets and to changing needs its personnel should be multiskilled and ready to change tasks if necessary. The question of organizational flexibility is also connected to flexible working hours.

The company's point of view seems to be forgotten quite often when discussing about production flexibility. There is no way to say right off that the FMS is not flexible if it produces for example only five different parts in very small batches. From the company's view it can be as flexible as required. If the end product is for example a big diesel engine and the company produces cylinder heads in FMS. It might be more critical to the lead time and small W-I-P to have small batches without internal set up time than to have bigger part family. Hence flexibility is a multidimensional concept.

2.4 Profitability

It is very difficult to say anything about FMS's profitability in general. The profitability is strongly connected to the company's situation (it's market, it's cost structure and it's position in production chain). FMS can be only a small part of a long production chain in the company or it can be the heart of the whole production.

If we simplify we have the trivial solution: FMS is profitable if it's benefits are greater than it's costs.

More over FMS is justified if it fulfills the expectations managers have put on it.

However the production cannot be profitable only by itself. Profitability is the function of the whole company and in fact it is the best indicator to show how well do the different parts of the company function together. Investing in advanced manufacturing technology should also need emphasize to marketing functions so that the properties of FMS could be used in a profitable way.

The factors of FMS which are affecting the profitability are listed below:

- capital productivity
    - zero inventories
    - small W-I-P
    - high utilization rate
    - high utilization %

- labour productivity
  - unmanned production

- material productivity
  - decrease of scrap
  - more stabile quality

- better ability to compete
  - short lead time
  - high quality

- flexibility
  - customers needs
  - delivery service

3. SOME EXPERIENCES OF FMS IN FINLAND

Most of the metalworking companies in Finland have used to operate in small batches and low volume production. Because of that history the progress of automation has been quite slow. Flexible manufacturing may change the situation. FM technology gives some opportunities to automate middle or even low volume part production.

If we look at the automation levels and production volume (ref. figure 1.) the hypothese is that most companies in Finland are advancing from right lower corner to upwards to have better productivity without loosing flexibility. Flexibility is a vital condition to most Finnish companies.

When we compare twelve Finnish FMS to other systems /13/ we find out that the mean value of the size of part family is much higher than in other systems (ref. figures in Appendix I).

3.1 History of Finnish FM systems

The first systems were installed in 1982 as can be seen from the figure 3. The growth of the number of systems has been quite steady during six years. The total amount of systems used in production is now twelve. All of the systems are in the metalworking industry. The upper line includes the systems in research and training application and then the total amount is 17 systems.

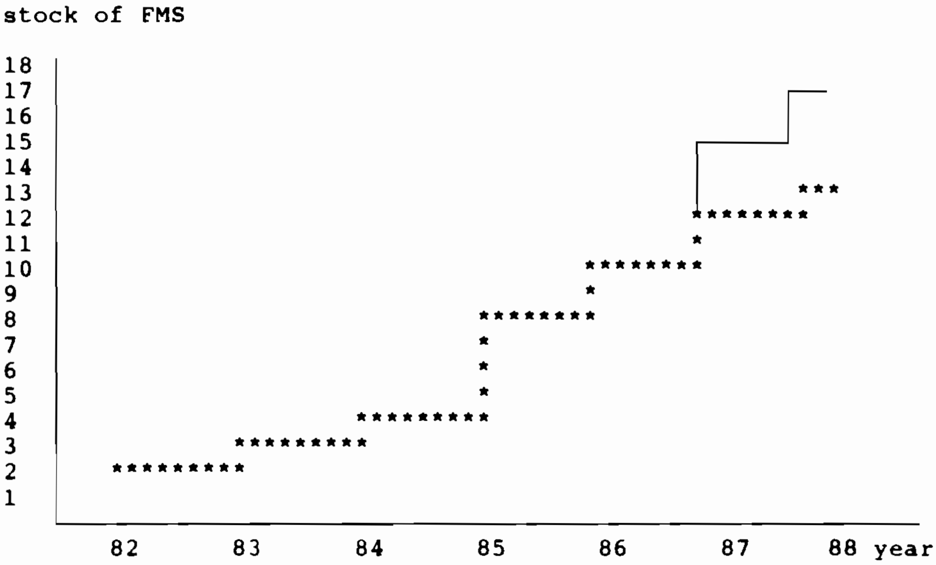

Figure 3. The cumulative stock of FMS in Finland.

3.2 Average system

The typical structure of a FMS in Finland is shown in figure 4. It includes an automatic storage and retrieval system for pallets (it includes stacker crane or robotcarrier for transportation), two or more machining centers, a washing machine, in average 120 tools in a magazine, a central computer control and loading-unloading places.

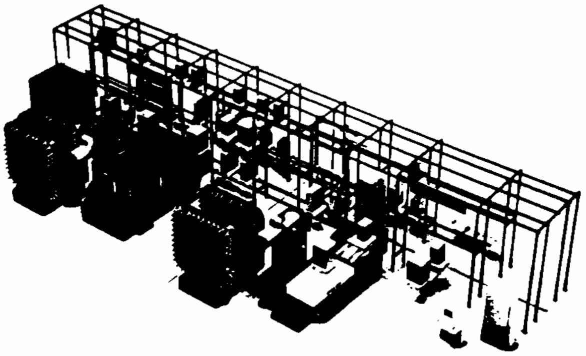

Figure 4. An example of common FMS configuration in Finland /company Valmet/.

There are also two systems which are based on open layout and AGVs.

The biggest FMS consist 9 CNC machines and 3 robots. Most of the systems are for prismatic parts. The part family produced in the systems is quite big. The largest part family is 200 and the smallest 5 parts.

The features of average Finnish FMS are:

- -it contains 3 machine tools *)
- -the part family includes 78 different part
- -it has no robots, 9/12 **)
- -it has automatic storage and retrieval system for pallets, 10/12
- -the high storage is equipped with a stacker crane
- -it usually makes prismatic parts, 11/12
- -it usually contains a washing machine
- -it is usually in a big company, 8/12
- -it is operated in three shifts, 7/9
- -it has increased the production capacity significantly

*) numbers are mean values
**) 9/12 means 9 cases out of 12 cases

3.3 Economical background

The economic indicators of the Finnish FM systems are *):

- -decrease of capital in stocks, 70 % (mainly WIP and product inventories)
- -capital in machines, little increased **)
- -reduction of machines, 66 %
- -utilization %, 72 % (based on 24 hours)
- -reduction of direct labour, 68 %
- -increase in productivity, 170 %
- -size of investment, 7.28 MFim (= 2 M USD) ***)
- -pay-back-time, 2.8 year

*) all numbers are mean values
**) Although the number of machines is lower, companies consider that they are more expensive to have.
***) The different investments is expressed by constant prices of 1988.

Usually a Finnish FMS is a relatively small compact system which has been paid back quite rapidly.

3.4 Flexibility in Finnish FMS

As can be seen from average system the nominal flexibility (number of different product and size of batches) is quite high in most of Finnish systems. The average number of different parts is 78 and the average batch size is 25 parts. If we compare these numbers to international numbers /13/ we find out that Finnish systems are much more flexible in average measured with these two primitive measures.

Because of difficulty to measure absolute flexibility a couple of examples are given.

Case I: Flexible organization

One of the FMS users has solved the problem connected to disturbances in long period of unintended (unmanned) production by using students from technical high school as operators during weekends and other vacations. The students can change the broken tools, clear the chip jams and so on.

Case II: Flexible organization

One company is using three operators in two shifts. Third shift is unmanned. Two highly skilled operators are working in different shift and one unskilled (for loading and unloading) is working between the shifts.

The schedule of the work is:

6.00 skilled worker 14.00 skilled worker 22.00

10.00 unskilled worker 18.00

Case III: Flexible capacity

One small subcontracting company uses a very sophisticated FMC to increase production capacity and particularly to help to balance the workload and manning level. When the demand is high they use the cell 24 hours per day 7 days per week. When the demand is decreasing they just make the unmanned time shorter. So no recruiting or firing is necessary. It is very important in the areas where there are lack of workers. Companies can not balance their production so easily with people as they can with machines.

Case IV: Nominal flexibility and product flexibility

120 different parts of a company's main product are machined in FMS. The scale of the parts varies from 10 * 10 mm to 700 * 700 mm and different materials (steel, aluminum, brass and plastics) are used in the same system. The parts are machined in batches of 2, 4 or 8. So system has a large nominal flexibility.

On the other hand the company considers that one of the greatest advantages of FMS is that they can change more easily the whole product generation. So they also have large product flexibility.

3.5 Near future

Some of the installed FM systems are already enlarged and two of them are going to have more machines in the near future. So the systems have proved to be at least to some extent strategically flexible.

Some of the notable metalworking companies have already made strategical decisions to continue to invest only in system technology. That altogether with the fact that the volume of the Finnish metalworking industry is increasing about 5 % per year /7/ will guarantee that FMS technology will continue to penetrate in the Finnish metalworking industry at least at the same speed as in thelast four years.

4. FLEXIBILITY AND THE CLOTHING INDUSTRY

4.1. Introduction

The clothing industry has been a declining sector in many countries. E.g. in the OECD area its share of the total manufacturing employment has decreased from about 8% in the 1960s to 3-4 % today /14/. The same trend has also been seen in Finland, although there are some differeces, especially delays.

Because of the described trends there has been discussions whether new technology and a wide use of information technology could improve productivity and to some extent compensate the great differences in labour costs in the clothing industry which traditionally has been very labour intensive. Also the question whether the new technology can give new competitive advantages due to possibilities for better overall flexibility has been rised. In the Finnish TES-programme these questions have been studied and the focus has been on new technology and its impacts: can the new technology reverse the current trend? In the following section some results of the study are given. For more detailed information see e.g./14/.

4.2. Main findings

Until 1982 the Finnish clothing industry grew due to the increased demand in major export markets in the Nordic countries and especially in the Soviet Union. The output has since that time decreased and the volume is today 15% lower than in the early 1980s. The Finnish clothing industry seems to have met the same problems as the industry in many other countries met 10-15 years ago.

The flexible production technology has mainly been used for the pre-assembly phases. Tese CAD/CAM solutions have improved the competitional strength of many large firms and they have got larger product differentiation due to better flexibility.

The assembly i.e. the sewing is still manual and this phase counts for 70-80 % of the total labour costs in the production. There are yet no major technological means for the automation of this phase, but there are many attempts going on in different places. However, still only small parts assembly or some specific solutions are available. The main problem is the material handling due to the characteristics of the fabric. A solution to these problems is not expected to be found within the next few years. The breakthrough will, however, be necessary to ensure the competiveness of the clothing industry in many idustrialized countries.

The Finnish clothing industry has rather rapidly adopted new technology. The fast application of technological innovations has been a necessary but not sufficient condition for the relative success of many firms. Other factors lye in design, marketing and management. Because the industry is mainly dependent on imported technology, the technology transfer is of great importance which indicates the need of high level of the education in the industry.

For the Finnish clothing industry the described development seems to continue in the near future. The output volume will continue to decrease and the import will increase which means that the trade balance will turn into a deficit already in the near future. However, the new technology will be a necessary condition to slow down this trend. Flexibility and fast response will be an advantage in new market areas of Western Europe. A competitive edge can be created by new technology, design, marketing and management skills. This implies because of large investment requirements that the structure of the industry seems to change in favour of large companies, which may be integrated into fabric production and distribution and market networks.

5. TECHNOLOGICAL DEVELOPMENT EFFORTS IN COMPANIES

5.1 Introduction

The main aim of the efforts is to develop the technological level in two different regions. The work is done on the enterprise level, where the aim is to support the enterprises to modernize their production and other functions. The transfer of technology and its regional support is also of great importance in this connection. Because of the difference in the studied regions available support functions are also different.

The studied regions are Lapland in the northern and Häme in the southern part of the country. The industrial history of Lapland is short and traditions weak. The main sectors are forestry and agriculture. During the recent years the service sector has grown. Especially the share of public services is higher than the average in the country. The industry is clearly below the average.

Häme on the other hand has long industrial traditions. The structure of the industry is, however, problematic. Historically, Häme has been the heart of Finnish agriculture. Thus the share of food processing and other industrial sectors in keen relations to agriculture has also been high. These sectors are declining which means a strong pressure to restructure the industry. Further problems are caused by the need to employ people leaving agriculture.

In table 3. the nature of the industrial work in the regions is compared. Technological level is defined according to the R&D expenditures in the companies (high for R&D > 4%, medium for 1% < R&D ≤ 4%, low for R&D < 1%).

The figures for Häme cover a larger area than the studied. The area of greater Tampere, second biggest city in Finland, is included in the figures but not in the study. Thus the absolute figures are too high and the percentage may be biased towards high technology.

The table nevertheless clearly indicates that Häme is almost at the average technological level of the country, while Lapland is lagging far behind. However, there are quite many enterprises of low technological level in Häme. The unemployment rate in Häme is about the same as for the whole country, when the rate is the double in Lapland.

	Lapland	Häme	Finland
High level	1.0 (8%)	21.8 (22%)	534.4 (20%)
Medium level	8.2 (64%)	37.7 (39%)	239.4 (45%)
Low level	3.6 (28%)	38.1 (39%)	186.1 (35%)
Sum	12.8 (100%)	97.6 (100%)	534.4 (100%)
Unemployment	10.6%	5.0%	5.0%

Table 3. The distribution of the industrial work (thousand employees) in 1985 according to the technological level and the unemployment rate 1985.

Governmental support to economic development in peripheral areas like Lapland is quite remarkable. About 15 to 20 per cent of the public regional development support is directed to Lapland. The corresponding share of Häme is only c. 2 %.

5.2. Case companies

In both studied regions c. 10 small or medium sized companies were selected to be included in the study. The distribution of case companies according to the sectors is presented in table 4.. The types of development projects are described in table 5..

	Lapland	Häme
Metal processing	4	5
Wood processing	3	2
Clothing industry	1	2
Ceramics and rock proc.	5	0
Plastic industry	0	3

Table 4. The number of case companies in different sectors.

The development of production technology has in many case its starting point in the need of higher flexibility in the production. Hence, some projects are dealing with mechanization or automation of assembly and material handling. Also the possibilities to connect CAD directly to the production are studied in some companies. For some companies new processing and testing methods are studied.

Within product development the possibilities for improvements of old products are studied, e.g. material tests has been carried out. In one case, the suitability of old production equipment for production of new products has been evaluated.

	Lapland	Häme
Production technology development	5	6
Product improvement or new products	6	4
New information technology for administrative routines	2	0

Table 5. Number of different types of development activities in the studied regions.

5.3. Preliminary results

Because the development activities are still being continued it is too early to make any final conclusions. However, in more than a half of the companies promising development projects are proceeding, while the evaluation of ideas is still going on in the other companies. Some general results can, however, already be seen.

In many small firms the level of technologies in use is quite modest. Their first needs usually concern simple information technologies to develop the administrative routines. In these cases the work of the project has often been delayed by a lack of suitable persons in the firm to handle new development projects.

In both regions there are, however, also enterprises using very sophisticated technologies, e.g. large and effective CAD systems. They have even had considerable international success. Some other case firms seem to be very flexible and have a high potential for further development. Even companies with subdelivery or other connections to these firms seem to be influenced from their developments.

The main target of the project is to technological development but the problems in the firms are usually more mixed and diffuse. In many cases the development needs concern business plans, strategic planning or economic problems rather than technologies. To solve these problems experts of business have been included into the projects.

Local services are quite well available to the industry in both regions. In Häme they are already a part of the old infrastructure. In Lapland strong public efforts have created many new services. For example, five centers for information technology have been founded. The developing networks have so far perhaps not been able to offer relevant services to the industry in all cases.

In sparsely populated areas many activities seem to concentrate in certain persons. They can influence quite a lot in the course and speed of development. Strong personal commitment and slow circulation of people seem sometimes to be positive but sometimes to be an obstacle for new ideas.

One of the main findings is the importance of the starting effort. In small firms the fact that the companies do not have to take the initiatives themselves and that consultancy from specialists is free of charge and bureaucracy seem to have been crucial for the initiation of the development projects.

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APPENDIX I

The basic figures shown below are taken from Tchijov's and Scheinin's working paper (ref. 9). The Finnish averaged cases has been pointed out by arrows. Indicator n means number of cases information has been available and x means average value.

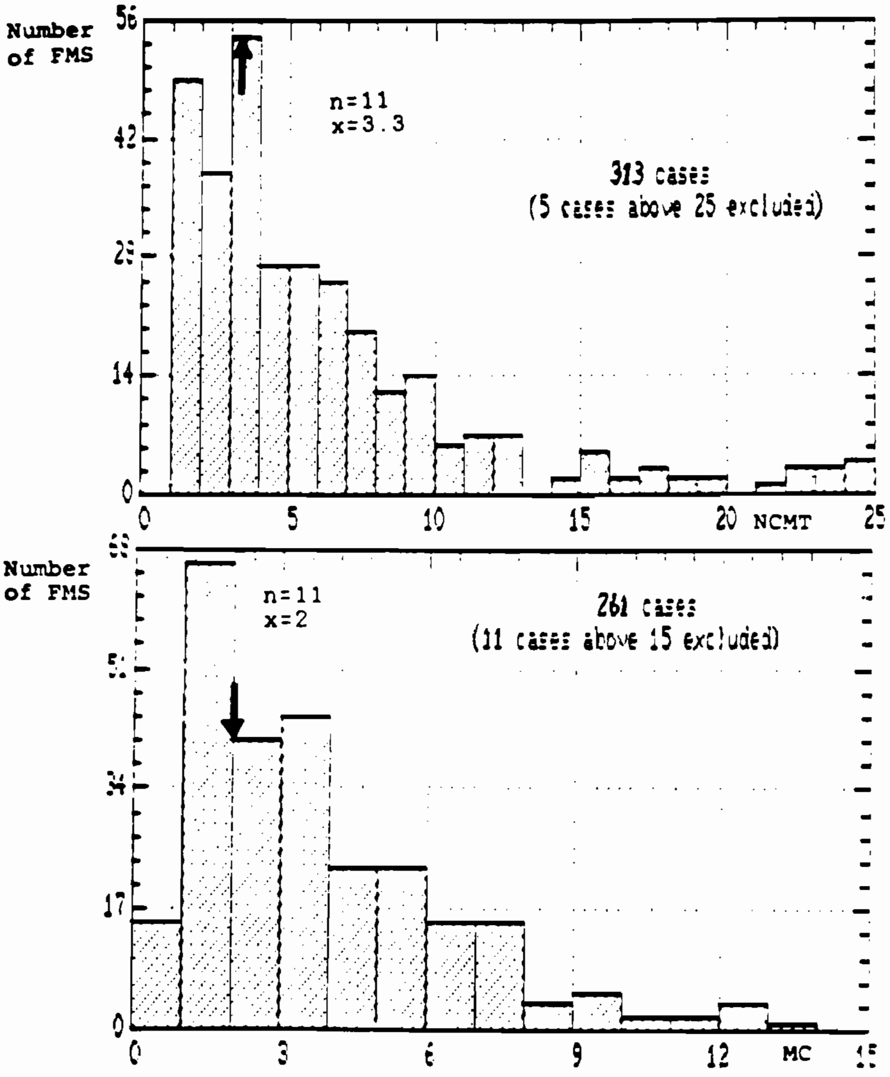

Figure A1. Distribution of FMS by their technical complexity. Number of FMS over numerically controlled machine tools (NCMT) and machining centers (MC).

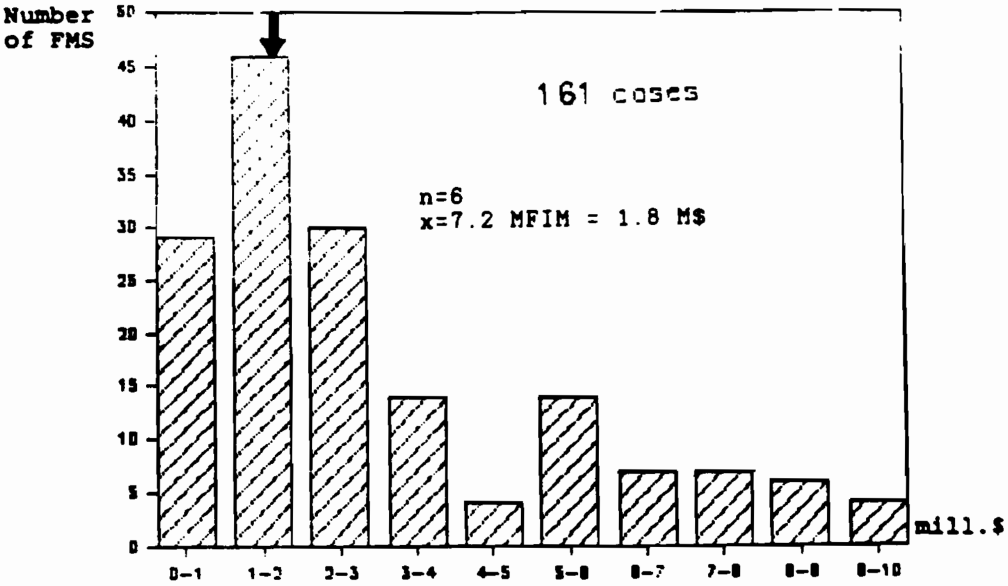

Figure A2. FMS distribution over investment cost.

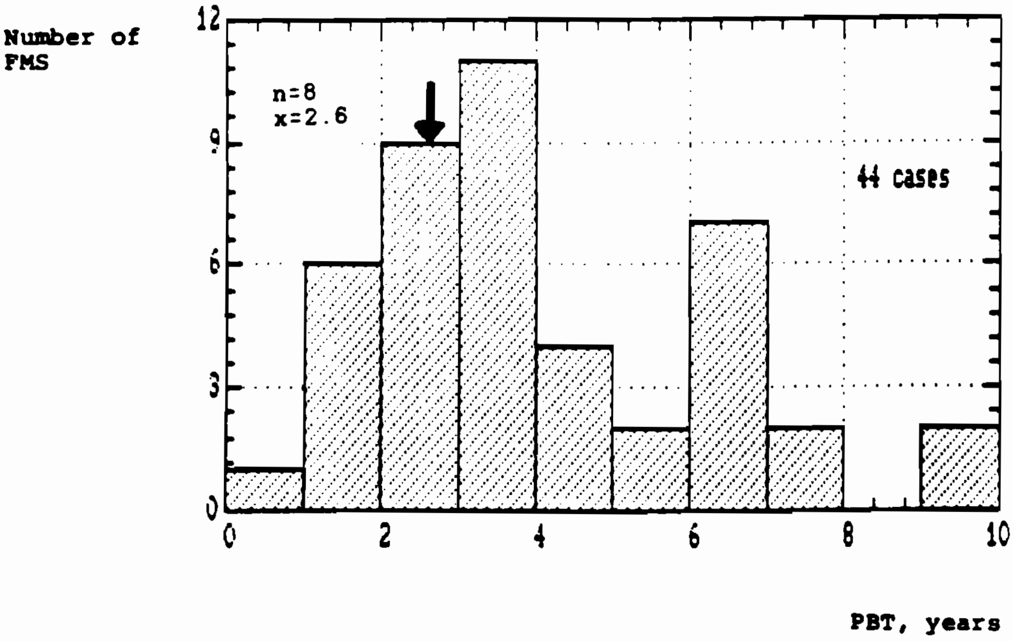

Figure A3. FMS distribution over pay-back time.

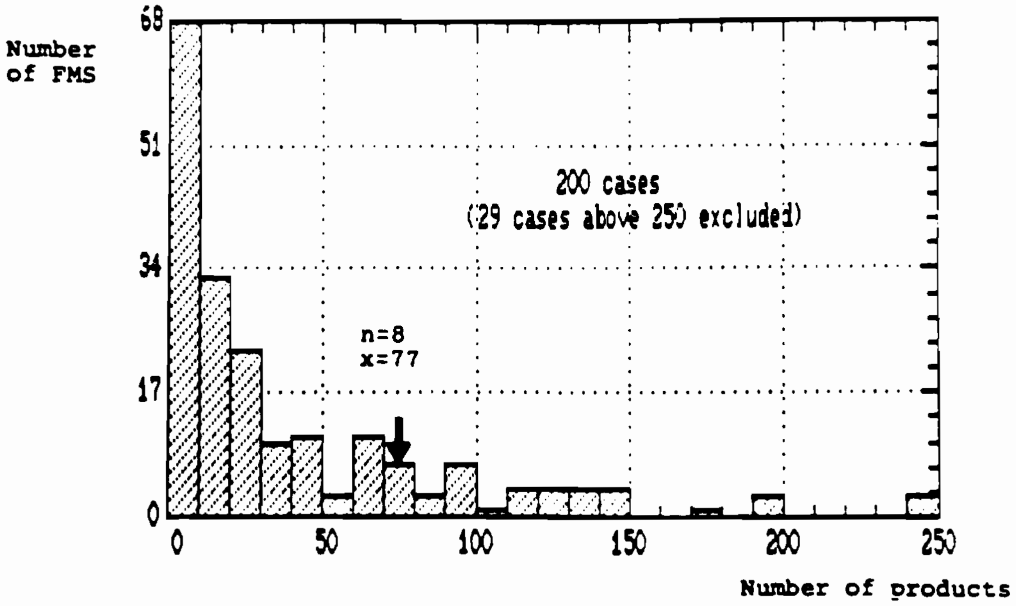

Figure A4. FMS flexibility, number of parts produced in FMS

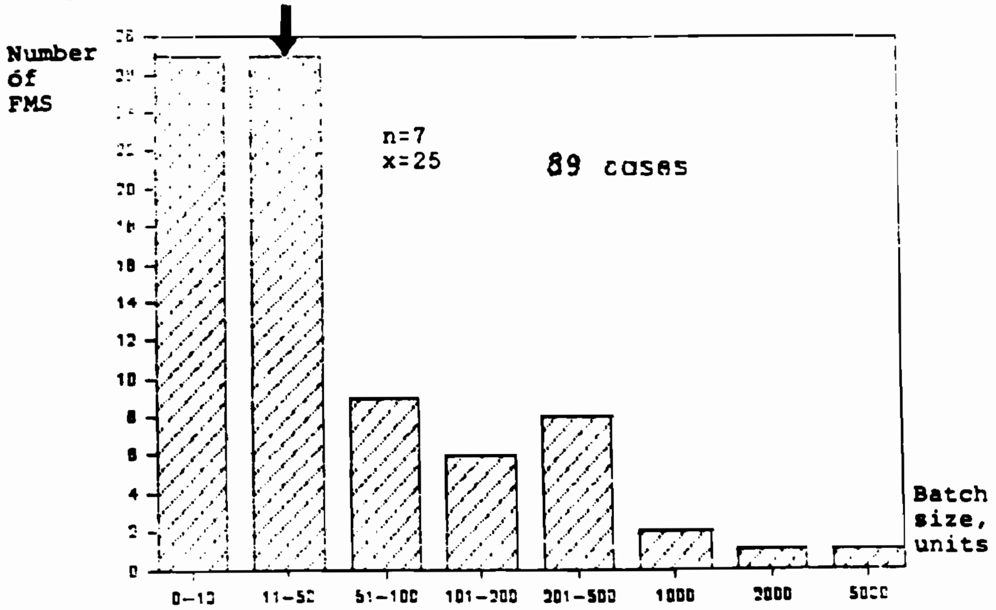

Figure A5. FMS distribution over batch size.

Trends and Problems of CIM in Japanese Manufacturing Industries - from Recent Surveys in Japan

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INTRODUCTION

Many researchers have reported the various kinds of the effects of CIM technologies based on case studies and surveys. [Bessant, 1985][Haywood, 1987] [Sheinin, 1987] [Tchijov,1988] Since these CIM technologies are still in their embryonic phase, there are not yet standard statistics. It is quite restricted to investigate the macro economic trend of these technologies based on the practical data.[Mori,1987]

In Japanese manufacturing industries, many factories have eagerly implemented computer aided production equipment, i.e. industrial robots, NC machine tools and CAD/CAM systems. Although the definitions of these technologies are not yet well established, the association of machinery industry and some journals have been interested in the present situations and future issues of these technologies. Fortunately, some of these survey results are available from Economic Research Institute of Japan Society for the Promotion of Machine Industry (JSPMI-ERI), NIKKEI Computer Graphics. etc.

The purpose of this paper is to introduce the results of these studies and extract the trends and the problems of CIM technologies through the comparison among survey results.

1.Contents of the Surveys

The surveys described in this paper are the followings:

1.[JSPMI,1985]:The Progress and Future Issues of FA, Economic Research Institute of Japan Society for the Promotion of Machine Industry (JSPMI-ERI), May, 1985
2.[JSPMI,1986]:The Progress of FA and Information Systems and the Structural Changes of Subcontracts and Small-medium Sized Companies, Economic Research Institute of Japan Society for the Promotion of Machine Industry (JSPMI-ERI), May, 1986
3.[JSPMI,1987]:The Trends and Issues of CIM and Design Automation, Economic Research Institute of Japan Society for the Promotion of Machine Industry (JSPMI-ERI), May, 1987
4.[NIKKEI,1987]:A Survey on CAD Systems, NIKKEI Computer Graphics, October, 1987

In the first survey achieved in 1984, 800 machinery industry factories are asked and 213 factories replied. The purpose of this survey is to obtain a basic information on the hardware (production equipment), the software (information system) and organization system. The questionaire consists of mainly three parts, namely, circumstances of production, present and future automatization and future problems of FA.

The second one surveyed the influence of CIM technologies upon the relations between main companies and subcontracts. 186 answers from main companies and 334 from subcontracts and small-medium sized factories are described. After the oil crisis, large companies have eagerly invested new production systems to reduce cost and adapt market changes. Information systems and FA are now quite common systems for the main companies. It follows that the subcontracts and small to medium sized factories face structural changes of production networks and are also forced to improve their production facilities. This survey aims at clarifying the trends and the subjects of FA systems for the subcontracts and small to medium sized factories.

The third one focused on the trends and issues of design automation as a part of CIM. 147 machinery factories are investigated. Since the design automation may be one of the key role of future CIM systems, this report focuses on the present position and the future possibilities of CAD. The outcome of CAD and the approach toward CIM are also presented.

The fourth report given by NIKKEI also reported the practical application of CAD systems based on the broad questionaire. 516 effective responses are presented. The application field, the type of computer systems, the purpose and the outcome of CAD systems are summarized.

Since it is impossible to refer all of the surveyed results, this paper mainly deals with (1).circumstances of Japanese machinery industry, (2).the purpose of FA, CAD or CIM, (3).trends of automatization rate, (4).the barrier and the outcome of CIM equipment. Some case studies are also shown.

2.Circumstances of Machinery Industry

Many researchers have discussed the driving force of CIM technologies other than direct cost reduction. For instance, Ayres [Ayres,1987] pointed out the five categories of CIM benefits. Namely, (1).labor force reduction, (2).capacity augmenting, (3).capital sharing, (4).product quality improvement and (5).acceleration of product performance innovation. Ranta[Ranta,1988] classified the technological means of flexibility into the following four categories:A.design flexibility, B.manufacturing flexibility which focuses on variations in product form, timing and volumes, C.material supply from the view of logistics, and D.distribution flexibility.

It may be true that all of these reasons are the driving force of the investment of computer aided systems. However, the importance of these reasons might be different among industries and economic conditions. Before comparing the reply patterns of the surveys, let me refer the economic and technological circumstances of machinery industries given by JSPMI-ERI[JSPMI,1985][JSPMI,1986].

Figure.1 and Figure.2 are extracted from the above survey. The distributions of the growth rates during 1981 to 1984 of product variations and component numbers in 213 factories are exhibited. One can observe that about 10% of surveyed factories in the transportation and precision machinery industries replied more than 200% growth of product variations as well as component numbers. The similar question is done by JSPMI in 1986. Figure.3 represent the trend of product variations in 186 main companies. Although the asked companies are different from those in [JSPMI,1985], one may conclude the fact that the product variations are still increasing.

This tendency is often compatible with shorter life cycle of the product. From Figure.4 to Figure.8, the distributions of average life cycle of the product are exhibited.[JSPMI,1985] They are also summarized in Table.1 as well as the mean repayment year of FA systems. It is noteworthy that the mean life cycle in the electric machinery industry and precision machinery industry declined more than one year during in three years.

Figure.9 to Figure.14 and Table.2 extracted from [JSPMI,1986] exhibit the economic trends of 186 main companies. One can easily observe that human saving technologies have worked well and that subcontract factories might have contributed to the productivity.

3.the Purposes of FA, CIM and CAD

Table.3 to Table.6 summarize the purpose of FA, CIM and CAD systems extracted from different data sources, i.e. [JSPMI,1985], [JSPMI,1986], [JSPMI,1987] and [NIKKEI,1987]. Although both the object and subject are different among these surveys, one can find out the fact - human power reduction is yet the main purpose of these technologies.

It should be pointed out that the product quality improvement was a important purpose in 1984. But the ranking of this item went down afterwards.

One interesting table is extracted from [JSPMI,1987] shown in Table.7, where the approaches toward CIM in the past and future are summarized. Most of the companies have implemented ME equipment as a revised component of traditional production systems and want to reconstruct them as CIM by topdown approach. In other words, many of the existing FA or CIM systems in Japanese industry are not established as the true conceptual CIM systems, or, the true CIM concepts are now penetrating in Japanese industry.

4.Trends of Automatization

The actual automatization rate of process line may be one of the most important information to investigate the effects of the new production systems. In case of labor substitutability of industrial robots, JIRA[JIRA,1985]'s survey data are available.

All the surveys given by JSPMI, fortunately, mentioned not only the present automatization rates of process line but also their assessment values in the future. The definition of "automatization rate" in these surveys is a subjective assessment value of the managers based on the number of process steps and process time achieved by computer aided equipment.

Table.8 is extracted from [JSPMI,1985]. Automatization rates are expected to increase rapidly after 1984. Table.9 shows the results of the same question in 1986 for the main companies. These are visualized in Figure.15 to Figure.24. Generally speaking, the managers expect to automate most of the process steps, especially design and drafting step and assembly of electric machine. Table.10 extracted from [JSPMI,1987] also shows this point. But through the comparison between Table.8 and Table.10, one can find out that the level of automatization rate in 1987 is almost similar to that of 1984 value in Table.8. Moreover, the future assessment values of design automatization are quite similar between these two surveys. Although the coverages of these surveys are different, one might conclude that the design automatization by CAD/CAM is long hoped but less easy than the expected.

The assessed score of CAD facility in Table.6 indicates that the present CAD systems are still only design support tools and yet insufficient to substitute human workers. Table.11 and Table.12 extracted from [NIKKEI,1987] may support this finding, since the process speed of all CAD systems are hoped to be improved. Nonetheless, CAD is still regarded as a main part of future production systems and planned to be implemented. Table.13 summarizes this tendency.

5.the Barrier and the Outcome of FA, CIM and CAD systems

Since the computer aided production systems are implemented by various reasons, it is quite difficult to evaluate the outcome of computer aided production systems quantitatively. Especially in case of CAD systems, it is still doubtful whether present CAD systems provide economic outcomes comparing with their investment. The assessed score of CAD systems in Table.6 indicates that they have not reached the design process revolution. The survey on CAD systems by NIKKEI [NIKKEI,1987] presented some comments:

"It is clear that the CAD systems are effective. But the quantitative evaluation of their outcomes is very hard." (construction industry)
"Although it is difficult to evaluate the benefits of CAD systems, no engineers can design without them." (automobile industry)

The following comments are the negative opinions:

"Present CAD systems are effective to adapt the increasing product variation but hardly contribute to design time reduction."(electric machinery industry)
"More effectively one wants to utilize CAD systems, more expensive the total system costs." (general machinery industry)
"It is hard to reduce design process time by CAD systems. They work as only drafting tools."(electric machinery industry)

Needless to say, the role and the outcome of CAD systems are different by industries. JSPMI [JSPMI,1987] surveyed the outcomes of CIM. Table.14 indicates that CIM systems have contributed to the design time reduction and design manpower savings for all machinery industries. JSPMI pointed out that the outcome of 3.progress of standardization was important.

The above two contradictory results may suggest that present CAD systems provide intangible effects and are expected to contribute to all the production systems after overcoming some problems. The barriers against CIM penetration is shown in Table.15. It should be noted that all industries pointed out the next three items as main problems: 1.huge investment, 5.managemental issues and 6.products standardization. The last two points should be overcome by topdown total production design. In this sense, the results in Table.7, Table.14 and Table.15 are quite consistent.

On the other hand, the barriers against CIM for the subcontracts and small to medium sized factories show rather different issues as is shown in Table.16 [JSPMI,1986]. They pointed out the problems of manpower (item 4 and 5) as well as 1.huge investment. It may be serious for these factories to input more engineers for the new systems. Moreover, the high score for 7.no advantage of FA suggests that subcontracts and small to medium sized factories are suffering from the trends of CIM and FA of main companies. JSPMI[JSPMI,1986] mentioned that some of the subcontracts have implemented ME equipment (sometimes it does not directly contribute to the productivity improvement) responding to the demand of main companies. JSPMI also pointed out that ME equipment as well as FA is effective for the independent small to medium sized factories. Table.13 might support this point.

The economic benefits of FA and FMS are demonstrated in many case studies. Unfortunately, the question on the economic outcome of CIM systems is restricted within order cost reduction for the subcontracts in this survey. Therefore their actual economic benefits are unknown in the questionaire.

Here two case studies on the effects of FMS are extracted from JSPMI [JSPMI,1986}.

Case-A:a firm of construction vehicle industry (large company)

·Grouping technology:adopted - Subcontracts are restructured based on GT.

·Trends of components and products variation in this factory are shown in Table.17.

·230 CNC machine tools including 70 MC's and 5 industrial robots are implemented. Total investment was around twice of traditional production line.

- ·Average operating ratio is 80% and production capacity is doubled.
- ·Number of machining tools is reduced from 17 to 3.
- ·Number of human workers is reduced from 24 to 1.
- ·Average lead time from material input to the end of process is reduced from 1.5 month to 3 days.
- ·CAD/CAM systems are yet standalone type.

Table.17 Trends of Components and Products Variation

	1972	1985
components	16,000	95,000
products	95	870

source:[JSPMI,1986]

Case-B:middle sized company (machine tools industry)

- ·1984 in operation
- ·The production capacity and the comparison between before and after the FMS are summarized in Table.18 and Table.19.

Table.18 Production Capacity

number of manufacturing steps	550
average lot size	10/month
number of products	270/24h
process time	47min. per unit

source:[JSPMI,1986]

Table.19 Comparison between before and after the FMS

	FMS	old system	ratio
number of MC	10	16	.63
human workers	5	16	.31
operators	4	5	.8
standard man-hour	4920h/m	5084h/m	.97
operating ratio	.93	.64	1.45
effective man-hour	4576h/m	3254h/m	1.41

source:[JSPMI,1986]

Conclusion

Since the purpose of this paper is to show and compare recent surveys on FA, CIM and CAD systems, no quantitative analysis are presented in this paper. Through the comparison of these surveys, one may conclude the followings:

1.The penetration of computer aided equipment is still continuing.

2.The main area of automatization in these years is design automatization.

3.But the facility and the outcome of CAD systems is still low. For the integration of production systems, new topdown approach is needed. This concept is now being recognized.

4.The structure between main companies and subcontracts and small to medium sized factories is changing. Some subcontracts are involved in the FA systems of main companies and some small to medium sized factories utilize ME equipment effectively.

ACKNOWLEDGMENT

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Table.1 Life Cycle of Products and Repayment Year of ME Equipment

		TOTAL	General machinery	Electric machinery	Transport. machinery	Precision machinery
life cycle of products	1981	4.979	5.443	4.553	4.720	4.981
	1984	4.030	4.451	3.246	4.206	3.865
repayment year of ME system		6.201	6.792	5.085	6.775	6.000

Source:Advances of FA and Future Issues (JSPMI-ERI 1985)

Table.2 Trends of Cost and Output in 1980,1985
based on 1975 value

	year	TOTAL 186	General machinery 65	Electric machinery 48	Transport. machinery 57	Precision machinery 16
1.output in value	1975	100	100	100	100	100
	1980	177.4	178.3	181.3	175	169
	1985	253.2	242.3	300.6	224.5	253.2
2.number of product types	1975	100	100	100	100	100
	1980	127.9	135.2	120.9	122.5	138.5
	1985	158.2	176.4	145.2	147	158
3.direct labor cost	1975	100	100	100	100	100
	1980	99.5	95.7	98.1	103.2	107.9
	1985	106.9	100.5	106.9	109	129.9
4.indirect labor cost incl. R&D	1975	100	100	100	100	100
	1980	104.1	95.6	106.3	109	118.1
	1985	116.3	102.4	124.4	119.7	141.1
5.labor cost for R&D	1975	100	100	100	100	100
	1980	136.3	110.4	179.6	127.5	147.3
	1985	192.2	155.5	273.6	165	200.4
6.material cost	1975	100	100	100	100	100
	1980	190	200.8	189.9	177.4	185.5
	1985	273.6	266.3	343.2	223.2	259.8
7.expenditure for subcontracts	1975	100	100	100	100	100
	1980	188.7	209.6	192.6	171.3	139.8
	1985	287.6	273.6	390.3	234.5	209.8
8.number of ordered process	1975	100	100	100	100	100
	1980	163.9	170.7	175.8	154	125
	1985	396.5	243.2	879.5	204.5	124

source:Advances of Information and FA Systems and Structural Change of Subcontracts
and Small-medium Sized Factories (JSPMI-ERI, 1986)

Table.3 Main Purpose of FA in 213 factories

	TOTAL	General machinery	Electric machinery	Transport. machinery	Precision machinery
quality of products	54.5	45.0	64.1	65.1	37.5
lead time reduction	38.5	46.3	40.6	23.3	37.5
human saving	80.3	83.8	81.3	81.4	62.5
production capacity	39.4	45.0	48.4	14.0	62.5
flexibility	33.3	41.3	23.4	37.2	31.3
cost stabilization	8.9	11.3	3.1	9.3	12.5
safety of workers	12.7	7.5	7.8	30.2	.0
others	2.8	3.8	3.1	.0	.0

Source:Advances of FA and Future Issues (JSPMI-ERI 1985)

Table.4 Main Purpose of FA in Subcontracts or Small-medium Sized Factories
(in %, 1986)

	TOTAL 334	General machinery 82	Electric machinery 75	Transport. machinery 113	Precision machinery 33	Metal Molding 31
1.quality improvement	31.7	28	29.3	30	33.3	51.6
2.reduction of lead time	23.1	17.1	30.7	26.5	15.2	16.1
3.human saving	52.1	58.5	45.3	55.8	48.5	41.9
4.production capacity	39.5	43.9	38.7	33.6	42.4	48.4
5.expand order acceptance	14.4	15.9	10.7	14.2	12.1	22.6
6.expand product types	8.1	11	6.7	4.4	18.2	6.5
7.advice by main company	3	2.4	6.7	2.7	0	0
8.rental from main company	.9	0	1.3	1.8	0	0
9.others	1.8	3.7	1.3	.9	18.2	0

source:Advances of Information and FA Systems and Structural Change of Subcontracts and Small-medium Sized Factories (JSPMI-ERI, 1986)

Table.5 Ranking of Main Purpose of CIM by Machinery Industry
1:most important - 5:not important

	TOTAL 147	General machinery 51	Electric machinery 50	Transport. machinery 39	Precision machinery 7
1.quality of product	2.40	2.67	2.11	2.39	2.17
2.time for delivery	1.98	1.86	1.87	2.43	1.43
3.direct cost reduction	1.91	1.78	2.08	1.79	2.33
4.indirect cost reduction	1.98	1.97	1.91	2.17	1.50
5.design change	2.19	2.30	2.29	2.07	1.50
6.demand uncertainty	2.25	2.25	2.10	2.35	1.83
7.total integration;	2.70	2.91	2.47	2.79	2.40

source:Surveys and Prospects on the Present CIM Directions and Design-automatization (JSPMI-ERI, 1987)

Table.6 The Purpose of CAD/CAM (%) and their Outcome Assessment in 516 Factories

	expected(%)	assessed score
design manpower reduction	90.5	4.85
design quality improvement	62.4	6.05
design time reduction	67.3	3.15
design cost reduction	31.7	.95
drawings management	21.8	.7
presentation of drawings	25.9	5.85
better impression	12.7	4.65
adapting design variations	29.1	2.75
labor cost reduction	11.1	-1.05
higher R&D ability	17.2	1.2
technology improvement	17.0	1.85

The score of assessment;
10:well achieved 5:something achived -5:not achived -10:contrary result

Source:*Nikkei Computer Graphics* (1987)

Table.7 Approach towards CIM; present and future

		TOTAL	General machinery	Electric machinery	Transport. machinery	Precision machinery
		147	51	50	39	7
1.bottom up approach	present	123	39	42	35	7
	future	32	11	8	10	9
2.top down approach	present	14	7	5	2	0
	future	103	33	38	28	4
3.others	present	2	1	0	1	0
	future	4	4	0	0	0
4.unknown	present	8	4	3	1	0
	future	8	3	4	1	0

source:Surveys and Prospects on the Present CIM Directions and Design-automatization
(JSPMI-ERI, 1987)

Table.8 Automatization Rate by Job Type in 1984 and 1989 (%)

	year	TOTAL	General machinery	Electric machinery	Transport. machinery	Precision machinery
1.design & drafting	1984	17.556	15.493	22.143	23.158	16.923
	1989	49.780	45.278	49.091	54.444	58.462
2.forming	1984	14.656	6.383	29.268	12.143	10.909
	1989	32.154	17.778	45.000	37.692	36.000
3.machining	1984	30.843	32.533	32.340	29.333	36.667
	1989	55.000	56.857	49.565	51.111	69.091
4.assembly (machinery components)	1984	14.268	8.485	21.250	21.111	27.692
	1989	35.472	20.000	44.091	44.242	51.429
5.assembly (electric components)	1984	16.964	.625	25.283	13.750	35.556
	1989	38.929	16.471	50.196	36.000	62.000
6.inspection	1984	16.778	11.014	26.316	16.757	21.538
	1989	38.523	29.254	48.000	36.471	49.231
7.transfer & warehouse	1984	10.296	9.231	13.725	12.571	9.231
	1989	35.882	32.239	40.385	31.250	49.231
8.welding	1984	17.286	12.222	22.727	25.000	20.000
	1989	38.346	28.889	43.902	50.714	32.500
9.heat treatment	1984	9.217	5.000	14.595	15.833	12.500
	1989	21.964	29.423	25.143	30.476	24.444
10.painting	1984	10.000	8.136	16.216	14.545	.000
	1989	28.702	22.963	34.444	35.625	20.000
11.total system	1984	23.550	20.000	30.741	25.714	30.000
	1989	48.605	43.582	55.000	48.235	53.846

Source:Advances of FA and Future Issues (JSPMI-ERI 1985)

Table.9 Automatization Rate 1982,1985 and 1988 by Job Type

	year	TOTAL	General machinery	Electric machinery	Transport. machinery	Precision machinery
		186	65	48	57	16
1.design & drafting	1982	18.1	23.1	11.2	21.3	12.5
	1985	27	26.9	23.3	29.4	32.2
	1988	46.2	44.7	41.5	47.9	58.3
2.metal molding	1982	29.5	46.5	20.5	27.1	23.3
	1985	32.9	46.5	26.4	30.3	34.2
	1988	56.1	57.3	39.3	45.2	45.8
3.press	1982	37.3	40.1	37.3	32.7	50
	1985	47.4	48.7	47.6	41.9	61.7
	1988	57.2	60.9	58.3	51.8	70.8
4.plastic forming	1982	40.4	49.4	40	29	48
	1985	51.3	60	53.1	42.6	56.7
	1988	60.7	71.7	60.4	56.8	56
5.machining	1982	33.3	38.3	27.1	27.4	38.5
	1985	54.5	46.1	39.7	39.5	57.3
	1988	55.8	57.6	49.6	54.3	65.8
6.assembly (machinery)	1982	23.4	25.1	23.7	21.3	20
	1985	29.4	28	29	30.5	33.8
	1988	37.2	34.4	36.6	38.8	45.6
7.assembly (electric)	1982	23.2	23.1	23	21	25.7
	1985	32.6	31.6	31.8	31.4	36.8
	1988	46.4	38.6	44.7	50.9	56.4
8.welding	1982	32.7	33.6	37.9	34.5	46.7
	1985	39.6	34.8	37.8	44.3	42
	1988	51.3	44.2	48.2	58.3	58
9.painting	1982	42.2	41.1	53.6	38.6	42
	1985	48.7	48.1	47.2	49.6	50.7
	1988	55.2	52.6	51.2	57.9	62.1
10.total system	1982	25.5	23.6	27.3	26.8	24.1
	1985	35.3	34.3	37.7	33.3	39.1
	1988	48.4	43.5	52.1	48.6	57.7

source:Advances of Information and FA Systems and Structural Change of Subcontracts and Small-medium Sized Factories (JSPMI-ERI, 1986)

Table.10 Assessment of Automatization Rate in Designing Process
Present and Future (%)

		TOTAL 147	General machinery 51	Electric machinery 50	Transport. machinery 39	Precision machiner 7
1.analysis and simulation by CAE	1987	13.85	12.27	10.87	18.75	8.57
	1992	43.23	41.78	41.78	49.00	37.14
2.design of the basic concept	1987	13.64	15.65	13.78	11.56	11.43
	1992	44.29	46.52	42.27	43.57	37.14
3.basic design ;by CAE/CAD	1987	24.55	24.04	24.04	26.67	21.43
	1992	57.77	60.43	56.09	57.33	52.86
4.detailed design ;by CAD	1987	26.96	25.11	25.96	31.47	24.29
	1992	62.05	64.04	59.57	65.16	51.43
5.design process total ;by CAE/CAD	1987	21.77	21.09	20.71	24.33	21.67
	1992	54.72	55.00	54.42	56.21	51.25
6.total production ;by CAD/CAM	1987	14.05	10.00	14.13	26.67	21.43
	1992	47.30	46.74	46.28	50.34	44.29
7.process design ;by CAPP	1987	24.55	24.04	24.04	26.67	21.43
	1992	40.24	38.33	41.11	41.94	38.57
8.job design ;by CAM	1987	21.08	20.91	21.11	20.88	22.86
	1992	52.83	57.61	51.52	53.55	47.14
9.whole design process	1987	19.17	14.86	20.30	22.35	20.00
	1992	49.81	47.78	50.30	52.90	44.29

source:Surveys and Prospects on the Present CIM Directions and Design-automatization
(JSPMI-ERI, 1987)

Table.11 The Assessment of CAD Systems (excluding PC-CAD systems)
387 responses

subject	score
reliability of software	3
reliability of hardware	3.15
flexibility for expansion	1.5
process speed	-.05
drafting facility	3.15
man-machine interface	2.3

The score of assessment;
10:very good 5:good 0:indifferent
-5:not satisfied -10:bad

Source:Nikkei Computer Graphics (1987)

Table.12 **The Requests for PC-CAD Systems (215 responses)**

subject	percentage
process speed	61.9
data compatibility with other systems	40.5
flexibility for expansion	34.9
capacity of file size	33.5
easy operation	26.0
resolving power of displays	21.4
3 dimension processing	19.1
expansion towards CAE	14.4
linkage with CAM	9.3
accuracy	4.2
others	6.0

Source:Nikkei Computer Graphics (1987)

Table.13 ME Equipment already installed and will be additionary implemented in these 3 years in Subcontracts and Small-medium Sized Factories ; in %

		TOTAL 334	General machinery 82	Electric machinery 75	Transport machinery 113	Precision machinery 33	Metal Molding 31
CAD(stand alone)	1985	5.7	4.9	9.3	2.7	0	16.1
	1988	6.9	2.4	9.3	6.2	9.1	12.9
CAD(main frame)	1985	7.5	7.3	10.7	6.2	0	12.9
	1988	9.3	4.9	10.7	8.8	15.2	12.9
CAD(PC's)	1985	30	28	40	22.1	42.4	25.8
	1988	15.6	17	17.3	14.2	18.2	9.7
CAM(NC programming)	1985	27.8	34.1	28	15	27.3	58.1
	1988	10.5	8.5	12	11.5	6.1	12.9
CAM(est. job time)	1985	3	2.4	4	.9	6.1	6.5
	1988	9.6	12.1	13.3	5.3	3	16.1
NC machining tools	1985	62.9	75.6	45.3	59.3	60.6	87.1
	1988	14.7	15.9	12	15.9	12.1	16.1
industrial robots	1985	28.1	20.7	25.3	38.9	24.2	19.4
	1988	15.9	12.1	13.3	21.2	18.1	9.7
FMC	1985	1.8	1.2	4	1.8	0	0
	1988	3	3.7	4	2.7	3	0
FMS	1985	1.2	2.4	1.3	0	3	0
	1988	3.3	0	6.7	2.7	9.1	0
business computer	1985	60.2	52.4	56	64.6	75.8	58.1
	1988	15.6	15.9	13.3	15.9	18.1	16.1
scientific computer	1985	17.7	19.5	12	9.7	33.3	38.7
	1988	9.9	9.8	10.7	4.4	21.2	16.1
LAN	1985	3	3.7	5.3	0	6.1	3.2
	1988	4.5	2.4	8	3.5	9.1	6.5

source:**Advances of Information and FA Systems and Structural Change of Subcontracts and Small-medium Sized Factories (JSPMI-ERI, 1986)**

Table.14 Outcome of CIM (in 1987)

	TOTAL 147	General machinery 51	Electric machinery 50	Transport. machinery 39	Precision machinery 7
1.design time reduction	55.10	52.94	56.00	53.85	100.00
2.production time reduction	27.89	23.53	30.00	33.33	71.43
3.progress of standardization	46.26	45.10	48.00	46.15	14.29
4.quality improvement	20.41	13.73	22.00	25.64	42.86
5.monpower saving in design	47.62	50.98	40.00	53.85	28.57
6.improvement of drafting	47.62	43.14	44.00	53.85	42.86
7.less human errors	25.85	27.45	24.00	20.51	71.43
8.morality improvement	4.08	5.88	.00	5.13	57.14
9.supplement of skilled worker	8.84	9.80	12.00	5.13	14.29
10.reduction of order cost	6.80	9.80	4.00	5.13	.00
11.show-window effect	12.93	13.73	14.00	10.26	14.29
12.others	1.36	1.96	2.00	.00	14.29
13.unknown	10.88	11.76	12.00	7.69	.00

Table.15 The Barrieer against CIM Penetration; percentage of factories which checked the item

items \ number of factories	TOTAL 147	General machinery 51	Electric machinery 50	Transport. machinery 39	Precision machinery 7
1.huge investment	64	65	64	64	57
2.price of ME equipment	35	31	38	31	57
3.insufficient facility	20	14	18	28	29
4.insufficient preparation	29	31	22	36	29
5.managemental problems	49	59	44	44	43
6.products standardization	50	35	56	56	71
7.standardization of ME	13	12	14	10	29
8.economical difficulties	7	4	6	10	14
9.labor union problem	0	0	0	0	0
10.anxiety to secure demand	9	8	8	13	0
11.back up of top managers	6	6	8	5	0
12.others	5	6	4	3	14
13.unknown	5	6	10	0	0

source:Surveys and Prospects on the Present CIM Directions and Design-automatization (JSPMI-ERI, 1987)

Table.16 Problems of FA for Subcontracts or Small-Medium Sized Factories

	TOTAL	General machinery	Electric machinery	Transport. machinery	Precision machinery	Metal Molding
	334	82	75	113	33	31
1.huge investment	46	47.6	54.7	37.2	45.5	54.8
2.few data compatibility	18.9	17.1	21.3	15.9	15.2	32.3
3.low equipment reliability	.9	0	1.3	1.8	0	0
4.few engineers for FA	27.9	24.4	29.3	28.3	36.4	22.6
5.few maintenance engineers	22.8	22	14.7	31	18.2	19.4
6.additional job (data input)	12.9	15.9	17.3	9.7	9.1	9.7
7.no advantage of FA	24.3	29.3	22.7	24.8	21.2	16.1
8.merit only for main company	6.9	6.1	6.7	8.8	3	6.5
9.others	2.4	2.4	2.7	2.7	0	3.2

source:Advances of Information and FA Systems and Structural Change of Subcontracts and Small-medium Sized Factories (JSPMI-ERI, 1986)

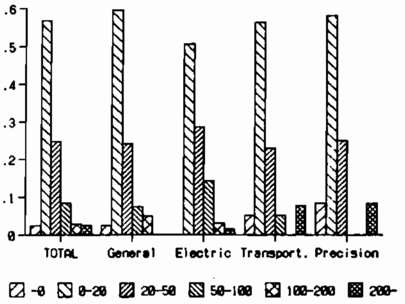

Figure.1 Distribution of the Growth Rates of Product Variations (%) during 1981 - 1984
source:[JSPMI,1985]

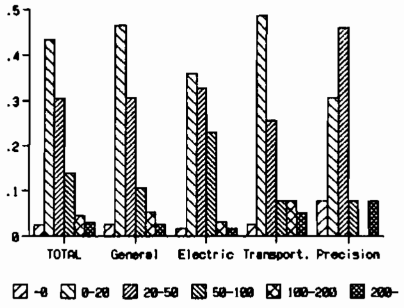

Figure.2 Distribution of the Growth Rates of Component Numbers (%) during 1981 - 1984
source:[JSPMI,1985]

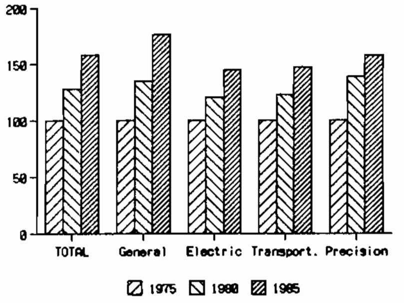

Figure.3 Trends of Product Variations 1975 to 1985
source:[JSPMI,1986]

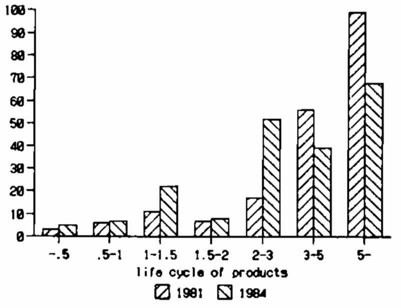

Figure.4 Distribution Product Life Cycle (year) in Total Machinery Industry
source:[JSPMI,1985]

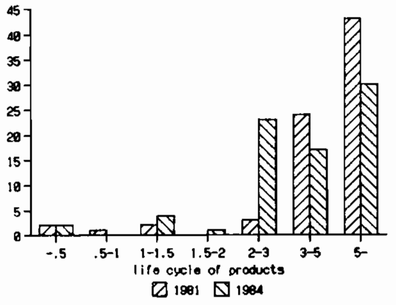

Figure.5 Distribution of Product Life Cycle (year) in General Machinery Industry
source:[JSPMI,1985]

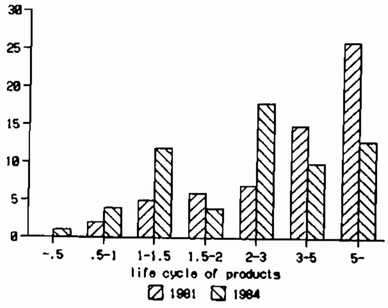

Figure.6 Distribution Product Life Cycle (year) in Electric Machinery Industry
source:[JSPMI,1985]

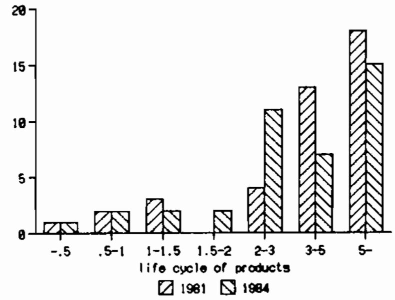

Figure.7 Distribution of Product
Life Cycle (year)
in Transportation Machinery Industry
source:[JSPMI,1985]

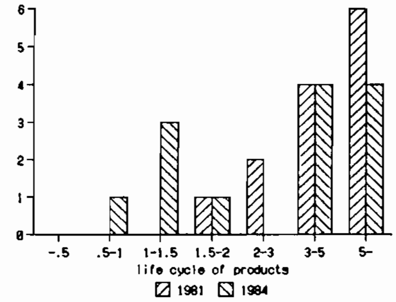

Figure.8 Distribution Product
Life Cycle (year)
in Precision Machinery Industry
source:[JSPMI,1985]

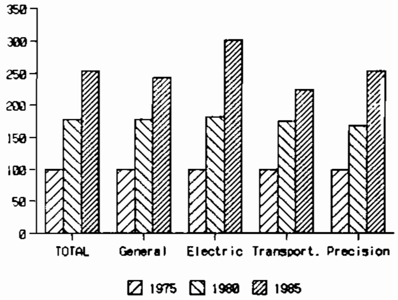

Figure.9 Trends of Output normalized
in 1975 values
source:[JSPMI ,1986]

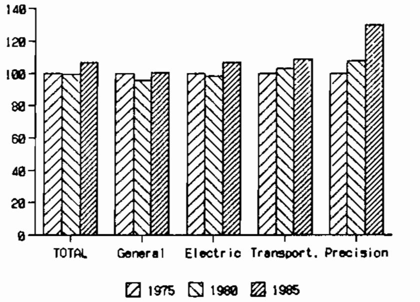

Figure.10 Trends of Direct Labor Cost
normalized in 1975 values
source:[JSPMI,1986]

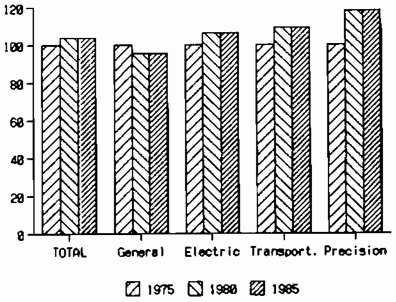

Figure.11 Trends of Indirect Labor
Cost normalized in 1975
source:[JSPMI,1986]

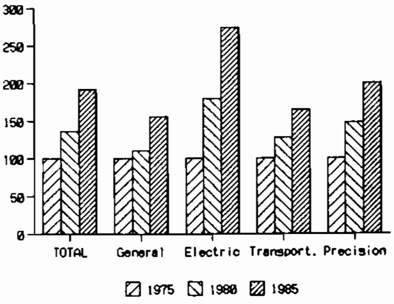

Figure.12 Trends of R&D Labor Cost
normalized in 1975 values
source:[JSPMI,1986]

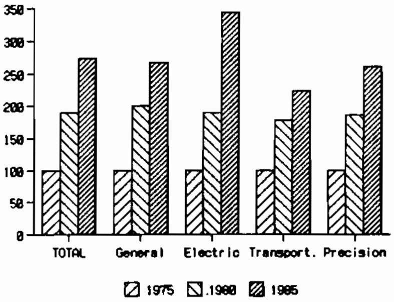

Figure.13 Trends of Material Cost normalized in 1975 values
source:[JSPMI,1986]

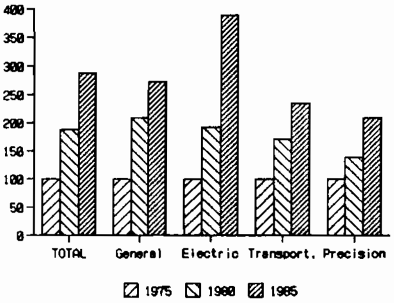

Figure.14 Trends of Expenditure for Subcontracts in 1975 values
source:[JSPMI,1986]

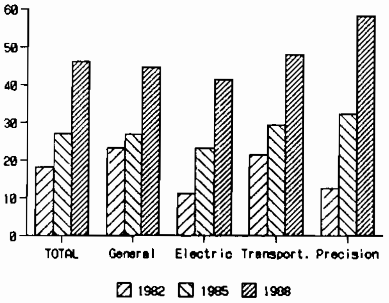

Figure.15 Trends of Automatization Rate in (%)
Design and Drafting
source:[JSPMI,1986]

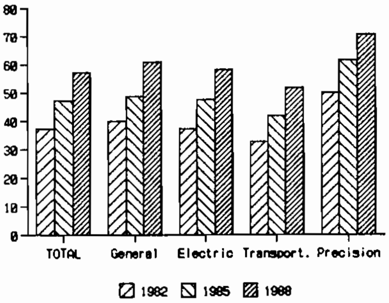

Figure.16 Trends of Automatization Rate in (%)
Press
source:[JSPMI,1986]

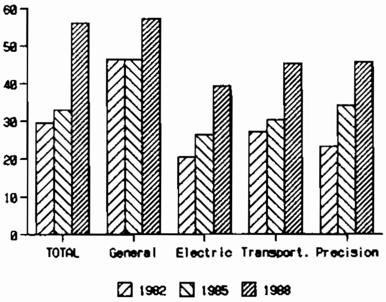

Figure.17 Trends of Automatization Rate in (%)
Metal Molding
source:[JSPMI,1986]

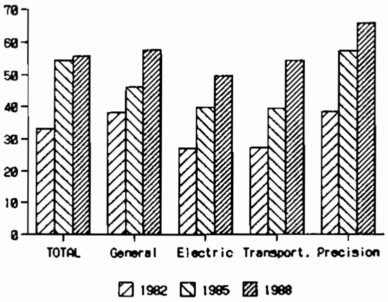

Figure.18 Trends of Automatization Rate in (%)
Machining
source:[JSPMI,1986]

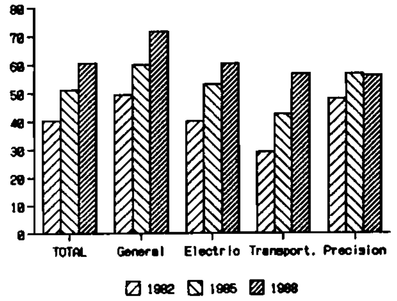

Figure.19 Trends of Automatization
Rate in (%)
Plastic Forming
source:[JSPMI,1986]

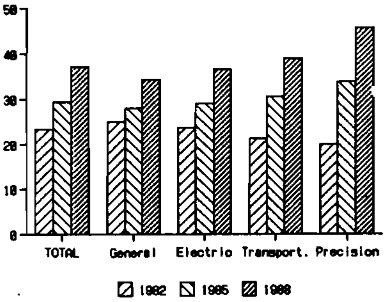

Figure.20 Trends of Automatization
Rate in (%)
Assembly (machinery)
source:[JSPMI,1986]

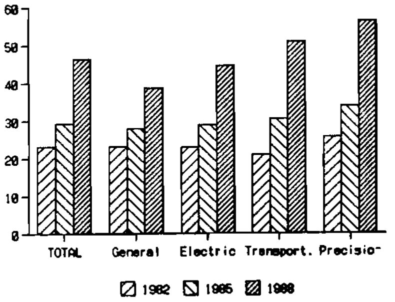

Figure.21 Trends of Automatization
Rate in (%)
Assembly (electric parts)
source:[JSPMI,1986]

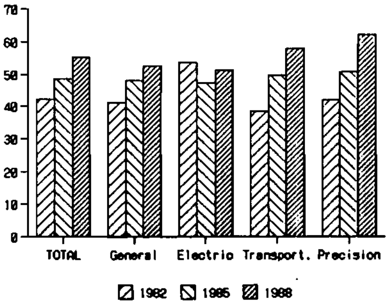

Figure.22 Trends of Automatization
Rate in (%)
Painting
source:[JSPMI,1986]

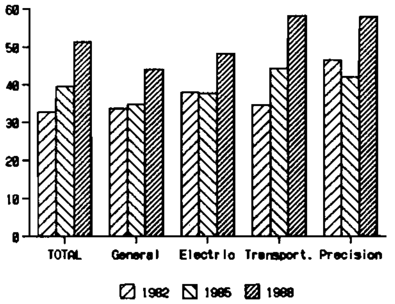

Figure.23 Trends of Automatization
Rate in (%)
Welding
source:[JSPMI,1986]

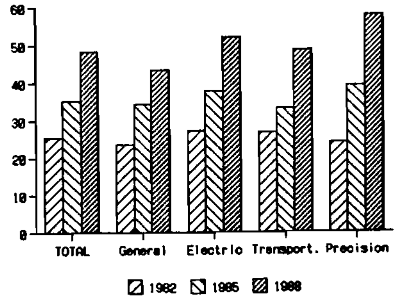

Figure.24 Trends of Automatization
Rate in (%)
Total System
source:[JSPMI,1986]

DIFFUSION TRENDS, EMPLOYMENT AND MACROECONOMIC IMPACTS

FACTORS GOVERNING THE EVOLUTION AND DIFFUSION OF CIM

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Computer Integrated Manufacturing (CIM) Project

Introduction: Technological Progress vs. Diffusion

It is important not to confuse the processes of technological innovation and diffusion/adoption. Although they commonly overlap to some degree, they are driven by different forces and controlled by different mechanisms. The adoption/diffusion process sometimes occurs alone, as where a product or process is essentially fully developed before it reaches the marketplace. An example of the latter might be a new drug such as penicillin or a chemical additive, such as tetraethyl lead (TEL). A variant of this situation occurs where complex technologies are developed and introduced in distinguishable "generations", as in the case of commercial jet aircraft or early computers. At the other extreme is a technology, like the telephone or the electric light, that is introduced in relatively primitive form and continuously improved thereafter. Here progress and diffusion occur in parallel, and interact closely.

Computer-integrated manufacturing (CIM) is an example of the latter type. In fact, the term "diffusion" may even be misleading, since it seems to imply a single center where CIM technology is created, and from which it spreads out spatially in all directions. This image is clearly wrong, inasmuch as there are many such centers, in scores of institutions located on several continents. The most that can be said in terms of identifying "leaders" and (by implication) "followers", is that leadership in the underlying electronics technology does not necessarily coincide, or co-locate, with leadership in downstream applications technology. This is as unusual pattern, in historical terms.

The purpose of this paper is to identify the elements of CIM and to decompose the complex changes that can be observed -- insofar as possible -- into distinguishable elements of progress and diffusion. It is also interesting to examine the interaction between technological progress and the diffusion/adoption process in the case of CIM.

Manufacturing Productivity

At the aggregate level advances in CIM technologies are reflected in manufacturing productivity. Of course, manufacturing productivity (defined in terms of output per unit factor input) has been increasing more or less continuously since the beginning of the industrial revolution. In the earliest period great gains were achieved simply by specialization of tasks or "division of labor", as exemplified by Adam Smith's famous pin-making factory. A century later Frederick Taylor and others formalized and systematized the notion of reducing a complex job to a series of simple tasks that could, in turn, be scientifically analyzed and optimized. Further gains resulted from the substitution of water power or steam engines for animal or human muscles for the driving of machines. This permitted substantial increases in machine size and speed. Machine tool capabilities, in terms of "degrees of freedom" and accuracy, increased dramatically during the 19th century, culminating with the development of "production" type grinding machines in the first decade of this century.

These changes were both facilitated and necessitated by the introduction of harder and stronger engineering materials, initially the substitution of steel for wrought or cast iron, and later the introduction of many specialized alloys (e.g. "high speed" steel) and synthetic carbides for cutting and grinding. The latter development, alone, is responsible for gains in machining speed of the order of 600-fold since the 1860's.[1] Further gains in manufacturing productivity resulted from the substitution of individual electric drive for centralized shaft power in the first third of the present century. Finally, the moving assembly line and the mechanical integration of a large number of machine tools linked by a transfer line yielded further gains, culminating with the large but terminally inflexible automobile engine plants built in the 1950's and 60's.

However the last-named development seems to have signified the end of an era. While technological progress in "conventional" production technologies such as those noted above has not ceased by any means, the economic gains to be had from further increments in machine size, speed or accuracy seem to be less and less significant. Two factors seem to be responsible. One is the increased competition in U.S. and world markets resulting from the rise of Japan and the other East Asian export-oriented economies. This has destroyed the postwar hegemony of General Motors in the (world) auto industry. It has also made obsolete

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[1] This figure refers to a standard steel axle, approximately 100 cm in length and 10 cm in radius. It is derived by combining two sources. For the period 1859-1895 productivity for steel axles increased by a factor of about 5.5 according to a specific study by the US Department of Labor in 1898. For the period 1900-1970, machining time for an axle of the dimensions noted declined from 105 minutes to less than 1 minute, according to data from Sandvik Steel Co. (Coromant Div.), cited by the American Machinist 100th Anniversary issue (1977).

GM's formerly dominant strategy of gradual "managed" innovation (the annual model-change), with its emphasis primarily on exterior appearance. In current market conditions the relative importance of performance and quality vs. style has increased sharply, requiring a correspondingly greater emphasis on manufacturing. The second, and related, trend is towards increased product complexity, not only in the auto industry, but throughout manufacturing industry [Ayres, 1988].

The consequences of the two trends noted above are also two-fold. In the first place, the rate of change of product design has accelerated, in the auto industry and elsewhere. Whereas in the 1950's and 1960's the auto industry phased-in design changes rather slowly so as to permit mass production facilities a 20-year useful life before major renovation and retooling, this is no longer possible. But, on the other hand, increased complexity has made the design process increasingly expensive and risky. This led to the so-called "productivity dilemma", an apparent contradiction between the need to cut manufacturing costs by maximizing standardization and specialization and the need to keep introducing new and improved products [Abernathy, 1978].

The possibility of a way out of this dilemma through increasing the **flexibility** (economies of scope) of manufacturing technology was not clearly recognized until this decade[2], although the facilitating technologies -- computers and numerically controlled machines -- began filtering into the manufacturing world about thirty years ago. We return to the issue of flexibility later.

Elements of Computer-Integrated Manufacturing (CIM)

For purposes of this paper, CIM is taken to comprise the whole range of programmable, computer-driven technologies -- from machines to information systems -- that are beginning to make their appearance in factories (and offices of manufacturing firms). From the perspective of the factory floor, these technologies have the effect of eliminating "hands on" contact of the workers with the product or workpiece, and sharply reducing or eliminating the role of humans as machine controllers, materials handlers, assemblers or inspectors. From the perspective of higher management, they can be regarded as assistance to and extensions of traditional methods of human decision-making, but with far greater information-handling and

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[2] The importance of flexibility was not recognized explicitly until the publication of Abernathy's book [ibid], which focussed attention on the problems associated with its absence. For some other discussions of the issue see [Ayres & Miller 1982; Ayres & Miller 1983; Goldhar & Jelinek 1983; Ayres 1984; Brödner 1985; Bullinger et al 1985; Talaysum et al. 1986; Talaysum et al. 1987]. The importance of economies of scope in economics has also received theoretical attention during the last decade, in the context of its implications for "contestability" of markets [e.g. Baumol 1982; Farrow 1985].

information reduction power than previous generations of office automation.

The underlying motivation for this substitution of computer-driven machines for human hands and eyes is a matter of conjecture. Surveys of managers seem to reveal a wide variety of justifications, ranging from direct labor savings to notions about increasing "flexibility". A major factor which has received relatively little attention, thus far in the management literature is the increasing need to control errors and product defects arising from human carelessness [e.g. Ayres op.cit., 1988].

The major elements of CIM technology, for purposes of this paper, are as follows:

- Numerically controlled (NC) machine tools, and follow-on technologies such as Computer Numerical Control (CNC), and Direct Numerical Control (DNC).
- Robots (programmable manipulators).
- Flexible manufacturing cells (FMC's) and Flexible Manufacturing Systems (FMS's) consisting of groups of programmable machines linked by programmable materials handling devices, such as robots.
- Computer-Aided-Manufacturing (CAM) and related operating systems such as Materials-Resource-Planning (MRP).
- Computer-Aided-Design (CAD), Computer-Aided-Process-Planning (CAPP) and Computer-Aided-Engineering (CAE) systems to assist managers in planning functions.

In addition to systems, there are a variety of devices, such as micro-processors, machine controllers, sensors, servo-mechanisms, communications interfaces and sensory-interpretation (e.g. "machine vision") devices that are important components of CIM systems. Sub-units, such as FMS's are typically controlled by mini-computers. Finally, such systems may well be controlled at the highest level by large main-frame computers, although distributed control strategies seem increasingly attractive, at least in theory.

Measures of Technological Progress in CIM Technologies

Direct measures of technological capability for NC machines, robots and other elements of CIM could be developed, in principle, based on parameters such as degrees-of-freedom, shaft power, weight and dimensions of workpieces, spatial resolution and accuracy of tool position, etc. Unfortunately we know of no publication or archive where such performance data is gathered, systematically, year by year. While there is ample qualitative evidence that performance has increased significantly over the past two decades, this cannot be demonstrated quantitatively on the basis of generally published data.

Nevertheless, some composite indexes of performance have been compiled, from time to time. One of the most interesting is an index of performance of machine tools, known as the Productivity Criteria Quotient (PCQ), compiled for the years 1950-64 [Hackamack, 1965]. Taking the U.S. output of machine tools as a whole, this index increased from 1204 in 1950 to 3497 in 1964, for an annual rate of improvement of the order of 7%. Unfortunately, the index has not been updated in recent years.

An alternative approach might be to use "benchmark" tests of performance, simulating realistic manufacturing situations. For example, machining speed increases over the past century (cited above) have been documented in terms of the time required to machine a steel axle of given dimensions. Comparable measures of performance for NC machine tools, robots and so forth can certainly be conceived, but again, this has not been done systematically in practice, so far as we are aware.

Lacking more direct measures, we are forced to fall back on a somewhat roundabout argument. As noted above, the common element in all CIM technologies is electronic data sensing and processing. It can be argued, indeed, that CIM is "driven" by computer technology (in its most general sense). It was, after all, the advent of the electronic computer in the 1940's and early 50's that induced people like Norbert Wiener and John Diebold to imagine that computers could, eventually, control manufacturing processes [Wiener, 1948; Diebold, 1952]. In fact, fears of the potential adverse impact of automation on employment surfaced as early as the mid-1960's[3], long before any measurable effects (if, indeed, any such effects are even now observable).

Actually, computers **per se** were only applied in the continuous process industries to any significant extent before the 1970's. Numerical controls, as applied to machine tools, only involved some of the computer peripherals such as magnetic tape readers/writers until the advent of the minicomputer. The large scale application of computer technology in the fabrication industries required the microprocessor, which was introduced to the marketplace in 1971 and first applied to the control of machine tools, robots, transfer lines, etc. in the 1974-75 period. Machines controlled directly by mini- and micro-computers were distinguished from their predecessors by the CNC designation. This was the facilitating breakthrough for CIM. Some quantitative measures of technological progress in the electronics sector are given in an accompanying paper [Ranta, 1988].

In effect, we therefore suggest that the most appropriate measures of technological capability for CIM, as applied to the fabrication industries, are derived from its "backward linkages" to the electronics sector (semiconductors, computers and telecommunications equipment). A schematic diagram showing these relationships is given in Figure 1. The "motive" effect of

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[3] A major study of the problem was published in 1966 by the National Commission on Technology, Automation, and Economic Progress, although the section on automation in the fabricating industries was focussed almost entirely on the impact of NC machine tools and automatic assembly [Schwartz & Prenting 1966].

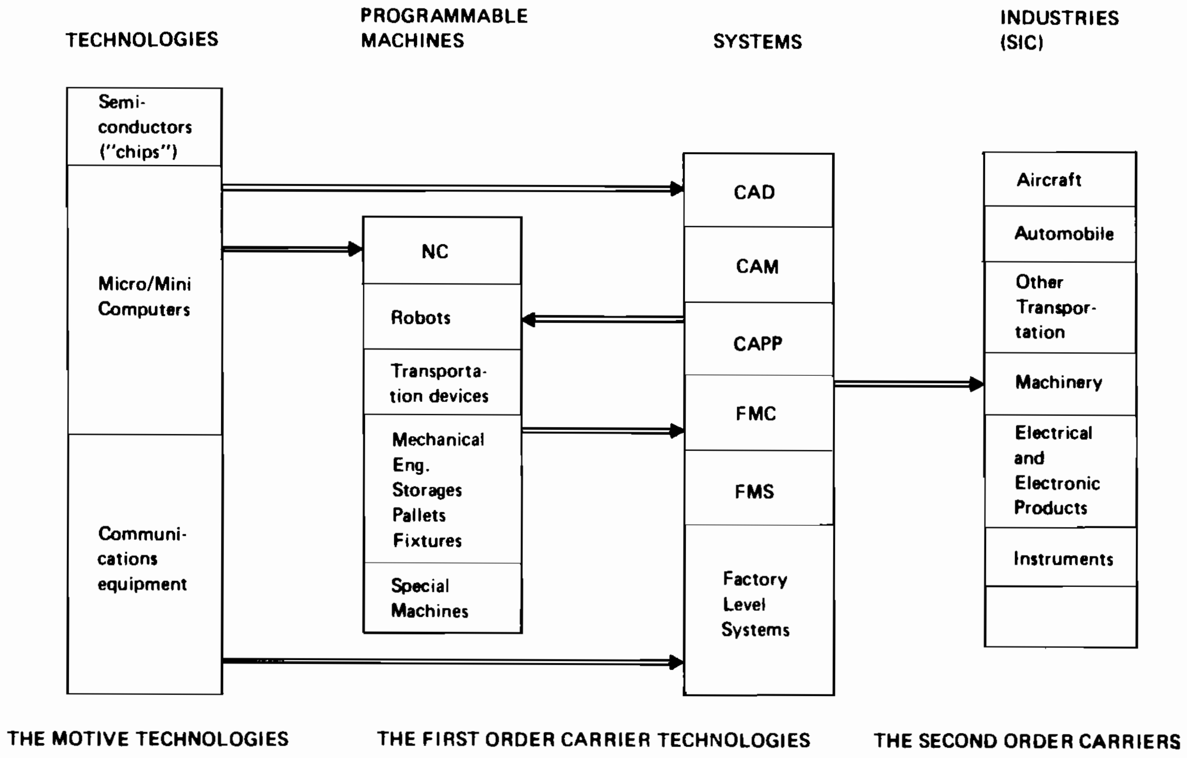

Figure 1. Foreward (and backward) linkages between motive and carrier technologies.

technological progress in the electronic industries scarcely needs further discussion. These industries have also been the earliest adopters of advanced computerized manufacturing technologies. The machine tool building industry has contributed less and less to manufacturing technology in recent decades. Meanwhile, the applications engineering and systems integration are increasingly carried out by downstream users, especially auto, truck, farm equipment and aircraft manufacturers.

The Flexibility Problem

As noted above, the "productivity dilemma" noted by Abernathy [op.cit., 1978] created an imperative to increase capital savings through economies of scope, which requires greater flexibility of capital equipment and organization.[4] Flexibility implies the ability to produce a number of variants of the basic product, including new designs and "custom" versions. It also implies competitiveness with regard to quality, short delivery times, small batch sizes and responsiveness to the market. In general terms, the flexible factory is one with a cost structure that is insensitive (or inelastic) to variations in volume and product configuration. Needless to say, the goal is to increase flexibility without increasing capital costs or sacrificing product quality.

Strategies (or means) to increase flexibility are not limited to the use of programmable automation in place of fixed automation. In addition, there are organizational considerations, financial considerations and logistic factors. The latter are discussed, for instance, in [Ranta & Wandel, 1988]. We limit the present discussion to technological means alone.

The first step towards flexibility is to provide for modular product design. This phase necessitates an investment in a computer aided design system (CAD). The CAD system decreases the total delivery time and gives possibilities to generate different variations and design choices in a rapid and cost-efficient way.

The second step usually is to enhance manufacturing flexibility. In this phase, usually, a subcontracting network is built up. A possible approach is to utilize a flexible manufacturing system (FMS). This is a major investment. The prerequisites for a successful implementation of FMS are a clear product strategy, with a well-defined focus and differentiation. Such systems can decrease delivery times and even increase production capacity without loss of flexibility.

In summary, there are several different types of flexibility, each related to a specific strategic function. We can classify them as follows:

<u>Design flexibility</u> focuses on variations in product form. It permits specialized and customized versions of a product to be

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[4] Note that the "dilemma" was not created by Abernathy, although he was the first to articulate it clearly.

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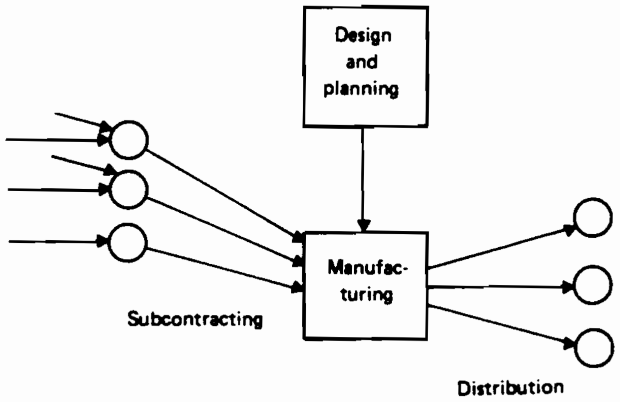

Figure 2. Network of flexibility.

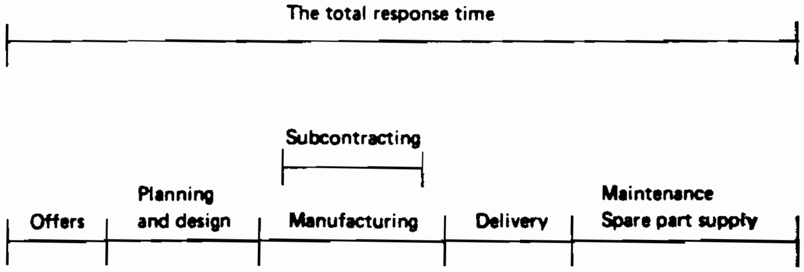

Figure 3. Flexibility factors.

- product flexibility implies an easy shift to a new product or a new part family; and

- production flexibility implies minimal barriers to a change in production volume, in the routing of the workpieces, in tooling sequences etc.; it is also referred to as routing and sequencing flexibility of structural flexibility. In any case, is reflects the basic structural limitations of the system and it is related to the properties of the transportation system, warehousing system, interfacing system, systems control and software modularity.

Of course, it is possible to define the above notions in still greater detail. There are many different definitions, but these brief characterizations provide some insight before the economic tradeoffs are considered.

FMS Capabilities: 1972 vs. 1987

Unfortunately, for reasons noted above, it is not a simple matter to measure increases (over time) in the "flexibility quotient" of CIM systems in any straightforward way. One can, however, note a significant increase, over time, in the capabilities of the "leading edge" systems reported occasionally in the engineering literature with respect to "part family" size, part complexity, lead time, etc.

The first successful FMS system in the U.S. was the "Omnicontrol" system developed by Sundstrand Corp. beginning in the late 1960's [Cook, 1975]. It began round-the-clock operation in 1972 in the Roanoke, Va. plant of Ingersoll-Rand Corp., a manufacturer of hydraulic pumps, hoists, winches and other equipment. It consisted of six NC-machine tools: two 4-axis milling machines, two 5-axis milling machines and two 4-axis drills [ibid.]. Parts were transferred from machine to machine by pallets on a transfer-line. Each machine was served by a tool-changing carousel with up to 60 tools, selected by the controlling computer (an IBM 360/30) [ibid].

The Sundstrand system as a whole accommodated 500 different tools (200 at a time) and produced up to 500 different prismatic parts (16 at a time) in sizes up to 1 meter cube. It was manned by 3 operators and a supervisor per shift. Equivalent output in a conventional shop would have required 30 machines and operators, plus supervisors. One of the key features of the "Omnicontrol" system was a CRT display screen, next to each machine, describing the piece being worked on and the progress made [ibid].

It is interesting to contrast the "Omnicontrol" system with one of the most recent FMS systems, designed and built by Ingersoll Milling Machine Co. (Rockford, Ill.) for its own use [Warndorf & Merchant, 1986], [Ingersoll Co., 1986]. It began operation in 1983 with a cell consisting of 5 NC milling centers (MC's) to produce heads, gearboxes and brackets. A second cell consisting of 3 MC's and a third with 4 vertical lather completed the FMS in 1987. The FMS also incorporates an inspection station with 2 Zeiss Mauser coordinate measuring machines, also computer controlled. They included a CNC materials handling system with automatic loading capability.

Control is exercised by a hierarchy of computers. At the top is an IBM 3090/200 mainframe, which is the host for the corporate management information system. This system includes the master schedule (order, entry and confirmation together with all significant dates), the bill of materials, the geometric models generated on CADAM, a master scheduling program known as a "dispatch list", and other factory-wide planning programs. The FMS itself is controlled by a VAX-750 computer in 2-way communication with the IBM 3090/200. The VAX reports back to the mainframe data needed by the M/S system, including personnel statistics, work progress reports, tools inventory, machine condition, etc.

The $ 20 million Ingersoll system was designed to manufacture 25.000 different parts types annually, with 70% in lot sizes of one, and 50% of which are unique and will never be made again. The system replaces 40 stand-alone machines and reduces the number of operators by 75%, although the primary economic benefits were expected to be in the reduction of overhead costs, especially work-in-progress.

The 1987 Ingersoll FMS is obviously many times more flexible than the 1972 model Sundstrand system. However a true comparison must be multi-dimensional. A suitable methodology remains to be developed.

The Diffusion of CIM

The diffusion of a technology, such as CIM, may be regarded as a special case of a more general social diffusion process, viz. the diffusion of ideas, language, or lifestyle. One may also identify "similar" diffusion processes, such as the spread of an infectious disease or a pest. However, while these processes may offer some useful analogs, they also lack two key features of the process of technological diffusion. The first is the element of choice and decision. While people do "choose" whether to adopt a new concept, a new slang word, or a new hairstyle, much of the decision process is subconscious and is probably governed by factors such as the extent to which people want to behave like others, unlike others, or just don't care. While not necessarily easy to determine in advance for a particular individual, such things can probably be determined with fairly high accuracy for large populations. In the case of an infectious disease, of course, there is no conscious choice involved, except to the extent that people can control the extent of their exposure. If the latter is not controllable, the rate of spread is essentially deterministic.

By contrast, the adoption of a new product (other than an "impulse" item) does generally involve comparison, evaluation and explicit choice. In most cases, there is not only a choice of "brands" or suppliers, but also a generic choice among alternative strategies or systems at several "nested" levels of abstraction. For instance, a factory manager may choose among robot vendors only after making prior choices among robot architectures (rectangular, cylindrical, spherical, revolute), drive systems (pneumatic, hydraulic, electric), and even between robots, ACV's, transfer lines, or human workers in the particular application.

This multi-level choice is always a factor in the adoption decision. Because it is so complex, the market success of a new product is extremely difficult to predict. Hence, new consumer products are seldom introduced without extensive market studies -- often involving distribution of the actual product in selected "typical" localities. Based on the results of such studies, changes in the product -- or its packaging and presentation -- are often made before full scale introduction. New producer goods or processes, unfortunately, cannot be pretested in this manner because the major cost is the development itself, not the distribution and marketing. Thus, even with the most careful attention to all controllable factors, many R&D efforts result in failure, at least from an economic perspective. Sometimes the amounts of money involved are extremely large, as in the case of GM's "Saturn" project.

Once a new product has passed this initial hurdle, however, the uncertainties with regard to acceptance seem to be sharply reduced. In effect, there is often a "yes/no" reaction from the marketplace that is quite hard to predict, at least on the basis of currently available methods. On the other hand, once the level of adoption has passed a certain point -- rule-of-thumb puts it at about 5% of the "potential" market -- the remaining question is to estimate the subsequent trajectory of the penetration. In effect, this involves choosing among a set of available forecasting models, using the information gained from the early adoption history to make the selection and to parametrize the chosen model [e.g. Mahajan & Wind, 1986].

Unfortunately, most of the available diffusion models do not deal with the case of interest here, since they all assume, at least implicitly, that the "product" remains unchanged after the diffusion process starts. Yet, in the real world of CIM technology there is an active, conscious, **feedback** between the primary technology developer and the market. While controlled market-testing is seldom possible, the early adopters of a new, evolving industrial technology (such as CIM) do provide a constant stream of useful information to the developers and manufacturers of producer goods, both in terms of the performance and reliability of the equipment and systems that have been put in service, and the ever-more clearly understood (and changing) needs of their customers.

A further complication is the fact that the technology in the case of CIM, (and other cases as well) arises from a variety of sources, not least of which are the early users themselves. Early users of NC machines, robots and FMS systems, for instance, needed to learn **how** to use these things effectively. In many cases, this depended on the development of special-purpose software, which remains proprietary (i.e. it does not diffuse to other potential users). It also depends on organizational learning which, by its nature, is not easily transferable. Another important source of basic technology, possibly the major one in this case, is the electronics industry, especially semiconductors and computers.

Having made these points, it must be emphasized that the dominant mechanism governing diffusion is the calculus of costs vs benefits. While technological information may not have been available equally around the world as recently as 30 years ago, when NC machines began to diffuse, this cannot be assumed today. In the major industrialized countries, at least, there cannot be significant differences in terms of basic technical information availability. Nor does it make sense to assume that decision-makers in one country are more or less rational than those in another. Any observed "lags" in diffusion between countries must, therefore, be explained by differences in the economic structure or the socio-political environment. Real labor costs, interest rates, energy costs, inventory ratios, domestic market size, labor, anti-trust and trade policy, currency stability, fiscal, monetary and tax policy and a host of other factors do differ from country to country.

Diffusion rates will obviously vary from sector to sector, also for rational reasons. Here the factors involved are more `micro' than `macro'. Some typical company level factors and design issues are described below.

Usually the starting point for economic analysis is capacity. Typically there are variations in the required volume, as well as expected (or unexpected) future changes in product mix. In small and medium size companies increase of production capacity through capital sharing can be the most important justification for investment in a flexible manufacturing system. Thus the first economic goal is <u>volume flexibility</u>: the ability to share capacity among products according to demand fluctuations. To achieve an economic operation, there are three critical factors: (1) a steady and high level of total volume, (2) a high machine availability, and (3) a suitable product mix.

The second important economic goal is the ability to vary the product within general parameters. These parameters define a "part family". Usually a larger part family means less total production capacity for the same capital cost. This conflicting situation is usually presented graphically by a picture like Figure 4. The maximum size of the part family is restricted by technological factors as well as by economic factors. The larger the part family is, the more tool changes and setups are necessary, which decreases the effective production time and thus also the annual volume.

A factor related to the size of the part family is the complexity of the parts, or simply the number of different surfaces needed for each part. Other things being equal, an increase in complexity will decrease the maximum production volume because of time-consuming tooling and set-up operations. The more complex the parts the system is able to produce, the larger the part family can be. The complexity of parts made by a given system is also restricted by many technological and

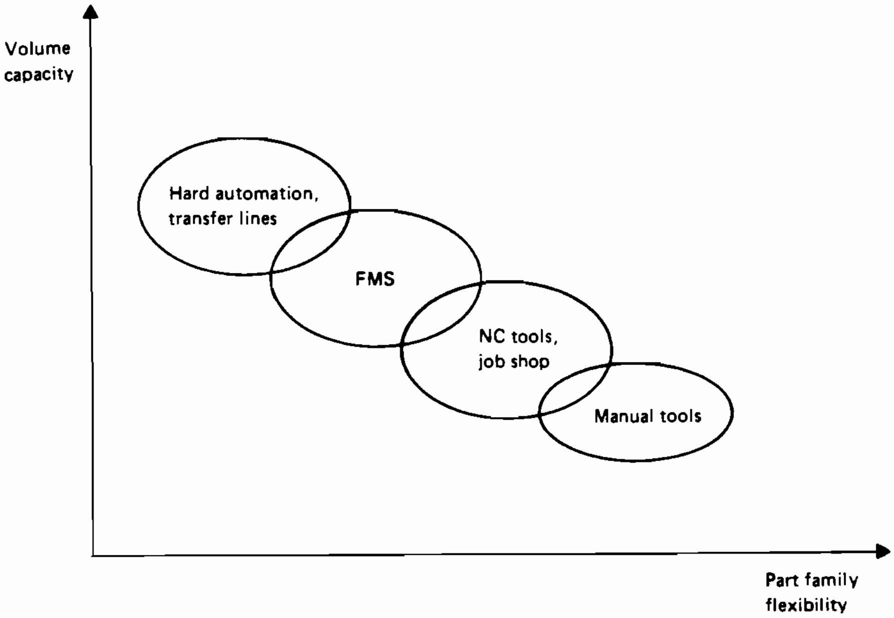

Figure 4. Flexibility vs. volume.

economic factors. In any case, an investment to increase allowed part complexity can be seen as an investment for the future, to cope with potential future market changes.

A third economic goal for flexibility is minimum batch size, to minimize work-in-progress. A small batch size will also decrease total delivery time. But again, smaller batch sizes decrease maximum production capacity because of tool changes, etc. Short delivery times and decreased work-in-progress are usually related to each other and are usually realized by a suitable compromise of batch sizes, part family, and system capacity.

Each of the flexibility goals has its tradeoffs, of course. One of the aims of the design is to have an overall cost/benefit ratio as high as possible.

Usually we can observe the following simple tradeoffs:

1. <u>Increase of part family</u>

- will increase the need for machine flexibility as well as process and production flexibility, because of the required routing possibilities and new dimensions;
- will increase software costs, because more NC-programs are needed as well as more integration software;
- device or hardware costs will increase, because more pallets, fixtures, storage space, robot capacity are needed;
- will decrease material costs and capital fixed in storage, work-in-progress and inventory.

2. <u>Increase of volume or capacity</u>

- will increase hardware and machinery costs (other factors held constant);
- will increase auxiliary device costs;
- will increase the need for production and process flexibility, due to increased tooling requirements;
- will increase software costs, because of more complex systems control.

3. <u>Increase of Part complexity</u>

- will increase the need for machine and product flexibility.
- will increase software costs, because of more complex part programs and a more complex systems control integration;
- will increase tool, pallet and fixture costs.

4. Decrease of batch size

- will increase the need for process and production flexibility;
- will increase software costs, because of a more complex systems control;
- will increase auxiliary device costs, because more (and more complex) pallets are needed.

Supplementary data on observed relationships between these factors is presented in Appendix A (summarized from [Sheinin & Tchijov, 1988]).

Concluding Remarks

In summary, the imperative for increased flexibility depends on the nature of the product and the market, even within a single country. There is no such imperative, for instance, in the case of products -- such as factories, power plants, office buildings and bridges -- that have always been custom-designed. Increased flexibility has nothing to contribute in these cases. At the other extreme, there is also no imperative for increased flexibility in the case of components like ball and roller bearings, nuts and bolts, electrical connectors, light-bulbs, sparkplugs, fractional horsepower motors, or a number of other products that are, and are likely to remain, highly standardized.

In fact, the domain of flexible manufacturing is generally considered to be restricted to parts normally produced in families of at least ten to a hundred and batches of less than a thousand or so. These figures are imprecise, but certain products are clearly excluded: tools and dies and industrial patterns, at the low end, and anything truly standardized at the other end of the spectrum. It is for these reasons, for instance, that the auto industry uses robots primarily in the final assembly process (for welding and painting), but not for parts manufacturing or subassembly operations.

In the case of flexible (i.e. robotic) assembly, the economic restrictions are even tighter. Since even the most flexible machine cannot compete in flexibility with a human worker, the minimum batch size necessary to justify the investment in automation is considerably larger: in the thousands. In fact, product (model) families of the necessary size are particularly characteristic of cameras, watches and consumer electronics. All of these are industries dominated by Japan. Thus it is not surprising, and certainly not an indication of "lag" on the part of other countries, that Japan has far more robots than other industrial countries, a very large percentage of which (40%) are involved in assembly tasks. By contrast, the U.K. and West Germany have, respectively 9.7% and 8.6% of their robots doing assembly tasks [Tani, 1987].

In as much as flexible automation occupies the middle of a spectrum ranging from labor-intensive "job shops" at one end and capital-intensive automatic transfer-systems at the other, the middle ground of batch production is, itself, quite heterogeneous. From the labor-intensive job shop end of the spectrum it may make sense to extend the technology in the direction of highly flexible but compact and inexpensive low-volume systems. From the mass-production end of the spectrum, it may make sense to move in the direction of increasing some variability in high-capacity systems. These two cases are illustrated in Figure 5.

There is some evidence, in fact, that there are really two categories of FMS systems, differentiated along the above lines [Sheinin and Tchijov, 1988]. This difference in use would incidentally, explain the otherwise surprising results observed by Jaikumar and reported in his widely publicized article in Harvard Business Review [Jaikumar, 1986]. Summarizing a survey of 35 FMS' in the U.S. and 60 in Japan he noted that the average number of parts made by the U.S. system was 10, with an average annual volume of 1.727. On the other hand, the average number made by the Japanese FMS' was 93, with an average annual volume of 258. Jaikumar asserts that this statistic proves that US manufacturers were using FMS "the wrong way". However it seems possible that he was inadvertently comparing applies and oranges. Although he claims that the two samples "had similar machines and did similar work", his Japanese sample was very heavily weighted by FMS' used for machine tool production, while <u>none</u> of the U.S. FMS' were used for this purpose. (The Ingersoll system described earlier was not included). The U.S. sample was heavily weighted, on the contrary, by firms like Caterpillar and Deere, which are volume manufacturers of standardized items of heavy equipment.

It may well be true that U.S. industry has lagged in the application of flexible automation, but the data available to date do not yet unambiguously support such a conclusion. It also shows the difficulties to make solid conclusions regarding benefits and costs of CIM technologies.

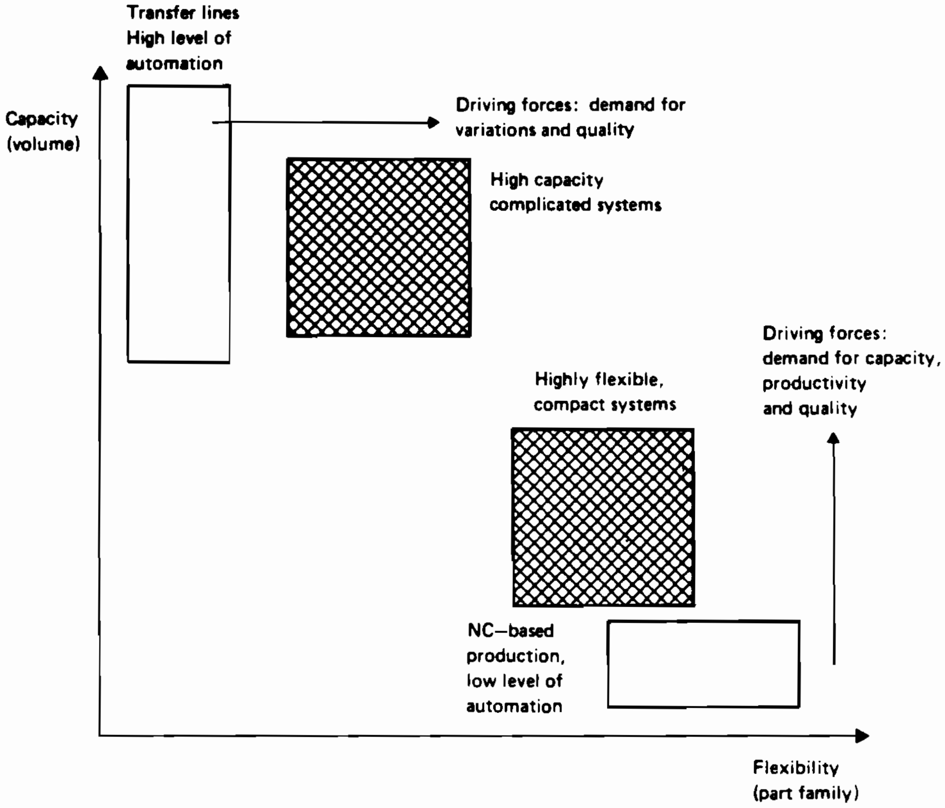

Figure 5. Substitution of manufacturing systems.

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APPENDIX

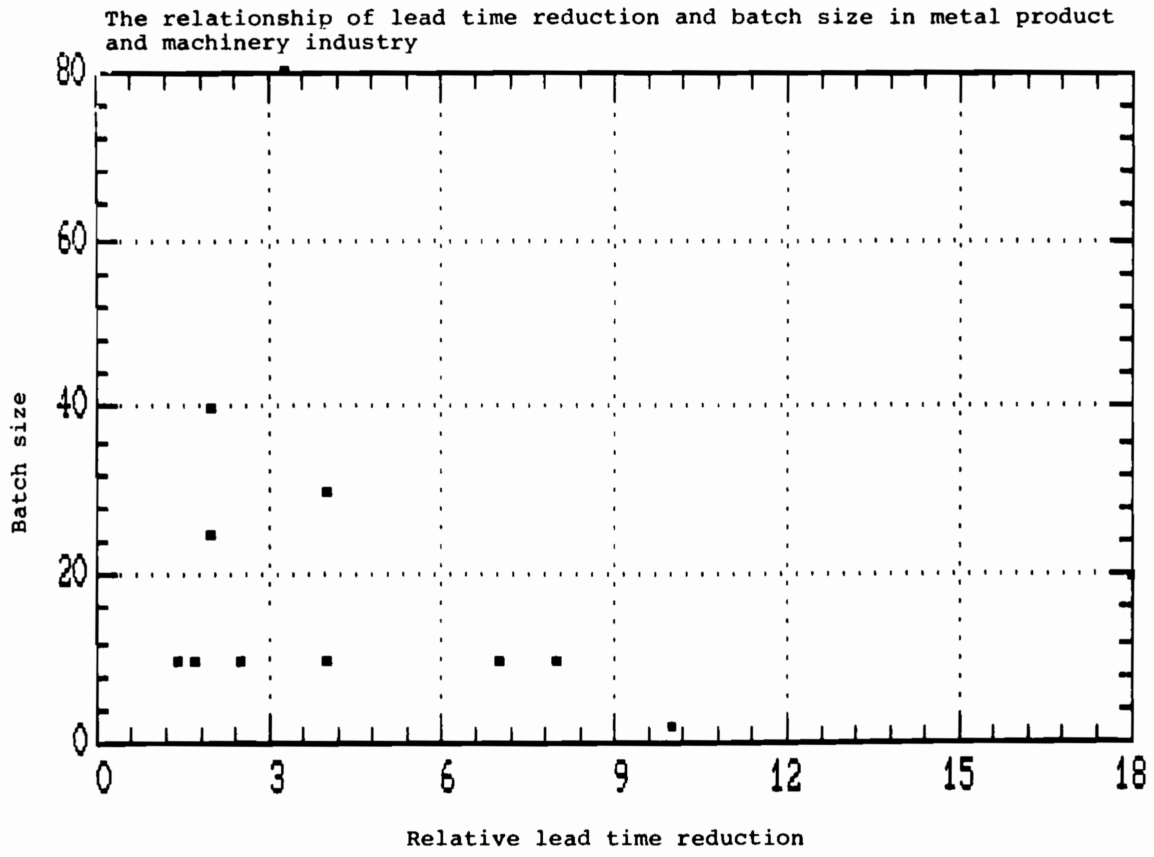

Figure A2. The batch size versus the lead time reduction in metal product and machine industry (IIASA-CIM data base, Sheinin-Tchijov, 1988).

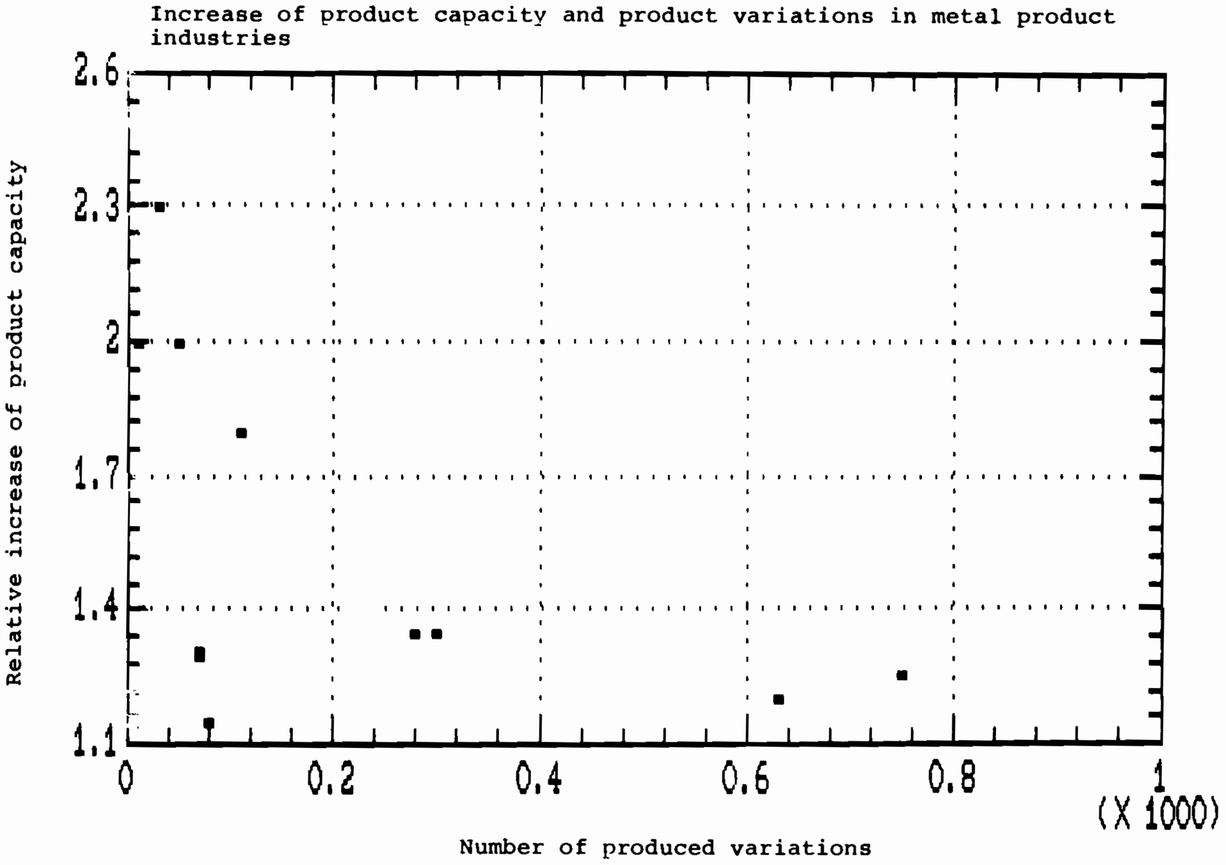

Figure A3. The Increase of production capacity versus the part familiy in metal product and machine industry (IIASA-CIM data base, Sheinin-Tchijov, 1988).

INTERNATIONAL COMPARISONS OF INDUSTRIAL ROBOT PENETRATION

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1. Introduction

It is of great importance to investigate the diffusion of high-technologies such as CIM (Computer Integrated Manufacturing) from the viewpoint of international comparisons. Some countries introduced these new technologies earlier than other countries. As a result, we can see the different penetration levels not only between the developed countries and the developing countries, but also among the developed countries.

As a part of the international comparisons of the diffusion of CIM technologies, we focus in this paper on the penetration of industrial robots for major developed countries.

Several papers have so far reported on international comparisons of industrial robots.[1] However, the comparisons in these papers have been faced with the following difficulties:

(1) Definition and classification of industrial robots are different among the countries to be compared;

(2) Statistics of the industrial robots are usually compiled from the viewpoints of I.R. suppliers. The data from the viewpoints of I.R. users are often not available.

(3) There are only a few time-series data of I.R. population which are internationally comparable.

In this paper we made an effort to collect and review the data of industrial robot population reported recently in various countries, and to make international

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[1] see |Edquist & Jacobsson 86|.

comparisons of the penetration levels and patterns of industrial robots. In other words, this paper tries to answer the following questions:

(a) How big are the differences of the present I.R. penetration among the developed countries?

(b) Do the penetration trend curves show the different patterns among the above countries?

(c) How many years of time-lag in diffusion of I.R. has each country?

(d) Does the applications of I.R. show the different distributions among the countries?

(e) Are there differences in industrial distribution of I.R. among the countries?

(f) If there are differences in application and industrial distribution, does the relationship exist between both of them?

2. Industrial robot penetration in selected countries

2.1 Definitions

Definition of Industrial Robots

As mentioned in the previous chapter, different definitions of industrial robots are employed among countries. This makes it difficult to compare *Industrial Robots* data internationally. Especially the Japanese Industrial Robot Association (JIRA) employs a much wider definition than other major countries. Japanese robot data include "manual manipulators" and "fixed sequence robots", which are not classified as robots but rather as automatic machines in other countries [Edquist & Jacobson 86].

In this paper we use the following definition of I.R., which has been proposed by the International Organization for Standardization (ISO):

> *The industrial robot is an automatic position-controlled reprogrammable multi-functional manipulator having several degrees of freedom capable of handling materials, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks. [ECE 85]*

According to the definition by ISO we have, in order to compare the data of industrial robots internationally, adjusted the Japanese data in this paper by excluding "manual manipulator" data and "fixed sequence robot" data. (Edquist and Jacobsson also made an effort to adjust in their paper; however, the adjustment is insufficient.)

In addition, some statistics of I.R. in Italy also include "fixed sequence manipulators". Therefore, the same adjustments are made for the Italian data.

Definition of the Penetration Level

Some alternatives are considered as an indicator showing the penetration level of I.R. in a country. It is important to select the indicator from the viewpoint of international comparability. In this paper we use the following I.R. population density as an indicator of I.R. penetration level:

$$I.R.\ population\ density = (U/L) \tag{1}$$

where U and L denote I.R. population (in units) and paid employment in manufacturing (in thousand persons), respectively. The reasons why the above indicator is selected are as follows:

I.R. stock in value is an alternative which can take into account the quality of I.R. in terms of prices for various types of robots. However, if we use this indicator, it is very difficult to compare the time series data internationally, because recent exchange rates are not stable and robot prices have been decreasing for the same type of robot. Therefore, we use the robot population in this paper instead of robot stock in value.

For a comparison of the degrees of robotization among different countries, robot population is not adequate as a comparable indicator because of the different size of national socio-economic activities.

Therefore, we use I.R. population density in this paper. The reasons why paid employment in manufacturing is selected as a denominator are partly due to availability of reliable and comparable time-series data for many countries, and they are partly due to the fact that almost all I.R. are used in the manufacturing sector.

Edquist and Jacobsson [Edquist & Jacobsson 86] have chosen to use employment in the engineering industry in the denominator since most robots are actually used in this industrial sector. As they mentioned, however, the picture is very much the same if employment in the whole manufacturing sector is used.

2.2 Comparisons

In Table 1 the industrial robot populations for 1974 to 1985 are shown for eight developed market economy countries, namely: Japan, the U.S.A., the U.K., the FRG, Italy, France, Belgium and Sweden. This table was compiled by reviewing the statistics and papers reported in those countries.

According to Yonemoto [Yonemoto 87], more than 90 percent of I.R. in the OECD countries are installed in the above eight countries.

Table 1. Industrial robot population in selected countries

Year	*Japan*	*USA*	*UK*	*FRG*	*France*	*Italy*	*Belgium*	*Sweden*
1974	1000	1200	50	130	30	90		85
1975	1400							
1976	3600	2000						
1977	4900		80	541			12	
1978	6500	2500	125			300	21	415
1979	9100						30	
1980	14250	3400	371	1255	580	454	58	795
1981	21000	4700	713	2300	790	691	242	950
1982	31857	6250	1152	3500	1385	1143	361	1400
1983	46757	9387	1753	4800	1920	1850	514	1600
1984	67300	14550	2623	6600	2750	2585	860	1900
1985	93000	20000	3017	8800				

The above data are mainly based upon the following references:

[JIRA 75-76]
[Yonemoto 87]
[JIRA 86]
[BRA 86]
[BIRI 85]
[SIRI 85]
[Revista Robotica 85]
[Edquist & Jacobson 86]
[AFRI 85]

We calculate the I.R. densities according to equation (1), using Table 1 and paid employment in manufacturing as shown in Table 2. Table 3 shows the past trends of I.R. density for the eight countries.

According to Table 3, Japan has been the leading country since 1981, while Sweden was the leading country until 1980. If we look at robot density in 1984, we find Japan with 5.553 robots/thousand employment, Sweden with 3.565, Belgium with 1.126, and other countries with less than 1.0.

In smaller countries with one million workers in manufacturing, such as Belgium and Sweden, special situations as, for example, some big company's installation of I.R., might greatly contribute to the high level of robot density for whole country.

From the above statistical viewpoints we will compare the robot density among the six major countries with more than 4 million employments in manufacturing.

Figure 1 shows the international comparisons of robot penetration trends among six countries. We can see a big gap of I.R. density between Japan and the other five countries during the whole period from 1974 to 1985. Japan has been six to eleven times higher than other countries as shown in Figure 1.

In order to compare the patterns of penetration trends, the robot density of the vertical axis in Figure 1 will be changed into a logarithmic scale as shown in Figure 2.

According to Figure 2 we can see the similar gradients of the penetration curves, which denote the annual increase rates of robot density among the six countries, excluding the U.S.A. curve until 1980. In the U.S.A. the annual increase rate of robot density during the latter half of the 1970's was lower than the usual case, which may be called a "slowdown of robotization." The U.S.A. has, however, recovered its robotization speed since 1980, which has thus become similar to the usual case.

Table 2. Paid employment in manufacturing [ILO 86]
(in thousand workers)

Year	*Japan*	*USA*	*UK*	*FRG*	*France*	*Italy*	*Belgium*	*Sweden*
1974	12010	20277	7873	9000	5660	5189	1100	667
1975	11380	17081	7526	8555	5501	5201	1033	669
1976	11330	18997	7281	8375	5458	5215	991	664
1977	11260	19682	7327	8340	5443	4771	952	634
1978	11090	20505	7293	8340	5365	4698	913	608
1979	11070	21040	7260	8389	5285	4715	888	608
1980	11350	20285	6939	8433	5230	4745	870	608
1981	11520	20170	6216	8193	5065	4639	823	602
1982	11510	18781	5889	7913	4995	4535	792	579
1983	11750	18430	5592	7601	4882	4404	773	548
1984	12120	19378	5506	7516	4742	4205	764	533
1985	12350	19314	5508	7596				

Table 3. Industrial robot population density
(units of I.R. per thousand workers)

Year	*Japan*	*USA*	*UK*	*FRG*	*France*	*Italy*	*Belgium*	*Sweden*
1974	0.083	0.059	0.006	0.014	0.005	0.017		0.127
1975	0.123							
1976	0.318	0.105						
1977	0.435		0.011	0.065			0.013	
1978	0.586	0.122	0.017			0.064	0.023	0.683
1979	0.822						0.034	
1980	1.256	0.168	0.053	0.149	0.111	0.096	0.067	1.308
1981	1.823	0.233	0.115	0.281	0.156	0.149	0.294	1.578
1982	2.768	0.333	0.196	0.442	0.277	0.252	0.456	2.418
1983	3.979	0.509	0.313	0.631	0.393	0.420	0.665	2.920
1984	5.553	0.751	0.476	0.878	0.580	0.615	1.126	3.565
1985	7.530	1.036	0.548	1.159				

Figure 1. I.R. Population Density Trend

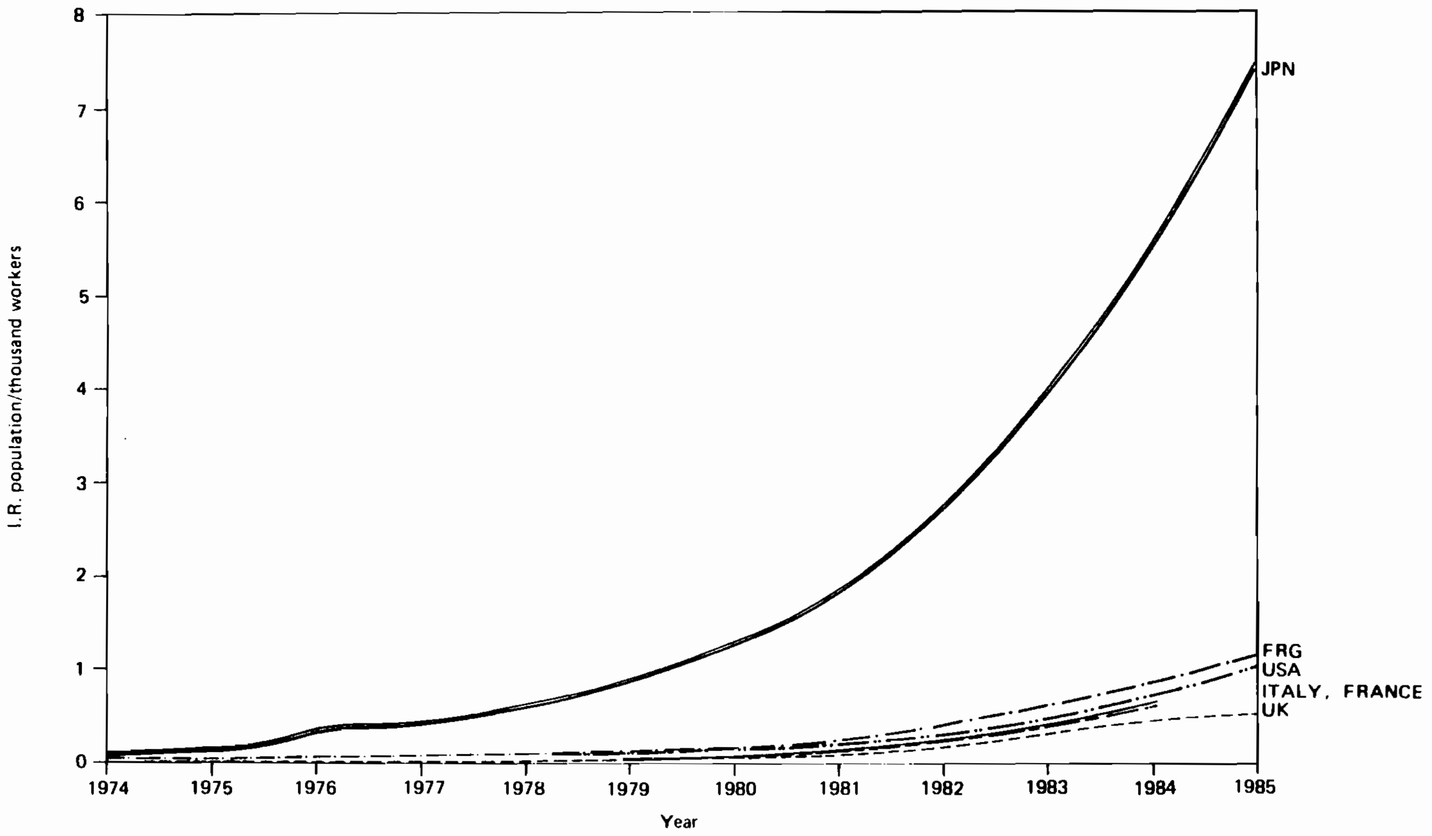
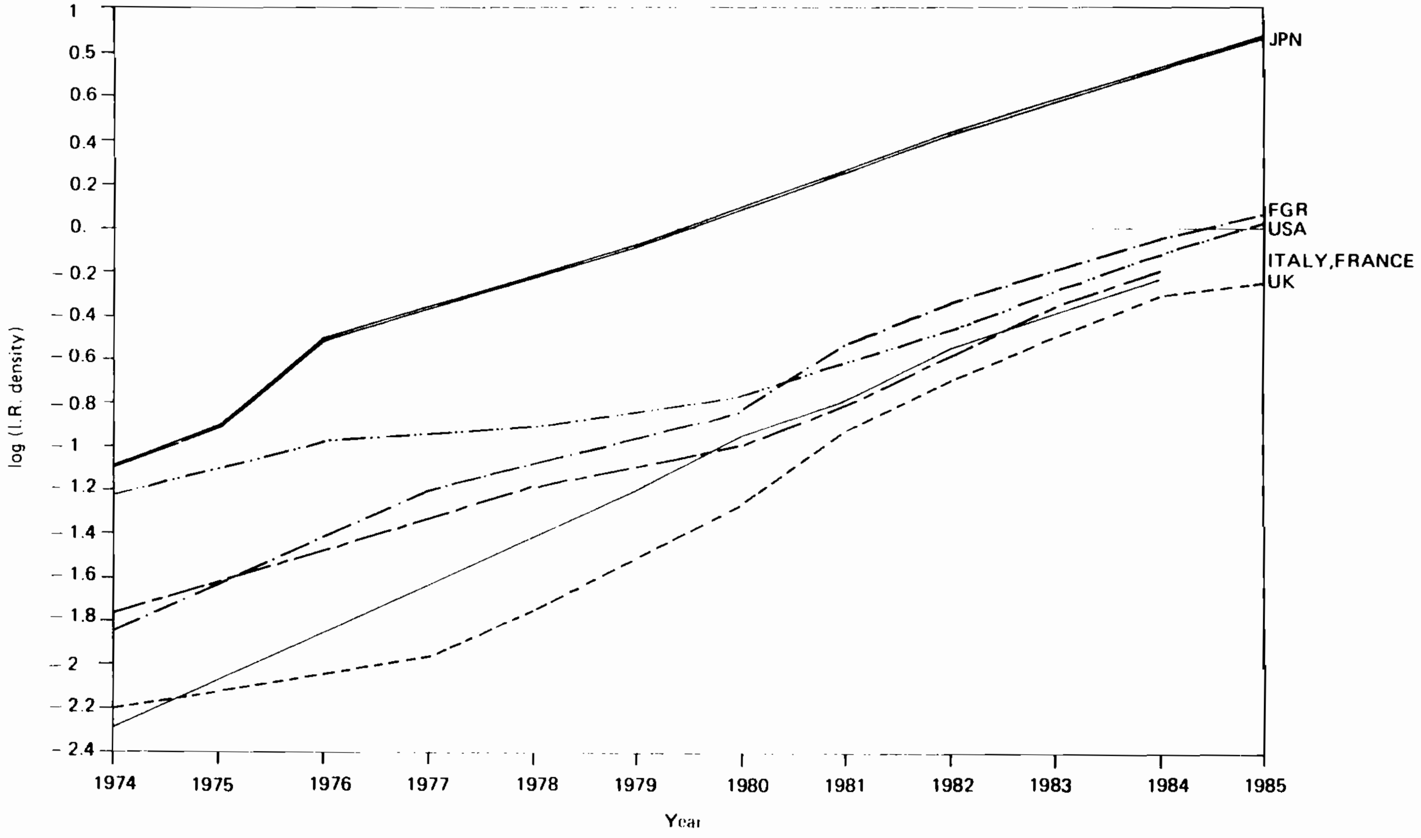


Figure 2. I.R. Population Density Trend – log (density)



3. Penetration trend analysis

3.1 Method of multi-national time trend analysis

As shown in Figure 1, there is a big gap of I.R. penetration in terms of absolute figures between Japan and other countries. But the annual increase rates are almost similar among these countries as shown in Figure 2. This implies that a common trend pattern exists for penetration of I.R. In other words, the differences of I.R. densities can be expressed by introducing *time-lag* parameters for each country.

In order to compare the trend patterns among several countries, simple time trend analysis is usually used for each country. After that, comparisons of the estimated parameters of the trend curves are made among several countries. However, such a simple method can not give us the time-lag parameters explicitly. Therefore, we introduce in this paper a method of multi-national trend analysis as described below, in order to clarify the above structure.

In this method we firstly introduce a *country dummy* variable X_i for the i-th country as defined below.

$$X_i\ (j) = \begin{matrix} 1 --- & if\ j=i \\ 0 --- & if\ j \neq i \end{matrix} \tag{2}$$

By adding these dummy variables to time variable t as explanatory variables, the robot density of the i-th country at the time t, namely $(U/L)_{it}$, can be expressed in the following form:

$$\log\ (U/L)_{it} = A + \sum_{j=2}^{m} b_j \cdot X_i(j) + a \cdot t \tag{3}$$

where m denotes the number of countries. A, b_j and a are parameters to be determined later in the regression analysis.

The reason why j ranges from 2 to m in the second term of the right-hand side of equation (3) is that the number of independent dummy variables is m-1, because of the following relationship among them:

$$\sum_{i=1}^{m} X_i\ (j) = 1 \tag{4}$$

In this paper we set forth that Japan is the first country (i=1).

In order to clarify the meaning of parameters A, b_j (j=2˜m) and a, we can write down equation (3) explicitly for each country as shown below.

Japan $(i=1)$ (4)

$$\log\ (U/L)_{it} = A + a \cdot t$$

Other country $(2 \leq i \leq m)$

$$\log\ (U/L)_{it} = A + b_i + a \cdot t \tag{5}$$

Equation (5) can also be expressed in the following form by introducing the time-lag parameter C_i instead of b_i:

$$\log\ (U/L)_{it} = A + a \cdot (t + C_i) \tag{6}$$

$$\textit{where}\ C_i = b_i / a \tag{7}$$

By comparing equation (6) to equation (4), the parameter C_i can be interpreted as a time-lag of the i-th country behind Japan.

The parameter a denotes the common annual increase rate of robot density.

As explained above, one regression analysis is applied for all of the multi-national time-series data through the introduction of country dummy variables.

As a result of this regression analysis, the common speed of robotization among the countries and the time-lag of I.R. penetration in each country will be estimated explicitly.

3.2 Results of the Analysis

Table 5 summarizes the results of this analysis, and the data used are shown in Table 4. As can be seen from Table 4, the regression analysis gives us the good results in statistical form.

If we shift the penetration trend curve by the time-lag for each country, almost the same trend curve can be drawn as shown in Figure 3.

According to this estimation the annual increase rate is 47%, at which the robotization has so far proceeded in major developed market economy countries.

As to the time-lag, Japan is the leading country, the USA is the second with a time-lag of 4.3 years behind Japan, the FRG comes next with 4.9 years behind, and 5.8 years, 6.3 years, and 7.5 years are the respective figures for the FRG, France and the UK.

The above results are considered useful for predicting future penetration of IR in various countries. If we investigate the penetration curve in the leading country, this result can also be applied to other countries, taking into account time-lag parameters.

Table 4. Data for trend analysis

Year	*Log(U/L)*	*Year*	*USA*	*UK*	*FRG*	*France*	*Italy*	*Nation*
1974	-1.0795	-6	0	0	0	0	0	JAPAN
1975	-0.9100	-5	0	0	0	0	0	JAPAN
1976	-0.4979	-4	0	0	0	0	0	JAPAN
1977	-0.3613	-3	0	0	0	0	0	JAPAN
1978	-0.2320	-2	0	0	0	0	0	JAPAN
1979	-0.0851	-1	0	0	0	0	0	JAPAN
1980	0.09881	0	0	0	0	0	0	JAPAN
1981	0.26076	1	0	0	0	0	0	JAPAN
1982	0.44212	2	0	0	0	0	0	JAPAN
1983	0.59980	3	0	0	0	0	0	JAPAN
1984	0.74451	4	0	0	0	0	0	JAPAN
1985	0.87681	5	0	0	0	0	0	JAPAN
1974	-1.2278	-6	1	0	0	0	0	USA
1976	-0.9776	-4	1	0	0	0	0	USA
1978	-0.9139	-2	1	0	0	0	0	USA
1980	-0.7756	0	1	0	0	0	0	USA
1981	-0.6326	1	1	0	0	0	0	USA
1982	-0.4778	2	1	0	0	0	0	USA
1983	-0.2929	3	1	0	0	0	0	USA
1984	-0.1244	4	1	0	0	0	0	USA
1985	0.01515	5	1	0	0	0	0	USA
1974	-2.1971	-6	0	1	0	0	0	UK
1977	-1.9618	-3	0	1	0	0	0	UK
1978	-1.7659	-2	0	1	0	0	0	UK
1980	-1.2719	0	0	1	0	0	0	UK
1981	-0.9494	1	0	1	0	0	0	UK
1982	-0.7085	2	0	1	0	0	0	UK
1983	-0.5037	3	0	1	0	0	0	UK
1984	-0.3220	4	0	1	0	0	0	UK
1985	-0.2614	5	0	1	0	0	0	UK
1974	-1.8402	-6	0	0	1	0	0	FRG
1977	-1.1879	-3	0	0	1	0	0	FRG
1980	-9.8273	0	0	0	1	0	0	FRG
1981	-0.5517	1	0	0	1	0	0	FRG
1982	-0.3542	2	0	0	1	0	0	FRG
1983	-0.1996	3	0	0	1	0	0	FRG
1984	-0.0564	4	0	0	1	0	0	FRG
1985	0.06389	5	0	0	1	0	0	FRG
1974	-2.2756	-6	0	0	0	1	0	FRANCE
1980	-0.9550	0	0	0	0	1	0	FRANCE
1981	-0.8069	1	0	0	0	1	0	FRANCE
1982	-0.5570	2	0	0	0	1	0	FRANCE
1983	-0.4052	3	0	0	0	1	0	FRANCE
1984	-0.2366	4	0	0	0	1	0	FRANCE
1974	-1.7608	-6	0	0	0	0	1	ITALY
1978	-1.1947	-2	0	0	0	0	1	ITALY
1980	-1.0191	0	0	0	0	0	1	ITALY
1981	-0.8269	1	0	0	0	0	1	ITALY
1982	-0.5985	2	0	0	0	0	1	ITALY
1983	-0.3766	3	0	0	0	0	1	ITALY
1984	-0.2113	4	0	0	0	0	1	ITALY

Table 5. Results of regression analysis for multi-national trends

Constant	0.07183
Std Err of Y Est	0.14496
R Squared	0.96243
No. of Observations	51
Degree of Freedom	44

	Year	*USA*	*UK*	*FRG*	*France*	*Italy*
Regression coef.	0.1675	-0.7285	-1.2500	-0.8167	-1.0563	-0.9752
Std Err of Coef.	0.0060	0.0641	0.0642	0.0666	0.0728	0.0691

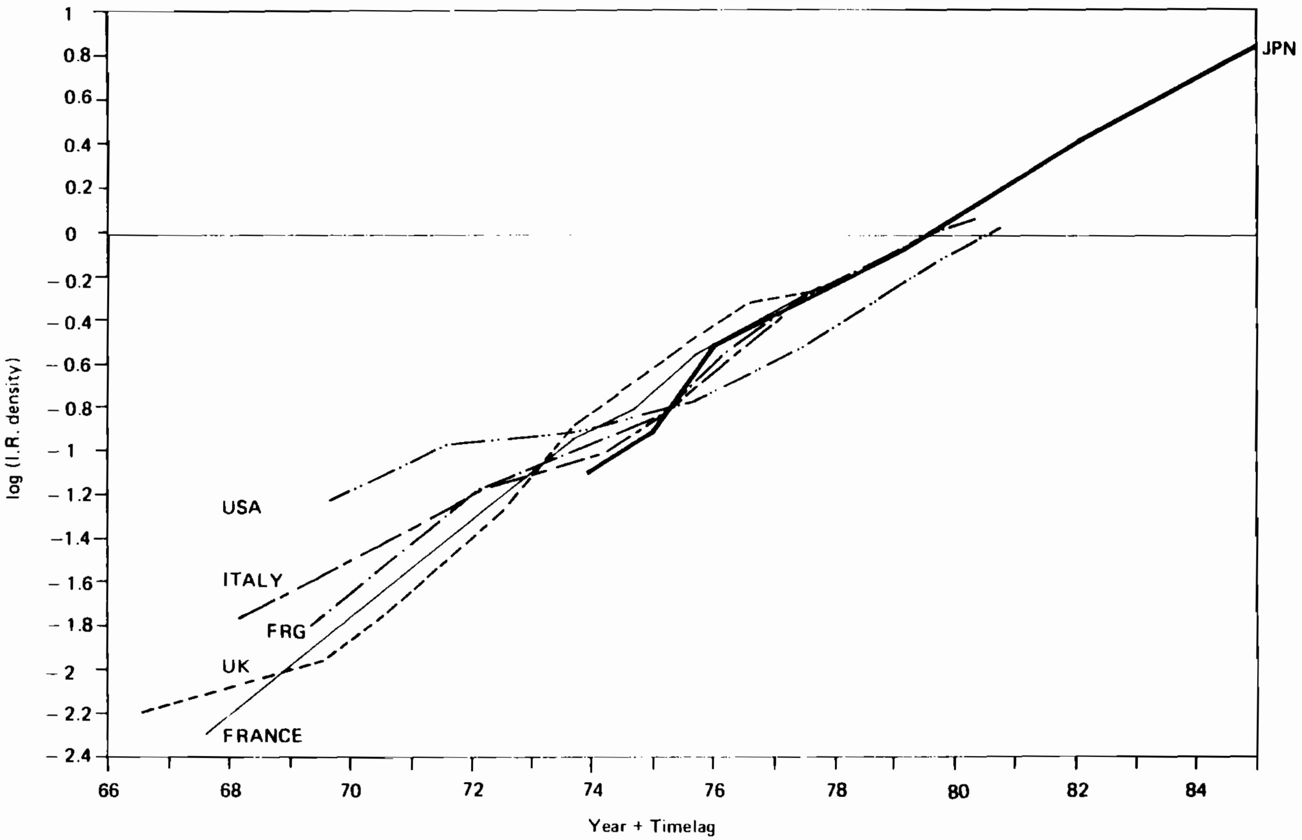
Regression Equation

log(U/L) = 0.07183

+0.1675*	YEAR	(=19XX-1980)	TIMELAG
+0 *	JAPAN	(1 or 0)	0
-0.7285*	USA	(1 or 0)	-4.3491
-1.2500*	UK	(1 or 0)	-7.4619
-0.8167*	FRG	(1 or 0)	-4.8753
-1.0563*	FRANCE	(1 or 0)	-6.3057
-0.9752*	ITALY	(1 or 0)	-5.8214

$$\log(U/L) = 0.1675 * (YEAR + TIMELAG) + 0.07183$$

Figure 3. I.R. Penetration Trend with Timelag Shifts



4. Cross-sectional analysis

In this chapter we will investigate the reasons why I.R. penetration levels in 1984 are different among countries.

Although there are many factors inducing such differences, we focus on the wage rate factor in this paper. The reason is as follows:

According to Mori [Mori 87] and Tani [Tani 87], the ratio of wage rate to robot price is one of the most important factors affecting the degree of robotization. In the case of international comparisons, the price difference among countries is considered small for the same type of robot, because I.R. are exported/imported internationally.

Based upon the exchange rates in 1984 [OECD 86], the relationship between wage rate [ILO] in the U.S. dollars and robot density in 1984 are tested as shown in Figure 4. The result of the regression analysis is shown in Table 6. According to Table 6, the correlation coefficient squared between these variables is 0.808 in case of excluding the U.S.A., while it is 0.191 for all of the eight countries. If we exclude the data of the USA, we can see the general tendency that a country with higher wage rates has introduced more I.R. This tendency is also observed in nationally-based analyses.

Exchange rates have greatly changed since 1984, especially as the US dollar is getting lower at present compared to the values of 1984.

If the point of the USA were shifted to the left on the line of the regression equation in Figure 4, the exchange rate could be 124 yen/US dollar, which is very near to the latest rate in 1987.

Table 6. Cross-sectional regression analysis
I.R. density vs wage rate (US$/hr) in 1984

Data for regression analysis					
	U/L	*W.rate*		*log(U/L)*	*log(W)*
USA	0.751	9.19	USA	-0.1244	0.9633
UK	0.476	4.89	UK	-0.3224	0.6893
FRG	0.878	5.44	FRG	-0.0565	0.7356
FRANCE	0.580	4.08	FRANCE	-0.2366	0.6107
ITALY	0.615	4.86	ITALY	-0.2111	0.6866
BELGIUM	1.126	4.88	BELGIUM	0.0515	0.6884
SWEDEN	3.565	6.51	SWEDEN	0.5521	0.8136
JAPAN	5.553	6.82	JAPAN	0.7445	0.8338

Regression output: case with USA data

Constant	-1.0966
Std Err of Y Est	0.37902
R Squared	0.19079
No. of observations	8
Degrees of freedom	6

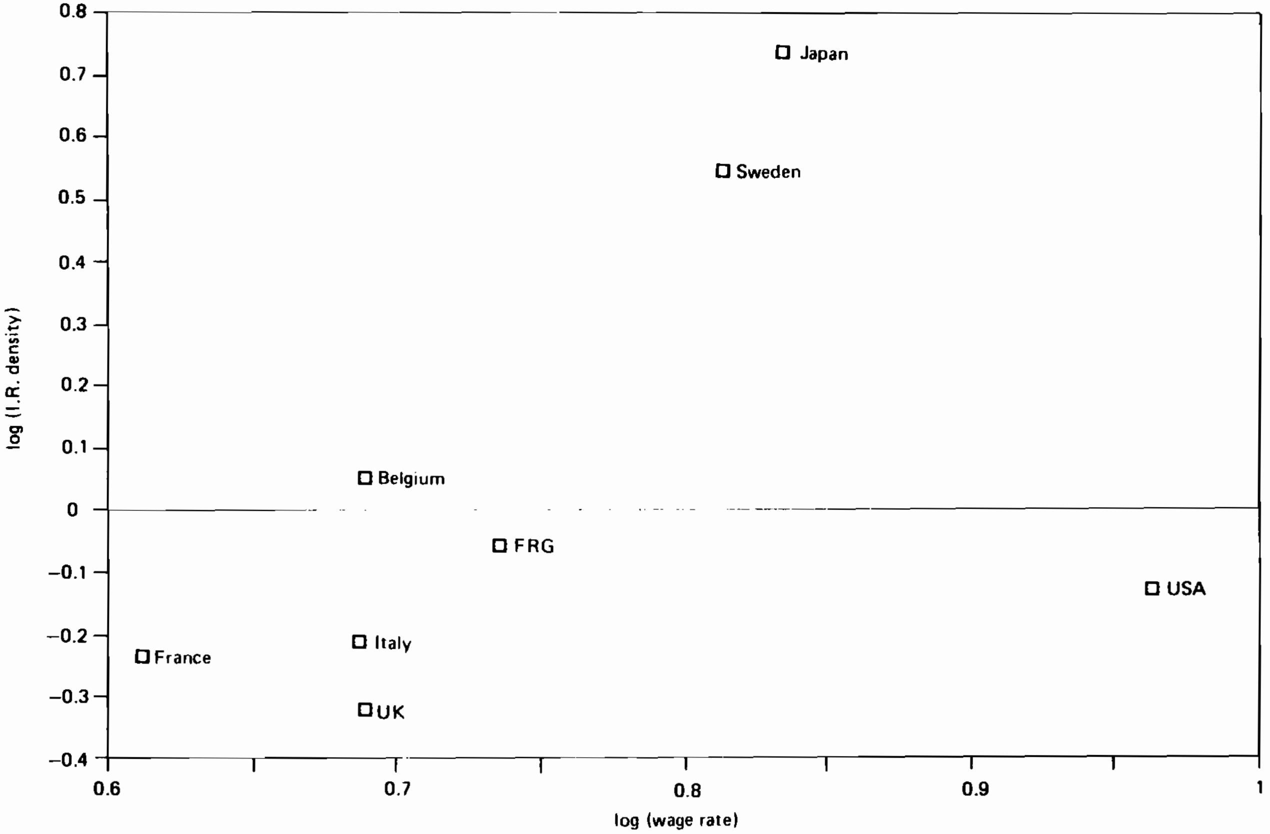
X Coefficient(s) 1.52292
Std Err of Coef. 1.28042

Regression output: case without USA data

Constant	-3.3580
Std Err of Y Est	0.19882
R Squared	0.80821
No. of observations	7
Degrees of Freedom	5

X Coefficient(s) 4.75044
Std Err of Coef. 1.03489

Figure 4. I.R. Density vs. Wage Rate



As we have seen from the above, it is very difficult to compare the monetary value indicator among the various countries during a period of unstable exchange rates. However, the wage rate can be pointed out as one of the most important factors in the case of international comparisons of I.R. penetration.

5. Applications

Table 7 shows the international comparison of industrial robots by applications.[2] I.R. are used mainly in the fields of welding (spot welding and arc welding), loading/unloading, assembly and painting. Plastic injection moulding is also one of major applications both in the UK and Japan. Among the major applications welding and assembly are most important at the present stage of robotization in the world.

(a) Welding

Welding robots accounted for 67.2% in Belgium, 63.5% in Spain, 49.2% in the FRG, 38.8% in Italy, 30.5% in the UK and 23.1% in Japan. In the European countries it can be said that welding is the most important application of I.R. Although Japan apparently has the lowest share, it must be noted that the absolute level of I.R. penetration in welding is more than two times higher than in the European countries. As explained later, a high share of welders in I.R. is related to a high share of automotive industry.

Within welding applications, spot welding was dominant in the European countries, while arc welding was dominant in Japan.

(b) Assembly

Japan has a much higher share of assembly robots compared to that of other countries. In Japan this share was about 40% during the period from 1982 to 1985, while it was only about 10% in other countries.

The gap of introducing assembly robots leads to the gap of I.R. penetration as a whole.

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[2] Only few statistical data are available about robotization in the USA. The comparisons between Japan and the USA are shown in Appendix A. The detailed data of Table 7 is shown in Appendix B.

As explained later, most assembly robots are used in the electric machine industry (including the electronics industry) in Japan. With regard to the absolute level, Japan has a more than twenty times higher penetration of assembly robots than other countries.

Table 7. Application distribution of I.R.

Application	*(1)* Japan (82-85) [%]	*(2)* UK (1985E)* [%]	*(2)* FRG (1985E) [%]	*(3)* Italy (1984E) [%]	*(4)* Belgium (1984E) [%]	*(5)* Spain (1985E) [%]
Welding (Spot)	9.2	16.9	29	28	60	50.2
(Arc)	13.9	13.6	20.2	10.8	7.3	13.3
Assembly	39.9	9.7	8.6	11.8	0.5	6.4
Loading/Unloading	6.3	9.5	9.2	26.5	8.4	15.4
Painting	2.2	6.4	8.8	8.9		6.8
Injection moulding	13.9	18.3				
Inspection/Test	1.2	1.9		1.2		2.1
Others	13.9	23.7	24.2	12.8	23.8	5.8
(Educational, etc.)		(5.5)	(2.4)		(11.4)	

* "1985E" means "at the end of 1985."

(1) [JIRA 75-86]
(2) [BRA 86]
(3) [SIRI 85]
(4) [BIRA 85]
(5) [Revista de Robotica 85]

6. Industrial distribution

Table 8 summarizes the international comparison on the industrial distribution of I.R.[3]

The automotive industry and the electric/electronics industry are considered to be the most important industries with regard to I.R. penetration.

(a) Automotive Industry

The automotive industry is the largest user of industrial robots in European countries. The share of automotive industry is about 70% in Spain and Belgium, about 50% in Italy. The recent US Industrial Outlook published in 1987 reported that nearly half of the installed units were in automotive and automotive-related industries.

On the other hand, the Japanese automotive industry has about a quarter of all robots in Japan. With regard to the absolute level, however, it must be noted that the Japanese automotive industry has a more than two times higher robot density than other countries.

(b) Electric/Electronics Industry

This industry is the largest user of I.R. in Japan, whose share is about 34%. In contrast, the share of this industry is much lower in other countries than in Japan. For example, it is about 10% in the UK and Italy, and less than 2% in Spain and Belgium.

This gap is related to the gap of assembly robot penetration.

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[3] The detailed data of Table 8 is shown in Appendix C.

Table 8. Industrial distribution of I.R.

Sector	*(1)* Japan (1985E) [%]	*(2)* UK (1985E) [%]	*(3)* Spain (1985E) [%]	*(4)* Belgium (1984E) [%]	*(5)* Italy (1984) [%]
Automotive	24.4	34.3	72.3	66.9	48.9
Electric/Electronics	33.9	11.5	1.9	1.7	9.4
Mechanical Engineering	18.2	16.3	11.4	11.9	24.1
Plastics	16.7	17.3		2.1	1.9
Others	6.8	20.6	14.4	17.4	15.7

(1) [JIRA 75-86]
(2) [BRA 86]
(3) [Revista de Robotica 85]
(4) [BIRA 85]
(5) [SIRI 85]

7. Relationship between application and industrial distribution

The conclusions of the previous two chapters are summarized as follows:

In Japan, the largest user is the electric/electronics industry and the largest application is assembly, while the automotive industry and welding robots have the largest share in other countries.

In order to investigate the differences mentioned above, we will look at the applications of I.R. in the Japanese automotive and electric machinery industries. Table 9 shows the application share of these two industries.

As shown in Table 9, the share of welding robots is 65% in the Japanese automotive industry, which is similar to other countries. In contrast, 82.5% of I.R. in the Japanese electric machinery industry are occupied by assembly robots. Roughly speaking, the following relationship can be observed.

Industry vs application

Automotive <--------> Welding

Electric/Electronics <-------> Assembly

Taking into account the time-lag and the differences in industrial distribution of I.R. between the leading country, Japan, and other countries, the following hypothesis may be considered.

Robotization has started mainly in the automotive industry for welding at the first stage of diffusion. The second stage of robotization started mainly in the electric/electronic industry for assembly about five years after the first stage.

However, the actual Japanese diffusion pattern of I.R. by industry is not so simple. According to Table 10, the share of the electric/electronics industry was over 30 percent even before 1980, while the share of the automotive industry has decreased from 37.2% in 1978 to 24.4% in 1985. The electric machinery industry has, since 1978, taken an important role as leading the robotization as well as the automotive process in Japan.

Table 9. Application distribution of I.R. in Japanese automotive and electric/electronics industries

Automotive Industry		*Electric/Electronics Industry*	
Application	(82-85) [%]	Application	(82-85) [%]
Welding (Spot)	35.0	Assembly	82.5
(Arc)	33.0	Machine loading	4.9
Assembly	14.4	Others	12.5
Machine loading	9.1		
Others	8.5		

The above data are estimated by excluding Manual Manipulator and Fixed Sequence Robots.

Source [JIRA 75-86]

Table 10. Japanese industrial robots by sector (VSR-ITR)

(accumulated units since 1978)

Sector	*1978*	*1979*	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*
Metal and its products	14.6%	10.7%	8.8%	7.5%	6.2	6.2%	6.1%	5.8%
Electric machinery	36.7%	29.2%	33.3%	32.3%	31.2%	31.2%	33.5%	33.9%
Automotives	37.2%	32.7%	32.6%	30.8%	28.0%	27.1%	25.5%	24.4%
Other machinery	5.6%	15.7%	9.5%	9.1%	9.8%	10.4%	11.9%	14.2%
Plastics	5.3%	9.7%	12.8%	17.9%	21.6%	21.3%	18.3%	16.7%
Others	0.6%	2.0%	3.0%	2.4%	3.1%	3.8%	4.7%	5.0%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

8. Conclusions

As described in Chapter 1, this paper tries to answer the six questions about the differences of I.R. penetration in various countries. The conclusions of this paper are summarized below:

(a) Differences amounting to a factor of more than five in I.R. penetration are not only observed at present, but they also existed ten years ago between the leading country, Japan, and other major countries.

(b) The penetration trend curves show a very similar pattern among the above countries, including Japan.

(c) The differences of I.R. penetration can be expressed by introducing a time-lag for each country. The time-lags behind Japan range from 4.4 to 7.8 years fro the USA and the major European countries.

(d) The application distribution of I.R. is different between Japan and other countries, i.e., assembly robots prevail in Japan, while welding robots prevail in other countries.

(e) The industrial distribution of I.R., as well as their application, is also different between these countries, i.e., they are mainly applied in the electric/electronics industry in Japan, and in the automotive industry in the other countries.

(f) Industrial robots have so far been used mainly as welders in the automotive industry and as assemblers in the electric/electronics industry. The above two distributions are strongly correlated.

Finally, the latest data on industrial robots in various countries are still being collected. For example, we received the news that the robotization in some countries showed the slowdown in 1986. Therefore, we plan to revise this working paper by updating the data next year as soon as possible.

Nevertheless, it might be said that the data and the results of the analysis described in this paper can be regarded as a useful tool for further investigations on international comparisons of high technology diffusion such as CIM.

Appendix A

Comparisons of industrial robots between Japan and U.S.A.

	JAPAN	U.S.A.
I.R. Population at the end of 1985	65,513 (1) (93,000)	20,000 (2)
User Industries at the end of 1985	(3)	(4) Nearly half of these installed units are in the automotive or automotive-related industries.
Automobiles	29%	
Electric Machines	41%	
Others	30%	
(I.R. distribution)		

Recent Application in 1984 and 1985	Domestic Shipments (3)	Shipments (5) (Servo-)	Imports (6) (Japan exports)
Welding	27%	34%	27%
Assembly	51%	16%	55%
Others	22%	50%	18%

Robot Price (US$thousands)	Domestic (7)	Exports (7)	Shipments (8)	Imports (8)
1984	48.2	35.4	77.0 [34.51]	[27.0]
1985	32.8	34.1	90.7 [54.8]	[29.2]

(1) JIRA domestic shipment data: amount of 1978 to 1985 for advanced type robots, namely, playback robots, numerical controlled robots and intelligent robots. (93,000) is an estimated population of industrial robots including variable sequence control robots by Yonemoto.

(2) British Robot Association, ROBOT FACTS 1985.

(3) JIRA data for advanced type robots.

(4) U.S. Industrial Outlook 1987 - Metalworking Equipment, 21-6

(5) BUREAU OF THE CENSUS, U.S. Department of Commerce, Current Industrial Reports: Robots (Shipments), MA35x(85)-1 August 1986. The data in Table are for servo-controlled robots, excluding nonservo-controlled robots (less than 20% compared to servo-type) and other robots (such as educational, hobby, experimental robots). Shipment data include exports.

(6) Industrial Outlook 1987 - Metalworking Equipment, 21-6. U.S. imports of complete robots are estimated to have increased again in both units and value in 1986 and to have captured 80 percent of the U.S. market. Currently, Japan's share of U.S. robotics imports amount to 80 percent of all U.S. robotics imports. Therefore, JIRA exports data for advanced type robots are used in Table. The share of conventional type robots in exports is only 8.8 percent of total exports.

(7) JIRA data for advanced type robots. Exchange rates: 237.52 Yen/US$ in 1984 and 238.54 Yen/US$ in 1985.

(8) BUREAU OF THE CENSUS, U.S. Department of Commerce, Current Industrial Reports: Robots (Shipments), MA35x(85)-1 August 1986. The data in Table are for servo-controlled robots. [ ] means averaged price for all of industrial robots based upon the CIR recently revised.

Appendix B

Applications of I.R. in selected countries

(1) JAPAN [JIRA 75-86]

Industrial robot shipment by application and type :82-85

Application	*Units*	*Percent*
Casting	126	0.1%
Diecasting	1737	1.96%
Plastic moulding	12979	13.9%
Heat treatment	49	0.1%
Forging	40	0.0%
Press loading	524	0.6%
Arc welding	12973	13.9%
Spot welding	8559	9.2%
Gas welding	16	0.0%
Painting	2029	2.2%
Plating	168	0.2%
Machine loading	5830	6.3%
Assembly	37161	39.9%
Palletizing/Packaging	1912	2.1%
Inspection/Test	1160	1.2%
Others	7733	8.3%
(Special purpose)	148	0.2%
Total	93144	100.0%

(2) UK and FRG [BRA 86]

Industrial robots by application at the end of 1985

Application	*UK*	*(Percent)*	*FRG*	*(Percent)*
Surface coating	193	6.4%	775	8.8%
Spot welding	511	16.9%	2548	29.0
Arc welding	411	13.6%	1781	20.2%
Grinding/deburring	52	1.7	25	0.3%
Assembly	294	9.7%	753	8.6%
Investment casting	15	0.5%		0.0%
Glueing/sealing	43	1.4%		0.0%
Laser cutting	5	0.2%		0.0%
Water jet cutting	6	0.2%		0.0%
Other tool manupilation		0.0%	293	3.3%
Diecasting	40	1.3%	174	2.0%
Injection moulding	551	18.3%		0.0%
Machine loading	287	9.5%	806	9.2%
Press loading	74	2.5%	173	2.0%
Inspection/test	56	1.9%		0.0%
Handling/palletizing	130	4.3%		0.0%
Forging	10	0.3%	84	1.0%
Other workpiece manupilation		0.0%1179	13.4%	
Other applications	174	5.8%	0.0%	
Education/research	165	5.5%210	2.4%	
Total	3017	100.0%	8800	100.0%

(3) ITALY [SIRI 85]

Application	*Units*	*1984E* *Percent*
Loading/unloading	686	26.5%
Spot welding	723	28.0%
Arc welding	280	10.8%
Painting	230	8.9%
Assembly	304	11.8%
Inspection	30	1.2%
Others	332	12.8%
Totals	2585	100.0%

(4) SPAIN [Revista de Robotica 85]

Application	*Units*	*Percent*
Sealing	20	3.0%
Inspection/test	14	2.1%
Work loading	104	15.4%
Grinding/deburring	3	0.4%
Medicion	5	0.7%
Assembly	43	6.4%
Painting	46	6.8%
Arc welding	90	13.3%
Spot welding	339	50.2%
Others	11	1.6%
Totals	675	100.0%

(5) BELGIUM [BIRI 85]

Application	*1984E* *Units*	*Percent*
Machine loading	72	8.4%
Spot welding	516	60.0%
Arc welding	63	7.3%
Handling	21	2.4%
Assembly	4	0.5%
Education Others	98	11.4%
Others	86	10.0%
Totals	860	100.0%

(6) USA [U.S. Doc 86]

Total shipments of complete robots USA (1984 + 1985)

Application	*Units*	*Percent*
Welding, soldering, brazing, and/or cutting	1992	16.2%
Foundry, forging, and/or heat treating	32	0.3%
Inspection, measuring, guaging, and/or sorting		0.0%
Spraying, painting, gluing, and/or sealing	1075	8.7%
Machine tool loading and/or unloading	120	1.0%
Assembly	958	7.8%
Material handling and others	1508	12.2%
Others (nonservo- & servo-[continuous path type])	1329	10.8%
Other robots (educational, hobby, experimental, etc.)	5316	43.1%
Total	12330	100.0%

The above data include exports, without imports (Imports=8220[1984+1985]. Imports are estimated to have increased again in both units and value in 1986 and to have captured 80 percent of all U.S. market. Currently Japanese imports amount to 80% of all U.S. robotics imports.

Appendix C

Industrial distribution of I.R. in selected countries

(1) JAPAN [JIRA 75-86]

Industrial robot shipments by sector and type: 1978-1985

Sector	*Total*	*Percent*
Food processing	610	0.7%
Textiles	86	0.1%
Lumber products	154	0.2%
Pulp and paper	150	0.2%
Chemicals	652	0.7%
Oil and coal products	184	0.2%
Rubber products	131	0.1%
Ceramic and stone products	404	0.5%
Steel	352	0.4%
Non-ferrous metals	1186	1.3%
Metal products	3649	4.1%
Boilers and motors	210	0.2%
Construction machinery	928	1.0%
Metal processing machinery	2805	3.1%
Other general-use machinery	3428	3.8%
Electric machines	30284	33.9%
Automobiles	21739	24.4%
Bicycles	608	0.7%
Shipbuilding	146	0.2%
Precision machinery	4518	5.1%
Synthetic	14930	16.7%
Other manufacturing	1028	1.2%
Other industries	1064	1.2%
DOMESTIC	89246	100.0%
EXPORTS	19707	
TOTAL	108953	

(2) UK [BRA 86]

Industrial robots by sector at the end of 1985

	Units	*(Percent)*
Energy/water supply	46	1.5%
Metal manufacture	17	0.6%
Metal goods	273	9.0%
Mechanical engineering	221	7.3%
Electrical/electronics	348	11.5%
Automotive	1036	34.3%
Aerospace/Shipbuilding	105	3.5%
Food/drink/pharmaceutical	26	0.9%
Timber/paper/furniture	17	0.6%
Rubber/plastics	522	17.3%
Other industries	406	13.5%
Total	3017	100.0%

(3) ITALY [SIRI 85]

Industrial Sector	*Units*	*1984* *Percent*
Mechanical engineering	150	13.8%
Transport machinery		
Automotive	533	48.9%
Others	112	10.3%
Electrical/electronics	102	9.4%
Textiles	8	0.7%
Plastics	21	1.9
Others	164	15.0%
Total (including FSM)	1090	100.0%

(4) SPAIN [Revista de Robotica 85]

	1985E *Units*	*Percent*
Automotive	488	72.3%
Metal processing	63	9.3%
Electric/electronics	13	1.9%
Bicycles	10	1.5%
Others	101	15.0%
Total	675	100.0%

(5) BELGIUM [BIRI 85]

Industrial sector	*1984E* *BELGIUM*	*Percent*
Automotive	575	66.9%
Machinery	87	10.1%
Plastics	18	2.1%
Electronics	15	1.7%
Education	98	11.4%
Others	67	7.8%
Total	860	100.0%

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SATURATION LEVEL OF NC MACHINE-TOOL DIFFUSION

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1. INTRODUCTION

Investigation on the diffusion of NC (numerical control) machine-tools is one of the fundamental and important tasks of the CIM (Computer Integrated Manufacturing) Project at IIASA. NC machines-tools are regarded as basic components of the FMS (flexible manufacturing system), which takes a central part in the CIM system.

The populations of NC machine-tools in several countries are summarized as follows:

Country	Year	Population of NC machine-tools	Source
USA	1983	103,308 units	[AM, 1983]
Japan	1987	70,255 units[1]	[MITI, 1988]
FRG	1985	50,000 units	[Fix-Sterz & Lay, 1986]
France	1985	35,000 units	[Margirier, 1987]

Tchijov analyzed the past development trends of the US MWI (metalworking industry) from the viewpoint of NC machine-tools and estimated the saturation level of NC machine-tools diffusion as a fraction of the total number of machine-tools installed by applying the logistic curve method to the past trend data of the NC share for five time-points (1963, 1968, 1973, 1977 and 1983) [Tchijov, 1987].

According to his paper, the NC share in total machine-tools of the US MWI will saturate in the 1990's and reach a level of 5.8-8.0%.

This estimation is considered to be quite low, because a recent survey on machine-tools in the Japanese machine industry shows that the NC share had reached already 9.2% by the end of September 1987, even in case of including metal-forming machines.

It is very difficult to make a reliable estimate of the saturation level by logistic curve methods based only on data of the early stage of diffusion.

In the foreword of the paper Ayres suggested the necessity of establishing a bridge between two kinds of data -- production

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[1] The survey was carried out for all establishments of more than 50 employees in the machine industry.

and installation data -- to make the forecasts of the NC share more reliable.

It would be more correct to use the term "consumption" rather than "production".

A similar logistic curve method was also applied to the forecasts of FMS in the world [Tchijov & Sheinin, 1988]. Ranta commented on the results as shown below [Ranta, 1988]: "The simple estimate gives above 1800-2000 systems for the year 2000, which is also the saturation level of the diffusion. Although there are a lot of barriers for the diffusion, the saturation level seems to be extremely low -- this poses a question concerning the validity of logistic methods."

As mentioned above, simple logistic curve methods should be revised to improve the reliability of forecasts.

Therefore, this paper proposes a method to establish a bridge between two kinds of data -- consumption and installation data -- to make the forecasts of the NC share more reliable, and especially the forecasts of the saturation levels.

In addition, this paper analyzes the past and recent trends of NC machine-tool diffusion in the USA and Japan, and applies the proposed method to the forecasts of the saturation level of NC shares.

The results concerning NC machine-tools in this paper show that the saturation level will be about five times higher than the previous estimates.

As mentioned before, recent statistical data support such a tendency.

2. TWO KINDS OF NC SHARES IN MACHINE-TOOLS: THEORETICAL CONSIDERATIONS

2.1 Definitions and Assumptions

In order to forecast the diffusion of NC machine-tools, the following three steps are usually taken:

1) to forecast the share of NC machine-tools in total machine-tools (NC share);
2) to forecast the number of total machine-tools in the future;
3) to forecast the number of NC machine-tools by multiplying the NC share to total machine-tools.

The first step, the forecast of the NC share, can be regarded as the most important task among the above three steps.

Therefore, we focus on the forecast of the NC share in this paper.

Definitions

As stated before, two kinds of data concerning the NC shares are theoretically available for the forecasts, namely "NC share in installation" and "NC share in consumption".

a) NC share in installation of machine-tools: $g(t)$

$$g(t) \equiv u(t)/U(t) \tag{1}$$

where $u(t)$ and $U(t)$ denote the number of NC machine-tools (population) and the number of total machine-tools installed at the end of year t, respectively.

This share can be called a "stock-type variable" in the terminology of system dynamics.

b) NC share in consumption of machine-tools: $f(t)$

$$f(t) \equiv x(t)/X(t) \tag{2}$$

where $x(t)$ and $X(t)$ denote the number of NC machine-tools and total machine-tools consumed in year t, respectively.

This share can be called a "flow-type variable".

Assumptions

The purpose of this chapter is to develop a method of more reliable forecasting by using the two kinds of NC share data, $g(t)$ and $f(t)$.

There is some relationship between stock-type variable $g(t)$ and flow-type variable $f(t)$. In order to clarify the relationship, we introduce the following assumptions on the pattern of replacement of machine-tools in this paper.

<Assumption I>

Replacement time = constant (m years)

In real cases, the replacement time of machine-tools can be regarded to be probabilistic. However, it may be said that the above assumption does not cause a significant forecasting error when we focus on the long-term trends of diffusion.

According to the above assumption and the definitions of U(t), u(t), X(t) and x(t), the following relationships can be obtained between the stock-type and flow-type variables.

$$\frac{dU}{dt} = X(t) - X(t-m) \tag{3}$$

or

$$U(t) = \int_{t-m}^{t} X(t')dt' \tag{3'}$$

$$\frac{du}{dt} = x(t) - x(t-m) \tag{4}$$

or

$$u(t) = \int_{t-m}^{t} x(t')dt' \tag{4'}$$

The above equations mean that the population at time t is equal to the accumulated number consumed (introduced) from t-m up to t.

<Assumption II>

$$1 \geq f(t) \geq 0 \tag{5}$$

$$\frac{df}{dt} \geq 0 \qquad (6)$$

$$\lim_{t \to -\infty} f(t) = 0 \qquad (7)$$

$$\lim_{t \to +\infty} f(t) = f_{\infty} \leq 1 \qquad (8)$$

These assumptions on the function f(t), the NC share in consumption, mean that f(t) increases monotonously from zero and saturates at the level of f_{∞}, which is a constant of less than 1. I.e., f(t) is assumed to be a growth curve. Condition (6) is considered to be the most severe among the above assumptions. However, it can be said that this condition is satisfied in most cases if short-term fluctuations of f(t) are eliminated.

<Assumption III>

$$X(t) \geq 0 \qquad (9)$$

The last assumption shown above is very obvious. This means that the consumption of machine-tools is non-negative.

2.2 Relationship Between the Two Kinds of NC Shares

In this section the characteristics of function g(t) are discussed, based upon the assumptions explained in the previous section.

(1) Value range of g(t)

Function g(t) can be expressed below in terms of f(t) and X(t) by substituting equations (2), (3') and (4') into equation (1).

$$g(t) = \frac{\int_{t-m}^{t} f(t')X(t')dt'}{\int_{t-m}^{t} X(t')dt'} \tag{10}$$

By applying the well-known "mean value theorem for integrals[2]" to the numerator in the above equation, it can be derived that there exists at least one c in [t-m,t] so that

$$\int_{t-m}^{t} f(t')X(t')dt' = f(c) \int_{t-m}^{t} X(t')dt' \tag{11}$$

where

$$t \geq c \geq t-m \tag{12}$$

The conditions where the mean value theorem is applicable are $f(t) \geq 0$ and $X(t) \geq 0$. Both conditions are satisfied in this case due to assumptions (5) and (9).

It can be derived that g(t) is equal to f(t) by substituting equation (11) into (10).

$$g(t) = f(c) \tag{13}$$

On the other hand, condition (6) and inequality (12) give us the following inequality:

$$f(t) \geq f(c) \geq f(t-m) \tag{14}$$

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[2] Mean value theorem for integrals:

If f and X are continuous for [a,b] and X never changes sign in [a,b], then there exists at least one c in [a,b] such that

$$\int_{a}^{b} f(t)\cdot X(t)dt = f(c) \int_{a}^{b} X(t)dt$$

With respect to this theorem, see [Pearson, 1974].

By substituting equation (13) into (14), the value range of g(t) is determined as shown below.

$$f(t) \geq g(t) \geq f(t-m) \qquad (15)$$

The limitation values of g(t) can be obtained by applying equations (7) and (8) to (15).

$$\lim_{t \to -\infty} g(t) = 0 \qquad (16)$$

$$\lim_{t \to +\infty} g(t) = f_{\infty} \qquad (17)$$

In other words, the limitations of g(t) are equal to those of f(t).

Moreover, the derivative of g(t), dg/dt, is expressed as follows:

$$\frac{dg}{dt} = \frac{1}{U} \{(f(t) - g(t)) \cdot X(t) + (g(t) - f(t-m)) \cdot X(t-m)\} \qquad (18)$$

Inequalities (9), (15) and U(t) > 0 show that dg/dt is non-negative. Therefore g(t) is also a monotonously increasing function as is f(t).

To summarize, g(t) has the same characteristics as f(t), which satisfy conditions (5) to (8).

In order to clarify the relationship between g(t) and f(t), we suppose that f(t) saturates at time T.

$$f(t) = f_{\infty} \text{ when } t \geq T \qquad (19)$$

In such a case, by using inequality (15) at time t = T+m, it can be proved that g(T+m) is equal to f_{∞}.

$$f(T+m) = f_{\infty} \geq g(T+m) \geq f_{\infty} = f(T) \qquad (20)$$

In other words, the NC share in installation g(t) saturates at least m years after the NC share in consumption f(t) saturates. I.e., f(t) can be regarded as leading series of g(t).

Supposing that the number of machine-tools consumed [X(t)] is approximately constant, g(t) can be expressed as follows:

$$g(t) = \frac{1}{m}\int_{t-m}^{t} f(t')dt' = F\left(t - \frac{m}{2}\right) \qquad (21)$$

where F(t) denotes the moving average of function f within the range [t - m/2, t + m/2].

Figure 1 illustrates an example of the relationship between the diffusion curves g(t) and f(t).

The results of this chapter might be summarized as follows:

- The NC share in consumption f(t) is a leading index of the NC share in installation g(t).
- The diffusion curve g(t) can be forecasted by using future f(t) and consumption of machine-tools X(t).
- The saturation level of the NC share in installation is equal to that in consumption, whereas the saturation time of g(t) lags some years behind that of f(t).

The above results show the possibility that we can estimate the saturation level in installation $g(\infty)$ more reliably by applying logistic curve methods -- not to g(t), but to f(t).

In most cases, forecasting is needed at the early stage of the diffusion level when the diffusion in stock-base is very low. In addition, there are only few data available at such a stage, because a stock-type survey is usually carried out about every five years. Therefore it is very difficult to make a reliable estimate of the saturation level.

On the other hand, flow-type data are available in most cases for each year.[3] There are a lot of sample points for

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[3] Strictly speaking, it is difficult to get the consumption data (user side). However, we can use the production data (supplier side) instead of the consumption data, because production-based data are available in most cases. In case of using production-based data, the data may have to be modified by export/import data.

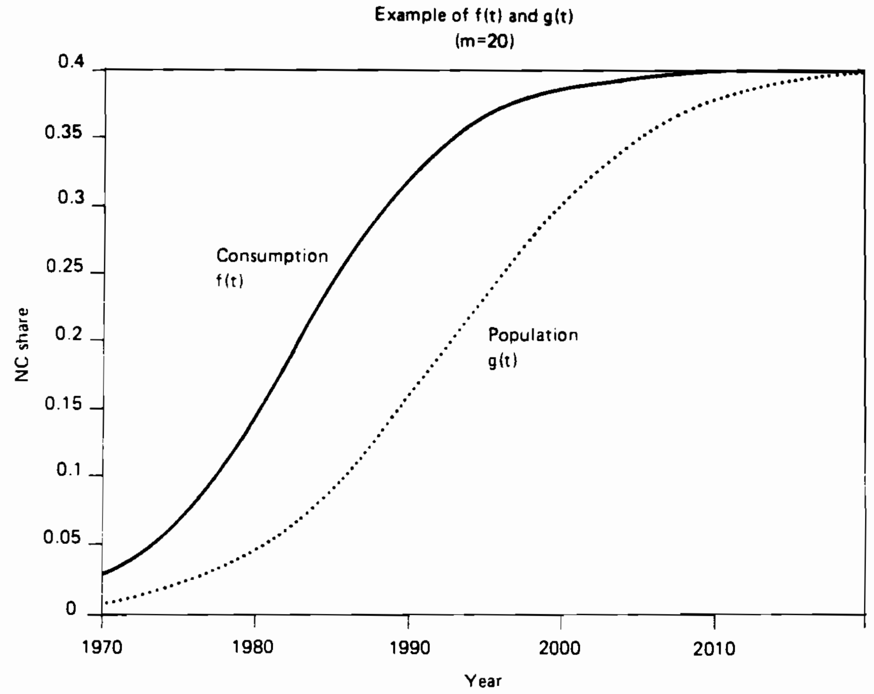

Figure 1. Example of relationship between f(t) and g(t).

statistical analysis. Moreover, the diffusion level in consumption shows to be much higher than in installation. The latest tendencies can be furthermore be included in the analysis.

Therefore it is strongly recommended to use the past data f(t) instead of g(t) for forecasting the NC share in installation.

3. ESTIMATION OF THE SATURATION LEVEL

3.1 The Case of the USA

Data on the machine-tool population are available as a survey on the inventory of metal working equipment for every five years (1963, 1968, 1973, 1977/78 and 1983) in the US MWI (metal working industry) [AM, 1983]. As the data after 1983 are not available, we cannot take into account any recent tendencies.

According to the surveys, the share of NC machine-tools in total machine-tools (metal cutting and metal forming) in the US MWI increased from 0.1% in 1963 to 4.7% in 1983.

Figure 2 shows the results of forecasting by the logistic curve method which is applied to these past trends [Tchijov, 1987]. The saturation level of the NC share in installation, percentage measured on a unit-base, is estimated to be 5.8%.

Table 1 summarizes the results of forecasting the NC share in installation by major types of machines, including the estimates of the saturation level and the NC shares of machines consumed during the period from 1979 to 1983.

In case of turning machines, the NC share in consumption reached 37.1% in the above period, which already exceeded the estimated saturation level of the NC share in installation (16.2%) as shown in Table 1.

Similar gaps can also be observed in the cases of boring machines, milling machines, machining centers and total machine-tools. For instance, the NC share of total machine-tools in consumption was 17.3%, while the saturation level of the NC share in installation was estimated to be only 5.8% from the present level, 4.7% in 1983.

The 13th survey on the inventory of metal working equipment gives us the shares of NC machine-tools by year of installation, which can be used as consumption data (Table 2).

NCMWI	
1958	0.01
1963	0.10
1968	0.49
1973	0.93
1977	2.01
1983	4.71

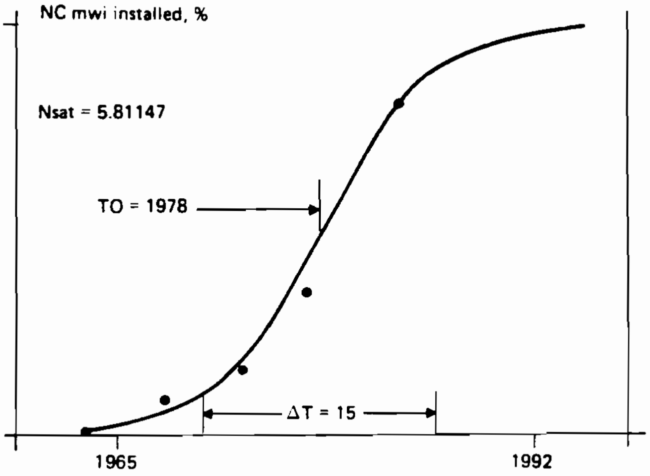

Figure 2. Logistic diffusion of NC-machines installed in US MWI, percentage measured on unit base. [Tchijov, 1987].

Table 1. NC shares of machine-tools in the US MWI (NC share in installation).

	NC share in installation 1983	NC share in installation Estimated saturation level**	(NC share in consumption 1979–1983)
Turning machines	9.1%	16.2%	(37.1%)
Boring machines	11.1%	14.4%	(30.7%)
Drilling machines	2.8%	4%***	(5.6%)
Milling machines	6.8%	10.4%	(20.7%)
Grinding machines	0.6%	2%***	(2.1%)
Machining centers*	4.2%	–	(20.3%)
Total metal cutting	5.5%	–	(19.2%)
Total metal forming	1.9%	–	(7.4%)
Total machine-tools	4.7%	5.8%	(17.3%)

* In sum of drilling, milling and boring machines.

** [Tchijov, 1987]

*** The logistic curves were not fitted for these two cases.

Table 2. NC shares of machine-tools in the US MWI (NC share in consumption).

	Year of installation**			
	-1963	1964-1973	1974-1978	1979-1983
Turning machines	0.6%	3.2%	15.5%	37.1%
Boring machines	4.3%	10.9%	19.4%	30.7%
Drilling machines	0.6%	3.3%	4.2%	5.6%
Milling machines	1.4%	4.4%	9.1%	20.7%
Grinding machines	0.1%	0.4%	0.6%	2.1%
Machining centers*	0.1%	1.8%	5.7%	20.3%
Total metal cutting	1.0%	3.0%	7.3%	19.2%
Total metal forming	0.5%	1.4%	3.0%	7.4%
Total machine tools	0.8%	2.6%	6.4%	17.3%

* In sum of drilling, milling and boring machines.

** Year of installation corresponds to the following generation of machine-tools:

Generation at 1983	Year of installation
0-4 years	1979-1983
5-9 years	1974-1978
10-19 years	1964-1973
more than 20 years	-1963

As shown in Figure 3, the NC share in consumption has increased rapidly year by year. In addition, the big gaps between consumption-base and installation-base can be seen for each year of installation.

According to the results of the previous chapter, the NC share in installation saturates at the same level as the NC share in consumption, with some time-lag.

By applying the above relationship to the case of the USA, the saturation levels of the NC share in installation are estimated to be at least higher than the following levels.

Machine type	Saturation level of NC share
total metal cutting	> 19.2%[4]
total metal forming	> 7.4%[4]
total machine-tools	> 17.3[4]

Figure 3 shows us that the NC share in consumption continues to increase even after 1983. Therefore, the real saturation levels are considered to be much higher than the above values.

3.2 The Case of Japan

Data on the machine-tool population are available for the years 1973, 1981 and 1987 in the Japanese machine industry as a survey on machine-tools installation by MITI [MITI, 1988].

According to this survey, the NC shares in installation are summarized in Table 3. The NC share of metal machine-tools (metal cutting) has increased very rapidly from 0.86% in 1973 to 11.3% at the end of September 1987. In the case of the secondary metal working machinery (metal forming), the NC share has also increased from 0.08% in 1973 to 2.2% in 1987, although the absolute value is even now very low.

On the other hand, as shown in Table 3, the NC shares in consumption, namely the shares of an NC type in recent installations, show much higher values than those in installation, as was also observed for the case of the USA.

According to the relationship between consumption-base and installation-base in the previous chapter, the saturation levels

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[4] NC share of machines consumed from 1979 to 1983.

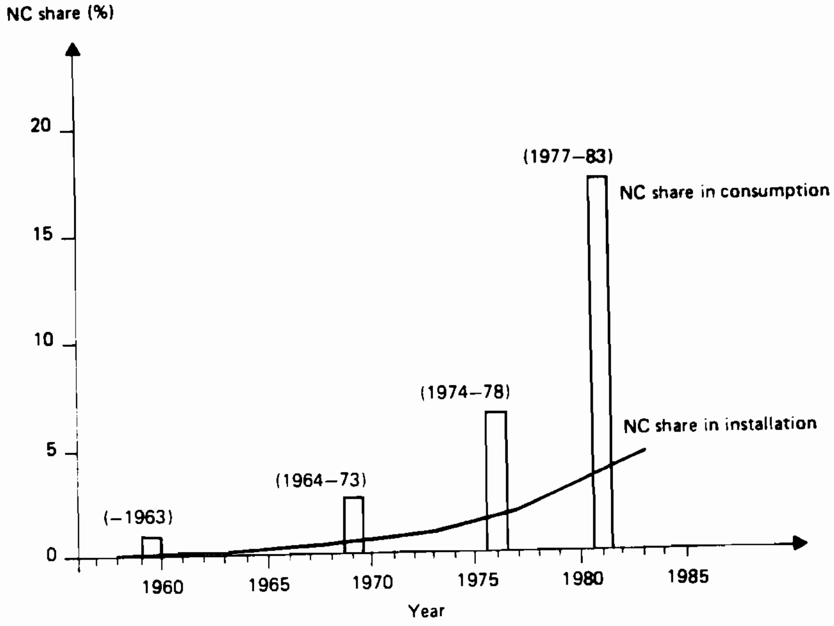

Figure 3. Trends of NC shares in the US MWI.

Table 3. Trends of NC shares in Japan.

	1973	1981	1987
Shares of NC type in machine-tools population			
Metal machine tools	0.86%	3.6%	11.3%
Secondary metal working machinery	0.08%	0.8%	2.2%
Total NC machine-tools	0.67%	2.9%	9.2%
Shares of NC type in recent installation			
Metal machine tools		12.1%*	33.2%**
Secondary metal working machinery		2.2%*	5.2%**

* Installation year: 1979–1981

** Installation year: 1985–1987

The above data are based upon the survey on Machine Tools Installation by MITI in Japan. The survey was carried out for all establishments of more than 50 employees in machine industry. The coverage of this survey by major sectors in 1987 are shown below in terms of employment.

SIC	Coverage
34	14.2%
35	42.4%
36	56.2%
37	64.8%
38	48.4%

of the NC share in installation are estimated to be at least higher than the following levels.

Machine type	Saturation level of NC share
Metal working machines	> 33.2%
Secondary metal machines	> 5.2%

Table 4 shows us that the NC share in consumption continues to increase even after 1987. This means that the real saturation levels of the NC share in installation are much higher than the above values.

The NC shares of machine-tools in production show a similar trends to those in consumption [MITI, 1970-1986]. Table 5 summarizes the trends of NC shares in production by type of machines. The NC share of the turning machine production already reached 62.8% in 1986. In the case of total metal cutting machines, the NC share in production exceeded 28% in 1986 and showed further diffusion.

In order to forecast the diffusion curve of the NC share, a logistic curve method is applied to the NC shares in production of total metal cutting machines as shown in Table 6.

The saturation level of the NC share in production is estimated to be 34.0%. In other words, 34% of the metal cutting machines will be of the NC type in future production.

By applying this logistic curve f(t) to equation (21) in the previous chapter, the NC share in installation g(t) can be obtained as shown in Table 7. In this estimation the annual production of total machines X(t) is, for reasons of simplicity, assumed to be constant. In addition, three cases are set with respect to the replacement years (m), namely, 12, 15 and 18. Among the three cases the last one (m = 18) is considered to be most realistic.

According to this estimation it can be said that the NC share in installation g(t) will show the biggest increase from 1985 to 1995 and approach the saturation level after 2000 in any of the cases, as shown in Figure 4. Moreover, it might be concluded that NC machine-tools will occupy about 30% of the total metal cutting machines in the year 2000.

Table 4. NC shares in machines installed by industrial sectors at the end of September 1987 in Japan.

		TOTAL	By installation year			
	[1981]	[1987]	85–87	83–84	78–82	–77
Metal working machines:						
General machines	4.57%	12.17%	36.32%	28.80%	19.09%	3.08%
Electrical	3.64%	13.46%	34.86%	27.92%	17.20%	2.60%
Transport	2.56%	9.80%	31.21%	20.01%	9.26%	1.66%
Precision	3.12%	9.15%	24.80%	21.84%	14.53%	2.02%
Machine industry	3.57%	11.26%	33.19%	24.90%	14.23%	2.44%
Production data		9.54*%	26.81%	20.59%	11.67%	1.58%**
Secondary metal machines:						
General machines	1.04%	3.28%	10.59%	7.96%	4.58%	0.85%
Electrical	1.19%	2.60%	4.39%	4.27%	4.02%	0.82%
Transport	0.42%	1.51%	4.08%	2.84%	1.35%	0.36%
Precision	0.22%	1.30%	4.98%	2.33%	1.18%	0.33%
Machine industry	0.81%	2.22%	5.18%	4.21%	2.75%	0.62%

* 1970–1986

** 1970–1977

Table 5. NC share in production for each type of machine-tools in Japan (in terms of units).

Year	Lathes	Drilling	Boring	Milling	Grinding	MC/CBM*	Total**
1970	0.93%	0.12%	2.63%	1.22%	0.16%	0.27%	0.57%
1971	1.42%	0.15%	2.24%	1.79%	0.14%	0.37%	0.75%
1972	1.57%	0.25%	2.88%	1.71%	0.15%	0.48%	0.82%
1973	2.94%	0.36%	3.66%	2.31%	0.29%	0.64%	1.30%
1974	3.92%	0.46%	2.35%	3.29%	0.29%	0.80%	1.80%
1975	7.07%	0.40%	2.25%	4.62%	0.19%	1.26%	2.48%
1976	9.66%	0.33%	1.69%	5.35%	0.33%	1.12%	2.78%
1977	16.19%	0.65%	2.29%	5.52%	0.67%	1.88%	4.14%
1978	21.80%	0.66%	2.78%	7.16%	0.26%	3.12%	5.37%
1979	28.85%	0.35%	2.45%	10.61%	1.00%	5.55%	8.72%
1980	34.72%	0.62%	4.14%	14.00%	1.39%	9.81%	12.33%
1981	36.74%	0.87%	4.88%	20.24%	1.99%	15.09%	15.63%
1982	41.74%	0.61%	6.05%	21.93%	2.62%	15.12%	16.47%
1983	45.93%	1.70%	6.67%	25.41%	3.51%	18.85%	18.85%
1984	52.63%	1.60%	12.31%	25.88%	4.99%	19.74%	22.00%
1985	56.92%	1.82%	8.19%	23.37%	7.34%	27.68%	25.66%
1986	62.84%	5.07%	13.32%	27.24%	9.97%	30.82%	28.27%

* Machining centers in sum of drilling, milling and boring machines.

** Including other machine-tools.

Table 6. Logistic curve fitting to NC share in production of machine-tools in Japan.

f=1/(a+b*EXP(−c*t))
PARAMETERS(IT=8)

a = .0294022
b = 2.35723
c = .364993

SD of a (1) = (2.04186E–03)
SD of a (2) = (.592942)
SD of a (3) = (.0277865)

*R2 = .992445
R S S = 9.57137
D.W. = 1.10768

	Estimated(%)	Observed(%)
1970	.418999	.57
1971	.600309	.75
1972	.85807	.82
1973	1.22246	1.3
1974	1.7335	1.8
1975	2.44227	2.48
1976	3.41021	2.78
1977	4.70461	4.14
1978	6.38776	5.37
1979	8.49847	8.72
1980	11.0282	12.33
1981	13.9007	15.63
1982	16.9689	16.47
1983	20.0396	18.85
1984	22.9188	22
1985	25.4579	25.66
1986	27.579	28.27

Table 7. Forecasts of NC share in Japan.

	NC share (%) in production	NC share (%) in installation		
Year	f(t)	m=12 g(t)	m=15 g(t)	m=18 g(t)
1970	0.42	0.11	0.09	0.08
1971	0.60	0.16	0.13	0.11
1972	0.86	0.23	0.19	0.16
1973	1.22	0.33	0.27	0.23
1974	1.73	0.48	0.38	0.32
1975	2.44	0.68	0.55	0.46
1976	3.41	0.95	0.77	0.65
1977	4.70	1.34	1.08	0.91
1978	6.39	1.87	1.51	1.26
1979	8.50	2.56	2.07	1.73
1980	11.03	3.47	2.80	2.34
1981	13.90	4.60	3.72	3.11 (3.6%)*
1982	16.97	5.98	4.84	4.05
1983	20.04	7.60	6.17	5.16
1984	22.92	9.44	7.68	6.43
1985	25.46	11.46	9.34	7.84
1986	27.58	13.61	11.14	9.36
1987	29.27	15.85	13.04	10.97 (11.3%)*
1988	30.57	18.11	14.99	12.64
1989	31.55	20.35	16.98	14.36
1990	32.26	22.50	18.97	16.11
1991	32.77	24.53	20.93	17.86
1992	33.14	26.37	22.82	19.60
1993	33.40	27.99	24.62	21.32
1994	33.58	29.38	26.30	23.00
1995	33.71	30.52	27.81	24.61
1996	33.80	31.42	29.13	26.14
1997	33.86	32.12	30.26	27.54
1998	33.91	32.65	31.19	28.82
1999	33.94	33.04	31.92	29.93
2000	33.96	33.32	32.49	30.87

* Observed data for the establishments of more than 50 employees in mechanical industry at the end of September.

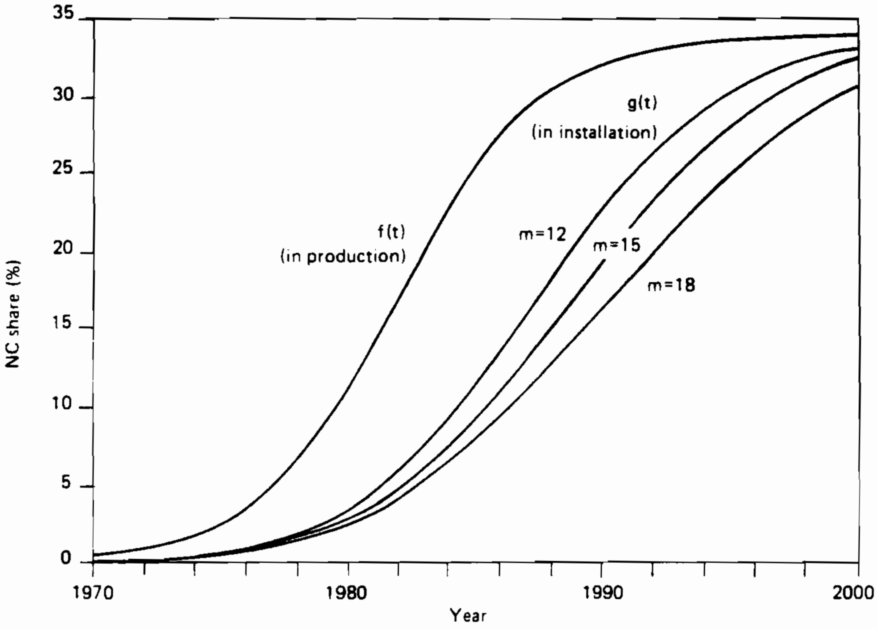

Figure 4. Forecasts of NC share in Japan.

If we focus on large establishments of more than 50 employees, the NC share in installation was already 33.2% in 1987 and will be about 40% in 2000.[*]

4. CONCLUSIONS

(1) Comparisons between the USA and Japan

The comparisons of the past trends of NC shares of machine-tools between the USA and Japan are summarized in Figures 5 and 6. The NC shares by sectors are described in Appendix B.

Figure 5 shows the past trends of the NC share in the population of total machine-tools (metal cutting & metal forming) in the USA and Japan, and Figure 6 shows these trends in the consumption of metal cutting machines.

In both cases similar trends can be observed in the USA and in Japan.

The NC shares in installation and in consumption are considered to be about 10% and about 30% at present in both countries.

The gap between the two kinds of NC shares implies the further diffusion of NC machine-tools in terms of installation-base.

(2) Method to estimate the saturation level of diffusion

As explained in the previous chapters, it is very difficult to estimate a reliable saturation level of diffusion in installation-base by a simple logistic curve model. However, there is some relationship between the diffusion in installation-base and that in consumption-base, as described in Chapter 2, if the diffusion of an advanced type is mainly due to the replacement of conventional types such as NC machine-tools. In such a case the diffusion in consumption can be regarded as a leading index of installation-based diffusion.

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[*] The NC shares in production show lower values than those in consumption. For instance, the NC share in production is 28.3% in 1986, while that in recent installations (1985-1987) is 33.2%. The main reason for this gap is as follows. The data in consumption do not cover small establishments of less than 50 employees. The NC shares in small establishments are considered to be lower than those in large establishments as observed in the case of industrial robots.

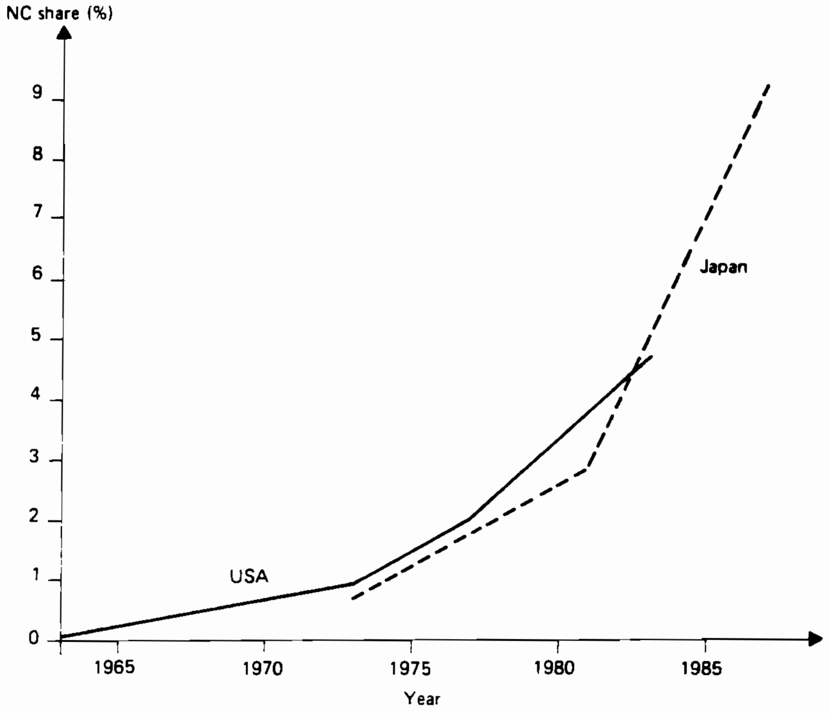

Figure 5. Past trends of NC share in installation, metal cutting and metal forming in the USA and in Japan.

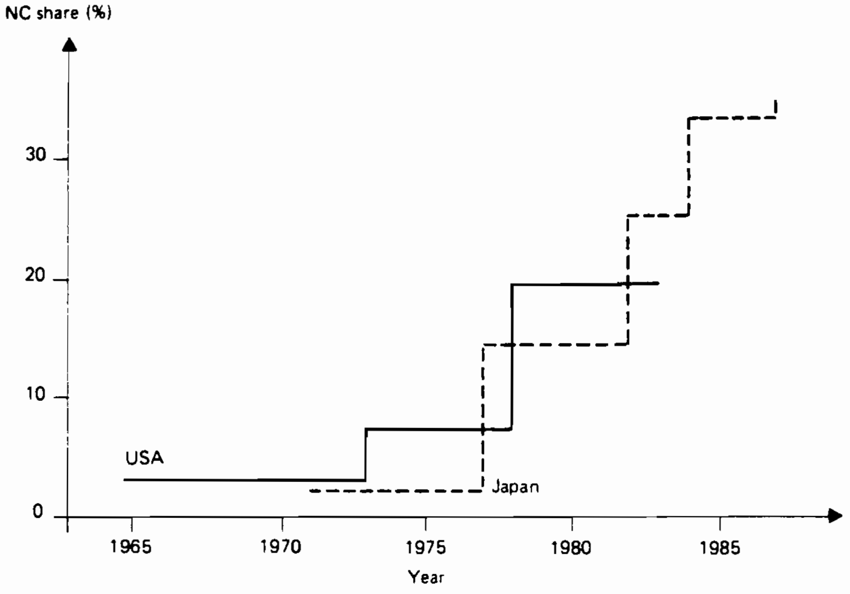

Figure 6. NC shares by installation year in the USA and in Japan (metal cutting).

Therefore, the forecasting of diffusion, and especially the estimation of the saturation level, will be more reliable if the trends of diffusion in consumption-base are taken into account.

(3) The strong impacts of NC machine-tools in the next decade

There were 601 000 metal machine-tools (metal cutting machines) in establishments of more than 50 employees relating to the Japanese machine industry at the end of September 1987. As described in the previous chapter, the NC share in recent installations is 33.2%, while that in 1987 was 11.2%. According to the relationship between the two kinds of NC shares, the NC share in installations will reach about 40% in 2000. This means that about 240 000 NC machine-tools will be used in the above Japanese establishments in the year 2000, while the corresponding number was 66 000 in 1987.

In other words, we are going to face a substantial diffusion of NC machine-tools from now up to 2000. A similar tendency can also be pointed out for the USA.

Such a large diffusion will cause various and significant impacts for our economy and society during the next decade.

(4) Diffusion of FMS

A high diffusion of NC machine-tools affects the diffusion of FMS, because NC machine-tools are regarded as basic components of FMS.

One way of estimating the diffusion of FMS can be expressed in the following equation.

$$\text{Number of FMS} = (N \times h)/d \qquad (22)$$

where

$$N = \text{number of NC machine-tools} \qquad (23)$$

$$h = \frac{\text{number of NC machine-tools used in FMS}}{N} \qquad (24)$$

$$d = \text{average number of NC machine-tools per FMS} \qquad (25)$$

According to the literature [ECE, 1986; Darrow, 1987], the coefficient d is estimated to be 7.5 machines/FMS in the case of Japan. The number of NC machine-tools (N) was 66 166 units in 1987 [MITI, 1988] and the saturation level is estimated at about 240 000, as described before.

On the other hand, the number of FMS for metal cutting in Japan was 186[a] at the end of September 1987 [MITI, 1988].

As a result, the number of NC machine-tools used in FMS is estimated to be 1395 at present in Japan. This indicates that the coefficient h is now 2.11%. If we investigate the FMS by installation year, the coefficient h is estimated as below.

Installation year	Number of FMS	h
before 1984	90	1.62%
1985-1987	96	2.95%

As shown above, the share of NC machines used in FMS (h) has been increasing.

It is very difficult to estimate the saturation level of h because the diffusion of FMS is now at a very early stage. However, it can be said that at least 5% of the NC machine-tools will be used in FMS at the saturation stage of FMS diffusion.

According to the assumptions described above, the number of FMS for metal cutting is forecast to be at least 1600 systems at saturation stage. If we add other types of FMS (metal forming, etc.) to the above figure, the total number of FMS will exceed at least 2000 systems only in Japan at the saturation stage of FMS diffusion.

In the above forecasts the future population of machine-tools is assumed to remain unchanged at the present level.

However, the number of machine-tools might decrease in the future for the following reasons:

a) Different functions are now going to be integrated into one machine.

b) The utilization of machine-tools is now going to be improved as a result of the benefits of FMS.

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[a] Other types (metal forming) of FMS ... 68 systems.

It is important to take this factor into account in further investigations on the future diffusion of NC machine-tools and FMS.

APPENDIX A. NOTATION OF VARIABLES

$u(t)$	Population of NC machine-tools at the end of year t
$U(t)$	Population of machine-tools at the end of year t
$g(t) \equiv u(t)/U(t)$:	NC share in population of machine-tools at the end of year t
$x(t)$	consumption of NC machine-tools in year t
$X(t)$	consumption of machine-tools in year t
$f(t) \equiv x(t)/X(t)$:	NC share in consumption of machine-tools in year t
m	replacement time (years)
$f\infty$	saturation level of NC share in consumption.

Appendix–B. NC shares by sector in USA and Japan.

NC machine-tools in Japan

		Industrial sector				
	Year	SIC 34	SIC 35	SIC 36	SIC 37	SIC38
NC share in population						
NC share Metal machine tools	1973	0.46%	1.25%	0.93%	0.55%	0.50%
	1981	2.24%	4.57%	3.64%	2.56%	3.21%
	1987	7.40%	12.17%	13.46%	9.80%	9.15%
NC share Secondary metal machine	1973	0.08%	0.07%	0.13%	0.06%	0.02%
	1981	0.59%	1.04%	1.19%	0.42%	0.22%
	1987	2.08%	3.28%	2.60%	1.51%	1.30%
NC share in consumption	Installation year					
Metal machine tools	-77	1.29%	3.08%	2.60%	1.66%	2.02%
	78–82	10.60%	19.09%	17.20%	9.26%	14.53%
	83–84	15.57%	28.80%	27.92%	20.01%	21.84%
	85–87	23.31%	36.32%	34.86%	31.21%	24.80%
Secondary metal machine	-77	0.31%	0.85%	0.82%	0.36%	0.33%
	78–82	2.98%	4.58%	4.02%	1.35%	1.18%
	83–84	3.82%	7.96%	4.27%	2.84%	2.33%
	85–87	7.06%	10.59%	4.39%	4.08%	4.98%

NC machine-tools in USA

		Industrial sector				
	Year	SIC 34	SIC 35	SIC 36	SIC 37	SIC38
NC share in population						
Metal cutting	1983	3.33%	7.09%	5.29%	5.79%	4.86%
Metal forming	1983	1.88%	2.04%	2.00%	1.63%	2.40%
NC share in consumption	Installation year					
Metal cutting	-63	0.78%	0.65%	1.08%	1.79%	0.29%
	64–73	1.81%	3.66%	2.52%	4.16%	2.46%
	74–78	4.17%	10.04%	6.45%	7.08%	6.03%
	79–83	13.98%	23.48%	18.13%	19.26%	15.39%
Metal forming	-63	0.61%	0.44%	0.54%	0.32%	0.00%
	64–73	1.58%	1.32%	1.06%	1.16%	1.12%
	74–78	2.90%	3.35%	2.05%	3.00%	4.87%
	79–83	7.75%	6.96%	8.73%	5.77%	7.83%

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PROGNOSTIC MODEL FOR INDUSTRIAL ROBOT PENETRATION IN CENTRALLY PLANNED ECONOMIES

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I. INTRODUCTION

One of the most important components of Computer Integrated Manufacturing (CIM) is that of Industrialized Robots (IR). We are now witnessing many attempts to forecast the future of IR penetration in many different countries [see, for example, Blair and Vickery, 1987; Edquist and Jacobsen, 1986; ECE, 1985; Filemon, 1987; and Yonemoto, 1987]. The forecast is usually based on econometric models, using mainly different forms of production functions.

It is worthwhile stressing that IR adoption entails a number of consequences, the most important of which is, from the economic point of view, labor substitution. The effectiveness of this substitution is the key point of the speed of industrial robot (IR) penetration in different manufacturing systems. It may be plausible to assume that the conditions for the rate of penetration differ with companies, enterprises and industries as well as with economic systems.

The latest newly developed models at IIASA for the forecast of robotization of industrial production -- expressed in terms of number of applied IR and worked out by Shunsuke Mori [see Mori, 1987] and Akira Tani [see Tani, 1987a and 1987b] are also based on the production function. The core of these prognostic models is the ratio of prices of individual robots to wages.

Econometric models of that kind are mainly applied to market economy countries. Models based on the ratio of IR prices to wage levels turn out to be too simplified under the conditions of centrally planned economies. For this reason one cannot use a model which is based on salaries and IR prices for centrally planned economies. Instead, one must include other factors in the model which are important for IR penetration in these economies.

The second reason is sometimes the lack of available data due to the confidential nature of a great part of the required material. The information systems, in general, need some improvement, and there exist various suggestions for improving the current situation.

The main reason, however, is that the management mechanisms of centrally planned economies are fundamentally different. While the prognosis of the future penetration in market economies is theoretically based on an equilibrium wage and IR price development, in centrally planned economies wages and IR prices are planned and regulated centrally.

Under the conditions prevalent in many centrally planned economies in the past, the use of econometric models of this type has been irrelevant. Nowadays practically all those economies are trying to improve their economic mechanism and increase the relative economic independence of enterprises and companies. The main goals of these new perestroika or restructuring policies are to increase the initiative and socialist entrepreneurship of the companies' management and to hasten technological progress and the introduction of new technologies. Such goals -- which have already been realized in some areas -- create completely new conditions for the adoption of econometric methods in centrally planned management.

The main aim of this paper is to demonstrate the possible utilization of prognostic models under the conditions of centrally planned economies, mainly on the governmental level. Under the changed economic conditions, the government can manage the planned robot diffusion by applying indirect tools, such as price and tax measures.

It must be stressed that this kind of model is one of the first attempts to forecast industrial robot penetration in centrally planned economies. In our opinion Czechoslovakia, a centrally planned economy with a very high level of industry, automation of industrial production and a relatively high population of robots per capita, provides a good case for the application of this prognostic model.

II. THE PROGNOSTIC MODEL

Let us start from the annual time series and let t be that time, which the values of the time series are referred to.

We denote the growing rate of the number of IR in a given production system in time to by the following equation:

$$I_t = \frac{U_{t+1} - U_t}{U_t} \qquad (1)$$

where U_t is the number of industrial robots in time t.

We can model IR diffusion in the manufacturing process from the presumption that the rate of growth in time t is partly dependent on the relation between labor and robot costs, and partly on the relation between the marginal product of human labor and robot labor.

The <u>marginal product of human labor</u> is the increase in output of the manufacturing system resulting from the addition of one worker to the system while providing the system with all other manufacturing resources.

The <u>marginal product of robot labor</u> in that system denotes the possible increase of production of that particular system by the installation of one robot while providing the system with all other manufacturing resources.

If the ratio of labor costs to robot costs and the marginal product of one robot to the marginal product of one worker in a system is growing, then there are favorable economic conditions for IR adoption in this respective manufacturing system.

If we assume $g_{1,t}$ to denote the ratio of human labor cost to robot installation cost and $g_{2,t}$ the ratio of marginal product of robot labor to the marginal product of one worker, then the growth rate of the number of IR can be expressed as a function

$$I_t = f(g_{1,t}, \quad g_{2,t}) \tag{2}$$

where function f satisfies the following conditions:

$$\frac{\partial f}{\partial g_{1,t}} > 0 \tag{3}$$

$$\frac{\partial f}{\partial g_{2,t}} > 0 \tag{4}$$

These conditions are satisfied, for instance, by the function

$$I_t = k \cdot g_{1,t} \cdot g_{2,t} \tag{5}$$

If we denote human labor costs in time t $C_{L,t}$, then we can approximately define $C_{L,t}$ as follows:

$$C_{L,t} = W_t L_t + \omega_t W_t L_t + \gamma_t W_t L_t \quad , \tag{6}$$

where

W_t is the average annual wage of one worker

L_t is the number of workers

ω_t is the wage tax rate (paid by the company)

γ_t is the rate of additional costs (e.g. for social provisions, etc.).

If we denote the operational costs of one robot by $C_{R,t}$, then the following equation holds approximately true:

$$C_{R,t} = \delta_t P_t U_t + \lambda_t P_t U_t + \alpha_t P_t U_t \tag{7}$$

where

U_t is the number of IR (as above)

P_t is the robot price

δ_t is the robot depreciation rate

λ_t is the annual capital charge (based on the installation value of production capital goods)

α_t is the rate of additionally required costs.

Under these conditions the ratio $g_{1,t}$ holds true

$$g_{1,t} = \frac{C_{L,t}}{C_{R,t}} = \frac{W_t L_t + \omega_t W_t L_t + \gamma_t W_t L_t}{\delta_t P_t U_t + \lambda_t P_t U_t + \alpha_t P_t U_t} \tag{8}$$

hence

$$g_{1,t} = \frac{(1 + \omega_t + \gamma_t)}{(\delta_t + \lambda_t + \alpha_t)} \cdot \frac{W_t}{P_t} \cdot \frac{L_t}{U_t} \tag{9}$$

It is possible to derive the $g_{2,t}$ ratio from a dynamic production function of the following type:

$$Y_t = a_t K_t^{b_t} L_t^{c_t} EN_t^{d_t} U_t^{e_t} , \qquad (10)$$

where

Y_t is the gross production of the manufacturing system in constant prices

K_t are the production capital costs without IR in installed prices

EN_t is electricity consumption in kWh

a_t, b_t, c_t, d_t, e_t are variable proportional parameters.

The marginal product of human labor and robot labor is -- on the basis of the above-mentioned model (10) -- directly dependent on a partial derivative of the production function by the number of workers and the number of IR.

Under such conditions $g_{2,t}$ can be expressed in the following form:

$$g_{2,t} = \frac{\dfrac{\partial Y_t}{\partial U_t}}{\dfrac{\partial Y_t}{\partial L_t}} = \frac{e_t}{c_t} \cdot \frac{L_t}{U_t} \qquad (11)$$

The proportional parameters of the production function can be specified, e.g., by means of the least square method in logarithmic form with exponential forgetting.[1]

The resultant relationship for the growth rate of the number of IR can be defined as follows:

$$I_t = k \frac{e_t}{c_t} \frac{(1 + \omega_t + \gamma_t)}{(\delta_t + \lambda_t + \alpha_t)} \frac{W_t}{P_t} \frac{L^2_t}{U^2_t} , \qquad (12)$$

or, let us say for the number of installed robots in the respective manufacturing system the following recurrent relationship holds:

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[1] The dynamic production function is a square root filter for real time multivariable regression. For more details, see [Zaruba, 1985].

$$U_{t+1} = U_t + k \frac{e_t}{c_t} \frac{(1 + \omega_t + \gamma_t)}{(\delta_t + \lambda_t + \alpha_t)} \frac{W_t}{P_t} \frac{L^2_t}{U_t} \qquad (13)$$

Constant k can be determined from the previous period by means of a simple linear regression.

The augmentation of the number of installed robots can then be expressed on the basis of the following five partial factors:

f_1: $\frac{e_t}{c_t}$	expresses the ratio of the influence of technological conditions of the manufacturing system on the IR adoption;
f_2: $\frac{1 + \omega_t + \gamma_t}{\delta_t + \lambda_t + \alpha_t}$	expresses the ratio of the influence of the government on the penetration of IR in the respective manufacturing system;
f_3: $\frac{W_t}{P_t}$	expresses the influence of the robot price and wages on the penetration of IR;
f_4: $\frac{L_t}{U_t}$	expresses the influence of the so-called regressive effect of robotization. During the first phase the robots are introduced above all at the workshops with a low labor productivity and in the course of time the substitution process involves the workshops with increasingly higher labor productivity, which is inhibiting IR diffusion;
f_5: L_t	expresses the influence of the tendency of release of manpower from the production area and the shift to the other areas (e.g. service).

III. UTILIZATION OF MODEL RESULTS

When we analyze the prerequisites and conditions for the adoption of the model results in detail, we can state that in centrally planned economic systems there is a very broad field for model results application. But the effective utilization of the models of this kind is only possible under the conditions of a so-called relative independence of the companies and enterprises, when centrally planned management is combined with the initiative and entrepreneurship of the company and enterprise management.

Under such specific conditions the government has very effective indirect economic tools to reach the target in production automation. The results obtained from the prognostic simulation model are very useful guidelines for specifying the level of IR prices, differentiation of taxes, assessment of production resources, such as capital goods, man-power, and inventories. Adoption of such tools can eliminate the bottlenecks which currently hamper the plan, and -- what is much more important --, the automation devices will be adopted more effectively.

If we assess the possibilities of utilization of prognostic simulation model results in the market and centrally planned economies mentioned above from a purely theoretical point of view, we come to the conclusion that the market economies can use the results "ex post", but the centrally planned economies have the possibility of utilizing the model results "ex ante", under the conditions of a combined centrally planned management and company management initiative and entrepreneurship.

An elaborated prognostic simulation model can serve for the simulation of robot diffusion in manufacturing systems in the different stages of aggregation, from the enterprise or company level to the whole industry. The model can be used mainly for the following situations and preconditions:

- for the simulation of the number of installed IR in the future at the current tax level of wages and production capital good charges, under the existing technological conditions, the existing wage development, the assessed price development and the disposable number of workers;

- for the analysis of the necessary changes of taxes in order to stimulate the manufacturing system to adopt the planned number of IR in that particular system;
- for the analysis of the IR price development under the existing conditions in order to stimulate the manufacturing system to adopt the planned number of IR in that particular system;
- for the analysis of robot demand in the respective manufacturing system.

Compared with the model so far used for market economies, which concentrates on labor substitution, other additional factors are included in our model and its utilization is logically broader.

For the future development of the model it will be useful to take into account the substantial difference in costs between individual and group implementation of IR. The other factor which can contribute to a higher precision of the model results is the division of IR into groups. Such attempts have, however, so far stumbled over the obstacle of the lack of necessary information.

IV. APPLICATION OF THE MODEL IN THE CZECHOSLOVAK INDUSTRY

The proportional parameters of the dynamic production function were specified from the input data (shown in Table 1), where Y_t, K_t are expressed in thousand Czech crowns, L_t is the number of so-called physical persons, EN_t is expressed in kWh and U_t is the number of IR.

In Table 2 the development of proportional parameters is calculated with the factor of exponential forgetting . = 0.9.

Table 3 shows the comparison of the real and the modelled value of Y_t and the relative error in % for various years.

Table 4 shows the testing of the model on the historical data. MAD (Mean Absolute Deviation) is 35,62. It proves that the model is of high sensitivity.

It turns out that for the conditions of the Czechoslovak

Table 1. **Historical input data for the Czechoslovak industry**

	Gross Output	Installed Capital (ex. IR) at cost	Labor (Workers)	Electricity Consumption	Industrial Robots
Year	Y_t	K_t	L_t	EN_t	U_t
1978	589589	643434	2489331	38345	2600
1979	611388	687297	2507768	38947	2750
1980	631502	734903	2520351	39090	2800
1981	645816	790480	2530154	39648	2900
1982	654706	833595	2548929	39923	3000
1983	673984	882474	2560260	40903	3119
1984	701482	936808	2576218	41807	3430
1985	726771	988645	2591187	43023	4033
1986	749817	1041010	2604136	43896	5027

Table 2. Development of proportional parameters of the dynamic production function

Year	a_t	b_t	c_t	d_t	e_t
1978	0.720496	0.286703	0.380626	0.359118	0.049482
1979	0.720751	0.286707	0.380627	0.359119	0.049483
1980	0.722394	0.286756	0.380659	o.359154	0.049508
1981	0.722334	0.286745	0.380657	0.359152	0.049506
1982	0.720989	0.286710	0.380639	0.359132	0.049489
1983	0.720131	0.286670	0.380635	0.359128	0.049485
1984	0.720901	0.286657	0.380636	0.359129	0.049486
1985	0.721373	0.286665	0.380636	0.359129	0.049486
1986	0.721139	0.286667	0.380636	0.359129	0.049486

Table 3. Comparison of real and modelled production Y_t

Year	Reality	Model	Rel. error, %
1978	589589	592291	0.45
1979	611388	610652	-0.12
1980	631502	627549	-0.62
1981	645816	645959	0.02
1982	654706	658505	0.58
1983	673984	676389	0.35
1984	701482	699056	0.34
1985	726771	725206	0.21
1986	749817	750673	0.11

Table 4. Testing of the model on historical data (Normalized to 1978)

Year	Real U_t	Model	Difference
1978	2600	2600	0
1979	2750	2725	25
1980	2800	2836	36
1981	2900	2940	40
1982	3000	3015	15
1983	3119	3084	35
1984	3430	3355	75
1985	4033	4050	17
1986	5027	4985	42

industry the ratio of proportional parameters is practically constant and the real figure is

$$\frac{e_t}{c_t} = 0.13.$$

In the Czechoslovak industry the ω_t, γ_t, δ_t, λ_t, α_t, W_t, P_t currently have the following values:[2]

$\omega_t = 0.2$
$\gamma_t = 0.15$
$\delta_t = 0.14$
$\lambda_t = 0.1$
$\alpha_t = 0.15$
$W_t =$ 36 780 Kcs
$P_t =$ 377 400 Kcs

Under the conditions presented above the value of constant $k = 1.41379 \cdot 10^{-5}$.

The prognoses of the number of workers in the Czechoslovak industry was taken from the official plan-prognosis by the year 2000.

1987	2 611 450
1988	2 617 500
1989	2 622 900
1990	2 627 700
1991	2 640 400
1992	2 652 800
1993	2 665 700
1994	2 679 000
1995	2 690 100

Four scenarios of IR diffusion in the Czechoslovak industry were carried out, using the above-mentioned model:

1. Scenario – V_1: For the same taxes as already applied with constant wage level and IR prices (most pessimistic with regard to economic changes);

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[2] Raw data have not been released for publication.

2. Scenario - V_2: For the same taxes as already applied, but with 2% annual growth of wages and 1% annual decline of IR prices;
3. Scenario - V_3: For a deliberate increase in wage taxes of man-power at a rate of $\omega_t = 0.5$ and a constant level of wages and robot prices;
4. Scenario - V_4: For a deliberate increase of the taxes of wages at a rate of $\omega_t = 0.5$, but with a 2% annual growth of wages and a 1% annual decrease of IR prices (most optimistic from the point of view of economic changes).

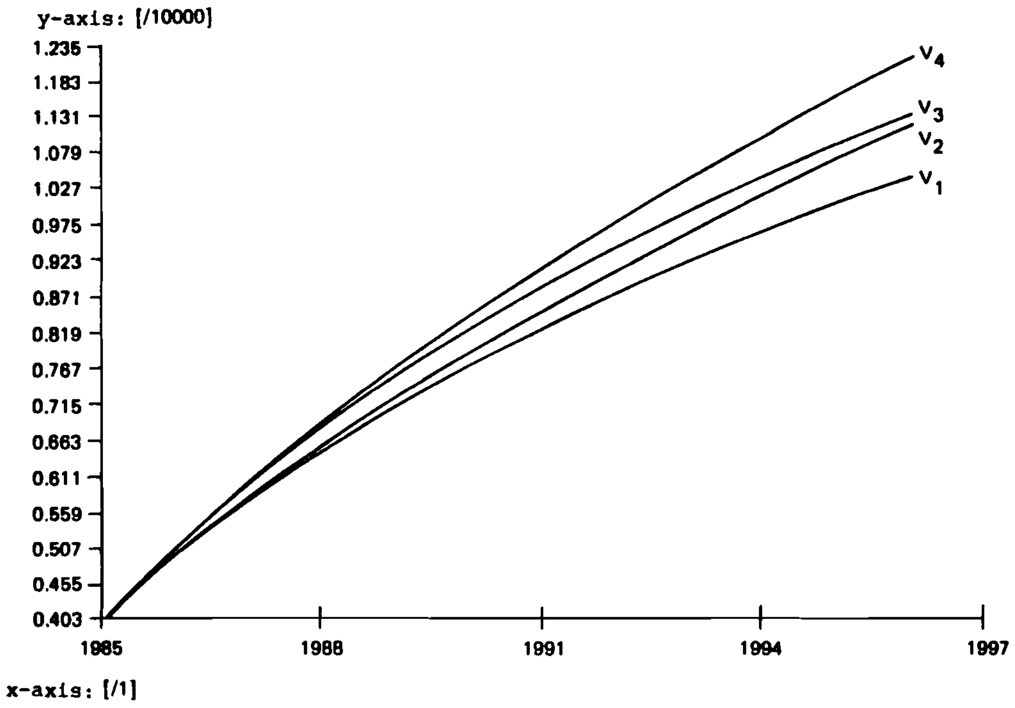
The figures for the different scenarios V_1, V_2, V_3, and V_4 are shown in Table 5.

The graphical illustration of these four scenarios is given in Figure 1.

From the current development of the economic conditions in Czechoslovakia we can infer that the most probable scenario is V_4.

Table 5. Scenarios of robot penetration in Czechoslovakia

Year	V_1	V_2	V_3	V_4
1987	5832	5856	6018	6048
1988	6530	6594	6851	6927
1889	7156	7273	7585	7722
1990	7730	7909	8252	8460
1991	8264	8514	8867	9156
1992	8767	9099	9444	9825
1993	9247	9668	9992	10474
1994	9705	10225	10515	11103
1995	10147	10773	11016	11728
1996	10573	11314	11499	12339



Notes:
x-axis: years
y-axis: number of IR expressed in 10 000 pieces

Figure 1. Graphical representation of the scenarios of IR penetration in Czechoslovakia.

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DIFFUSION DYNAMICS
OF FLEXIBLE AUTOMATION

by

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1. Introduction

The seventies have marked the onset of an historical phase of great instability and uncertainty in the development of world economy. Repercussions on the manufacturing environment have been such as to place in doubt the traditional success-seeking approach models adopted by companies. The models, basically, exerted pressure on consumer demands in continually expanding markets and on mass production economy. Moreover, economic operators have determined a steady growth in the demand for flexibility and for the capability of adopting production resources to the turbulence of the environment.
Such demands have found correspondence in an interdependent reality of new technological opportunities, which, according to the conceptualization proposed by some experts (see Freeman, 1987; Perez, 1983 and 1985), have generated a new "technical-economical meta-paradigm, capable of radically changing manufacturing functions and the behavioural rules of companies. Such meta-paradigm, based on a new low-cost input media - the microelectronics chip - biases production technologies of every sector of industry and is identifiable through some distinctive traits: (a) the shift to information intensive processes and products rather than high energy and materials contents, (b) the introduction of production processes, based on economies of scope, capable of effectively producing diversified ranges of products, (c) the evolution of managerial practices towards the total integration of functions to enhance the capability of dynamically responding to external stimuli.

A vigorous upswing of innovation in production processes has been thus witnessed, which, on the other hand, has taken on characteristics of growing complexity. In fact, innovation to a process often demands innovations to the organizational-managerial and product spheres, to fully exploit the potentialities offered by the technologies introduced (Colombo and Mariotti, 1987).

In the reality of this scenario and within discontinuous production processes, the change from "rigid" automation, typical of production line manufacturing models , to flexible automation (FA) occurred, just as synergical models of production and management became to be established together with the management of differentiated product families (Colombo and Mariotti, 1985). The potentialities offered by the introduction of microprocessors and computers to design and manufacturing technologies have been increased, on the one hand, by the development of conceptual and application software capable of supporting highly sophisticated and intelligent control systems and on the other hand, by the crucial developments introduced through automation techniques and auxiliary plant oriented technologies.

It is important to point out how AF related technology radically transforms the elements of scientific and technical progress previously mentioned, through their original combination, which in fact hinges on the concept of system integration. Deep discontinuity is thus present, with respect to the past, in the techniques and the tools to manage the whole manufacturing activity and its relations with the managerial activities of the company.

The diffusion of FA implies and finds its drive in a new definition of the success model for firms (Nelson and Winter, 1982) in which the main ingredients are a new equilibrium in the trade-off between dynamic and static efficiency and the adoption by firms of production strategies better tuned to market requirements and more intimately based upon product innovation/differentiation.

Typical of every deep change, the introduction and spread of FA has required a long period of gestation meeting difficulties and immobilities, particularly when complementary innovations were requested in the organizational area and in the technical-managerial approach of the company. Freeman (1987) observes how already in the fifties Diebold (1952) was able to outline with extreme clarity the technological trajectories of the "automatic factory" and the implications as referred to the scale of the investments required, the re-design of products and processes, the re-training of the manpower and, lastly, the necessity bringing about fundamental changes in the attitudes and habits of management.

Nevertheless, only the eighties and under the firm pressure of a worldwide economy restructuring rush, a few "solutions" to the problems posed by the development of techniques and human resources are ripening. The rate of introduction of FA in the most developed countries has been consistently high and following trajectories apparently strongly influenced by the demand generated by the large manufacturing firms involved in mass production roles. It is, in fact, these firms that have undergone the deepest changes and disruptions in the oligopolistic structures of markets. In turn, the markets solicited the search for production alternatives such to allow the introduction of flexible management techniques on large production lines aiming to increase the innovation and differentiation rate of products.

These evolutionary assumptions have conditioned the growth of FA systems. Only recently have configurations appeared having a wider spectrum of utilization such to satisfy the growing demand, even though, at times, rather untimely and poorly focalized by heterogeneous classes of companies. The present diffusion phase has overcome the introductory period and has reached levels appropriate to the performance of significative quantitative analysis to identify and qualify the salient economic traits of its development dynamics.

The intention of this paper is to provide a cognitive contribution within the said guidelines, by illustrating the main results of a research conducted on the diffusive dynamics of FA systems in the Italian metalworking industry. The research has drawn upon the information contained in the FLAUTO database, processed by the Laboratorio di Economia dei Processi di Automazione of the MIP - Milan Polytechnic and updated to June 30, 1987. The mentioned database interests a sample of nearly 3,000 companies and is considered as being the largest and most recent font of information on the considered phenomenon available in Italy.[2]

The logical subdivision of the paper considers, first of all, the economic factors connected to FA that influence in a determining way the diffusion process. Follows the illustration of the dynamics of the diffusion of the various typologies of flexible systems in Italy, from the origins to today. Subsequently the basis of the adopted "diffusive model" is described, with reference to some classic variables: sectorial diffusion, territorial, by size of classes and by type of company that adopted it. This allows to enucleate a series of interpretations useful to the economic debate risen around the FA theme, both for the definition of industrial policies to uphold the productive apparatus of the Italian industry.

2. Nature of Flexible Automation and their Influence on the Diffusion Process

2.1. Innovations System and System Innovation

The term FA generally is referred to a "cluster" of process innovations deriving from the same technological paradigm. Herein the attention is concentrated on FA Systems, defined as integrated hardware and software assemblies of machinery and devices, the purpose of which is to design and/or produce a defined range of products, in automatic mode. Within FA systems, an intense generation of new products has been witnessed, each displaying distinctive capabilities and characteristics. Such products are characterized both by relationships of competitiveness, as they offer technical solutions, with different levels of efficiency and cost, to similar economic problems and by relationships of complementarity originated by technological convergencies and through mutual learning processes.

In spite of the diversity of the technological solutions and the degree of liberty still available for an evolutionary development, it is possible to identify a series of characteristics that link the various FA systems and influence their diffusion process.

Firstly, let the functional and sectorial spread be considered. Potentially, FA applications span the whole arc of discontinuous type industrial processes and extend to every phase and function of the productive transformation, that is; design, manufacturing, assembly, measurement and plant logistics. Such spread, at intra-company level, is strengthened by the complementarities that establish between the various applicational spheres (particularly between the design/production engineering of the product and the subsequent transformation phases) and, above all, by the modular and open characteristics typical of flexible systems. These latter characteristics, that rely on hardware and software interfaces and allow to a fair extent the addition and/or the substitution of various elements and subsystems, confer to the system the metamorphic ability of changing its inherent structure to mold it to market changes and new requirements.

The modular potentialities of the systems can only become evident if industrial standards, concerning the "system architecture" and the compatibility among the equipment, become accepted. On this point there still is a condition of uncertainty due to the combined absence of a strategy agreement among the leading manufacturers and the limited knowledge of the users.

The uncertainty over standards completely slows down the diffusion process and favours the realization of customized solutions, applicable only to a single user. These solution, though offering a contingent answer to demands, prevent the mid-term rationalization of supply and the attainment of the adequate economies of scale to manufacture the systems. Resulting high market costs in turn slow down further the diffusion rate.

Secondly, the mentioned variety of FA products induces a diffusion of flexible systems along a continuum of technological solutions, starting from the simplest stand-alone work stations to the complex FMS systems and to the technological frontier represented by total integration of company functions (CIM). Diffusion is thus marked by a wide variety of intermediate forms, which, in exchange for a reduction of performance, with respect to border-line solutions in terms of flexibility of range and of operability in degraded conditions, involve a lowering of investments and of the know-how required to efficiently run the plants.

Thirdly, the innovative potential of FA is only partially present within the machines, in the devices and in the management software that make up a flexible plant. To ensure high profitability for the adoption of a flexible system, some complementary innovations, mainly in the organizational-managerial areas, become necessary. The innovations are proportional to the size and complexity of the installed systems and are linked to the product mix, to the organizational procedures and to the market strategies.

Moreover, it has been pointed out by several sources that,although the advantages introduced by the adoption of new technologies in terms of costs and yields should not be minimized, companies can expect to draw considerable advantages upon the competition [3]. A different market positioning can be achieved through FA and those strategies that deeply innovate the commercial relationship of the company with its customer base can be adopted; strategies that are based on non-price competition; such as quality and service levels and product differentiation and diversification policies.

The implementation of such strategies and the exploitation of the potentialities offered by FA often imply the integrated redesign of the product/process and the restructuring of considerable portions of the logistic organization of the installing company. Flexible Automation appears, to express it in other terms, a radical innovation to the system. It not only requires the acquisition of complex technical knowhow to integrate the traditional orientation typical of mechanical technologies to that of computer based systems, but also and above all, the cumulative development of designing capabilities and managerial expertise to obtain mutual adaptation between the new technologies and the structure-strategy of the company. Learning processes play in this way an essential role in determining system performance and in encouraging the continuation along the "paths of automation", bringing companies closer to the technological frontiers, in the aim of reaching higher levels of automatic integration of the production activities.

2.2. **The Barriers to Adoption**

In relation to what said and considering the state of the art emerging from previous studies [4], it is possible to derive which are the main barriers to the adoption of FA systems. Whenever reference is made to the more complex solutions, perched on the technological frontiers, said barriers may be summarized as follows:

i) barriers attributable to the combined scale of production necessary to reach the saturation level of plants. These can be considered flexible in terms of range of products and mix, but display "steep" short-terms cost curves as the quantities vary. Such issue can be connected to various technical-production problems that not only concern the scale aggregated to the **output**, but also to its composition, in terms of the number of production variations and the size of the relative lots [5]. Generally speaking, the dimension of the company, is positively correlated to the adoption of commercial policies centred on a wide product mix and range, such to regularly saturate production potentialities;

ii) system dependent barriers. These cause the efficiency of the installed plants to depend upon the functional horizon and upon the level of integration foreseen by the systems. Particular reference is made to the effects of complementarity among the FA's installed during the design, the planning and the control of processing and of manufacturing;

iii) financial barriers. Are connected to the size of the investments required, be these in terms of fixed capital or human resources. Furthermore, the performance of an FA system is difficult to evaluate beforehand as they depend upon correlated changes in the strategy-structure of the adopter. The costs of capital consequently grow in direct proportion to the risk of failure;

iv) sunk costs barriers. These are the high costs that companies have to bear to introduce ex-novo FA systems. More " radical" is the degree of innovation and greater the technological leap forward required, greater is the irrecoverableness and the depreciation of the existing tangible resources (plants and equipment) and intangible ones (skills and organizational routines). Such costs can be spread out by introducing gradual changes, that is adopting intermediate solutions, technologically **second best.** This approach, obviously, involves a performance **trade-off**;

v) information and knowledge accumulation limits barriers. These limits are related to the cumulative characteristics and highly individualized knowhow necessary for the implementation, development and control of the various FA systems available. Considered the nature of these characteristics, knowledge diffuses among potential adopters rather slowly. The transmission of knowhow through market channels is not efficient and the possibility of relying upon mechanisms of imitation and external learning is rather limited;

vi) organizational-managerial barriers. Linked to the possibility of an across the board mobilization of managerial and technical resources either to conduct trials, to accumulate knowledge or to realize the necessary adjustments and fittings between technology and internal organization.

The mentioned barriers do not favour the adoption of flexible automation systems, particularly in small and medium sized companies. References in literature (Meredith, 1987; Freeman, 1987), on the other hand, sustain that although the efficient utilization of the new flexible technologies can become inhibited by the rigid allocation and specialization of tasks, typical of the organizational culture of larger concerns, it may be stimulated by the horizontal flow of information. This has a tendency to increase, **coeteris paribus**, the probabilities of successful adoptions on the behalf of smaller firms.

Such observations represent an area of unquestionable interest but must not be estranged from the context to which they belong; that is, the competitive international arena, fact that influences the implicit assumption of "average firm". It is the opinion of the authors that, whenever reference is made to dimensional notions closer to the interpretation of the Italian industrial reality (for which, a firm employing 500 or more, already belongs to the category of the large firms), it is beyond doubt that flexible automation creates an economic environment favourable to the larger rather than the smaller enterprise.

2.3. **Diffusion Paths**

It is possible to associate to the mentioned characteristics some stylizations of the diffusive model for FA systems.

Firstly, considered the typology of the adoption barriers, one can expect that company-specific structural features, such as the sectorial typology and size, play a decisive role in swaying the adoption to an extent greater than that highlighted in previous studies regarding the diffusion of "complex" process innovations (Davies, 1979). Both the pioneers of adoption and the quick imitators are to be found within large enterprises and units belonging to internationalized oligopolistic and scale-intensive sectors (Pavitt, 1984). The latter sectors are those which display a more settled process innovation culture.

Secondly, technological and market instability, difficulties in the accumulation of knowledge, combined to the action of the barriers to adoption, favour a step-by-step approach to FA systems; this not only allows the abatement of initial investment costs, but also initiates a learning process intimately linked to the new technologies.
The behaviour of companies, as can be seen, becomes oriented towards a **localized search** model (Cainarca, Colombo and Mariotti, 1987a), which is an innovation process that develops "around" combined knowledge pools and tends to optimize the **trade-off** between the advantages offered by the new technology and the replacement costs relative to the previous equipment and to the immaterial resources, such as the acquired knowledge connected to the superseded technology.
The innovative gradualism is encouraged by the potential modularity of the systems and, above all, by the presence of **intermediate forms** of FA systems. These latter take on a relevant role mainly in the first stages of diffusion and have been inexplicably neglected by the greater portion of national and international literature dealing with the FA topic[6].

Lastly, the paths of diffusion seem dominated, in the short and medium term, by a **persistent market disequilibrium.** In correspondence with the localized search of the adopters, the behaviour of producers of FA cannot systematically follow the demand and develop highly

sophisticated and customized systems without incurring into prohibitive costs merely to privilege specific design and acquire an intimate knowledge of products/processes of potential customers. Moreover, FA system manufacturers are unable to rationalize demand and impose their prevailing models. The missing convergence between supply and demand induces the potential adopters to design and realize in-house systems capable of executing specific functions and in line with the requirements of **localized search.**
This tendency often results in the installation of facilities that integrate new architectures by introducing new machinery and devices into existing plants. System knowhow and the necessary skills can be alternatively purchased on the market (engineering companies or system houses), or developed internally.

The phenomenon of generating FA systems in-house, with the possibility of partially utilizing existing equipment, hence referred to as **retrofitting**, concerns various factors. Partially it has a physiological characteristic, being it connected to non-transferable personalization requirements on the user behalf which can not be satisfied through market channels. Yet, to a greater extent, it has pathologic origins in the inability of the market to balance and regulate the relationships between supply and demand, particularly in the phase when complex innovations are being introduced and developed.

3. The Diffusion of Flexible Automation in the Italian Metalworking Industry

3.1. Empirical References

The analysis of the dynamics and of the diffusion model of Flexible Automation in the Italian metalworking industry is based upon the information contained in the FLAUTO[7] database. The database, that concerns the adoption of new FA systems and holds a sample of 2,927 plants to represent about 25,000 manufacturing plants, each with over 10 employees, is continually updated. The units all belong to the Italian metalworking industry.

The empirical results presented through this paper refer to the following typologies:

i) as far as the adopted technologies are concerned, systems of any complexity, for the manufacture and design and manufacture/design interfaces, are considered. Systems, be these new installations or obtained by retrofitting, are classified in 6 categories, in adherence with the definitions provided in the Appendix, that is, flexible NC, CNC and DNC manufacturing systems, CAM, CAD and CAD/CAM design systems. NC systems represent the main body of the intermediate forms of FA systems;

ii) as far as the adopter units are concerned, the sectorial belonging and localization are considered. Sizes refer both to the buildings in which the equipment is installed and to the firms to which the buildings belong. The analysis of adoption rates also considers the company structure and, in particular, the ownership share to Italian or foreign industrial or financial groups.

3.2. General Dynamics of FA System Diffusion

Figures 1 and 2 and Table 1 illustrate the evolutionary dynamics of the adopters in the various FA system typologies, starting from their introduction in the seventies to today (June, 1987) as per the FLAUTO sample.

The diffusion curves invariably show the rise towards the end of the seventies. The growth of the adopters of FA systems nevertheless becomes particularly sharp in the latter period. The number of adopters, both for manufacturing and design systems more than doubled in two and a half years. By June 1987 the incidence of adopters on the FLAUTO total sample reaches 2.5% for manufacturing systems, while adoptions for design systems nearly reaches 12%. These values, projected on the universe of Italian companies, indicates that the diffusion of FA solutions in Italy has amply overtaken the introductory phase.

The acceleration in the last years supports the hypothesis that in said period firms were particularly active in process innovations. What's more, it explains the increase of initiatives and strategic actions undertaken by system builders who, by take-overs and agreements, by aiming for technological, productive and trade complementarities such to meet a rapidly evolving demand, in terms of quantity and quality.

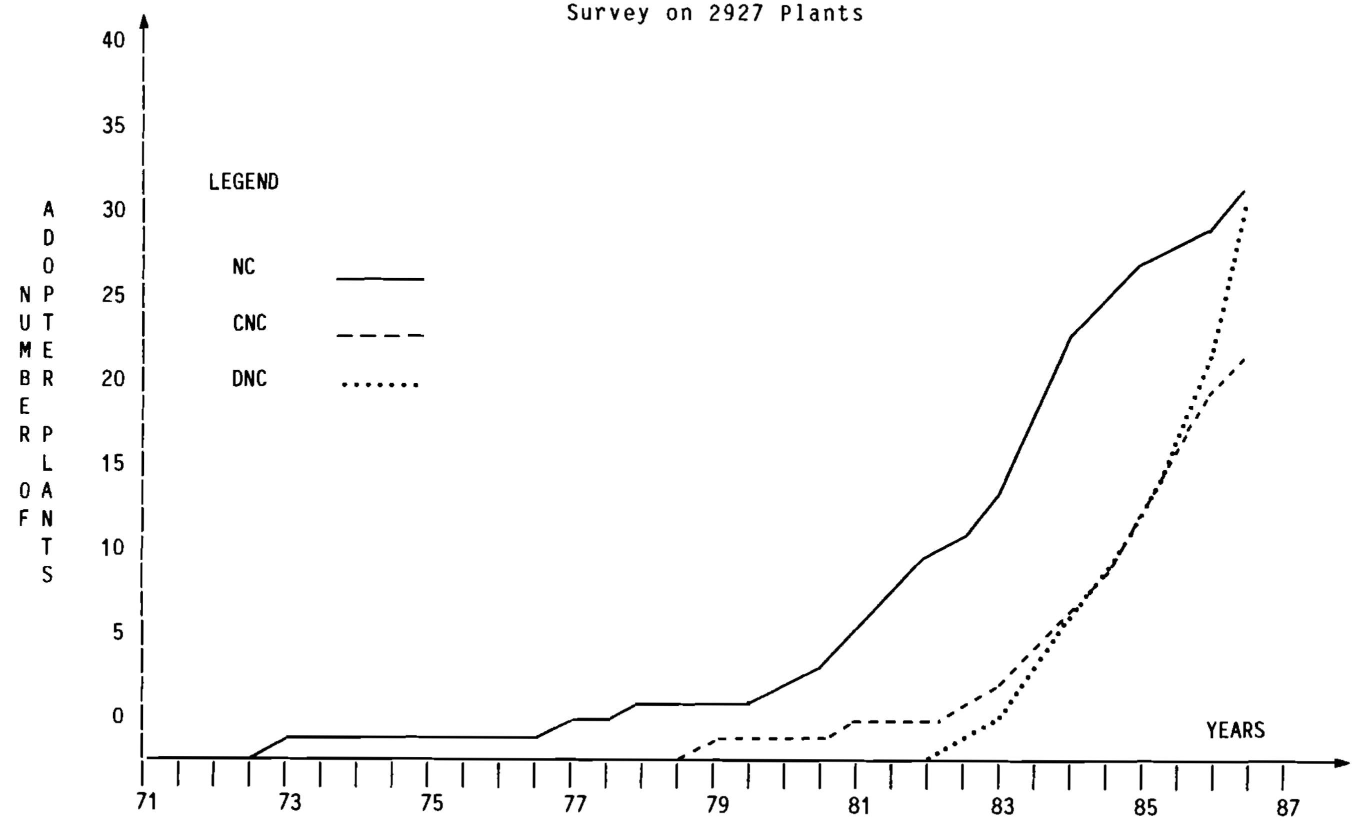
It is nevertheless useful to point out that the emerging image of FA from the FLAUTO database is rather distant from the CIM scenarios or from the totally integrated and automatized plants, which, presently, are quite far away and hardly significative for the purpose of describing the realistic growth paths of FA within firms.

The distribution of the number of systems installed, by technological types illustrated in Table 2, suggests that, within the manufacturing systems (which implies investments greater by an order of magnitude), the **intermediate forms** of FA continue to play a relevant role in the diffusion process. Even today NC systems represent the category with the greatest weight, with an incidence of 36% of the total installations of flexible manufacturing systems.

Fig. 1 - **FLEXIBLE MANUFACTURING SYSTEMS IN THE ITALIAN METALWORKING INDUSTRY**

ADOPTION RATES

Survey on 2927 Plants

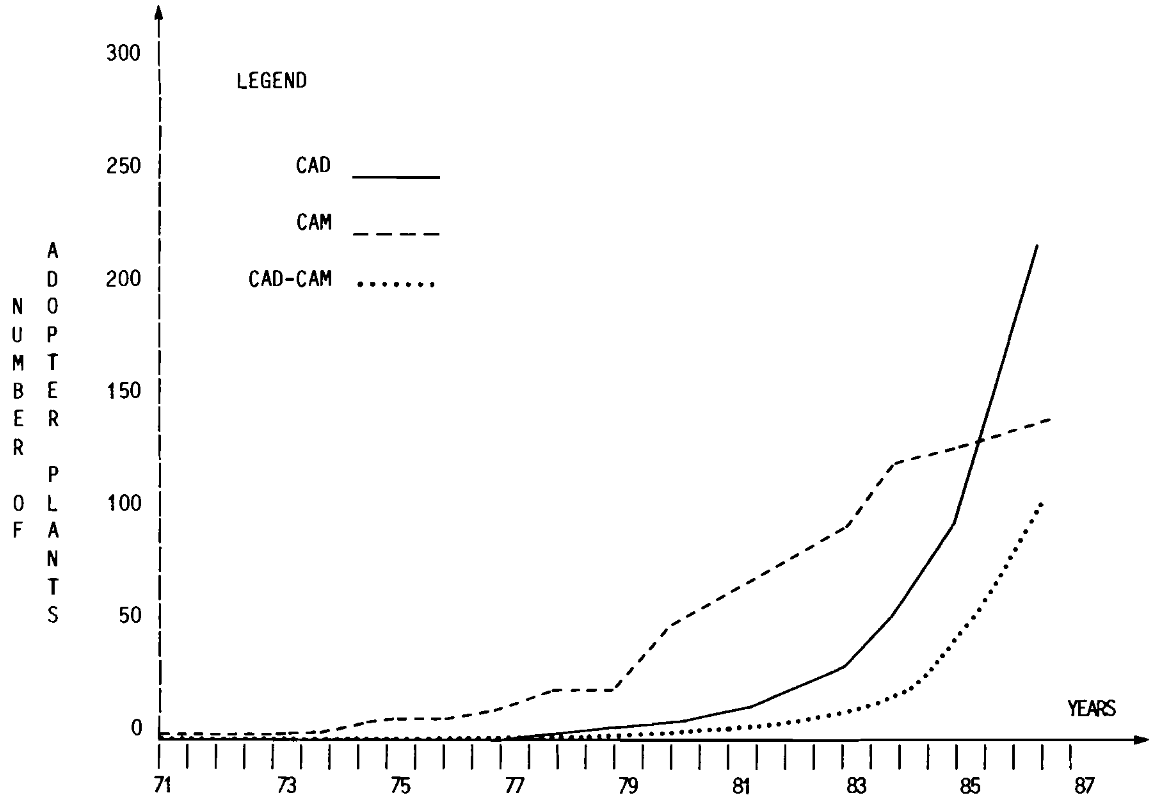


Source: FLAUTO Data Base - MIP - Milan Polytecnic

Fig. 2 - DESIGN / INTERFACE SYSTEMS IN THE ITALIAN METALWORKING INDUSTRY

DIFFUSION RATES

Survey on 2927 Plants



Source: FLAUTO Data Base - MIP - Milan Polytecnic

Table 1 - FLEXIBLE AUTOMATION IN THE ITALIAN METALWORKING INDUSTRY

NUMBER OF ADOPTER PLANTS AND ADOPTION RATES

Survey of 2927 Plants at 31/12/1984 and 30/06/1987

System Typology	ADOPTER PLANTS at 31/12/1984 No. of Plants	ADOPTER PLANTS at 31/12/1984 % on Sample	ADOPTER PLANTS at 30/06/1987 No. of Plants	ADOPTER PLANTS at 30/06/1987 % on Sample	VARIATION 1984-1987 (B-A)/(A)
1 - Flexible Manufacturing Systems	33	1.13	73	2.49	121.21
NC	23	0.79	31	1.06	34.78
CNC	8	0.27	22	0.75	175.00
DNC	8	0.27	30	1.02	275.00
2 - Design / Interface Systems	162	5.53	340	11.62	109.88
CAD	54	1.84	203	6.94	275.93
CAM	110	3.76	134	4.58	21.82
CAD/CAM	19	0.65	93	3.18	389.47

Source: FLAUTO Data Base - MIP - Milan Polytechnic

Table 2 - FLEXIBLE AUTOMATION SYSTEMS
IN THE ITALIAN METALWORKING INDUSTRY
DIFFUSION BY SYSTEM TYPOLOGY

Survey on 2927 Plants at 31/12/1984 and 30/06/1987

System Typology	Systems Installed at 31/12/1984		at 30/06/1987		Variation 1984-1987
	(A)		(B)		(B-A)/(A)
	N°	%	N°	%	%
1 - Flexible Manufacturing Systems	79	100	144	100	82.28
NC	36	45.6	52	36.1	44.44
CNC	27	34.2	46	31.9	70.37
DNC	16	20.3	46	31.9	187.50
2 - Design / Interface Systems	183	100	444	100	142.62
CAD	54	29.5	213	48.0	294.44
CAM	110	60.1	131	29.5	19.09
CAD/CAM	19	10.4	100	22.5	426.32

Source: FLAUTO Data Base - MIP - Milan Polytechnic

Furthermore, Table 3 shows how the retrofitting solutions are diffused within the adopter firms, reaching, at June 1987, 30% of the total number of adopters of flexible manufacturing systems. It is of worthy notice that clearly the highest rate (nearly 41%) is reached by adopters of systems displaying intermediate sophistication in technology and management intelligence, as those associated with the CNC approach.

These phenomena confirm the orientation of a significative slice of firms towards the step-by-step approach. As already illustrated elsewhere (Cainarca, Colombo and Mariotti, 1987a), innovative gradualism is considerably influenced by the technical-managerial profile of the adopter firms and by the size and depth of knowledge by these accumulated. However, the learning processes most frequently experimented by firms are quite intense and the analysis of the variation rates on the number of installed systems (see Table 2) shows how such gradualism is leading the firms towards systems possessing ever increasing levels of technological sophistication.

The rate of growth of DNC manufacturing systems, in the 1984-87 period, was more than double that of the total for manufacturing systems and four times greater than that of the simpler systems. While CAD systems installations grew three times in the same period, those referred to the more advanced CAD/CAM systems actually quadrupled. In fact, a closer computer driven integration between the phases of design and manufacturing is becoming a reality, particularly through the effect of mutual induction, when the two complementary technologies are adopted.

This positive and compound movement nevertheless hides peculiar traits and unbalances of the diffusion system that can be identified only through an opportune disaggregation of data.

3.3. Intersectorial Diffusion

Rates of adoption of FA systems appear heavily differentiated by sectorial typology (Tables 4a and 4b).

Oligopolistic sectors relying upon mass production and those possessing engineering skills and tendencies towards process innovations are at the forefront in adopting the new technologies. Transportation equipment, household appliances and transmission equipment confirm the role of innovators in the field of manufacturing systems, while aerospace equipment and machine tools rank first in automated design. The last couple of years have witnessed a vigorous upswing of the "imitators", which have undertaken a consistent adoption process in data processing with CNC and CND systems and electronics and telecommunications with CAD systems.

Table 3 - FLEXIBLE AUTOMATION SYSTEMS
IN THE ITALIAN METALWORKING INDUSTRY
NUMBER OF ADOPTERS AND RETROFITS AND INCIDENCE ON TOTAL

Survey on 2927 Plants at 31/12/1984 and 30/06/1987

	Adopter Plants					
	at 31/12/1984			at 30/06/1987		
System Typology	Retrofit (A)	Total (B)	% (A/B)	Retrofit (A)	Total (B)	% (A/B)
1 - Flexible Manufacturing Systems	8	33	24.24	22	73	30.14
NC	4	23	17.39	8	31	25.81
CNC	2	8	25.00	9	22	40.91
CND	2	8	25.00	6	30	20.00

Source: FLAUTO Data Base - MIP - Milan Polytechnic

Table 4a - FLEXIBLE MANUFACTURING SYSTEMS IN THE ITALIAN METALWORKING INDUSTRY

ADOPTION RATES BY SYSTEM TYPOLOGY AND SECTORS OF ACTIVITY

Survey on 2927 Plants at 31/12/1984 and 30/06/1987

Description of Sectors of Activity	TOTAL SYSTEMS		NC SYSTEMS		CNC SYSTEMS		DNC SYSTEMS	
	% 84	% 87	% 84	% 87	% 84	% 87	% 84	% 87
Production and transformation of metals	-	1.3	-	-	-	0.7	-	0.7
Foundries and related processes	-	0.9	-	-	-	0.3	-	0.5
Metal products	1.4	2.5	1.4	2.1	0.2	0.6	-	0.2
Sheetmetal containers (boilers, tanks, etc)	-	-	-	-	-	-	-	-
Other metal-working workshops	-	-	-	-	-	-	-	-
Milling machines	1.1	2.5	0.8	0.9	0.3	1.1	0.3	0.8
Machine tools	0.3	1.4	0.3	0.3	-	-	-	1.4
Transmission equipment	3.2	4.8	1.6	1.6	1.6	3.2	-	-
Other machinery and equipment	1.6	3.1	1.6	2.6	-	-	-	0.5
Data processing and office equipment	-	16.7	-	-	-	8.3	-	8.3
Electrical supplies	-	-	-	-	-	-	-	-
Electrical equipment	1.5	3.9	0.8	0.8	0.8	2.3	-	1.6
Electronics and telecommunications	0.9	0.9	-	-	0.9	0.9	0.9	0.9
Household appliances	4.3	6.4	4.3	4.3	-	2.1	-	2.1
Pubblic transport equipment	4.7	8.7	1.7	2.9	1.2	1.2	2.9	5.8
Vehicle bodies	-	-	-	-	-	-	-	-
Other transportation equipment	-	-	-	-	-	-	-	-
Aircraft	-	-	-	-	-	-	-	-
Instrument engineering	-	-	-	-	-	-	-	-
TOTALS	1.1	2.5	0.8	1.1	0.3	0.8	0.3	1.0

Source: FLAUTO Data Base - MIP - Milan Polytechnic

Table 4b - DESIGN / INTERFACE SYSTEMS IN THE ITALIAN METALWORKING INDUSTRY

ADOPTION RATES BY SYSTEM TYPOLOGY AND SECTORS OF ACTIVITY

Survey on 2927 Plants at 31/12/1984 and 30/06/1987

Description of Sectors of Activity	TOTAL SYSTEMS		CAD SYSTEMS		CAM SYSTEMS		CAD-CAM SYSTEMS	
	% 84	% 87	% 84	% 87	% 84	% 87	% 84	% 87
Production and transformation of metals	1.3	4.6	-	3.3	1.3	1.3	-	0.7
Foundries and related processes	1.7	3.7	0.3	0.6	1.4	2.3	-	1.7
Metal products	1.4	5.0	0.2	2.5	1.0	1.7	0.4	1.5
Sheetmetal containers (boilers, tanks, etc)	6.3	15.6	3.1	12.5	6.3	6.3	-	-
Other metal-working workshops	-	11.1	-	11.1	-	-	-	-
Milling machines	5.9	14.2	2.2	9.0	3.7	5.0	0.8	3.6
Machine tools	11.6	18.8	1.2	7.2	10.1	11.6	0.9	5.8
Transmission equipment	4.8	9.5	-	3.2	3.2	4.8	1.6	1.6
Other machinery and equipment	7.3	10.9	2.6	7.3	5.7	5.7	-	0.5
Data processing and office equipment	8.3	8.3	-	8.3	8.3	8.3	-	-
Electrical supplies	-	-	-	-	-	-	-	-
Electrical equipment	6.9	16.3	4.6	14.7	2.3	2.3	0.8	4.7
Electronics and telecommunications	6.6	20.8	4.7	16.0	2.8	4.7	-	4.7
Household appliances	4.3	12.8	4.3	12.8	-	-	-	-
Pubblic transport equipment	9.3	17.4	4.7	11.6	6.4	7.6	0.6	5.2
Vehicle bodies	4.2	4.2	-	-	-	-	4.2	4.2
Other transportation equipment	3.9	7.8	2.0	3.9	-	-	3.9	5.9
Aircraft	33.3	42.9	19.0	28.6	9.5	9.5	14.3	28.6
Instrument engineering	6.8	17.6	2.7	12.2	5.4	5.4	-	5.4
TOTALS	5.5	11.6	1.8	6.9	3.8	4.6	0.6	3.2

Source: FLAUTO Data Base - MIP - Milan Polytechnic

All together, the above are the sectors in which, presumably, the most intense demand for flexibility has occurred. This has been determined as response to the increasing international market turbulence combined with the presence of a technical-managerial company culture capable of finding advanced solutions to its requirements. The largest accumulation of knowhow and of material and immaterial resources leads the **localized search** model of potential adopters towards the most advanced solutions.

The data appearing in Tables 4a and 4b also show how, all being equal, specific technical-economic characteristics of production (for example, the size of production lots) influence the diffusion at sectorial level, imposing restrictions to the adoption of certain system typologies. The aerospace industry is emblematic. In accordance with other research areas (Rees and others, 1984), aerospace has the highest adoption rates for design systems (28.5% both for CAD and CAD/CAM for 1987). In flexible manufacturing system instead, they are totally absent in Italy. This can be related both to the size of the companies and to the manufacturing typology of the domestic industry, which results based on jobbing with small production lots, slotted below the minimum economic threshold allowed by the present technological solutions [8].

A mention is to be made to the machine tool sector. It has an adoption rate for manufacturing systems equal to only 1.45% for 1987, which is certainly under the 2.49% average. The datum is in clear contrast with the characteristics of supply of equipment from other countries, such as Japan, where producers are also their greatest users. Product fragmentation in the sector and the orientation towards dedicated equipment, probably is at the base of the results. It nevertheless poses questions upon the capability of national manufacturers to design and produce systems competitive with those of the large international concerns, especially in a sector where the **learn by doing** concept takes-on great importance, particularly in the present tumultuous phase in which industrial standards are being selected.

3.4. Territorial Diffusion

A certain caution is necessary when data belonging to the geographic placing of the FA adopters, illustrated in Tables 5a and 5b, are interpreted. The degree of coverage of the various regional samples of the FLAUTO database, with respect to the number of companies sampled there located, is, for Central and Southern Italian regions, on average, 20% lower than the Northern ones. If one assumes, and it would be understandable, that the samples relative to such areas are biased, it is because the more technologically advanced companies [9] located in such areas have responded more compactly and the adoption rates could be considered as overrated, as reference is made to the various typologies of automation systems.

Table 5a - FLEXIBLE MANUFACTURING SYSTEMS IN THE ITALIAN METALWORKING INDUSTRY

ADOPTION RATES BY SYSTEM TYPOLOGY AND GEOGRAPHIC AREAS

Survey on 2927 Plants at 31/12/1984 and 30/06/1987

Description of Geographic Areas	TOTAL SYSTEMS		NC SYSTEMS		CNC SYSTEMS		DNC SYSTEMS	
	% 84	% 87	% 84	% 87	% 84	% 87	% 84	% 87
NORTH WEST ITALY	1.2	2.6	1.0	1.2	0.3	0.8	0.3	1.1
of which:								
- Piedmont	1.5	3.0	1.0	1.3	0.5	1.8	0.5	0.8
- Lombardy	1.0	2.4	0.8	1.0	0.2	0.5	0.3	1.2
NORTH EAST ITALY	1.3	2.9	0.8	1.1	0.2	0.9	0.3	1.1
of which:								
- Veneto	1.2	2.6	1.2	1.8	-	0.3	-	0.9
- Emilia Romagna	1.6	3.3	0.5	0.5	0.5	1.4	0.7	1.4
CENTRAL ITALY	0.3	1.3	-	0.3	0.3	0.3	-	1.0
of which:								
- Lazio	-	1.8	-	-	-	-	-	1.8
SOUTH ITALY AND ISLANDS	0.6	1.1	0.6	1.1	-	-	-	-
of which:								
- Campania	1.3	2.6	1.3	2.6	-	-	-	-
TOTALS	1.1	2.5	0.8	1.1	0.3	0.8	0.3	1.0

Source: FLAUTO Data Base - MIP - Milan Polytechnic

Table 5b - DESIGN / INTERFACE SYSTEMS IN THE ITALIAN METALWORKING INDUSTRY

ADOPTION RATES BY SYSTEM TYPOLOGY AND GEOGRAPHIC AREAS

Survey on 2927 Plants at 31/12/1984 and 30/06/1987

Description of Geographic Areas	TOTAL SYSTEMS		CAD SYSTEMS		CAM SYSTEMS		CAD-CAM SYSTEMS	
	% 84	% 87	% 84	% 87	% 84	% 87	% 84	% 87
NORTH WEST ITALY	5.3	11.7	1.5	6.8	3.7	4.4	0.8	3.4
of which:								
- Piedmont	6.3	13.5	1.3	7.1	4.6	4.8	1.0	4.6
- Lombardy	4.5	10.7	1.2	6.4	3.2	4.0	0.6	2.9
NORTH EAST ITALY	6.2	12.7	1.7	7.7	4.6	5.4	0.3	2.9
of which:								
- Veneto	6.4	11.7	1.5	5.8	5.0	5.8	0.6	3.8
- Emilia Romagna	5.1	12.4	1.9	8.4	3.3	4.2	0.2	2.1
CENTRAL ITALY	4.5	10.0	1.9	6.1	2.6	3.9	0.3	2.3
of which:								
- Lazio	8.8	12.3	3.5	7.0	5.3	7.0	-	5.3
SOUTH ITALY AND ISLANDS	6.2	8.4	5.1	6.2	2.2	2.8	1.7	3.9
of which:								
- Campania	10.5	13.2	7.9	9.2	2.6	3.9	3.9	7.9
TOTALS	5.5	11.6	1.8	6.9	3.8	4.6	0.6	3.2

Source: FLAUTO Data Base - MIP - Milan Polytechnic

With that assumption, the diffusion gap between the North and the other regions of Italy becomes evident. The rates of Northern regions take on values equivalent to more than twice those relative to other regions. The differentials for design systems are less evident, even though substantial differences still exist, particularly to the disadvantage of Southern Italy areas. Moreover, the 1984-1987 adoption dynamics further widen the gap; a partial exception is represented by the Campania Region, which has an adoption rate higher than the national average, both for 1984 and 1987. The exception is perfectly justifiable by the fact that an important research and manufacturing centre for the Italian aerospace industry is located there.

Overall, regional diffusion differentials are the direct expression of the more general disequilibria of the Italian industrial development model. However, these focalize the added difficulties that the lesser developed areas have in adopting complex technologies. The absence of adequate external services that could promote a "diffusive" attitude towards the rapid spread and assimilation by the firms of the innovative results provided by technical progress, with particular reference to those not integrated in plants and machinery, is a determining factor.

3.5. Intercompany Diffusion

Within the scenario of rapid diffusion of FA systems, the analysis of diffusion by classes of plant size, brings forward for each system typology a significant and systematic positive correlation between the adoption rates and the size of the adopter companies. Rate variations are considerable and, even though marginal convergencies are noticed by mid 1987, orders of magnitude are those shown in 1984.

In the smaller plant class, with 10 to 199 employees, the only typology of systems that does not show marginal or null adoption rates (2.68% at the end of 1984) is also the most consolidated, that is the CAM driven systems. The situation undergoes a partial change towards the middle of 1987, mainly due to the diffusion of CAD and CAD/CAM systems, with adoption rates os 3.88% and 1.88%, respectively, and NC manufacturing systems with rates of 0.68%. However, adoption rates, for all typologies, remain drastically below the average values of the FLAUTO sample.

The situation improves in the medium sized plants, that is firms with 200 to 499 employees, in which the diffusion rates come relatively closer to those of the next up class. The 1987 flexible automation adoption rates, both for manufacturing and for design/interface systems, take on values roughly half of those recorded for companies with 500 or more employees. The behaviour of medium sized plants clearly differs from that of the small units particularly when the more advanced systems, such as CND, CAD and CAD/CAM solutions, are considered.

Table 6 - FLEXIBLE AUTOMATION SYSTEMS IN THE ITALIAN METALWORKING INDUSTRY

ADOPTION RATES BY SYSTEM TYPOLOGY AND BY PLANT SIZE CLASSES

Survey on 2927 Plants at 31/12/1984 and at 30/06/1987)

	PLANT SIZE - BY MANPOWER STRENGTH							
Description of System	10 to 199		200 to 499		> 499		TOTAL	
Typology	% 84	% 87	% 84	% 87	% 84	% 87	% 84	% 87
FLEXIBLE MANUFACTURING SYSTEMS of which:	0.52	1.36	3.08	6.18	7.06	13.61	1.13	2.49
- NC	0.44	0.68	2.31	2.70	3.53	4.14	0.78	1.06
- CNC	0.08	0.40	1.15	1.93	1.76	4.14	0.27	0.75
- DNC	0.04	0.40	0.38	2.70	3.53	7.69	0.2	1.02
DESIGN / INTERFACE SYSTEMS of which:	3.20	7.64	11.15	25.87	31.18	48.52	5.52	11.62
- CAD	0.36	3.88	4.62	17.76	19.41	35.50	1.84	6.94
- CAM	2.68	3.36	5.00	6.18	17.65	20.12	3.75	4.58
- CAD/CAM	0.28	1.88	2.31	7.72	3.53	15.38	0.65	3.18

Source: FLAUTO Data Base - MIP - Milan Polytechnic

Data would seem to indicate that this dimensional belt represents the "critical threshold" for the adoption of the more advanced technologies.

The overall consideration is that the larger sized manufacturing units are the clear leaders. In fact, they had by mid 1987 reasonably high adoption rates, with 13.61% for compound flexible manufacturing systems, 35.5% for CAD systems, 20.12% for CAM systems and 15.38% for CAD/CAM systems. The correlation between diffusion rates and large company size is also supported, as the sectorial analysis has already shown, by the incentives that the adoption of FA systems derives from the dynamics of competition in sectors having high concentration and with oligopolistic and internationalization characteristics.

The analysis of distribution differentials, as a function of plant size, takes on particular interpretative meaning whenever it is compared with the typologies of the companies to which the FLAUTO sample manufacturing units belong. This, in fact, and on the basis of work hypothesis presented further on, allows the acquisition of useful information concerning the factors and constraints that baulk the diffusion of advanced solutions of automation.

It is interesting to distinguish, in the adoption barrier analysis, between technical-manufacturing barriers (minimum efficiency size, process/product typologies and effects due to technological complementarities) and the financial, organizational and/or managerial barriers that arise when knowhow is not available. The separation between the two effects appears rather useful if industrial policymaking is analysed. So much so, that while the first barriers are of a greater difficulty to remove, being these conditioned by the evolution of the technical process and by the direction it has taken, the second type can be tackled, in theory, by means of precise regulative norms, either of a financial nature or such to uphold the entrepreneurial activity.

What's more, in the first case, the areas of activities essentially concern the supply aspects and it becomes necessary to stimulate manufacturers to realize technological solutions befitting the smaller dimensional scales. In the second case, instead, industrial policy measures concern the demand side and the relative mechanisms of adoption.

The hypothesis assumed is that it seems possible to draw precious guidelines for interventions in the two categories of effects by analysing the adoption differentials of those manufacturing units belonging to the same dimensional classes, irrespective whether they belong to to larger scale groups or not. In fact, while to the size of the various plants can be associated to the influence of typically technical-manufacturing factors, their belonging or not to industrial groups can explain the different interactions of financial, knowhow availability and organizational and/or managerial constraints.

For identical conditions of manufacturing unit size and other operative conditions, highly differentiated adoption rates, typical of units belonging to industrial groups, find the availability of adequate resources an important determinant in overcoming the second adoption barrier. In terms of industrial policy, the measurement of such differentials leads to consider the feasibility of fostering adoptions, and to establish action lines not frustrated by stringent technological constraints.

Herefollowing are presented the results concerning the aforementioned analysis [10], carried out in adherence with the below classification of companies:

- "independent companies", by which is meant that one or more production units are present, but without any share or proprietary link through which it can be controlled by other companies, operating either in Italy or abroad;
- "industrial groups" of small to medium size (not exceeding 50,000 employees), by which is meant legally distinct, multi-company industrial or financial groupings. This category includes, by definition, companies wholly owned or controlled by foreign groups, as long as their size in within the stated;
- "large industrial groups", under Italian or foreign control, differing from the above category because of their size, it being above 50,000 employees.

The empirical evidence, illustrated in Tables 7 and 8, supports in an unmistakable manner the hypothesis that the belonging to industrial groups positively influences adoption rates.

Firstly, adoption rates are higher for all types of technological typologies, given equal plant size and if they belong to industrial groupings. The influence of the company make-up is particularly evident for the "small" manufacturing units. The adoption rates in the plants belonging to industrial groups of this class is 3 times greater than that relative to the plants of independent companies. Furthermore, such relationship remains quite steady as system typology changes, with the shift contained within 3 and 3.2.

Secondly, the gap between rates as a function of company make-up, generally decreases as the size class grows, even though the trend is less homogeneous for each technological typology. In particular, as far as FA systems are concerned in flexible plants, the relationship between the adoption rates in the two categories - groupings and independent companies - is high in the "large" plants, reaching a value of 2.2.

Table 7 - FLEXIBLE MANUFACTURING SYSTEMS IN THE ITALIAN METALWORKING INDUSTRY

ADOPTION RATES BY COMPANY TYPOLOGY AND BY PLANT SIZE CLASSES (a)

Survey on 2927 Plants

Class of Plant Size	INDEPENDENT PLANTS (A)	INDUSTRIAL GROUPS (b)			TOTAL	RATIO BETWEEN RATES	
		TOTAL (B)	<50.000 (C)	>50.000 (D)	(E)	(B/A)	(D/A)
From 10 to 199	1.6	4.8	3.6	9.1	1.8	3.0	5.7
From 200 to 499	9.7	9.5	6.6	15.0	9.6	1.0	1.5
500 and above	9.4	21.0	15.9	25.3	19.8	2.2	2.7

(a) Forecast at 31/12/1987
(b) Subdivided by total number of employed

Source: FLAUTO Data Base - MIP - Milan Polytechnic

Table 8 - DESIGN / INTERFACE SYSTEMS IN THE ITALIAN METALWORKING INDUSTRY

ADOPTION RATES BY COMPANY TYPOLOGY AND BY PLANT SIZE CLASSES (a)

Survey on 2927 plants

CLASS OF PLANT SIZE	INDEPENDENT PLANTS (A)	INDUSTRIAL GROUPS (b)			TOTAL	RATIO BETWEEN RATES	
		TOTAL (B)	<50.000 (C)	>50.000 (D)	(E)	(B/A)	(D/A)
From 10 to 199	6.7	21.4	24.1	12.1	7.6	3.2	1.8
From 200 to 499	18.1	35.3	31.6	42.5	25.8	2.0	2.3
500 and above	37.5	45.7	39.7	50.7	44.1	1.2	1.4

(a) Forecast at 31/12/1987
(b) Subdivided by total number of employed

Source: FLAUTO Data Base - MIP - Milan Polytechnic

This value is certainly higher than the values found both for "medium size" plants (in which with a ratio equal to 1 the difference between the two categories disappears) and for design systems (ratio of 1.2).

Lastly, the distinction carried out within industrial groups, as a function of absolute size, offers additional elements of appraisal. Generally speaking, differences between the adoption rates of independent companies and those of large groups are more evident as compared to the industrial grouping as a whole. In this case, the phenomenon is also particularly true for flexible manufacturing systems, while some exceptions are encountered for the other two system typologies.

Overall, it appears evident that a " technological explanation" alone is not sufficient to justify the differentials in adoption rates between plants of different size.
Holding good a hard core of constraints determined by the technologies directly connected to the scale of operations and, with it, to other production type characteristics, there are widely differentiated adoption trends. These seem to find in the "industrial group" and everything it represents, an important determinant. It is not considered arbitrary to lead back the explanation to the larger availability of material and immaterial resources of which company groupings have with respect to the smaller sized and independent companies. An essential role is certainly played by the availability of financial resources, with the possibility of facing the investment amounts and the risks connected to the adoption of the new technologies. This is particularly true for flexible manufacturing systems which, when compared to other two system types, require far greater investment thresholds. Coherently to what mentioned, the type of company make-up and to a greater extent the large groupings influences the adoption rates, even within the "large" plants.

However, sizable gaps in the adoption of design/interface systems exist in which technical and economic investments of limited proportions are possible. This fact proposes the thesis that management dependent factors and the availability of knowhow and knowledge, available or not in the human resources, assume in the above systems a decisive and propelling role for the acquisition and development of new automation initiatives.

Empirical results further confirm the complexity and the systemistic and cumulative characteristics of FA dependant technologies. In this reality, important factors determine the greater impetus given to innovation typical of the industrial groupings. Such factors include the enhanced mobility of diversified internal resources, both managerial and technical, the greater facility of acquiring feed-back from the technical progress not immediately incorporated in the capitalized goods and the availability of "internal laboratories" for researching and developing innovative applications.

4. The Flexible Automation Diffusion Model and Industrial Policy Interventions

The strong growth of the number of FA systems installed in the last years in the Italian metalworking industry can not be interpreted as the result of a "canonic" diffusion process such that, being it a successful innovation with features and performances already consolidated, it can spread in the economic texture and substitute the no longer competitive old technology. The present FA diffusion phase is, instead, deeply marked by a simultaneous innovation process of its manifold products and by an open competition to set-up "winning solutions". A *transition* phase is in act, dominated by uncertainty and consistent disorders in the diffusion mechanisms.

Uncertainty referred to production typologies and their prerogatives in terms of efficiency and flexibility. Uncertainty referred to industrial standards and to system architecture and compatibility requirements for the future. Uncertainty on the depth of the innovations to the system and to the organizational-managerial resources to provide the required performance from the installed systems.

All this influences the criteria of adoption, favours gradualism and promotes models of search for "localized" innovative processes. Moreover, it exploits the role of *learning through experience* and the accumulation of knowledge as determinants for the economic success of the adoption.

In this picture of uncertainty and limited rationality, diffusion mechanisms remain deeply unsettled. The empirical data illustrated in the previous paragraph confirm that the demand for and supply of systems have difficulty in finding a market balance, determining sizable phenomena of in-house generated solutions, dedicated and retrofitted. What's more, there is confirmation of the persistence of a noticeable unbalance in the adoption rates in favour of the large companies, of industrial groups and of the most industrialized areas of the country.

All mentioned above presses for a series of reflections to determine measures and interventions of industrial policies capable of correcting the present diffusion "model" to stimulate the modernization of the industrial apparatus of the country.

The first considerations concern the policy of incentives, in their various forms of delivery, such as, capital loans, credit facilities, etc.. The removal of financial barriers still remains a key point to favour the diffusion of new technologies in the weaker areas (Southern Italy and small-medium companies). The policies developed to the purpose in the past years have significantly contributed to the renewal of the company-based equipment and is desirable that this role becomes consolidated in the future.

A recommendation is made to ensure greater selectivity in the bestowal of grants, which should mainly be directed to investments having high innovation contents, such as those present in FA systems. A positive evolution in this sense must be noticed by the recently launched Government Decree (Law N° 212 of June 1987) which make explicit reference to investments in production "systems" and contemplate forms of incentivation for software products.

A second consideration interests the standardization and normalization issue for flexible automation systems, subsystems and hardware and software components. The issue takes on great value for the whole European industry, which has accumulated, with respect to Japan and the United States such a delay to place it in a strategically subordinated position. It is essential that at European institutional level and in agreement with and with the contribution of the manufacturers of FA systems of the various countries, an action program becomes rapidly defined. This program must consider the definition and diffusion of "open" standards (in adherence with what achieved for the Open System Interconnection), highlighting modularity and retrofitting and coherent with the most advanced standards of the American and Japanese markets. All this is to forestall the isolation and marginalization of the European industry and to favour, on the other hand, the link-up to winning standards and the possibility of participating to their definition.

An efficient standards policy is, for smaller companies, an essential assumption to progress towards automation in line with their economic possibilities, being these based on graduality of investments and on the reduction of capital investments and connected risks.
Standardization and normalization are conductive to the creation of a "certain" reference situation. On such basis, investments on equipment, conceived as modules of a system and intermediate forms that can be integrated into future and more complex architectures, through physical, logical and functional interfaces, can be planned. This approach reduces both costs and adaptation times and minimizes the depreciation of physical investment and of acquired knowhow.

The last series of considerations is connected to the reading of the results transpired from the survey, empirical but not wholly contemplative, and it goes beyond the discovery of the existence of asymmetries in adoption processes. In particular, the "industrial group" can be considered as an environment, in which individual manufacturing units operate and receive from it innovative stimuli and supports, in terms of material and immaterial resources. From the greater efficiency of its endogenous mechanisms, with respect to the market (that is, with respect to the environment in which the single and independent manufacturing units operate), it can be derived that industrial policymaking has wide margins to favour the diffusion of new technologies within the system of the small and medium companies. This consist in the correction of market "imperfections" by reproducing on a widened scale the economies, the services and the cognitive supports available within the group.

Difficulties, connected to the "exogenous" and diffused generation of such factors, can not be underestimated. On the one hand, they refer to knowhow, to scientific and managerial knowledge of a proprietary nature. This is the result of exclusive activities subjected to learning mechanisms derived from experience, which are not easily reproduced outside of the environment that generated them. On the other hand, one must influence and interact with rather complicated economic, social and institutional subsystems to the purpose of:

i) organizing the supply of information and knowledge on the technological progress generated by the international scientific and industrial community to make it transparent to the potential users;

ii) facing the problem of training human resources to different levels and roles. This is to overcome hiring difficulties and unavailability of personnel that companies are experiencing in the present transitional phase. The goal is to go towards forms of enhanced professionality with higher technology contents and more in compliance with innovation and permanent training;

iii activating services capable of supporting the "process" of introduction, development and management of system innovations by favouring the diffusion of experiences gathered in more advanced environments.

Such tasks go beyond the mere dimension of flexible automation, but are connected to more general policies to support that industrial development necessary to an advanced economy.

NOTES

(1) Perez (1983 and 1985), making reference to the theory of Kondratiev's long cycles, points out how each cycle has at its base a metaparadigm that draws advantage from the introduction of particular inputs of lesser cost with respect to the past: cotton in the first Kondratiev cycle, coal in the second, steel in the third, petrol in the fourth and, precisely, the chip in the present one.

(2) Specifically, data to which the present article refers were presented at the BIAS Seminar "Automazione - Una scelta per lo sviluppo" (Automation - A Choice for Development). See Mariotti (1987).

(3) See, among others, studies of Thompson and Paris (1982), Skinner (1983), Jelinek and Goldhar (1984), Voss (1985).

(4) Please refer again to Colombo and Mariotti (1985) and to Cainarca, Colombo and Mariotti (1987a).

(5) For further details on the technical problems connected to the adoption of FA systems by smaller industries, see Turco (1985)

(6) Credit is given to UCIMU - Milan Polytechnic (1987) for having tackled this issue with full sense of responsibility.

(7) The FLAUTO database was originally developed for a research program funded by "Progetto Finalizzato Tecnologie Meccaniche" of CNR.

(8) Literature most frequently considers the case of integrated aerospace manufacturing activities by making reference to the flexible system installed by MBB, consisting of 25 machines. It is just to remind that the German company, in addition to having a size one order of magnitude greater than the Italian one, also has much larger production lots. The different manufacturing conditions active within the German company are also supported by the utilization, previous to the installation of the mentioned system, of "dedicated" automatic lines specific for products and components.

(9) For further information, see UCIMU - Milan Polytechnic (1987).

(10) The analysis is drawn from a previous study. See Cainarca, Colombo and Mariotti (1987b).

APPENDIX

The present paper utilizes the following definitions whenever the allocation of a system to a typological class is established on the basis of the presence of the minimum requirements, be these of structural (typology and number of machines and equipment) or of functional (operations carried out) nature.

i) Flexible Manufacturing Systems

Said systems consist of at least two machines interconnected by means of automatic transport mechanisms and together of various forms of numeric control equipment. The type of the NC equipment adopted and the "quality" of the coordination between the various equipment making up the functional whole, defines the level of system flexibility. Such levels may be identified as: (a) flexible NC systems, (b) flexible DNC systems and (c) flexible DNC systems.

- Simple NC flexible systems: the system includes at least one NC machine, but there is no coordination among the various machines present. In other terms, the system does not include computers or microprocessors, or, if included, they exclusively oversee to the operation of the machine upon which they are mounted. It follows thus, that system "intelligence" is limited. Furthermore, reconfiguration attempts would involve updating system hardware elements.
- CNC flexible systems: the numeric controlled machinery is microprocessor driven to realize automatic system coordination. Reconfiguration, to the purpose of updating operative characteristics, is possible by acting on system software components, though with limited applicability.
- DNC flexible systems: characterized by a hierarchical computer structure, meaning that a centralized computer controls the activities of several NC machines. Reconfiguration is only possible by interventions on software components. Generally, the functionalities made available by such actions are considerably greater than those present in the previous configuration.

For the sake of completeness, it is worth stressing that the degree of system complexity is evaluated in terms of computer-driven coordination/control and of reconfigurability typologies, rather than in terms of the number of machines, as proposed in the past, by distinguishing between FMS and cell. This does not imply that the systematically acquired size of the system is not taken into due consideration, but to emphasize the necessity of differentiating on the basis of those structural elements that condition the effective capability of the system of providing flexible control to the manufacturing process.

ii) Design and Design / Manufacturing Interface Flexible Systems

- CAD Systems: computer aided systems, the functions of which span from simple drafting, to the more complex design tasks.
- CAM Systems: computer aided systems finalized to the generation of part-programs utilized by NC machines and, if required, to carry out more complex control functions within the manufacturing process.
- CAD/CAM Systems: computer aided systems that by utilizing a central data base realize the integration of the functions separately carried out by CAD and CAM systems.

The above definitions require some further considerations. The belonging to one of the classes of systems is determined by the presence of minimum requirements:

- for CAD systems, it is the possibility of being employed as simple electronic drawing boards, capable of realizing bidimensional mechanical drawings,

- for CAM systems, the lowest threshold is represented by the capability of automatically generating part-programs. Within the above scope, CAM technology is the most consolidated of the computer aided solutions, basically because it was the first to be introduced and practically towed by the growing diffusion of NC machines, around the sixties. This is considered an important aspect, both to understand what explained in this paper and for possible comparisons with other studies in which, usually, the term CAM is associated with this meaning to systems of greater functional complexity. In practice, such behaviour often leads to conceptual-determinative ambiguities, that thwart or complicate the evaluation of data gathered on system diffusion. Also in this case, a definition based on a minimum threshold of available functions has been privileged, the identification of which does not appear subjected to misunderstandings or inconsistent evaluations on the part of the interviewer or the interviewed.

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Some Considerations on Possible Macroeconomic Effects of Computer Integrated Manufacturing Automation

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0. INTRODUCTION

The effects of computer integrated manufacturing automation on economic growth and employment have been discussed very controversially in the last few years without having led to any final conclusion.

On the one hand there are hopes for the start of a new "long wave" of economic growth, for a revival of growth rates, which have been low since the mid-seventies, on the other hand there are fears of an aggravation of the problem of unemployment, which has been rising throughout the OECD-Countries even during the last cyclical upswing.

In this controversy often very short-cut conclusions on the macroeconomic effects of Information Technology (IT)[1] are drawn from observations on the micro level. This normally leads to an overestimation of either the growth of labor productivity when looking at the replacement following the installation of e.g. industrial robots or to the overestimation of the potential growth of the economy as a whole when looking at the speed of expansion of the most advanced firms using IT in the production process[2].

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[1] for a definition see Freeman/Soete 1985, pp 33

[2] for this misconception see BMWF 1985

To avoid such misjudgments and to reach a more adequate view of the effects of IT we need a (better) microfoundation of macroeconomic judgements on that topic.

In the following I would like to present some hypotheses of the effects of IT on accumulation, consumption, market situation/concentration and employment proceeding from some recent studies (UN/ECE 1986, LUTZ et al 1987, CAMAGNI 1988, TRIBOTECHNIK 1988) concerning diffusion and micro-level effects.

I. The Diffusion of CIM - Technologies

Obviously computer-guided means of labor in manufacturing are just in the take-off phase of their diffusion. Until now the spread of IT took place primarily in the offices (see LUTZ 1987, Figure 1) In manufacturing more complex types of production automation like FMS or CIM are rare and are partly reaching (temporary) saturation levels as in the case of first generation FMS (see AYRES 1987, 42; RANTA 1988, 33f, 44, 48; according to PROHASKA/WERDERITS 1988 the number of newly installed FMS is decreasing recently, see Figure 2). These were most of all "dedicated FMS", designed for the production of a rather small variety of parts - most of them employed in the car industry, which has now finished the "first-round" of IT-manufacturing automation.

Also, until now only a few linkages between the established "islands of automation" within the factories have been realized[1]. (LUTZ et al 1987, Figure 3). Hitherto the spread of the components of CIM-technology has been concentrated in a few branches (cars, electronics, metal working) on a few activities (handling and working of prismatic/rotational parts for (C)NC and FMS; welding and painting for industrial robots [see UN/ECE 1986, pp 45; TRIBOTECHNIK 1988, pp19]) and on large plants (see LUTZ et al 1987, Figure 4).

CAMAGNI has shown that the productivity-flexibility trade off still exists (see Table 1) and that from the possible paths of CIM

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[1] According to PROHASKA/WERDERITS (1988, 115) the concept of the "factory of the future" today can bee seen only in specific fields of big industry, if anywhere.

diffusion only one is realized to a greater extent: the flexibilization of mass production (see Figure 5).

Because of that slow and constrained diffusion the macroeconomic effects don't seem to be very large today. They might become important in the future with increasing integration, i.e. with "systemic rationalization". Only then IT will realize its full potential of productivity. RANTA supposes that only "around 2005 - 2010 the strategic part and the main share of the production of manufacturing industries is produced by FMS- or FMS-type systems." (see RANTA 1988, 55; Table 2)

Table 1:
RELATIONSHIP BETWEEN DEGREE OF AUTOMATION AND FLEXIBILITY REQUIREMENT - SIX COMPANIES IN JAPAN

	Number of product kinds	Average batch size	Number of machines per worker
FMS with high degree of automation and low degree of flexibility			
Company A	4	300	9
Company B	6	50	11
Company C	10	3	4
FMS with low degree of automation and high degree of flexibility			
Company D	3600	5	0.8
Company E	1500	5	2.3
Company F	106	16	1.2

Source: UN/ECE 1986, p 60

Table 2:
DIFFUSION OF FMS - AN INDIRECT ESTIMATION*

	1985	1990	2000
CNC: % of all machine tool investments (new + replacements)	40	50	70
CNC implemented as a part of systems, % of all CNC investments	50	70	80

*for western industrialized countries

Source: RANTA, J. 1988, p 55

II. AIMS OF INTRODUCING CIM - TECHNOLOGIES

Flexibilization of the production apparatus and economization of the fixed capital[1] are priority aims of the production automation and the introduction of IT. Both have been rendered feasible on an overall state only with the "material properties" of IT[2]. By flexibilization I mean the capability to respond to alterations in the structure and the volume of demand promptly and at low cost, in particular the possibility to work a great variety of different parts with the same machinery (for the various definitions of "technological flexibility" see BOYER/CORIAT 1986, 23ff; CAMAGNI 1988, 98f; RANTA 1988, 10f).

These objectives could be achieved by:

- increased transparency of the whole enterprise, thus enabling a better supervision of the flow of production

- better utilization of capital by reducing the lead- and transport time and by extending the number of shifts. This is made feasible by uncoupling labor and machine-running time both spatially and temporally.

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[1] TRIBOTECHNIK (1988, 31) mentions an VDMA-survey on the introduction of 17 FMS in Sweden, Switzerland, France, Great Britain and the FRG. As priority aims the enterprises quoted:

Increase in flexibility	76%
Reduction of total working time	59%
Cost reduction	24%

However, in only a few cases, the necessity to work a broader spectrum of parts was felt strongly. This points at the fact that is wasn't primarily an increase in the speed of change of the structure of demand that caused the introduction of IT.
CAMAGNI (1988, 106/7) reports a discrepancy, found in his study on Flexible Automation in the Lombardy: labor cost reduction and increase of labor productivity have been the main aims ex ante. Ex post, the "new aims" achievable with IT took the lead:

	ex ante	ex post
Increase of labor productivity	75%	45%
Increase of flexibilty & improvement of quality control	21%	45-50%

[2] Thus one can speak of a new type of technical progress or a new "technological paradigm".

- improved capabilities of design by IT (e.g. by simulating production processes) allow the construction of products that are easy to assemble. Thereby a potential for productivity improvement is created, which is perhaps more important than a further automation of the production.[1]

- Computer-aided quality control and higher precision of work enables a decrease of garbage output.

To sum up: Diffusion of more complex forms of production automation is still modest, but is increasing rapidly. In those companies which are already employing IT in the production process on a large scale good results can be noticed .

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[1] as the example of Northern Telecom clearly shows: by redesign of the product (Telephons) a reduction of parts from 325 to 156 was achieved and assembly time was reduced from 23 to 11 minutes. The following automatization reduced it further to 9 minutes. This means an improvement of more than 50% in the first step, and of "only" 15% by further automation (see WARNER 1988, p 22).

III. MICROECONOMIC EFFECTS OF CIM - TECHNOLOGIES

Several surveys (e.g. TRIBOTECHNIK 1988, LUTZ et al 1987, RANTA et al 1988) prove that the aims of the enterprises implementing IT have been achieved of even surpassed. (see Figure 6 and 7).

In particular, the enterprises report:

- an increase in labor productivity together with a sharp decrease in the share of direct labor costs and a further growth of capital intensity (Table 3).
- a reduction of the consumption of preliminary products and raw materials
- a reduction of the number of machines and thus a reduction also of the floor space required (Table 4)
- higher fixed costs owing to the increasing share of "labor in advance", e.g. in the form of increasing R & D expenditures and software costs (RANTA 1988, 15pp).
- also in the IT (not tantamount to Flexible Automation!) economies of scale remain relevant: ERNST (1987) shows that there are strong economies of scale, e.g. in the semiconductor industry, where the aim is to reach an almost continuous flow of production. Suppliers who can best realize the economies of scale have a capital-output-ratio far lower (thanks to better utilization rates, which are achievable by lower prices and therefore reduced costs)
- a shortening of the product life cycle and thus of the pay-back period (UN/ECE 1986, 126). This holds true also when the technical progress is so fast that the production apparatus (although flexible) is devaluated economically and must therefore be renewed earlier. This implies a shift in the proportion of the construction phase to the market phase in the latter's disfavor (both shortening at the same time)[1] .
- possibly a reduction of the (marginally potential) capital output ratio[2] (see WELZMÜLLER 1981, FREEMAN/SOETE 1985, GERSTENBERGER 1986, POLT 1987, GOLDBERG 1988, FLEISSNER

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[1] The IFO-Institute (IFO-Schnelldienst 1/87 + 2/87) found a shortening of the gestation period of new products for 36 % of the innovating enterprises. It is now less than 3 years for 60 % of the enterprises. For 45% of the them also the market phase was cut.

[2] One can distinguish between a type of technical progress that is saving fixed capital and one that is saving semi-finished goods, energy, and raw materials.

1988; see Table 10 and 11 as well as Figure 8). The extreme variants of possible developments are the following: on the one hand a drastic reduction of the necessary investment outlays (should the capacity be only maintained), on the other hand a rise of the initial capital requirement together with a strong capacity extension. These "ideal types" have been found by RANTA and others by observing the diffusion of FMS in Finland (see Table 8). Reality should lie somewhere in between: an increase in the capacity should be accompanied by an under-proportional increase in the initial capital requirement (see e.g. Table 1).

Table 3:
COMPARISON OF COST STRUCTURES

Type of equipment	C	Ov	O	L total	L_p	L_u
FMS	33.1	13.9	28.3	24.7	10.7	14
transfer line	29.8	23.7	26.8	19.7	13.3	6.4
stand alone machine tools	17.8	13.5	25	43.7	27.7	16

C = capital costs
Ov = overheads in manufacturing
O = other costs
L = labor costs, u = unproductive, p = productive

Source: Wildemann H., from: Wirtschaftswoche Nr. 15, 8.4.1988, pp. 110

Table 4:
ECONOMIC PARAMETERS OF AN FMS

	Conventional manufacturing	Flexible manufacturing system
shop floor (in m^2)	6.500	3.000
number of machines	68	18
number of employees	215	12
wage costs per year (in mio $)	3.96	0.227
lead time (days)	90	3
circulating material (mio $)	5.00	0.218
Investment (mio $)	14.0	18.0

Source: FLEISSNER 1987, p 101

Table 5:
SEMI-CONDUCTOR INDUSTRIES: A COMPARISON BETWEEN THE USA AND JAPAN

	Capacity utilization (%)	Unit manufacturing costs*	Plant size**	Average number products per line
Large japanese firms	50	17.52	5000	1-2
Large US-firms	30	24.76	2500	10-20
small US-"Start-ups"	10	49.32	1000	100-200

*$/sq.inch silicon
**Wafer Starts/week

Source: VLSI Research Letter, San Jose/Cal., Feb 1986, p.6, quoted. in: D. ERNST (1987)

Table 6:
SEMI-CONDUCTOR INDUSTRIES: CAPITAL PRODUCTIVITIES

	Capital expenditures 1984 (mio $) (I)	Incremental silicon starts 1983-84* (II)	Capital/Output ratio (=I/II)**
japanese firms	3191.5	290.6	10.98
US-firms	5395.7	147.8	36.51

*as Indicator for capacity, in mio. sq.inches silicon
**$/sq.inch silicon

Source: VLSI Research Letter, San Jose/Cal., Dec. 1985, p.3, quoted in: D. ERNST (1987)

Table 7:
SEMI-CONDUCTOR INDUSTRIES: CAPACITY UTILIZATION

	Production capacity 1984 (I)	Silicon starts 1984* (II)	Capacity utilization (=II/I)
japanese firms	1253.9	660.3	52.66
US-firms	2490.8	637.3	25.59
Rest of the world (excl. RGW)	1499.2	207.4	13.83
Total	5243.9	1505	28.70

* mio. sq.inches silicon

Source: VLSI Research Letter, San Jose/Cal., Dec. 1985, p.3, quoted in: D. ERNST (1987)

Table 8:
ECONOMIC IMPACT OF ADVANCED PRODUCTION AUTOMATION

Case 1: Constant production capacity

	Conventional	NC functional	FMS
Number of machines	N	N/3	N/9
Production capacity	C	C	C
Price	P	2/3P + ext.design	1/3P + ext. design

Case 2: Constant number of production units

	Conventional	NC functional	FMS
Number of machines	N	N	N
Production capacity	C	3C	(9-15)C
Price	P	2P + ext. design	3P + ext. design

Source: RANTA, KOSKINEN, OLLUS (1987), p 31

IV. MACROECONOMIC EFFECTS OF CIM - TECHNOLOGIES

IV.1. Effects on capital accumulation

Some of the indicators described above point at a reduction of the demand for preliminary materials and the investment per additional unit of output. So, e.g., the possibility of a faster adaptation of the production program to alterations of the structure of demand could result in a long-term reduction of the investment. One need not exchange specialized production equipments for each other and it is possible to shift to new variants of products without (substantial) new investments (see Table 9).

Table 9:
RE-USABLE PARTS OF EQUIPMENT* AFTER A CHANGE OF PRODUCTION PROGRAM (in the automobile industry)

Transfer lines	5-40%
Flexible manufacturing systems	50-80%
Flexible assembly systems	40-50%
Industrial robots	60-80%

*Value of equipment as part of the total instalment costs

Source: Wildemann H., from: Wirtschaftswoche Nr. 15, 8.4.1988, p106

That way the investment is increasingly uncoupled from alterations of the structure of demand, at the same time, however, more strongly tied to the overall level of demand, owing to the increasing weight of fixed costs. This should result in a lower accelerator. The reduction of inventories has the same effects: The demand for inputs of preliminary goods/products such as raw and auxiliary materials and energy is being diminished[1].

The effects of the reduced necessity of large investments depend on the particular situation of the economy. If, e.g., the actual stagnation period is caused predominantly by "capital shortage" [to be understood either as a stock of capital too small to meet the supply of labor, or as a sum of profits too small to maintain accumulation (views held by FREEMAN/SOETE 1985)], the effects will be positive. The stock of capital could now be enlarged even

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[1] Until now, however, Flexible Automation has not led to an acceleration of the ongoing reduction of inventories. This should not be reached until better integration is achieved.

with a smaller investment sum, the profit rate in the production will rise and be the base for an expansion of investments.
If, on the contrary, the slow growth is caused by chronic overaccumulation and restricted demand and, additionally, expansionary exogenous forces necessary for a boom are lacking, the stagnant tendency will be aggravated. This is because at the lower turning-point the components of aggregate demand, which regularly lead to a recovery are weakened: the investment demand and the demand for preliminary products. In such a blockaded upswing, with overcapacities persisting and the enterprises nevertheless gaining stable profits thanks to "administered prices" as well as to their strengthened position in class struggle, the structure of investment will turn to rationalization (and, possibly, to financial assets) instead of investment in expansion. Even if the connections described above need not necessarily entail an absolute decrease of investments, it holds true that a weaker dynamic than those of previous cycles develops (see Figure 9).
So far, the capital saving type of technical progress has not been able to be traced out, owing, on the one hand, to deficiencies in measuring the stock of capital on the other hand simply to the fact that diffusion of the IT in the production in only in its infancy. However, a hierarchy of industries with respect to level and development of the capital-output-ratio can be already noticed, with the fastest growing branches (EDP, computers, chemical industry) showing capital-output ratios rising only slightly or even falling (GOLDBERG 1988, pp 151; SOETE 1986, see also FREEMAN/SOETE 1985, Figure 8). As these spheres are input factors essential for the other trades, the whole economy is increasingly pervaded by a falling capital-output ratio in these branches. For example, the "EDP-rate" (the share of the investments in EDP in the total investments) has risen quickly during the past few years (and now amounts to 1/8 of total investment in machinery in the FRG).

Various industrial sectors in the Federal Republic of Germany show improvements of best practice capital productivity in recent years. In electronic data processing the capital output ratio, which has been declining in the eighties for 3% per year continues to decline even faster. From 1984 to 1986 it averaged a 9% per years reduction. In the electronic industry, capital productivity is also rising since 1984. Other sectors such as mechanical engineering or the automobile industry recently experienced a stagnation in the capital output ratio (GOLDBERG 1988, p 151 ff)

Table 10:
CAPITAL OUTPUT RATIOS IN THE F.R.G

	Effective COR All Enterprises*		Potential COR Industry**	
	absolute	average change per year	average change per year	
1950	2.5			
1960	1.8	-3.1	1970-75	1.3
1970	2	1.2	1975-80	1.1
1980	2.4 /2.5	1.5	1980-85	0.1
1986	2.7	1.3	1984-86	-0.4

*capital stock/value added, all enterprises (without housing) in prices of 1976, for 1980 and 86 in prices of 1980
**gross fixed capital/potential output

Source: GOLDBERG, J. 1988, p 149/50

Table 11:
DEVELOPMENT OF THE PRICES* OF CAPITAL GOODS

	Total	I	M	Eq	EDPq	CPI
1950-60	22.5	29.8	44.6			20.6
1960-70	13.9	24.3	39.3	9.9		28.5
1970-80	64.5	57.7	78.6	32.5	-16.4	62.1
1980-85	21.8	18.4	22	13	3.2	20.9

I = Investment goods
M = Machinery
Eq = Electric equipment
EDPq = Electronic data processing equipment
CPI = Consumer price index
*Changes in the price index (%)

Source: GOLDBERG, J. 1988, p 162

However, technical progress not only tends to weaken investment demand, but on the other hand can have also stabilizing effects:

Caused by initial capital requirements, the fast speed of technical progress and cost-cut competition investment in manufacturing has been rather stable despite temporary decreasing industrial output in recent years. A reduced speed of the technical progress or the gaining of oligopolistic positions on the new markets, however, would weaken this effect. Hence, the macroeconomic effect of this novel type of technical progress will vary according to the macroeconomic constellation and the "mechanism of regulation". If the productivity gains of the new technologies were (re)distributed to add to consumption (of individuals by cutting back their working hours and/or by raising their wages, or of the state, which could, in turn, improve the infrastructures of transports and environment protection), a higher growth could be realized. The speed of diffusion of the new technologies and their effects depend not so much on the technological possibilities themselves, but rather on the social background, such as the distribution of income, working time, consumption patterns etc (cf. the approach of the french "regulation school": BOYER/CORIAT 1986, BOYER 1988)

IV.2. NEW TECHNOLGIES, PRODUCT INNOVATION AND CONSUMPTION

One has to put the question now: Can this relative weakness of investment demand be compensated by an increase in private consumption arising from product innovations which is another important feature of technical progress?
There are, no doubt, signs that the enterprises strengthen their efforts to innovate their products[1] (ELIASSON 1987, IFO 1987), but, at the same time, there are also indications that it is more difficult now to dispose of product innovations, and that they do not automatically lead to a considerable increase of the demand (see esp. ZINN 1986 and IFO 1987):

According to an IFO survey (IFO-Schnelldienst 1/87, 2/87 quoted in KOWALSKI 1988, 46) in the FRG the motive of introducing new techniques in order to "introduce new products" has increased much less since the 60s than the motive "introduction of new production processes". In the mid-80s 20 % of the enterprises mentioned as their priority aim the introduction of new techniques for product innovation (as against 10 % at the end of the

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[1] According to ELISASSON 1987 marketing investments reach 1/3 of total investment costs in large Swedish enterprises (1978) - but this is only an indicator for the efforts of the enterprises and say noting about the success of these efforts.

60s), whereas 60 % of the enterprises aimed at process innovation (as against 20 % at the end of the 60s). A VDMA paper draws the same conclusions (quoted in TRIBOTECHNIK1988, 31): Up to now, changing the range of parts to be worked has not been the most essential motive to introduce new technologies into the production.

At present, another indicator of the subordinate role of production innovation is the structural shift of investment from capital widening (which should be connected rather - but certainly not strictly - with product innovation) to rationalization (which should run parallel rather to process innovation). It is true that the share in the sales figures of products settled in the introduction or growth phase of the product life cycle could be raised, but two thirds of the turnover are still products in the stagnation or senescence phase[1].

Even a successful product innovation, however, does not necessarily give rise to a sweeping upswing in consumption:

- Also new products are subject to the "Keynes-Gossen-law" (diminishing marginal utility - diminishing propensity to consume - monetary wealth formation/ see ZINN 1986) all the more as the "old" products have reached saturation levels. The pressure from the supply side plays a role as well: In a situation of chronic over-accumulation the enterprises are pushing into new markets. Consequently, also new spheres of growth will have overproduction before long. This is evidenced also by periodic temporary overproduction crisis also in the new fields of growth ("computer crisis" in the early eighties, ebbing waves of growth in biotechnology)

- The effects of product innovation are not so plain as is often claimed. A new product which can be consumed only after quite a long period of saving will even provoke first an increase of the propensity to save and a decrease of the propensity to consume.

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[1] IFO (Schnelldienst 1/87, 2/87) found about 30% of turn over of industrial products in the market introduction or in the growth phase in 1982 and 38 % in 1985. But still abuot 50% of the sales are made with products in the stagnation phase and 10% show decreasing volumes of sales.

- Product innovation by itself does not suffice to expand consumption strongly if existing goods are merely substituted (e.g. TV by High definition TV) and if the saving in costs is not or insufficiently passed on to the consumer.

- Success and the impact of product innovations depend on the macroeconomic constellation: In a stagnant phases with restricted private consumption product innovations are more risky. This may lead to a sub-optimal rate of innovation and to a focus on cutting costs.

- Necessitated by the increasing share of fixed costs, due to the introduction of CIM, the enterprises try to achieve high utilization rates and thus depend on a stable and high level of demand. So if the introduction of new products (and processes) needs a certain market volume[1] because of the increasing amount of fixed costs, product innovations may be hindered. There are historical examples which show that the success of product innovations depends strongly on the level of demand. The automobile, for example, (and thus the methods of mass production connected with it) was not able to prevail in Europe (in contrast to the U.S.) between the two world wars mainly because of the low level of income (see BOYER/CORIAT 1986, GOLDBERG 1988).

IV. 3. Effects on Employment

It can be expected that the impact of IT described above, which rather encourages stagnation, not only won't solve the problem of unemployment, but, quite on the contrary, will aggravate it.

Until its wide-spread diffusion, however, this negative effect won't be too sever. Its most essential effect in future may be the weakening of the VERDOORN-law (see BOYER/CORIAT 1986, 47). Then a decrease in growth rates need not necessarily be accompanied by a (proportional) decrease in the growth of productivity. This would certainly affect employment, resulting in "jobless growth".

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[1] Siemens estimates a future share in world market of 15% for picture transmission equipment necessary to cover costs (ARBEITSGRUPPE 1988, 104).

It is a fact that the most advanced branches in the use of IT themselves have the highest rates of growth in capital and labor productivity. Therefore they only have a underproportional demand for labor and for capital goods, even when production is growing quickly (GOLDBERG 1988 Table 10). CAMAGNI (1988, 109) states in his survey on the diffusion and the effects of Flexible Automation in the Lombardy (in this respect perhaps the most advanced region in Italy) that, owing to the increase of productivity, 15 - 20% of the jobs were lost in the first four years of implementation. These losses are not fully compensated for by the increase of employment due to better market positions in the following years (which amounts to 7-11%). Moreover, these gains are achieved in the disfavor of other companies and diminish employment there.

V. Conclusions

If the technical progress really has those characteristics described above, it follows that, at given political-economic circumstances (characterized by constrained demand), it will have effects rather encouraging stagnation. A weakening of the accelerator would tie investment more strongly up to consumption; increasing fixed costs would make the companies more dependent on a high and steady demand (and, besides, would encourage concentration). A future weakening of the VERDOORN-law due to the spread of IT, with falling growth rates in production and comparatively stable growth rates in productivity (in manufacturing), would affect employment adversely.

Therefore, for an adequate macroeconomic policy as regards the new technologies it is indispensable to support not only the diffusion of IT but also the demand (both private and public). Without support of the demand not only it is impossible to utilize fully IT in order to add to the wealth, but, on the contrary, economic difficulties will continue.

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Figure 1
Source: Lutz, B, Nuber Ch., Schultz-Wild, R.: Das große Probieren. Fabrik der Zukunft, Teil 6. In: Bild der Wissenschaft 9/1987, p. 111

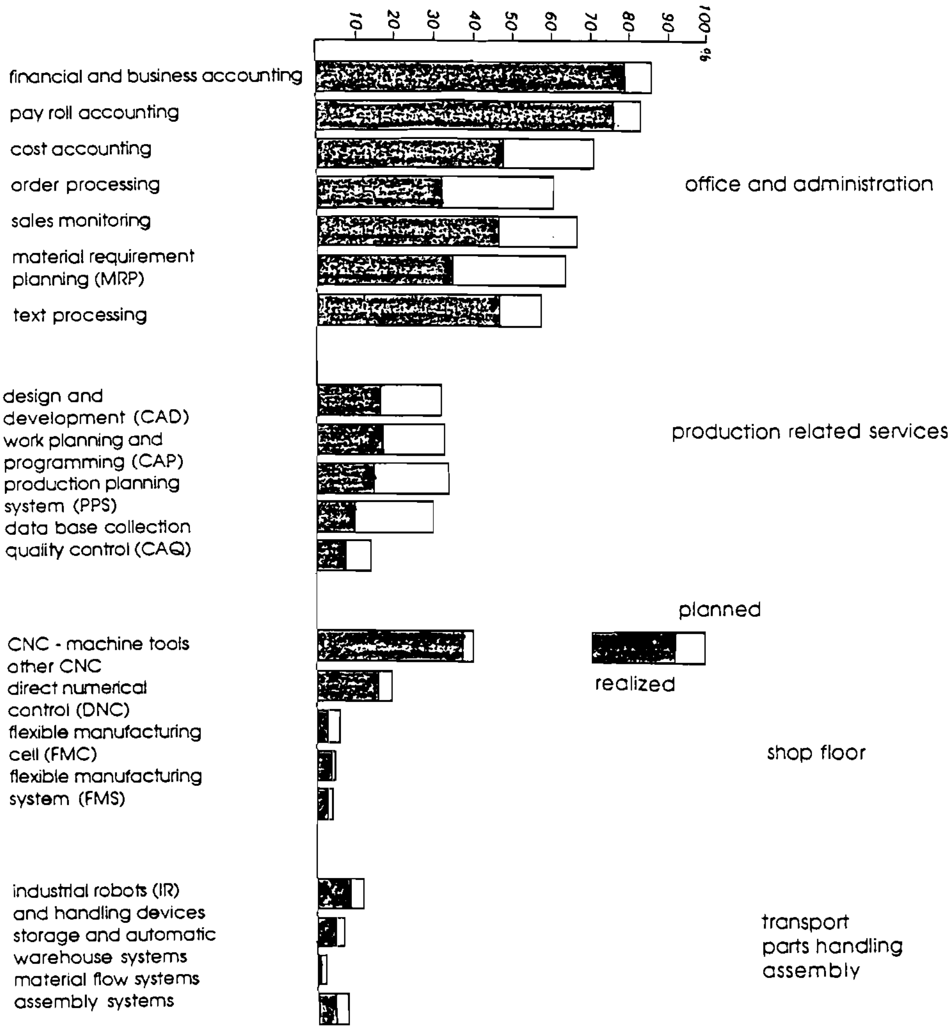

Figure 2

Source: Prohaska, M., Werderits, E.: Moderne Fertigungstechnologien - Verbreitung und Zukunftstrends, in: IHS: Mittelfristige Prognose, Wien 1987, p. 119

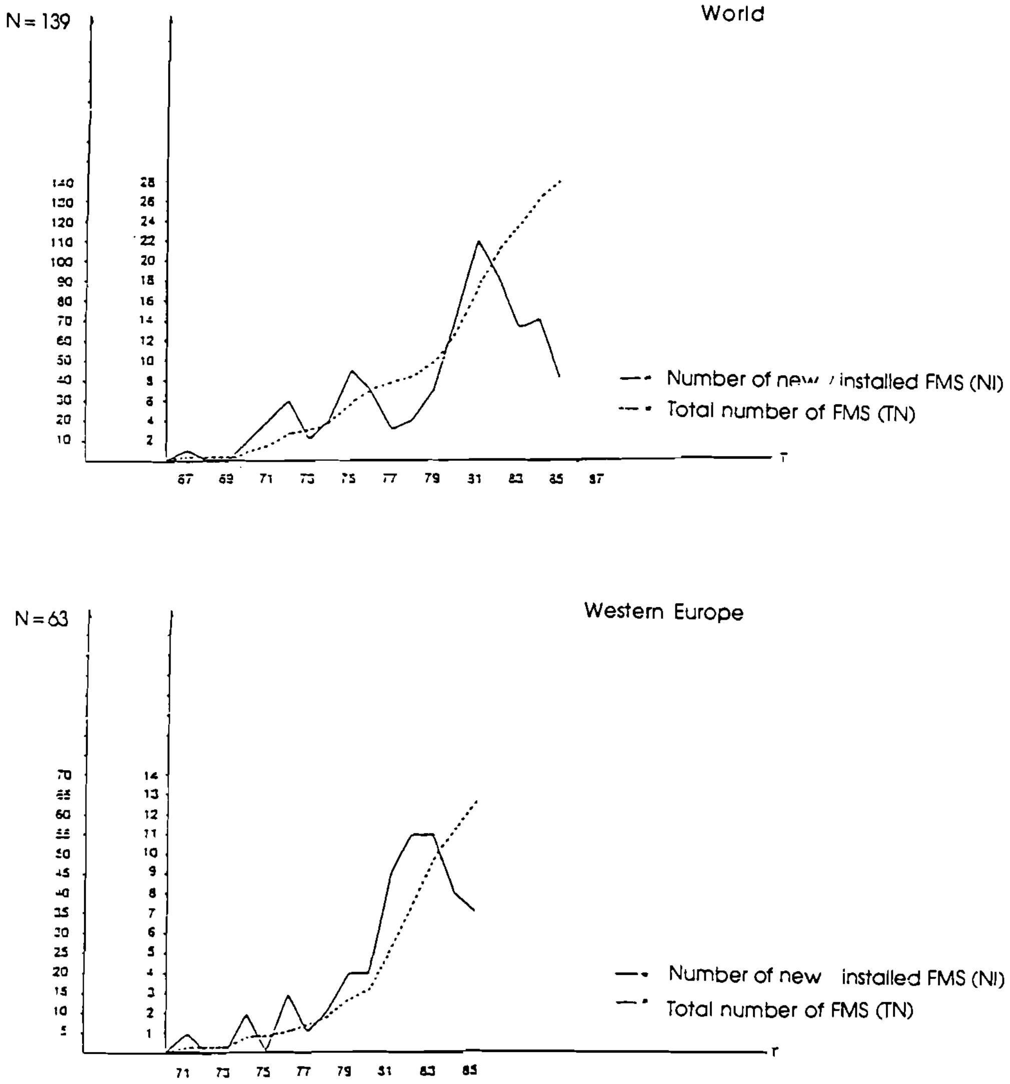

Figure 3
Source: Lutz, B, Nuber Ch., Schultz-Wild, R.: Das große Probieren. Fabrik der Zukunft, Teil 6. In: Bild der Wissenschaft 9/1987, p. 113

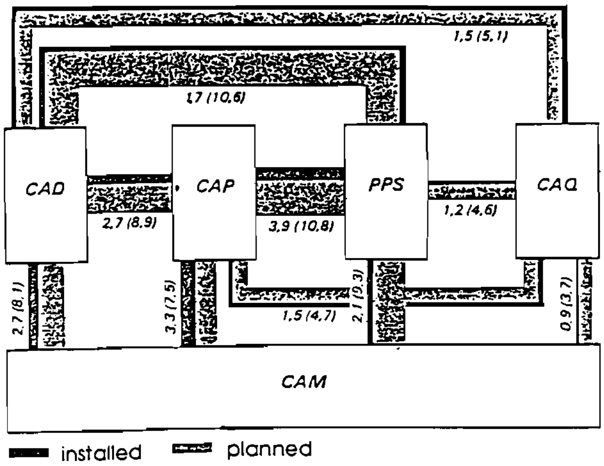

Figure 4
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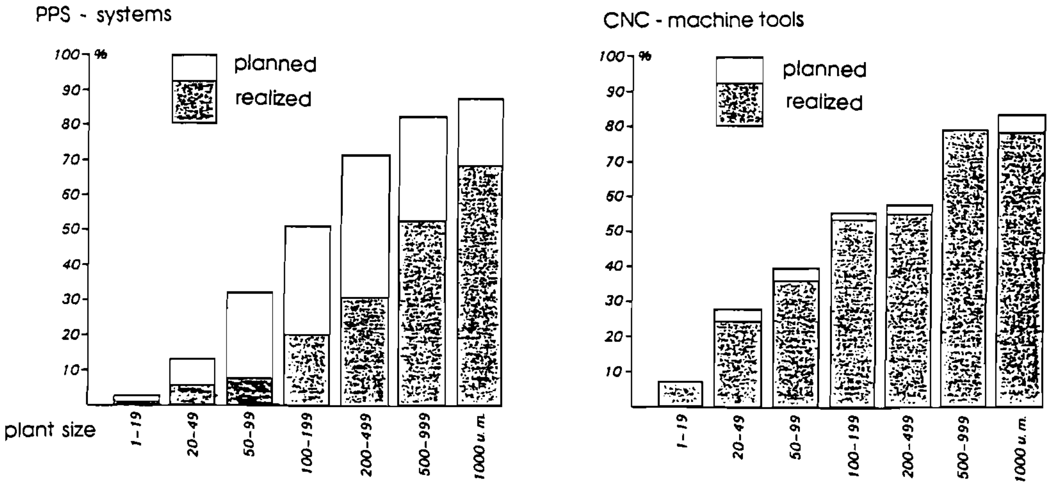
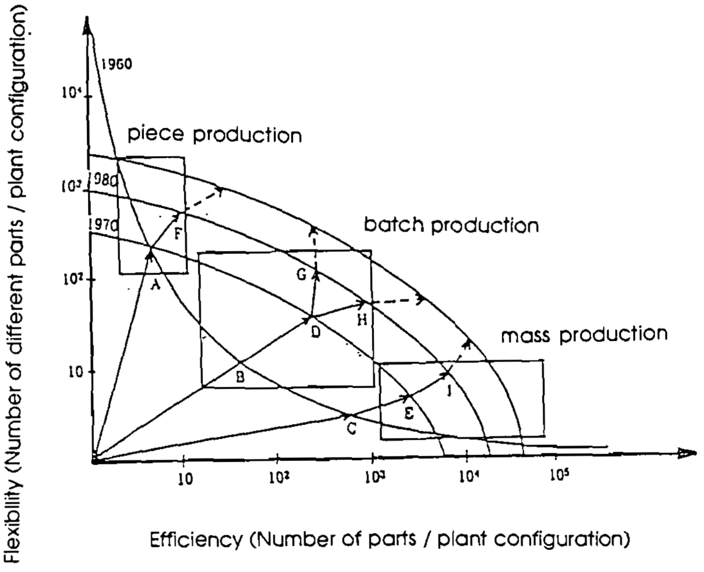


Figure 5

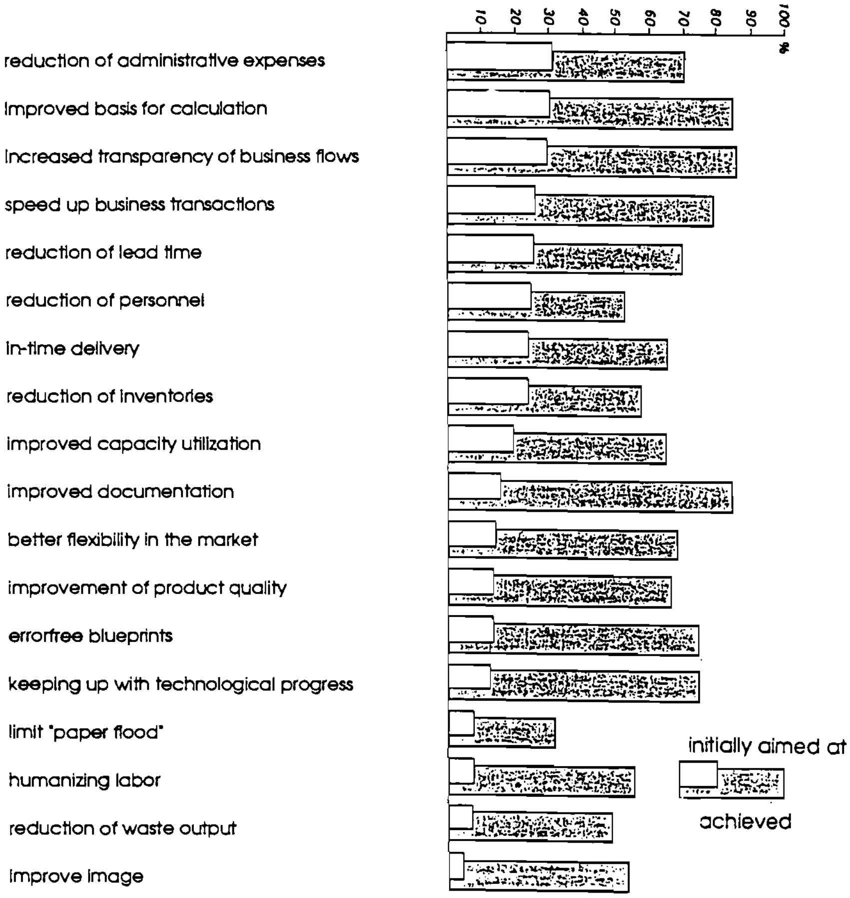
Source: Camagni, R.: L'Automazione Industriale. Milano 1988, p. 96



A = stand alone machine tool with manual control
B = semi-automatic machine tool
C = dedicated automatic machine
D = stand alone robot, NC machining centers
E = transfer line with CNC
F = semi-automatic or automatic machine tool
G = working cell
H = flexible manufacturing systems
I = flexible transfer line, robogate, multirobot, FMS

Figure 6

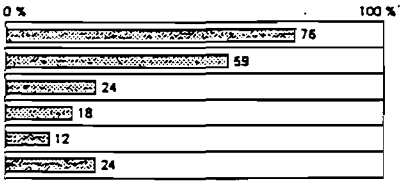
Source: Lutz, B, Nuber Ch., Schultz-Wild, R.: Das große Probieren. Fabrik der Zukunft, Teil 6. In: Bild der Wissenschaft 9/1987, p. 114



<u>Figure 7</u>
Source: Zentralsparkasse und Kommerzialbank (Hg.): Technologiemappe, Folge 21. Zusammengestellt und redigiert von der Tribotechnik Forschungs-GmbH, Wien, März 1988, p 30 and 31

Expectations before the introduction of FMS

Flexibility	Increase
Lead time	Reduction
Machine equipment	Improvement
Number of Machines	Reduction
Meeting daedlines	Improvement
Costs	Reduction



Improvements achieved with FMS

Lead time	Reduction
Utilization time	Increase
Number of machines	Reduction
Circulating capital	Reduction
Number of personnel	Reduction
Unmanned third shift	Practiced
Manufacturing unit costs	Reduction
Quality control	Reduction of expense

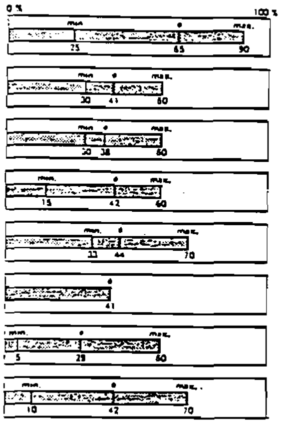


Figure 8
Source: Freeman C., Soete L.: New Technologies, Investment and Employment Growth. In: OECD (Ed.): Structural Change and Economic Growth, Paris 1985, p. 77

GROWTH IN BEST-PRACTICE LABOUR AND CAPITAL PRODUCTIVITY IN THE ELECTRONICS SUBSECTORS (MINIMUM LIST HEADING LEVEL) 1970-80

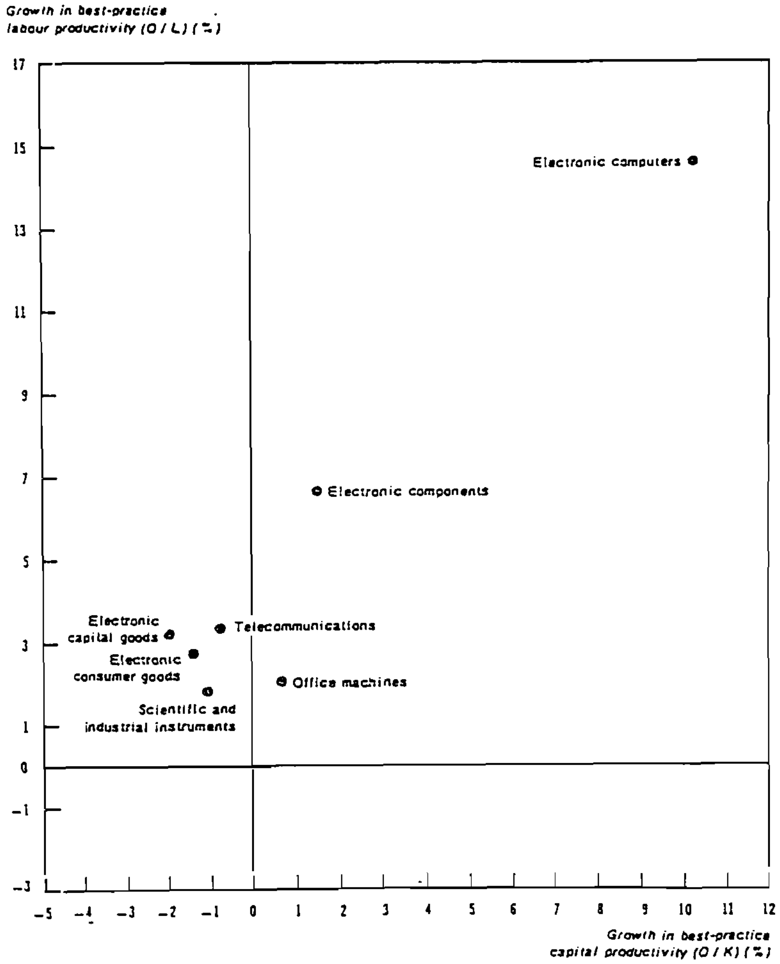
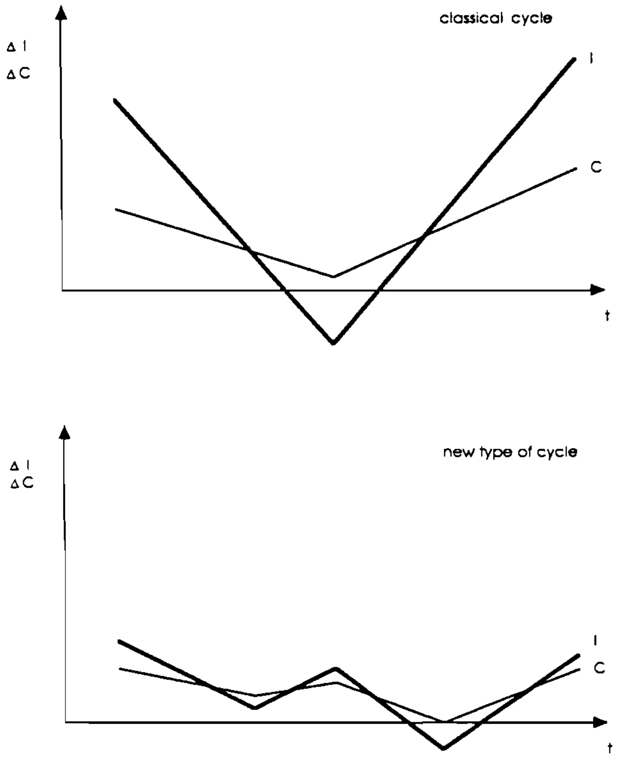


Figure 9



The Impacts of Robotization on Macro and Sectoral Economies within a World Econometric Model

by

Soshichi Kinoshita and Mitsuo Yamada

1. Introduction

In the past decade, especially since the early 80s, Japan has seen a strong trend toward robotization -with the introduction of industrial robots in the manufacturing proesses. A number of studies on the impacts of robotization have been conducted based on modeling and non-modeling approaches. A study by W. Leontief and F. Duchin is a recent one based on modeling approach.¹⁾ This paper addresses the same basic issues as these studies and analyses globally the probable impacts of robotization on the macro and sectoral economies within a world model of industry and trade.

The global model we use in this study makes it possible to evaluate two important impacts:

(1) The domestic impacts through the interindustry relationships in the dynamic input-output model, and

(2) The international impacts through the trade relationships among trade partners specified in the trade linkage model.

This paper is organized as follows. Section 2 is concerned with the main structure of the global model. In section 3, we explain the specification and some estimates of the international interdependence through commodity trade. Section 4 summarizes the difussion process of the impacts of robotization. Section 5 is concerned with the assumptions used in the simulation experiments. Section 6 provides some simulation experiments on the robotization in the machinery industries. And the last section provides a summary and conclusions.

2. Overview of the world industry and trade model

The world model in this study is based on a decomposition of the world economy into several multisectoral models for the countries and regions. The system is closed by the international trade linkage model by sector, which determines the export volumes and import prices of the individual countries and regions. This is to ensure world accounting consistency for the international trade flow.$^{2)}$

The current version of the model subdivides the world economy in the following countries or country groups:

Japan
U.S.A.
Korea
EC(4)(France, Italy, West Germany and U.K.)
ODC (OECD countries excluding Japan, U.S.A. and EC(4))
ANICs(Taiwan and Hong Kong)
ASEAN(Indonesia, Malaysia,Phillipines, Singapore and THailand)
ROW (Rest of the world).

Figure 1 graphically shows how the individual country and regional model could be linked with each other within a world industry and trade model.

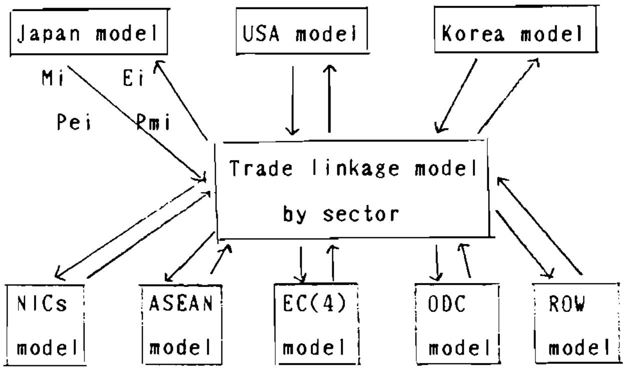


Figure 1 Linkage of country models

Domestic economy in the individual country or group of countries is disaggregated into 21 sectors as shown in Table 1.

Table 1 Sectoral Classification of the Model

1. Agriculture, forestry and fishing
2. Mining
3. Food, bevarage and tobacoo
4. Textiles
5. Apparels
6. Leather product and footwear
7. Wooden product anf furniture
8. Pulp, paper , printings and publishings
9. Rubber and plastic products
10. Chemicals
11. Petroleum and coal products
12. Non-metalic mineral products
13. Iron and steel product
14. Non-ferrous metals
15. Fabricated metal products
16. Machinery except electricals
17. Electrical machinery
18. Transport equipment
19. Precision instruments
20. Miscellaneous manufacturing products
21. Construction and tertiary industry

In regard to national and regional modeling, the model for Japan, U.S.A. and Korea is a large scale equation system that attempts to explain the input-output relation and Keynsian macro-economic behaviors simultaneously.3) Modeling for the group of countries, on the other hand, are based on a rather simplified formulation, in which the sectoral import volumes and export prices are related directly with aggregate economic variables, not with sectoral input-output relations. This simplification is mostly due to the availability of I-O based sectoral time series data.

Figure 2 shows the basic structures of the multi-sectotal model.

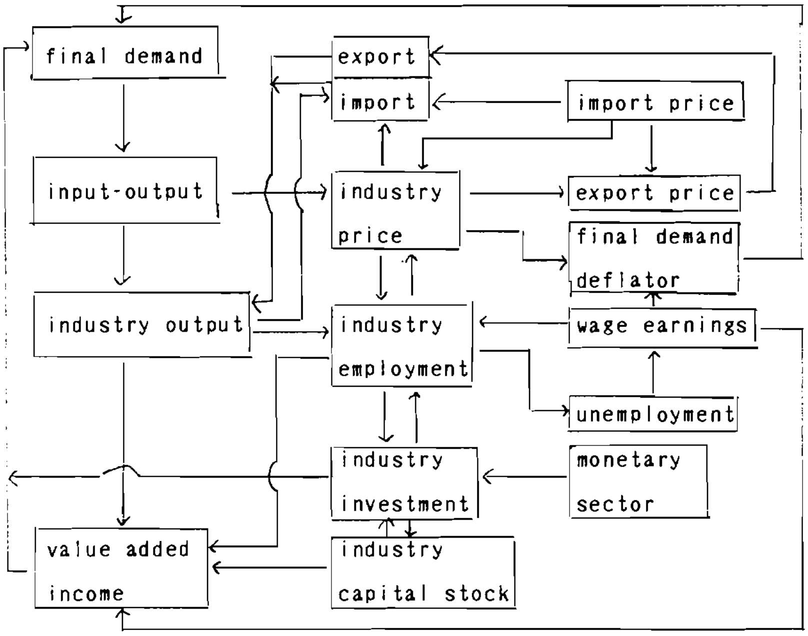


Figure 2 Structure of a Multi-sectoral Model

It is seen that the model includes the basic elements of economy-wide model, i.e.

(1) a final demand block

(2) a input-output and output block

(3) a factor demand block

(4) a income generation block

(5) a input cost and price block

(6) a wage and unemployment block

(7) a export-import block.

3. International Interdependence through Commodity Trade

To evaluate the international impacts of robotization, it is a prerequisite to model the trade-dependent relations among countries in the model. The trade linkage model is thus developed as a submodel of the world model. This was done in order to determine consistently the export volumes and import prices by sector for each country or region, given the import volumes and export prices determined in the national or regional model.

The idea of achieving consistency in export-import relationships in the world market is briefly explained below. Let the trade linkage matrix, m^{rs} be defined as,

$$m^{rs} = M^{rs} / \Sigma_r M^{rs} = M^{rs} / M^s$$

where M^{rs} is export from country r to country s and M^s , total import of coutry s.

Thus, m^{rs} is the market share of coutry r's export in country s's imports. Then , by definition, the total export of country r(E^r) is given by

$$E^r = \Sigma_s M^{rs} = \Sigma_s m^{rs} M^s \qquad \text{----------------(1)}$$

Since summation of m^{rs} over r is unity, we see that the export determined above satisfies the world identity in real trade flow,

$$\Sigma_r E^r = \Sigma^s M^s$$

Likewise, if there is no price discrimination in the export market, import price of country s(Pm^s) is given by the weighted average of the export prices of supplying countries(Pe^r) as follows:

$$Pm^s = \Sigma_r m^{rs} Pe^r \qquad \text{---------------------------(2)}$$

This import price guarantees that a companion world identity,

$$\Sigma_s Pm^s M^s = \Sigma_r Pe^r E^r$$

holds.

Thus, if the trade share matrix is given, export volumes and import prices are jointly determined so as to preserve the world trade accounting identities in both current and constant prices.

Our specification of the trade likage model is based on Moriguchi method. The advantage this method has over the alternative methods, lies in the fact that it includes both demand and supply factors in the bilateral trade flow equation.[4)]

Trade share matrix, m^{rs} in the Moriguchi approach is written as

$$\ln(m^{rs}) = a^{r} + b^{r}\ln(Pe^{r}/Pcom^{rs}) + c^{r}\ln(Ec^{r}/M^{s}) + \Sigma_{s}d^{rs}D^{s} \text{ ----------------------}(3)$$

where $Pcom^{rs}$ is the export prices of country r's rivals in country s market, Ec^{r}, export capacity of country r and D^{s}, the dummy variables for import country s to take into accounts the geographic and other trade linkage factors. This equation implies that the export share of country r in country s is determined through demand-supply interaction by price competitiveness, $Pe^{r}/Pcom^{rs}$ and non-price factor , Ec^{r}/M^{s} .

In estimating this equation by sector, we assumed that the market share elasticities with respect to price and non-price variables are equal across the import markets, and pooled time series of m^{rs} for each export country r. Furthermore, export capacity variable, Ec^{r} is approximated by the realized exports in the previous year, and if approapriate, additional dummy variables are introduced to adjust irregularities over the sample period 1970-84.

Table 2 summarizes the estimated results for the electrical machinery industry. From this table, we find first the direct impacts of export price changes as follows:

(1) A 10 per cent decrease in Japan's export price raises her export volume by 4.1 per cent in the first year and 7.7 per cent in the fifth year. The impacts on exports of other country or group of

Table 2 Estimates for electrical machinery industry

Impact on export volumes in	Increase in					
	export price in			import volumes in		
	Japan	U.S.A.	Korea	Japan	U.S.A.	Korea
Japan	-0.41	0.05	0.02	-	0.11	0.02
	-0.77	0.10	0.03	-	0.24	0.03
U.S.A.	0.09	-0.39	0.01	0.06	-	0.02
	0.10	-0.43	0.01	0.05	-	0.06
Korea	0.24	0.09	-0.99	0.06	0.18	-
	0.42	0.20	-2.17	0.12	0.41	-
EC(4)	0.06	0.05	0.00	0.00	0.01	0.00
	0.06	0.08	0.01	0.00	0.02	0.00
Asia NICs	0.23	0.06	0.03	0.03	0.33	0.01
	0.24	0.09	0.04	0.04	0.42	0.01
ASEAN	0.47	0.10	0.06	0.00	0.02	0.00
	1.04	0.32	0.20	0.00	0.05	0.00
ODC	0.02	0.01	0.00	0.00	0.03	0.00
	0.03	0.02	0.00	0.00	0.06	0.00
import prices in						
Japan	-	0.35	0.17			
	-	0.80	0.21			
U.S.A.	0.37	-	0.07			
	0.62	-	0.07			
Korea	0.44	0.17	-			
	0.74	0.28	-			
EC(4)	0.11	0.10	0.01			
	0.19	0.09	0.02			
Asia NICs	0.42	0.14	0.00			
	0.68	0.14	0.00			
ASEAN	0.29	0.13	0.01			
	0.39	0.24	0.01			
ODC	0.11	0.18	0.01			
	0.20	0.14	0.01			

Note: Figures in the table are elasticities and for each country or group of countries, the upper number indicates the impact in the first year and the lower one, that in the fifth year.

countries are all negative. In the fifth year impacts are -10.4 per cent for ASEAN and -4.2 per cent for Korea. Import prices are affected favorably, and significant decreases are seen in the US, Korea and Asia NICs.

(2) A 10 per cent reduction of U.S. export prices increases her own export by 3.9 per cent in the first year and 4.3 per cent in the fifth year. The favorable impacts on the US exports are small as compared with the case of Japan. The impact on exports of other economies in the fifth year are -1.0 per cent, -2.0 per cent, -3.2 per cent for Japan, Korea and ASEAN respectively. The impacts on import prices of the trade partners are quite small compared with those by Japan.

(3) A 10 per cent decrease in Korean export prices raises her own exports by 9.9 per cent in the first year and 21.7 per cent in the fifth year. This reflects the high price elasticity of Korean exports. But the impacts on other economies are rather modest, except for ASEAN.

Turning to the impacts of increased import volumes on the trade partners' exports, we see a slight increase from the impact from Japan and Korea. The reason for the small impacts from Korea may be due to the relative size of Korean import market to total exports of Japan and the US. The impacts from the US are relatively strong because of her large import volumes and high dependencies on exports from Japan and Korea. 10 per cent increase in the US imports raises exports in the fifth year by 2.4 per cent, 4.1 per cent, 4.2 per cent for Japan, Korea and Asia NICs respectively.

4. Diffusion Process of the Impacts of Robotization in the model

Before discussing the simulation experiments, it is convenient for us to look at, based on the specification of the model, the diffusion mechanism, through which robot investment in one industry affects aggregate and sectoral behaviors of other industries both domestically and internationally.

According to a report of the Japan industrial Robot Association(JIRA), wage cost pressure is the most important factor that encourages robot investment.5) This means that the impact of robotization is initially observed in the form of labor displacement or increased labor productivity in the robot using industry. Then this tends to induce the associated changes in the following two ways. First, output price will be depressed as a result of wage cost reduction by the increased labor productivity. Second, wage cost reduction will improve profitability which may induce additional investment.

The lower output price in the robotized industry will not only increase price competitiveness of this industry in the export market, but also decrease intermediate input price of related industries through input-output relations. Accordingly, the initial price decrease in the robot using industry influences output prices of all industries with varying degree. Further decline will be expected in the prices of output and exports if the wage pressure in the labor market is reduced by the labor displacement effects of robotization.

On the demand side, investment for robotization will increase production in the robot (capital goods) producing industry, and it in turn will require additional employment and fixed investment.

These impacts on price, production and factor demands will diffuse gradually into the income distribution block and affect private consumption and housing investment expenditures. Thus, the initial impact will be multiplied domestically through the interdependent relations of the model.

The domestic interplays initiated by robotization are transmitted to foreign countries through the international trade linkage. This is because the changes in the export prices and import volumes generated in the domestic economy are assumed to influence import prices and export volumes of all countries. Specifically, a export price decrease in the transmitting robotized country will depress exports from rival countries and decrease import prices of transmitted countries. In addition to this, import increase by the demand side effects of robotization in the tranmitting country will increase exports from partner countries and affect production there.

These effects in the foreign countries will be fed back with a certain time lag to the domestic economy through the channels of trade flow.

The intensity and scope of the impacts of robotization on individual sectors depends mostly on the estimated parameters and lag patterns in the world model, the details of which are given in a separate paper.

5. Assumptions on the demand-supply effect of robotization

As is clearly stated in a report of JIRA, business firms will make a decision for robotization depending on the labor displacement effect of robot investment. The larger the labor cost saving relative to the price of robot, the higher the probability of introducing robot in the production process in place of workers.

Then, the question arises what is the critical level of the real price of robot in term of per capita employment cost. Again, according to a JIRA report, the maximum amount of money that business firms can afford to invest for robot is about twice as much as the annual employment cost per worker.(6) This implies that given an industrial robot fully displacing one workers in the net term, investment for this robot will become profitable when the price of robot become less than the twice of annual employment cost.

Thus, assuming that annual employment cost per worker is 4 million yen in 1980 prices, business firm will plan to invest 8 million yens or less for the robot. Since the actual robot investment has to cover both the core and peripheral equipments, the total amount is estimated to be at least in the order of 10 million yens in 1980 prices.

In analyzing the overall impacts of robotization, the critical point is how to feed the direct impacts of them into the model. Our procedure is such that the labor displacement effect of robot use is given by a downward shift of labor demand function, and the investment demand for robotization is represented by the upward shift of investment function of a given industry. And five assumptions are introduced on the shifting patterns of two functions in the individual industries as follows:

A1: Based on the sectoral distribution of robot stock in Japan, robotization in the simulation is confined to the four machinery industries. These are, machinery except electricals, electrical machinery, transport equipment and instrument. Robotization in other industries is disregarded.

A2: Magnitude of the downward shift of labor demand function in Japan is set by 10,000 per year for three machinery industries and 5,000 for instrument industry. These figures are based on the estimates by JIRA and Prof. Mitsuo Saito.7)

A3: The same magnitude of direct labor displacement is introduced in the US, whereas the shift in Korea is reduced to one-fourth of that in Japan. These differences in the magnitude are justified by the relative size of each economy and are needed to makes our comparison with the US and Korea more realistic.

A4: Upward shift of the investment function is determined by per capita annual labor cost and labor displacement effect of robot investment. The required robot investment to displace 10,000 workers is estimated to be 65 billion yens in 1980 prices, and 32.5 billion yens is needed to decrease 5,000 workers. Additional investment is made in the order of 10 per cent of initial investment from the second year and afterwards.

A5. Two types of simulation are made in order to evaluate the relative importance of labor displacement effect and demand side effect. The first simulation (S-1) disregards demand side effects and the second simulation (S-2) includes both effects of robot investment.

6. Simulation Results on Robotization in Japan, the US and Korea

The procedure of robotization simulation with the estimated global model involves first the establishment of control solutions for the whole system. The control solutions in this experiment were given by solving the model without robotization assumptions for the period 1979-83.

The second step is to derive disturbed solutions based on the alternative robotization scenario. Given these two solutions, the impacts of robotization on the macro and sectoral economies are measured by the differences between the two.

We computed disturbed solutions for the following three scenarios:

S1: Robotization in the Japanese machinery industry.
S2: Robotization in the US machinery industry.
S3: Robotization in the Korean machinry industry.

In scenario 1 and 2, two types of simulation (Si-1 or Si-2), as described in A5 above, are conducted to compare the relative importance of demand side and supply side effects of robotization.

The results of simulation in each country are presented first on the macro-economic impacts on her own economy, and second on the external economies and third on the sectoral impacts in the domestic economy.

6.1 The case of robotization in Japan

Impacts of robotization on the macro level are shown in table 3-1 For Japan, the results are an improvement in GNP amounting to 0.35-0.37 per cent over the control solutions in the fifth year. Contributing factors for this are, the downward shift of the price trend and the resulting increases in exports and domestic investments.

The impacts on the US economy as a whole are small but negative. This is because the negative impacts on net exports and investment are not fully cancelled out by the positive effects on private consumption and housing investment.

For Korea, changes in the comparative advantage affect her exports negatively as is the case of the US. However, since the induced investment growth offsets most of the export decline, the negative impacts on GNP are negligible. And the slight but positive impacts are observed in the labor demands.

The observed differences in the investment response between the US and Korea, are explained by the fact that Korea depends heavily on Japan for her supply of capital goods - speficically the products of the machinery industry. Cheaper capital goods imported from Japan decrease the cost of capital in Korea significantly and as a result, stimulate domestic investment.

At the sectoral level, labor displacement effects of robotization in Japan are concentrated in the robotized industries, as shown in table

3-2, and amount to 36.9 thousand jobs in the first year and 62.3 thousand jobs in the fifth year when disregarding the demand side effects of robot investment. The results in table 3-2 also shows that the demand side effects of robot investment has worked to decrease the labor displacememt effects by about 10 thousand jobs in the short-run. It should be noted here that in both cases, the workers displaced in the robotized industries tend to be partially absorbed by other industries, and the negative impacts on jobs are reduced over time.

The impacts on sectoral output prices are shown in table 3-3, where the significant price decreases in the robotized sectors have diffused to all sectors through declining input prices and wage cost. After 5 years, price reductions from the control solutions are over 1 per cent for the robotized sectors and at least 0.5 per cent for the remaining sectors. The cumulative effects on output prices are considerable in transport equipment and precision instruments industries.

The effects on sectoral investments are positive for almost all sectors, though the magnitude of the effects varies among individual sectors. In the first year, over 40 per cent of the increases are concentrated in the robotized sectors. But in the fifth year the share of the robotized sectors declines to around 33 per cent and that of remaining sectors as a whole amounts to 67 per cent.

The positive impacts on sectoral exports, as shown in table 3-4, fall heavily on particular sectors, that is, electoral machinery and transport equipment. This is due to the combined effects of significant price decreases and the high price elasticity of exports in these sectors.

6.2 The case of robotization in the US

The next simulation represents the impacts of robotization in the US on aggreagte and sectoral economy. It is seen in table 4-1 that when disregarding the demand side effects, the effects on GNP are negative not only in Japan and Korea but also in the US. These results are contrary to those of Japan, since the robotization in Japan has a positive impacts on her own GNP.

The following four factors are responsible for these contrasting results:

1) Price decreases from robotization are relatively small.
2) The resulting impacts on export expansion from price reductions are weak.
3) Sectoral investments are less sensitive to increased profitability
4) Wage rate response is less sensitive to the labor market condition.

The negative impacts on economic growth are larger in Japan than in Korea. This is explained by the larger impacts of decreased US imports on the Japanese exports, especially on her machinery exports. And the positive effects on Korean investment, which were derived from the cheaper imported capital goods have partially offset the initial negative effects.

The total sum of labor displacements in the US are 37,000 in the first year, 69,000 in the second year and 87,000 in the fifth year. While the labor displacements in Japan record the peak in the fourth year and decreases afterward, the effect in the US shows an incresing trend and exceeds that in Japan. Regarding the sectoral distribution of labor displacements, magnitude of the robotized sectors shows little difference between the US and Japan. The larger labor displacements in the US are due to the smaller compensating increases in the tertiary industry employment.

For output prices, the effects in the US in table 4-3 are negative and comparable in size to those in Japan for general machinery and precision instruments. The effects for the electrical machinery and transport equipment,however, are considerably less than those in Japan. As a result of this and the small impacts on wage rates, the total effects on output prices in the non-robotized sectors are quite small as compared with those in Japan.

The impacts on foreign trade in the US, as seen in table 4-4, are more pronounced in the import substitution than in the export expansion. For example, after 5 years, the effects for electrical machinery and transport equipment are 0.06-0.08 per cent increase in exports and 0.4-0.5 per cent decrease in imports.

It is clear in tables 4-1 to 4-4 that the demand side effects of robot investment, partially or fully compensates for the negative impacts they have on key economic variables in the US. The impacts on economic growth becomes positive, and the labor displacements in the first year are reduced by around 20 thousand jobs. In the fifth year, however, due to the declining demand side effects, labor displacements as a whole, differ little from those in the case where demand side effects are disregarded.

6.3 The case of robotization in Korea

The impacts of robotization in Korea are summarized in tables 5-1 to 5-2. The international impacts are considerably small as anticipated by taking into account her relative size in the world economy.

For the domestic impacts, the effects on GNP growth in Korea are positive as is the case in Japan. The mechanism is that the increased productivity by robotization tends to depress output prices, which in turn expand exports and encourage domestic investments. But the positive impacts on Korean economy tends to spill over to other countries, especially Japan which is a major exporter of capital goods to Korea.

For employment, the net effects of robotization are 9,900 job decreases in the first year and 6,200 job decreases in the fifth year. In the robotized sectors, the figures are 10,200 and 9,600 respectively. Thus in the fifth year, about one-third of the job losses in the robotized sectors are absorbed by the job increases in the non-robotized sectors.

The effects on output prices are rather small,because the wage cost share in the production cost is not as high in Korea as they are in Japan or the US. As a result, the positive impact on exports through price effect becomes limited.

6.4 A comparison of the impacts on Korea of robotization in Japan and the US

Korea, which is one of the NICs, has a close economic tie with Japan and the US through international trade. It is interesting to compare the impact on the Korean economy due to the robotization of these two countries.

Table 6-1 presents a comparison of the macroeconomic impacts of robotization. Disregarding demand side effects, the impacts on economic growth in Korea are negative for both countries in the first two years. However, from the third year onwards, the effects of Japan become positive, while those of the US continue to be negative with an increasing trend.

The differences in the impacts of two countries emerge for the following reasons: first, the effects of Japan are growth-promoting, whereas those of the US are deflationary in nature; second, the larger impacts on output prices in Japan contribute to lower the price of capital goods in Korea and lead to a larger investment.

In the fifth year, the decreases in investment deflator in Korea are 0.37 per cent point in the case of Japan and 0.13 per cent point in the US. The resulting investment increases are 11.1 billion wons in 1980 prices in the case of Japan and 3.01 billion wons in the case of the US.

Comparing the case of S-1 with that of S-2, we see that the demand side effcts of robot investments promote economic growth in Korea. And the effects of the US exceed those of Japan in the first and second year, but from the third year, the relative magnitudes of macro effects are reversed. The larger short-run effects on Korea from the robotization in the US are generated by the higher propensity to imports in the US, which tends to increase Korean exports to the US.

7. Concluding Remarks

The purpose of this paper is to evaluate the probable, global impact of robotization on the macro and sectoral economies, using a world model of industry and trade. We find that robotization in Japan and Korea has a positive impact on their economic growth, while robotization in the US has a negative affect on her own economic growth. We also find that the international impacts of robotization in Japan, are negative on the US, but positive on the Korean economy.

Of course, these findings from the simulation experiments depend on the structure of the global model we use, as well as on the assumptions made for the simulation. We focus our attention on the robotization in the machinery industry, in which Japan has a comparative advantage over the US and the NICs. We are not concerned with robotization in industries such as textile products where the NICs has a comparative advantage over developed countries. Since exchange rate variables are exogenous in the current version of the model, the impacts through exchange rate changes are neglected.

In conclusion, continued efforts should be made for improving the whole model system, and for examining alternative cases in simulation studies.

Note:

1) Leontief W. and F. Duchin analyse the impacts of automation including robots on workers for the US economy. See Leontef W. and F. Duchin (1986).

2) This model was originally developed at the Economic Research Institute of Economic Planning Agency in Japan, and applied to measure sectorally and globally the effects of protectionism and other changes in international economic conditions. See Kinoshita S., et al.(1982) and Kinoshita S.(1983).

3) The current version of the national model contains about 470 equations for Japan, 360 for the US and 350 for Korea.

4) See Moriguchi C.(1973).

5) See JIRA(1985).

6) See JIRA(1985).

7) See Kinoshita S.,et al.(1987).

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Table 3-1 Impacts on Macro Economy (S1: Robotization in Japan)

Unit: %

	S1-1		S1-2	
	Period 1	Period 5	Period 1	Period 5
Real GNP				
in Japan	0.02023	0.37454	0.16357	0.36157
in USA	-0.00399	-0.03175	-0.00373	-0.03015
in Korea	-0.00495	0.00853	0.00514	0.01401
Nominal GNP				
in Japan	-0.11831	-0.63053	-0.06367	-0.57934
in USA	-0.00017	-0.02985	0.00045	-0.02871
in Korea	-0.02190	-0.12473	-0.02460	-0.11234
Consumption				
in Japan	0.00686	0.15176	0.05504	0.16539
in USA	0.00068	0.01740	0.00133	0.01791
in Korea	-0.00012	0.01293	0.00236	0.01894
Housing Investment				
in Japan	-0.12008	0.28680	0.00001	0.28766
in USA	0.00558	0.07257	0.00919	0.07325
in Korea	-0.00071	0.03139	0.01183	0.04150
Business Investment				
in Japan	0.09522	0.95958	0.92503	0.88230
in USA	-0.00282	-0.03279	-0.00257	-0.03218
in Korea	0.00862	0.11591	0.02869	0.11927
Export				
in Japan	0.07132	0.74230	0.10946	0.71651
in USA	-0.01683	-0.06254	-0.01183	-0.05284
in Korea	-0.03130	-0.06536	-0.00406	-0.05648
Import				
in Japan	-0.00584	0.03220	0.13731	0.06275
in USA	0.02257	0.30009	0.03072	0.29828
in Korea	-0.00015	0.04120	0.01428	0.04651
Employment				
in Japan	-0.07467	-0.12189	-0.04800	-0.11182
in USA	-0.00100	-0.00161	-0.00084	-0.00051
in Korea	0.00205	0.02480	0.00650	0.02814
Rate of Unemployment				
in Japan	0.24543	0.33396	0.15775	0.35164
in USA	0.02669	0.18568	0.02627	0.17548
in Korea	0.00499	-0.02009	-0.00518	-0.02462
GNP Deflator				
in Japan	-0.13851	-1.00132	-0.22688	-0.93752
in USA	0.00383	0.00206	0.00418	0.00143
in Korea	-0.01695	-0.13245	-0.02974	-0.12634
Wage Rate				
in Japan	-0.06307	-0.70312	-0.07498	-0.63126
in USA	-0.00120	-0.03769	-0.00154	-0.03681
in Korea	-0.02381	-0.16571	-0.03349	-0.15757

Note: S1-1 disregards demand side effects, and S1-2 includes both effects of robot investment.

Table 3-2 Effects on Employment (S1: Robotization in Japan)

Employment in Japan

Unit: thousand persons

	S1-1		S1-2	
	Period 1	Period 5	Period 1	Period 5
1 Agri.,forestry,fishing	0.434	6.663	3.684	6.674
2 Mining	0.000	0.000	0.000	0.000
3 Food,bevarage,tobacoo	0.026	0.694	0.129	0.677
4 Textiles	0.361	5.175	0.823	4.848
5 Apparels	0.087	1.198	0.307	1.179
6 Leather prod.,footwear	0.005	0.061	0.023	0.068
7 Wooden Prod,furniture	0.030	1.432	0.368	1.469
8 Paper & pulp,printing	0.029	0.762	0.348	0.743
9 Rubber & plastics	0.019	0.200	0.052	0.182
10 Chemicals	0.085	1.786	0.181	1.851
11 Petroleum & coal prod.	0.005	0.036	0.036	0.035
12 Non-metalic mineral prod.	0.115	1.920	0.379	1.935
13 Iron & steel product	0.036	0.793	0.109	0.787
14 Non-ferrous metals	0.033	0.592	0.083	0.575
15 Fabricated metal prod.	0.063	0.754	0.409	0.682
16 Machinery ex. elect.	-10.837	-34.790	-9.610	-33.885
17 Electrical machinery	-10.265	-16.344	-8.762	-16.278
18 Transport equipment	-12.358	-38.079	-11.567	-37.779
19 Precision instruments	-5.019	-9.966	-4.783	-9.947
20 Miscellaneous Manuf.	0.059	0.658	0.357	0.652
21 Tertiary Industry	0.193	14.162	3.713	18.389
Industry total	-36.900	-62.291	-23.721	-57.145

Table 3-3 Effects on Output Price and Investment (S1: Robotization in Japan)

Unit: %

Output Price in Japan	S1-1		S1-2	
	Period 1	Period 5	Period 1	Period 5
1 Agri.,forestry,fishing	-0.07365	-0.58454	-0.13103	-0.54771
2 Mining	-0.09963	-0.67421	-0.15518	-0.63375
3 Food,bevarage,tobacoo	-0.06242	-0.63147	-0.12130	-0.59488
4 Textiles	-0.05164	-0.42623	-0.09609	-0.39324
5 Apparels	-0.04909	-0.46159	-0.09058	-0.41254
6 Leather prod.,footwear	-0.05961	-0.65006	-0.11920	-0.60168
7 Wooden Prod,furniture	-0.06355	-0.54100	-0.11867	-0.50475
8 Paper & pulp,printing	-0.07793	-0.66299	-0.15081	-0.61699
9 Rubber & plastics	-0.05850	-0.52149	-0.11515	-0.48485
10 Chemicals	-0.05596	-0.47977	-0.10872	-0.44574
11 Petroleum & coal prod.	-0.05118	-0.35787	-0.10615	-0.33739
12 Non-metalic mineral prod.	-0.07305	-0.60091	-0.14591	-0.55051
13 Iron & steel product	-0.04594	-0.40924	-0.08812	-0.38055
14 Non-ferrous metals	-0.03787	-0.31211	-0.07279	-0.29151
15 Fabricated metal prod.	-0.05621	-0.49940	-0.12521	-0.45807
16 Machinery ex. elect.	-0.23841	-1.15077	-0.34385	-1.08986
17 Electrical machinery	-0.26149	-1.08271	-0.38880	-1.01652
18 Transport equipment	-0.46800	-2.05712	-0.54830	-1.99141
19 Precision instruments	-0.61287	-1.76206	-0.71259	-1.71436
20 Miscellaneous Manuf.	-0.07645	-0.69036	-0.15904	-0.63678
21 Tertiary Industry	-0.08146	-0.76884	-0.16318	-0.71432

Business Investment in Japan	S1-1		S1-2	
	Period 1	Period 5	Period 1	Period 5
1 Agri.,forestry,fishing	0.00139	0.04714	0.01184	0.06022
2 Mining	0.00000	0.00000	0.00000	0.00000
3 Food,bevarage,tobacoo	-0.03772	0.08943	0.00094	0.11338
4 Textiles	0.15441	1.86747	0.45129	1.62519
5 Apparels	0.03125	0.53687	0.10274	0.49232
6 Leather prod.,footwear	0.04009	0.54051	0.10700	0.53939
7 Wooden Prod,furniture	-0.19092	1.21076	0.21114	1.00402
8 Paper & pulp,printing	0.00583	0.17096	0.05827	0.20101
9 Rubber & plastics	-0.16538	0.63519	-0.11450	0.61417
10 Chemicals	0.00631	0.40058	0.03591	0.41246
11 Petroleum & coal prod.	0.05316	0.46815	0.38153	0.37905
12 Non-metalic mineral prod.	0.01456	0.17703	0.11899	0.16956
13 Iron & steel product	-0.03570	0.11292	-0.18303	0.18325
14 Non-ferrous metals	0.14262	1.35272	0.57484	1.29815
15 Fabricated metal prod.	0.0182	0.0390	0.15457	0.05943
16 Machinery ex. elect.	0.53908	2.77369	6.63774	2.73649
17 Electrical machinery	0.18967	1.52322	5.71329	1.33214
18 Transport equipment	0.29968	2.75685	6.31869	1.22879
19 Precision instruments	0.52652	1.75907	15.74241	5.24865
20 Miscellaneous Manuf.	0.09824	0.77956	0.29902	0.72956
21 Tertiary Industry	0.11274	1.14197	0.31482	1.09544

Table 3-4 Effects on Foreign Trade (S1: Robotization in Japan)

Unit: %

Real Export in Japan	S1-1		S1-2	
	Period 1	Period 5	Period 1	Period 5
1 Agri.,forestry,fishing	0.02238	0.35554	0.04250	0.34073
2 Mining	0.08684	1.28767	0.14555	1.28441
3 Food,bevarage,tobacoo	0.04095	0.55249	0.08514	0.52699
4 Textiles	0.00065	0.01388	0.00483	0.01137
5 Apparels	0.09040	1.19008	0.17278	1.08112
6 Leather prod.,footwear	0.00281	0.02556	0.00826	0.02401
7 Wooden Prod,furniture	0.02373	0.35122	0.04920	0.33901
8 Paper & pulp,printing	-0.00048	0.03259	0.00793	0.02990
9 Rubber & plastics	0.01174	0.18305	0.02801	0.17056
10 Chemicals	0.00726	0.16897	0.02729	0.16568
11 Petroleum & coal prod.	0.02907	0.15254	0.07568	0.14380
12 Non-metalic mineral prod.	0.03919	0.37764	0.08518	0.35344
13 Iron & steel product	0.01945	0.17485	0.03962	0.16148
14 Non-ferrous metals	0.03555	0.26717	0.08522	0.24759
15 Fabricated metal prod.	0.00882	0.16717	0.03025	0.16129
16 Machinery ex. elect.	0.05660	0.46797	0.08328	0.45132
17 Electrical machinery	0.21831	1.26204	0.33050	1.19954
18 Transport equipment	0.18133	1.46185	0.21211	1.43659
19 Precision instruments	0.11118	0.37399	0.12885	0.37008
20 Miscellaneous Manuf.	-0.00437	-0.03364	-0.00434	-0.03298

Real Import in Japan	S1-1		S1-2	
	Period 1	Period 5	Period 1	Period 5
1 Agri.,forestry,fishing	0.00261	0.07827	0.02249	0.09118
2 Mining	0.00181	-0.00592	0.15842	-0.00399
3 Food,bevarage,tobacoo	-0.00929	0.04349	0.05813	0.08307
4 Textiles	-0.01656	0.22084	0.08283	0.33253
5 Apparels	0.01464	-0.03616	0.11493	-0.02561
6 Leather prod.,footwear	-0.01710	-0.39888	-0.00771	-0.35343
7 Wooden Prod,furniture	0.03410	0.93653	0.35482	0.99134
8 Paper & pulp,printing	-0.04343	-0.47898	-0.02638	-0.43242
9 Rubber & plastics	0.02338	-0.26348	0.18110	-0.15492
10 Chemicals	-0.01922	0.00001	0.10224	0.02631
11 Petroleum & coal prod.	0.01443	0.13896	0.10635	0.14652
12 Non-metalic mineral prod.	-0.10986	-1.13712	-0.13643	-1.01853
13 Iron & steel product	-0.00400	-0.18255	0.06960	-0.12945
14 Non-ferrous metals	0.03636	0.44273	0.20664	0.45841
15 Fabricated metal prod.	0.00870	-0.08032	0.13955	-0.04134
16 Machinery ex. elect.	-0.10189	-0.41611	-0.04344	-0.39277
17 Electrical machinery	-0.12953	-0.31911	0.07527	-0.25732
18 Transport equipment	-0.26121	-0.50588	0.04808	-0.48856
19 Precision instruments	0.15613	0.42049	0.36524	0.47292
20 Miscellaneous Manuf.	0.03764	0.49937	0.26472	0.51996

Table 4-1 Impacts on Macro Economy (S2: Robotization in USA)

Unit: %

	S2-1		S2-2	
	Period 1	Period 5	Period 1	Period 5
Real GNP				
in Japan	-0.00223	-0.03369	0.01074	-0.02193
in USA	-0.00257	-0.00418	0.06592	-0.00488
in Korea	-0.00178	-0.01411	0.01524	0.00020
Nominal GNP				
in Japan	-0.00146	-0.02173	0.00341	-0.00974
in USA	-0.05700	-0.19607	-0.00295	-0.15382
in Korea	-0.00721	-0.05147	0.00751	-0.03527
Consumption				
in Japan	-0.00024	-0.01141	0.00387	-0.00393
in USA	-0.00328	-0.02296	0.00441	-0.02536
in Korea	-0.00016	-0.00440	0.00422	0.00615
Housing Investment				
in Japan	-0.00196	-0.04879	0.00764	-0.02636
in USA	-0.07557	-0.12517	-0.03878	-0.13193
in Korea	-0.00087	-0.01517	0.02144	0.00149
Business Investment				
in Japan	-0.00290	-0.05356	0.01431	-0.03575
in USA	0.00531	0.03700	0.59929	0.08578
in Korea	0.00348	0.01318	0.03962	0.03291
Export				
in Japan	-0.01122	-0.10859	0.06116	-0.07318
in USA	0.01186	0.06009	0.02077	0.07032
in Korea	-0.01001	-0.05938	0.04825	-0.03304
Import				
in Japan	0.00001	-0.01748	0.01453	0.00001
in USA	-0.00814	-0.04210	0.08839	0.00744
in Korea	0.00035	-0.01235	0.03018	0.00470
Employment				
in Japan	-0.00047	-0.00953	0.00206	-0.00430
in USA	-0.03752	-0.08497	-0.01729	-0.08089
in Korea	0.00009	-0.00013	0.00674	0.00665
Rate of Unemployment				
in Japan	0.00155	0.02609	-0.00678	0.01178
in USA	0.08019	0.12620	-0.37447	0.12945
in Korea	0.00180	0.00743	-0.01535	-0.00173
GNP Deflator				
in Japan	0.00077	0.01196	-0.00733	0.01219
in USA	-0.05442	-0.19191	-0.06882	-0.14895
in Korea	-0.00543	-0.03737	-0.00773	-0.03547
Wage Rate				
in Japan	-0.00030	-0.00751	-0.00128	-0.00127
in USA	-0.01608	-0.09943	-0.00559	-0.05268
in Korea	-0.00726	-0.04986	-0.00354	-0.04110

Note: S2-1 disregards demand side effects, and S2-2 includes both effects of robot investment

Table 4-2 Effects on Employment (S2: Robotization in USA)

Employment in USA

Unit: 10 thousand persons

	S2-1		S2-2	
	Period 1	Period 5	Period 1	Period 5
1 Agri.,forestry,fishing	-0.005	-0.020	-0.005	-0.014
2 Mining	-0.000	-0.000	-0.000	-0.006
3 Food,bevarage,tobacoo	0.005	0.057	0.001	0.026
4 Textiles	0.076	0.088	0.007	0.059
5 Apparels	0.022	0.141	0.018	0.033
6 Leather prod.,footwear	-0.001	-0.001	-0.003	-0.004
7 Wooden Prod,furniture	-0.000	0.006	0.027	-0.000
8 Paper & pulp,printing	-0.001	-0.012	0.001	-0.048
9 Rubber & plastics	0.003	0.036	0.023	0.028
10 Chemicals	0.000	0.007	0.007	-0.004
11 Petroleum & coal prod.	-0.000	-0.002	0.000	-0.002
12 Non-metalic mineral prod.	0.002	0.014	0.022	0.016
13 Iron & steel product	0.014	0.062	0.082	0.062
14 Non-ferrous metals	0.002	0.013	0.007	0.012
15 Fabricated metal prod.	0.013	0.039	0.071	0.057
16 Machinery ex. elect.	-1.473	-3.800	-1.168	-3.789
17 Electrical machinery	-1.064	-1.594	-0.741	-1.584
18 Transport Equipment	-0.894	-1.783	-0.812	-1.750
19 Precision instruments	-0.656	-2.632	-0.582	-2.595
20 Miscellaneous Manuf.	0.003	0.028	0.010	0.026
21 Tertiary Industry	0.358	0.690	1.344	1.230
Industry total	-3.666	-8.662	-1.689	-8.246

Table 4-3 Effects on Output Price and Investment (S2: Robotization in USA)

Unit: %

Output Price in USA	S2-1		S2-2	
	Period 1	Period 5	Period 1	Period 5
1 Agri.,forestry,fishing	-0.01944	-0.06411	-0.02419	-0.04516
2 Mining	-0.01874	-0.06678	-0.02178	-0.05233
3 Food,bevarage,tobacoo	-0.02132	-0.07087	-0.02707	-0.04889
4 Textiles	-0.01266	-0.02358	-0.01900	-0.00712
5 Apparels	-0.00957	-0.03503	-0.01201	-0.02534
6 Leather prod.,footwear	-0.02772	-0.08925	-0.03295	-0.05643
7 Wooden Prod,furniture	-0.01852	-0.06095	-0.02363	-0.04373
8 Paper & pulp,printing	-0.03211	-0.11304	-0.04093	-0.08277
9 Rubber & plastics	-0.01777	-0.07400	-0.02285	-0.05506
10 Chemicals	-0.01313	-0.06449	-0.01656	-0.04883
11 Petroleum & coal prod.	-0.02039	-0.07741	-0.02433	-0.05370
12 Non-metalic mineral prod.	-0.03051	-0.11156	-0.04144	-0.07058
13 Iron & steel product	-0.02423	-0.08718	-0.04171	-0.05544
14 Non-ferrous metals	-0.01706	-0.05605	-0.02071	-0.04233
15 Fabricated metal prod.	-0.03091	-0.11757	-0.04130	-0.08960
16 Machinery ex. elect.	-0.24417	-0.80624	-0.23755	-0.78444
17 Electrical machinery	-0.07201	-0.27780	-0.09465	-0.25419
18 Transport equipment	-0.05840	-0.37143	-0.07281	-0.34955
19 Precision instruments	-0.30539	-2.31872	-0.40603	-2.28692
20 Miscellaneous Manuf.	-0.02679	-0.10729	-0.03384	-0.08331
21 Tertiary Industry	-0.04470	-0.13079	-0.05768	-0.08242

Business Investment in USA	S2-1		S2-2	
	Period 1	Period 5	Period 1	Period 5
1 Agri.,forestry,fishing	0.01979	0.49354	0.02484	0.49616
2 Mining	-0.00010	0.42003	0.00024	0.37066
3 Food,bevarage,tobacoo	-0.01228	-0.03924	0.00263	-0.05328
4 Textiles	-0.00579	-0.05989	0.00734	-0.03727
5 Apparels	-0.01788	0.02830	-0.01796	0.03856
6 Leather prod.,footwear	-0.02239	0.04693	-0.08722	-0.02287
7 Wooden Prod,furniture	-0.00305	-0.20894	0.08811	-0.23323
8 Paper & pulp,printing	-0.03244	-0.10116	0.04868	-0.08951
9 Rubber & plastics	-0.00396	0.06137	0.15536	0.02136
10 Chemicals	-0.01944	-0.26577	0.27020	-0.30430
11 Petroleum & coal prod.	-0.00449	-0.05427	-0.00369	-0.03904
12 Non-metalic mineral prod.	-0.01795	0.03540	0.04116	0.08263
13 Iron & steel product	0.00924	0.28964	-0.05787	0.27030
14 Non-ferrous metals	-0.00050	0.02124	-0.01759	-0.00801
15 Fabricated metal prod.	0.00107	0.12819	0.05024	0.16851
16 Machinery ex. elect.	0.15039	0.24838	5.05146	1.45291
17 Electrical machinery	0.01167	0.06727	5.82752	0.41193
18 Transport equipment	-0.00381	-0.13647	3.76654	0.76087
19 Precision instruments	0.54729	3.61899	13.60921	4.45478
20 Miscellaneous Manuf.	0.02231	0.20284	0.08737	0.20609
21 Tertiary Industry	-0.00455	-0.04744	0.03012	-0.11001

Table 4-4 Effects on Foreign Trade (S2: Robotization in USA)

nit: %

Real Export in USA	S2-1		S2-2	
	Period 1	Period 5	Period 1	Period 5
1 Agri.,forestry,fishing	0.00144	-0.00281	0.00552	-0.00128
2 Mining	-0.00380	-0.01790	0.00709	-0.01462
3 Food,bevarage,tobacoo	0.00267	-0.00826	0.01000	-0.00431
4 Textiles	0.00910	-0.00494	0.02251	-0.00904
5 Apparels	-0.00166	-0.03708	0.00790	-0.01733
6 Leather prod.,footwear	0.00818	-0.02157	0.02800	-0.02046
7 Wooden Prod,furniture	-0.00357	-0.05432	0.01477	-0.02477
8 Paper & pulp,printing	-0.00066	-0.03368	0.00612	-0.03641
9 Rubber & plastics	-0.00179	-0.03612	0.00810	-0.02336
10 Chemicals	-0.00790	-0.04719	0.00082	-0.04071
11 Petroleum & coal prod.	0.00075	-0.00568	0.00842	-0.00255
12 Non-metalic mineral prod.	0.00607	0.01200	0.02094	0.01175
13 Iron & steel product	0.02077	0.09545	0.04257	0.06099
14 Non-ferrous metals	0.02662	0.11057	0.04573	0.09356
15 Fabricated metal prod.	0.00836	0.01327	0.02042	0.01871
16 Machinery ex. elect.	0.04426	0.15603	0.04833	0.17078
17 Electrical machinery	0.01605	0.05518	0.03528	0.07081
18 Transport equipment	0.01604	0.08217	0.03409	0.09735
19 Precision instruments	0.04481	0.49321	0.07708	0.52232
20 Miscellaneous Manuf.	-0.00078	-0.04626	0.02117	-0.01660
Industry total	0.01472	0.06477	0.02077	0.07032

Real Import in USA	S2-1		S2-2	
	Period 1	Period 5	Period 1	Period 5
1 Agri.,forestry,fishing	-0.01144	-0.05209	-0.00563	-0.04403
2 Mining	0.00006	0.10529	0.00123	-0.15773
3 Food,bevarage,tobacoo	-0.02837	-0.10370	-0.01988	-0.08618
4 Textiles	-0.03889	-0.11839	-0.01209	-0.08022
5 Apparels	-0.04149	-0.35698	-0.04192	-0.33869
6 Leather prod.,footwear	-0.06260	-0.22056	-0.18762	-0.31826
7 Wooden Prod,furniture	-0.03453	-0.14123	0.17109	-0.09382
8 Paper & pulp,printing	-0.03158	-0.12601	0.01648	-0.10884
9 Rubber & plastics	-0.00772	-0.03259	0.14336	0.02455
10 Chemicals	-0.01254	-0.05626	0.07769	-0.03881
11 Petroleum & coal prod.	-0.00885	-0.05765	-0.00573	-0.04908
12 Non-metalic mineral prod.	-0.02801	-0.16195	0.08384	-0.10919
13 Iron & steel product	-0.02107	-0.09390	0.04517	-0.05038
14 Non-ferrous metals	-0.00113	0.02238	0.20800	0.07153
15 Fabricated metal prod.	-0.01800	-0.11149	0.14449	-0.02428
16 Machinery ex. elect.	-0.01735	-0.29648	0.35871	0.04631
17 Electrical machinery	-0.06634	-0.41454	0.38651	-0.32507
18 Transport equipment	-0.02570	-0.46016	0.06522	-0.32759
19 Precision instruments	0.33454	4.24052	1.19235	4.57997
20 Miscellaneous Manuf.	0.03323	0.19808	0.13467	0.14214
Industry total	-0.01058	-0.05096	0.11489	-0.00081

Table 5-1 Impacts on Macro Economy (S3 : Robotizationn Korea)

Unit: %

		Period 1	Period 5
Real GNP			
	in Japan	0.00003	0.00071
	in USA	-0.00008	-0.00024
	in Korea	0.02699	0.07222
Nominal GNP			
	in Japan	-0.00009	-0.00006
	in USA	0.00001	-0.00023
	in Korea	-0.03730	-0.02203
Consumption			
	in Japan	0.00007	0.00050
	in USA	0.00003	0.00017
	in Korea	-0.00496	0.02306
Housing Investment			
	in Japan	-0.00004	0.00136
	in USA	0.00017	0.00063
	in Korea	-0.02552	0.06700
Business Investment			
	in Japan	0.00008	0.00139
	in USA	-0.00009	-0.00033
	in Korea	0.07927	0.13284
Export			
	in Japan	0.00106	0.00259
	in USA	-0.00024	-0.00047
	in Korea	0.05552	0.10245
Import			
	in Japan	0.00094	0.00203
	in USA	0.00057	0.00246
	in Korea	0.01530	0.05074
Employment			
	in Japan	-0.00001	0.00016
	in USA	-0.00005	-0.00000
	in Korea	-0.07172	-0.04267
Rate of Unemployment			
	in Japan	0.00003	-0.00044
	in USA	0.00056	0.00130
	in Korea	-0.02718	-0.03914
GNP Deflator			
	in Japan	-0.00012	-0.00077
	in USA	0.00009	0.00002
	in Korea	-0.06427	-0.09419
Wage Rate			
	in Japan	-0.00007	-0.00035
	in USA	-0.00004	-0.00033
	in Korea	-0.02777	-0.04984

Table 5-2 Effects on Sectoral Economies (S3 : Robotization in Korea)

		Employment in Korea (Unit: thousand persons)		Output Price in Korea (Unit: %)	
		Period 1	Period 5	Period 1	Period 5
1	Agri.,forestry,fishing	0.534	1.040	-0.00918	-0.02188
2	Mining	0.005	-0.037	-0.01738	-0.03950
3	Food,bevarage,tobacoo	-0.003	0.048	-0.01329	-0.03336
4	Textiles	0.072	0.252	-0.02827	-0.06210
5	Apparels	0.009	0.094	-0.03218	-0.06915
6	Leather prod.,footwear	-0.001	0.025	-0.01007	-0.04525
7	Wooden Prod,furniture	0.021	0.038	-0.02266	-0.04112
8	Paper & pulp,printing	0.017	0.042	-0.03217	-0.05298
9	Rubber & plastics	0.042	0.109	-0.03445	-0.06147
10	Chemicals	0.020	0.060	-0.03197	-0.05192
11	Petroleum & coal prod.	0.002	0.003	0.00482	0.00614
12	Non-metalic mineral prod.	0.016	0.037	-0.03670	-0.05313
13	Iron & steel product	0.034	0.050	-0.03949	-0.05394
14	Non-ferrous metals	0.013	0.022	-0.03724	-0.04716
15	Fabricated metal prod.	0.033	0.057	-0.07069	-0.12195
16	Machinery ex. elect.	-2.212	-2.211	-0.82718	-0.67544
17	Electrical machinery	-2.377	-2.287	-0.01671	-0.02388
18	Transport equipment	-2.401	-1.956	-0.08558	-0.12600
19	Precision instruments	-1.243	-1.239	-0.95062	-1.04424
20	Miscellaneous Manuf.	0.058	0.071	-0.04580	-0.09811
21	Tertiary Industry	0.240	1.915	-0.04103	-0.05768
	Industry total	-9.883	-6.243		

Unit: %

		Real Export in Korea		Real Import in Korea	
		Period 1	Period 5	Period 1	Period 5
1	Agri.,forestry,fishing	0.00911	0.10015	-0.00035	0.02001
2	Mining	0.00180	0.00315	0.03882	0.05941
3	Food,bevarage,tobacoo	0.00683	0.03628	-0.00445	0.05765
4	Textiles	0.01926	0.04987	-0.03460	-0.06310
5	Apparels	0.03730	0.13128	-0.00404	0.02884
6	Leather prod.,footwear	0.00219	0.02599	-0.02444	-0.02658
7	Wooden Prod,furniture	0.02821	0.04735	0.01072	0.03103
8	Paper & pulp,printing	0.00982	0.03397	-0.00025	0.01828
9	Rubber & plastics	0.01131	0.04100	0.03029	0.06694
10	Chemicals	0.02476	0.10250	0.02174	0.05603
11	Petroleum & coal prod.	-0.00271	-0.00691	0.08199	0.14604
12	Non-metalic mineral prod.	0.02372	0.03937	0.02051	0.06718
13	Iron & steel product	0.04464	0.13204	0.02539	0.03783
14	Non-ferrous metals	0.02544	0.02594	0.06838	0.10046
15	Fabricated metal prod.	0.06550	0.07532	0.00301	0.04114
16	Machinery ex. elect.	0.15211	0.18051	-0.09163	-0.01493
17	Electrical machinery	0.01281	0.03517	0.05903	0.08825
18	Transport equipment	0.26467	0.34151	0.03482	0.07003
19	Precision instruments	-0.00038	0.00316	0.06367	0.10287
20	Miscellaneous Manuf.	0.30501	0.18764	0.34574	0.51560

Table 6-1 Impacts of Robotization in Japan and USA on Korean Economy

	S-1		S-2	
	Period 1	Period 5	Period 1	Period 5
Real GNP (10 mil. Won)				
Effect of Japan	-1.976	3.778	2.074	6.683
Effect of USA	-0.702	-6.516	6.103	0.230
Consumption (10 mil. Won)				
Effect of Japan	-0.027	3.735	0.585	5.656
Effect of USA	-0.039	-1.290	1.043	1.937
Housing Investment (10 mil. Won)				
Effect of Japan	-0.016	0.948	0.272	1.206
Effect of USA	-0.019	-0.419	0.492	0.103
Business Investment (10 mil. Won)				
Effect of Japan	0.691	10.803	2.306	11.114
Effect of USA	0.281	1.080	3.177	3.009
Export (10 mil. Won)				
Effect of Japan	-3.696	-11.295	-0.447	-9.442
Effect of USA	-1.171	-10.667	5.734	-5.823
Import (10 mil. Won)				
Effect of Japan	-0.018	8.131	2.163	9.143
Effect of USA	0.058	-2.539	4.545	0.896
Employment (1000 persons)				
Effect of Japan	0.285	3.735	0.901	4.199
Effect of USA	0.014	-0.036	0.932	0.995
GNP Deflator (1980=100)				
Effect of Japan	-0.012	-0.182	-0.021	-0.073
Effect of USA	-0.004	-0.051	-0.005	-0.047
Investment Deflator (1980=100)				
Effect of Japan	-0.037	-0.391	-0.053	-0.371
Effect of USA	-0.014	-0.133	-0.017	-0.127
Wage Rate (%)				
Effect of Japan	-0.024	-0.167	-0.034	-0.157
Effect of USA	-0.007	-0.051	-0.004	-0.041

Note: S-1 disregards demand side effects, and S-2 includes both effecys of robot investment.

ORGANIZATIONAL, MANAGERIAL AND STRATEGIC IMPLICATIONS

STRATEGIC, ORGANIZATIONAL AND SOCIAL ISSUES OF CIM: INTERNATIONAL COMPARATIVE ANALYSIS

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1. INTRODUCTION

The Computer Integrated Manufacturing (CIM) Project as a part of the Technology-Economy-Society (TES) Program at IIASA emerges from the idea that the choice by firms, industries, and governments of specific strategies to take advantage of CIM will depend on how well the relevant decision makers understand the mechanisms through which CIM will benefit different firms and industries. The deeper the level of understanding, the more productive will their strategic choices be.

This Working Paper aims at contributing to a better understanding of the mechanisms of CIM adoption in companies and enterprises. The dominating idea is that the probability of a successful adoption of CIM is to a great extent dependent on managerial forms and methods applied to different phases of CIM adoption, such as the planning phase, in which the strategic goals and prerequisites are specified, the implementation phase, where the proper organizational conditions for the adoption are created, and the daily operation, where the importance of social aspects is increasing.

From prior studies we can find many examples supporting the idea of the high importance of managerial factors in CIM or FMS adoption.

Willenborg [Willenborg, 1987] pointed out that not only financial and technical factors, but also organizational aspects impede the successful implementation of FMS.

Ranta [Ranta, 1986] assumes that managerial and social factors (management practice, the managerial design process, training, etc.) are more immediate issues than purely technical questions when studying application possibilities.

Bessant and Haywood [Bessant & Haywood, 1985] carried out interviews at 23 manufacturing engineering companies and 10 suppliers of machine tools and software in the UK. Almost all of the firms interviewed for this study have stressed that one of the major consequences of planning and/or installing FMS has been a change in the management/organizational side of the company. This has had considerable implications for improvement strategies, shifting the emphasis away from technology per se, towards the way in which it is used.

Our methodological approach is based on testing of alternative strategic, organizational and social hypotheses, taken from published sources, with the results acquired from the IIASA questionnaire database. The special comparison of the results such as centrally planned vs. market economies, large vs. small countries, different industry branches, Western Europe vs. USA vs. Japan, etc., allow us to develop some new conclusions and hypotheses. Generalized conclusions for different environmental, economic, cultural and other conditions will be drawn from the results of our investigation in its final stage.

In the first stage of our research work the Finnish-Czechoslovakian pilot study, covering 9 FMS as a part of CIM, has been carried out. The data were compiled and computerized. The main purpose of this step was to conceive the hypotheses and to carry out a preliminary testing of some of them, due to the relatively small number of statistical data at that stage. The comparison is also limited to centrally planned vs. market economies. The results from this stage and the first conclusions present the substantial part of this Working Paper.

A further result from that stage was the final refinement of the questionnaire as a consequence of the experiences gained from the pilot study. The final version of the questionnaire is, of course, the result of many other previous steps of its development and improvement starting in the middle of 1987 at the IIASA CIM project workshop in Ivalo, Finland. Its development also includes a number of consultations with experts of different countries.

The questionnaire now covers about 400 items and the following structure:

- General indicators of company adopting FMS
- General indicators of FMS
- Technological and logistic specifications of FMS
- Economic consequences of FMS
- Social issues of FMS
- Managerial issues of FMS
- Logistic issues of FMS.

In the second stage of our research work it is intended to increase the data base substantially (we expect responses from

100) and all the managerial hypotheses will be tested on the broader basis. We expect responses from 5-6 centrally planned economies (USSR, Czechoslovakia, GDR, Bulgaria, Hungary and Poland) and from 10 market economies (USA, Austria, Italy, France, Sweden, Finland, Japan, FRG, UK, Netherlands). The final results from that stage will be contained in a Working Paper on Managerial Issues of CIM - Part II.

2. SURVEY OF MANAGERIAL HYPOTHESES

The managerial hypotheses are divided into the following areas of managerial activities:

- strategic issues of FMS adoption;
- organizational issues;
- socio-economic issues and consequences.

The managerial hypotheses were specified by means of literature sources (either theoretical studies or published case studies). The main purpose was to outline the basic tendencies of different factors as a result of the production automation and integration development. The stages of production automation and integration are understood to be the following steps:

- conventional machines;
- NC-machines;
- MC (machining centers);
- FMS;
- CIM;
- A.F. (automated factory).

On the above-mentioned basis we can now specify the predicted tendencies of the development of different factors.

2.1. Strategic Issues of FMS Adoption

The strategic decision makers are facing in these days complex and very complicated questions, i.e. what are the main reasons for introducing CIM or FMS, what are the main driving forces behind the strategic decision of companies top management to adopt CIM or FMS? An investment in that case is a strategic decision for the entire company to which management should be fully committed. If we go through different literature sources we will find many different reasons for FMS adoption.

The first strategic question is the basic orientation of production. Brödner [Brödner, 1986] shows the two main variables for alternative product strategies, the type of competition to which they are exposed, and the volume in which they are produced. According to these conditions production could, in the past, be divided into low-volume production of customized quality-competitive goods, or into high-volume production of standardized price-competitive goods. New technologies, such as CIM or FMS, permit to apply another type of production: high-volume production of customized quality-competitive goods.

The latter technology may be able to react to a substantial shift on the world markets, characterized by an excess of products and the need to react quickly to very frequent changes of customer demands. The CIM technology promises to become highly flexible as to product and process innovations, higher productivity, production times reduction and increase of quality and functionality of the products.

Similarly, but in more detail, Kristensen [Kristensen, 1986] presents two main strategies by means of which mass production firms can respond to the pressure of increased competition. The first strategy, called neo-Fordism, is to cut the production costs of the existing line of standard goods. The second strategy, called Flexible Specialization, is to avoid competition on prices and to shift to the production of specialized goods, catering to changing niches in the market.

An ECE survey [ECE, 1986] shows the main motives for FMS investment specified as follows:

- <u>strategic investment</u>, including those projects, whose economic return is difficult to calculate. It includes
    - <u>pilot investment</u>, the purpose of which is to evaluate the technology and to gain knowledge advantages over other firms, and <u>"showroom investment"</u> used mainly by FMS component manufacturers as a sales argument to show potential customers the advantages of the system.
- <u>rationalization investment</u>, whose main objective is to reduce the costs, increase profits and competitiveness of the company. It also includes

- <u>expansion investment</u>, whose purpose is to increase capacity and remove bottle-necks, and <u>replacement investment</u>, replacing worn-out machines or shop-floors.

Bessant and Haywood [Bessant and Haywood, 1985] specified in their study, devoted to small and medium-size companies, the range of motives for moving into FMS technology:

- the need to reduce lead times;
- the need to reduce working capital costs;
- the need to replace an existing plant;
- the need for more accurate control;
- the need for improved machine utilization;
- the need to offer a wider range of product variants to retain the marketing edge;
- the need for higher quality.

Bullinger [Bullinger et al., 1987] specifies four goals of production, which were conflicting in the past:

- high capacity utilization;
- high productivity;
- short throughput time;
- much flexibility.

Conflicts of goals arose between capacity utilization and throughput time and between productivity and flexibility. FMS is able to weaken or almost eliminate the above conflicting goals.

Lim [Lim, 1987] analyzed the management objectives for FMS development in 12 companies in Britain and found that the most important aims were predicting customer demands (the main aim), followed closely by the need to maintain a competitive edge internally (among subsidiaries) and externally (local and overseas competitors in similar market segments) as well as to provide extra capacity for rising demand. The next, so-called operational objectives, were reduction in inventory and work-in-progress, followed by reduction in manufacturing costs, improvement in quality of output and machine utilization.

One of the examples of the case studies on that topic is Margirier's study embracing French FMS. Margirier [Margirier, 1987] investigated 19 FMS in the machining industry in France.

One of the major questions was: what economic reasons are behind their introduction by the industrialists in this sector.

Two main strategies for maximizing profit were specified and tested:

- to reduce unit costs by means of time, capital and labor saving;
- and to improve product diversity and reach market demand more rapidly by offering greater flexibility.

The main conclusion from that investigation is that product diversity and rapid reaction to the market do not seem to be major criteria for introducing flexible equipment. The findings of the Margirier's survey lead him to the conclusion that "... it is the reduction of the unit costs which above all determines the choice of this type of equipment, rather than a strategy aiming at product diversity."

On the other hand, many other authors [Jelinek & Goldhar, 1984; Talaysum, Hassan & Goldhar, 1987] mention flexibility as a main driving force for FMS adoption. This is also connected with the discussion about the shift from economies of scale to economies of scope.

Ayres [Ayres, 1986] suggests that from the long-term point of view, quality increase is one important driving force behind FMS, or better -- in our case --, CIM adoption.

Summarizing the goals of FMS or CIM adoption, we get the following list of different motives:

- production increase;
- elimination of bottlenecks;
- productivity increase;
- capacity augmentation;
- cost reduction;
- labor saving;
- lack of labor force or of highly skilled workers;
- material saving;
- energy saving;
- reduction of machine-tools;
- floor space saving;
- inventories reduction;
- W-I-P reduction;

- product range extension;
- product mix extension;
- different time reductions (lead, set-up, cutting, throughput, tendering, delivery);
- revenue and profit increase;
- decrease of return on investment, payback time reduction;
- market share expansion;
- acquiring experiences as a pilot plant;
- costumer claims reduction;
- reject fraction reduction;
- quality standards (tolerance) improvement, etc.

Analyzing the above-mentioned examples we can specify the following main groups of factors of FMS adoption:

1. cost reduction;
2. production increase;
3. flexibility increase;
4. quality increase including service.

From the above and from other literature indications we come to the conclusion that CIM can attain different goals depending on the strategy a firm prefers. <u>CIM is multi-objective and the goals can be changed in the course of time</u>. In many cases CIM fulfills not only one but different goals. If we divide the company strategies into a defensive and an offensive, or according to Lim [Lim, 1987] into a survival and a growth strategy, we can now combine the CIM goals with these strategies. We can logically conclude that the defensive strategy is connected mostly with rationalization investment, while the offensive strategy corresponds to strategic investment, flexibility and quality increase. Moreover, the higher and more expansive stages of production automation and integration also aim to meet the offensive strategies.

The hypothesis regarding the tendencies in strategy goals development is represented in Figure 1.

Figure 2 gives a survey of the preferential strategic goals in Finnish and Czechoslovak FMS. The picture clearly shows the combination of strategic goals, i.e. mainly flexibility (expressed in such factors as delivery time -- mostly in

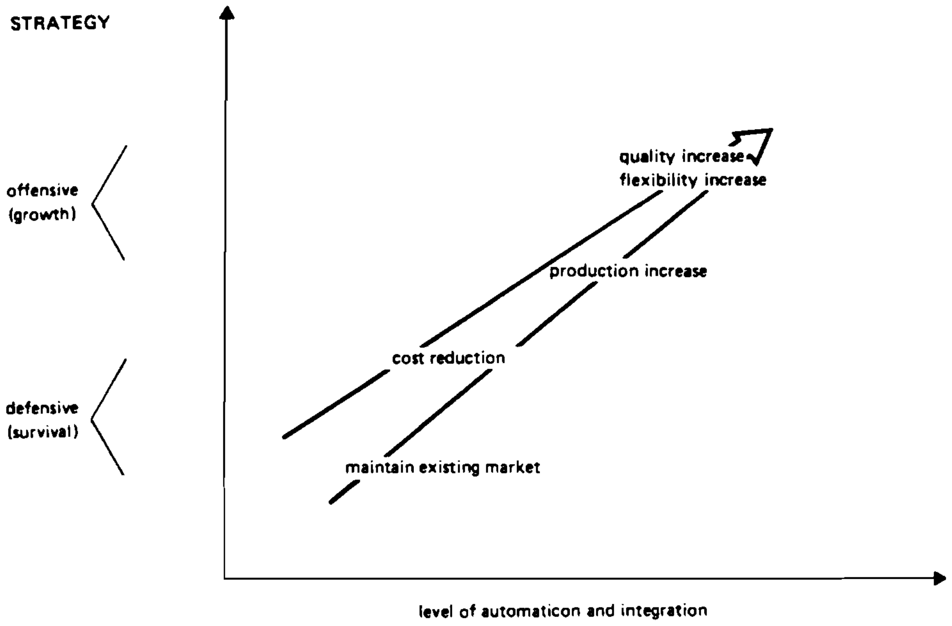


Figure 1. Strategic goals.

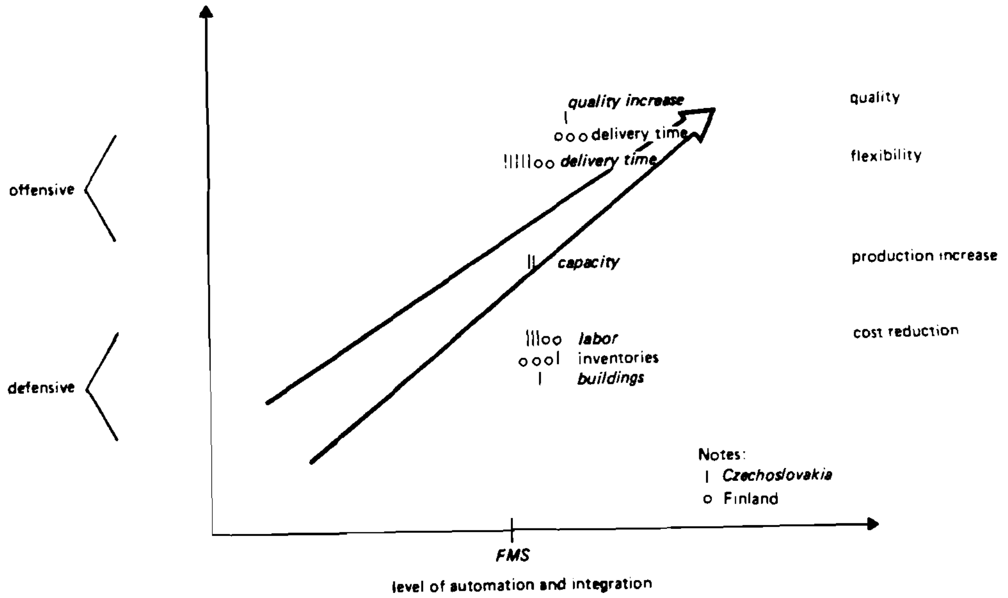


Figure 2. Strategic goals -- F-CS Pilot Study.

Czechoslovak FMS), quality (expressed in delivery service -- mainly in Finnish FMS) and cost reduction (expressed in labor reduction -- mainly in Czechoslovak FMS, and labor and inventories reduction in Finnish FMS).

In Finnish FMS the main emphasis is on quality increase (delivery service). In Czechoslovak FMS the practical absence of quality increase as a priority strategic goal is somewhat surprising. This factors appears only in one FMS. But, on the other hand, this is the case of most sophisticated FMS in Czechoslovakia. This example supports our hypothesis about the tendency of strategic goals in connection with the level of automation and integration. The opposite example can be found in the case of FMS consisting only of NC-machines where the priority goal is cost reduction (inventories and buildings), which supports our hypothesis as well.

The number of the highest priority factors ranges from 1 to 5 in one system. In one case only 1 factor of the highest priority is presented (inventory decrease). Three FMS have a combination of 2 factors, in two systems there is a combination of 3 factors, two systems show a combination of 4 factors, and one FMS presents a combination of 5 factors. In Finnish FMS the average number of dominating factors is 2.75, and in Czechoslovak FMS the corresponding number is 3.00.

From the above we can assume that there are no substantial differences between the strategies chosen in planned and in market economy systems. We can state that the companies combine offensive and defensive strategies. Even in the most sophisticated systems the same combination exists. But the ways of realizing the offensive strategy are different. Finnish FMS stress mostly quality and Czechoslovak FMS stress, on the other hand, flexibility increase.

The task of choosing a proper strategy is, of course, a complicated process, in which we have to take many different system connections into account. The most important factors influencing the choice of the strategic goals are represented in Figure 3.

Strategic decision-making has to reflect mainly environmental conditions such as shifts in the international division of labor, market conditions and changing customer

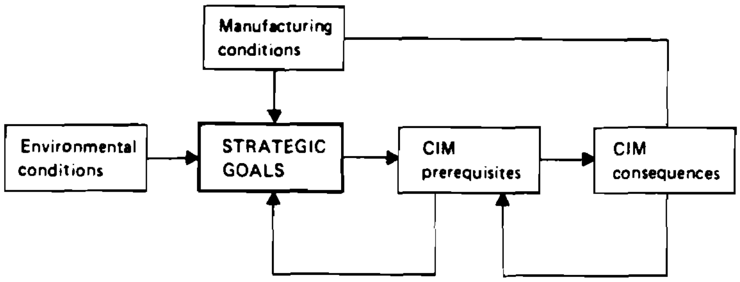


Figure 3. Model of strategic decision making of CIM adoption.

demands. Warnecke [Warnecke, 1987] sees the shifts mainly in the changes in highly developed countries which start to produce more competitive and more know-how intensive products, and in buyer markets with weak demand and excess production capacities. Under such conditions profit depends mainly on the speed and quality of fulfilling of the customer's needs. By speed and quality we understand flexibility, faster responses to customer demands, excellence in product design, higher reliability and uniqueness of products. The effective use of new technologies in products and processes becomes a key factor in international competition.

The feedback between strategic goals and CIM prerequisites expresses a very tight connection among financial prerequisites, such as a good independent financial position for investment, the possibility to obtain venture capital, loans, state subsidy, etc., technological prerequisites connected with the possibilities of hardware and software vendors, of system integrators and the quality of their products, and social prerequisites, such as the necessity of improving working conditions (monotonous, dangerous, hard work), the educational level of the employees, the qualifications as well as training and retraining conditions, etc.

The feedback between CIM prerequisites and consequences plays an important role in the process of iteration between design and real possibilities. Socio-economic consequences expressed, e.g., in the cost-benefit model, expected cost reduction, productivity increase and capacity augmentation, flexibility and quality increase, changes in operation rate, flexible working hours, job rotation and other factors like logistics, create the manufacturing conditions with a close feedback to the strategic goals.

2.2 Organizational Issues

The development to higher levels of manufacturing automation and integration requires adequate changes of organizational forms and managerial structure according to many authors [Bessant & Haywood, 1985; Jaikumar, 1986; Kristensen, 1986; etc.]. The old, so-called Taylor type of structure is noted for differentiation of functions, tasks and organizational roles, and a tall hierarchy with a high number of organizational (hierarchical) levels, with an essentially top-down authority for decision making.

Diffusion of automation to the production process calls for substantial changes of the organizational structure, such as a more flexible and organic structure, and a closer collaboration between all functions. A new development requires the elimination of the traditional boundaries between marketing, design and production, and a closer collaboration among researchers, suppliers, vendors and sales people with management, manufacturing engineers, plant managers and users. The role of application engineering is rising.

The above described development leads to the drastic reduction of hierarchical levels and gives rise to very small self-managed groups with high responsibility, consisting of highly skilled generalists.

The hypothesis drawn from these ideas are represented in Figure 4.

Case studies published in literature confirm the above-mentioned development. For example, Toikka, Hyötyläinen and Norros [Toikka, Hyötyläinen & Norros, 1986] describe the organizational changes in one Finnish middle-size machine engineering factory, producing diesel engines. Six workers from the present production scheme were selected to operate the system in two shifts. The task of this group is to be collectively responsible for the functioning of the system. The group also takes care of the production planning, scheduling and sequencing as well as of the method development and of part of the maintenance. Another example came up with similar conclusions [Jaikumar, 1986; Braczyk, 1986; Kristensen, 1986].

The results from the Finnish-Czechoslovakian pilot study clearly confirm the first hypothesis regarding the decrease of the hierarchical level. The average decrease in Finnish FMS is 4:2, while in Czechoslovak FMS it is 4:2 or 3:2.

The second hypothesis (small highly qualified self-managed groups) was not sufficiently confirmed, because only 3 examples are available. In other cases the responses looked like a misunderstanding of the question.

The other hypothesis is based on the notion that the most acceptable form of labor organization is job rotation in order to

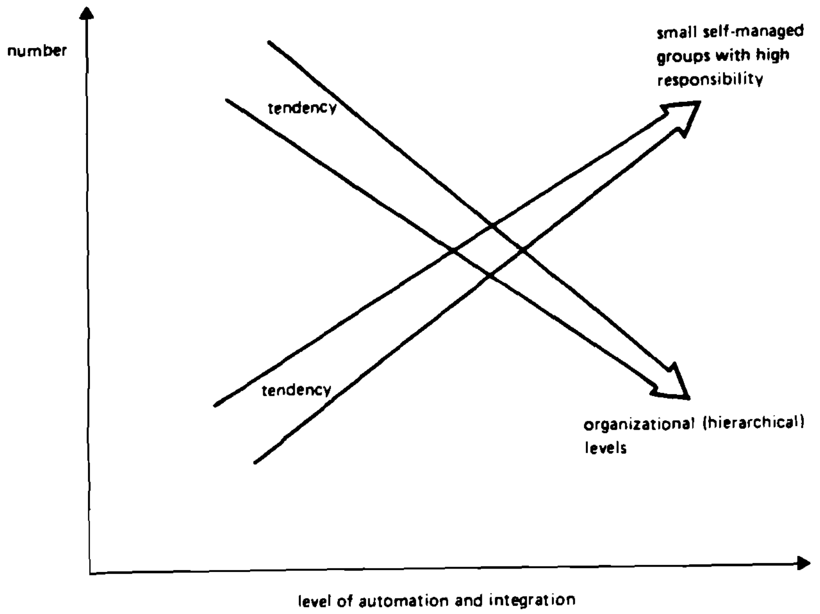


Figure 4. Organizational structure development.

increase motivation and skills of personnel. This idea prevails in literature [Bessant, 1986; Bullinger & Warnecke, 1985; Ferdows, 1983, Graham, 1986; D'Iribarne, 1983; Jones & Scott, 1986; Toikka, 1986]. The hypothesis established on this basis is represented in Figure 5.

Brödner [Brödner, 1984] on the other hand asserts that most installed systems have job specialization.

Willenborg's [Willenborg, 1987] empirical data showed neither extreme forms of job specialization, nor of rotation. In fact, the work on CIM (mainly when we analyze less sophisticated systems) can be characterized as very diverse: both complex and simple tasks have to be performed and managers have to decide what labor organization to choose: job specialization or job rotation. The third alternative, i.e. the combination of both of them, is, of course, possible too.

Our pilot study confirmed the hypothesis of job rotation (Figure 5). The example of Finnish FMS shows that in 3 out of 4 FMS (for one FMS data is not available) all working places use job rotation. In Czechoslovak FMS 2 places use job rotation on the average.

The next hypothesis is connected with the operation rate (number of shifts, unmanned time period). The logical expectation is that the unmanned time period is getting longer, up to its theoretically possible limit, as a consequence of the higher level of automation and integration.

In this case the number of shifts is expressed in the so-called "shift" coefficient Sk:

$$Sk_1 = \frac{\text{total number of operators in system in all three shifts}}{\text{number of operators in system in the morning shift}}$$

This information holds true for men. Similarly we can define the shift coefficient for machine-tools:

$$Sk_2 = \frac{\text{total number of machine tools in system in operation in all three shifts}}{\text{number of machine tools in system in operation in the morning shift}}$$

The practical limit values of Sk_1, Sk_2 are <1;3>.

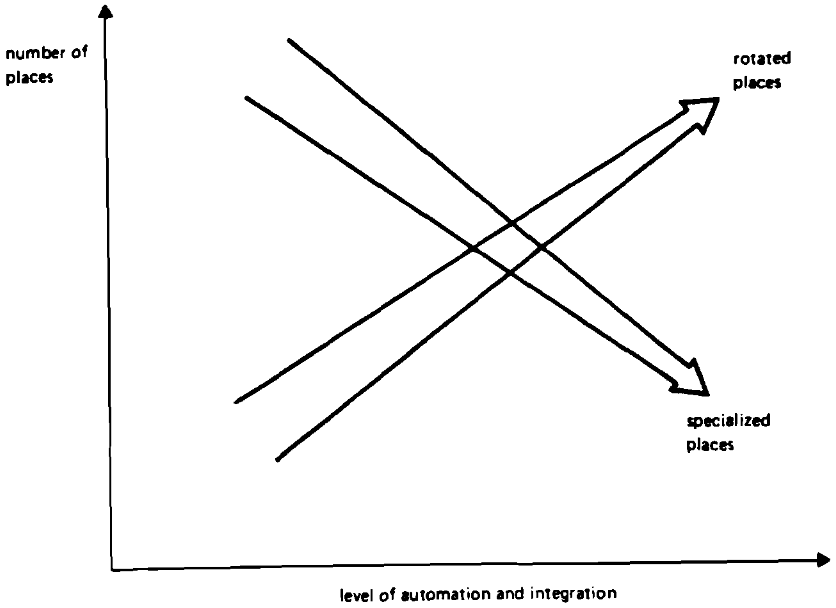


Figure 5. Job specialization and job rotation.

We also logically expect that Sk_2 will increase as a consequence of the higher level of automation and integration.

The development of the value of Sk_1 is not so simple. Sk_1 is closely connected with the unmanned time development but it is not a linear interdependence.

At first we have to assume that the economic reasons imply the necessity of a maximal value of Sk_2 as soon as possible. The only possibility from the beginning is to increase Sk_1.

Later on, when the system is able to work one or more unmanned shifts, we can decrease the number of manned shifts or decrease Sk_1 while keeping Sk_2 on a maximum level.

But there is another possibility to decrease the number of manned shifts earlier, without decreasing Sk_2. The solution lies in operation rate changes or in the adoption of flexible working hours. For example, at the moment when a system is able to reach the period of 4 hours unmanned time (in an 8-hour shift system), this allows us to change the normally used system (morning shift from 6 a.m. to 2 p.m., evening shift from 2 p.m. to 10 p.m. and night shift from 10 p.m. to 6 a.m.) to a two-shift system of the following type: morning shift from 6 a.m. to 2 p.m., 4 hours unmanned time, evening shift from 6 p.m. to 2 p.m., 4 hours unmanned time. Of course, there are many other possible variants solving these problems.

Such a type of solution can resolve the lack of skilled work-force, the negative social consequences of a 3-shift system, etc. The above discussed hypothesis is represented in Figure 6.

The results from our pilot study show that the possible unmanned time ranges from 25 minutes to 30 hours (but the latter is only a theoretical possibility, practically 8 hours shift is in use). Mostly (in 6 from 9 analyzed cases) the period of unmanned time is 8 hours. This allows to work on 2 manned and 3 machine shifts, i.e. $Sk_1 = 2$ and $Sk_2 = 3$.

One example of the Finnish FMS is very interesting. The system is working during working days in 3 shifts, on Saturdays and Sundays moreover 1 morning shift, utilizing students from a technical school as operators. Compared with conventional or stand-alone NC-machines the operation rate changed and the number of machine tools shifts increased on the average by 1 shift (5 cases).

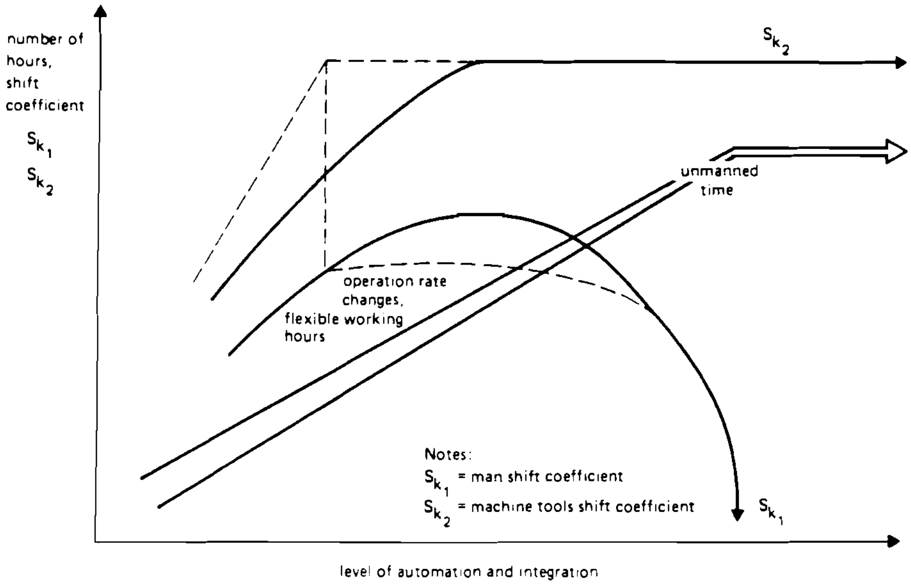


Figure 6. Operation rate, unmanned time.

Flexible working hours and periodical rest of employees are not used in any case. This shows the big reserves for the rest of the systems, where the unmanned time is smaller than 8 hours and where the machine tool operation rate has not yet changed. The possible use of flexible working hours is described above.

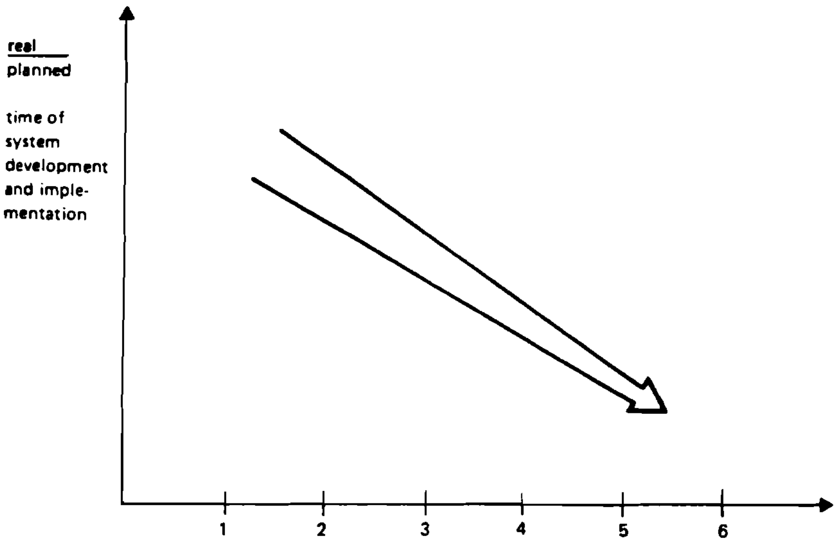
The next hypothesis ranks among the so-called open hypotheses, which can be tested after analyzing the data from the final version of our questionnaire in part II.

The hypothesis shown in Figure 7 expresses the interconnection between development and implementation times of CIM adoption and organizational forms of top management involvement in CIM development and implementation. The more intensive the involvement of the top management in this development and implementation is, the shorter will the time of development and implementation be.

Different configurations and investment costs do not allow to compare real values of the development and implementation time. This is why we use real time to planned time ratio for the comparison.

The following three "open" hypotheses are similar and express the interdependences between development and implementation time on one side, and organization of designers and operators involvement in that process as well as basic organization of project implementation on the other side. The interconnections are represented in Figures 8, 9, and 10.

Another hypothesis concerns the infrastructure of the industries. The idea is that FMS and CIM are able to manufacture more complex parts, the part family and product mix are getting broader, and flexibility is increasing. All these factors have important consequences on the number of subcontractors, on the level of imports of semiproducts and parts, and on international specialization and cooperation. We expect changes of the location of the subcontractors, moving more closely to the manufacturers, and improvements in the balance of payments in the national economies. The basic interconnection between complexity, part family and product mix increase on the one hand, and the number of subcontractors causing closer links between manufacturers and their subcontractors on the other, is represented in Figure 11.



Organizational forms of top management involvement:

1. any special organizational forms, consultancy
2. ad hoc meetings
3. temporary advisory committee, indirect participation of top management, consultancy
4. special organizational unit with direct participation of top management
5. top management on the head of the special organizational unit

Figure 7. Organizational forms of top management involvement.

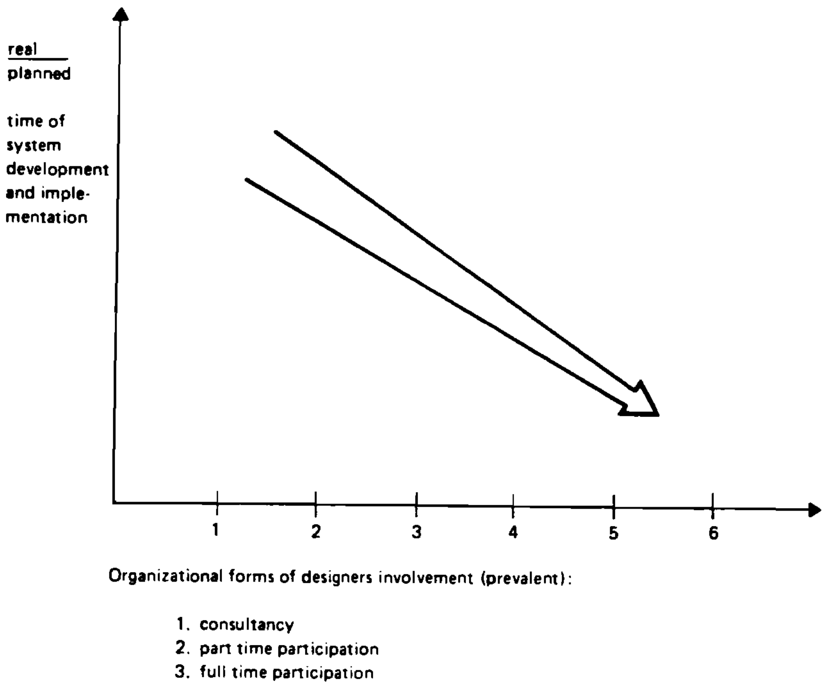
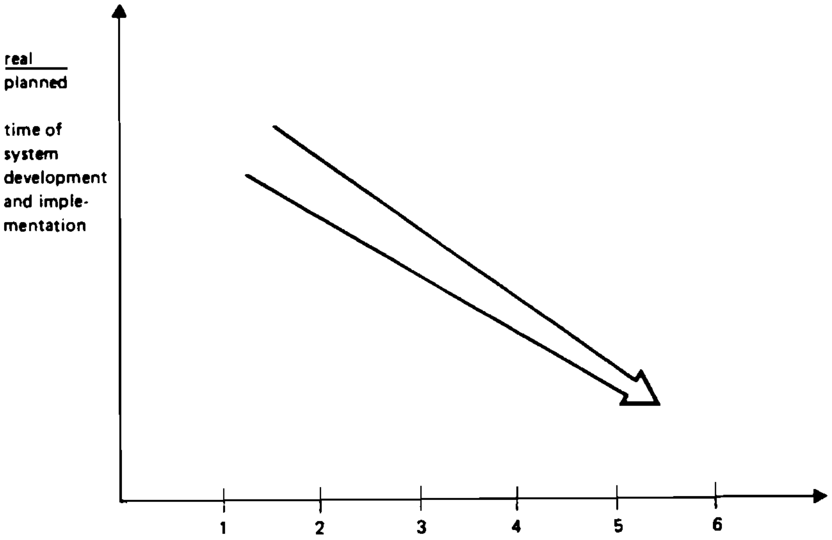


Figure 8. Organizational forms of designers involvement.



Organizational forms of operators involvement (prevalent):

1. consultant company
2. joint teams
3. system vendor
4. in-house team

Figure 9. Organizational forms of operators involvement.

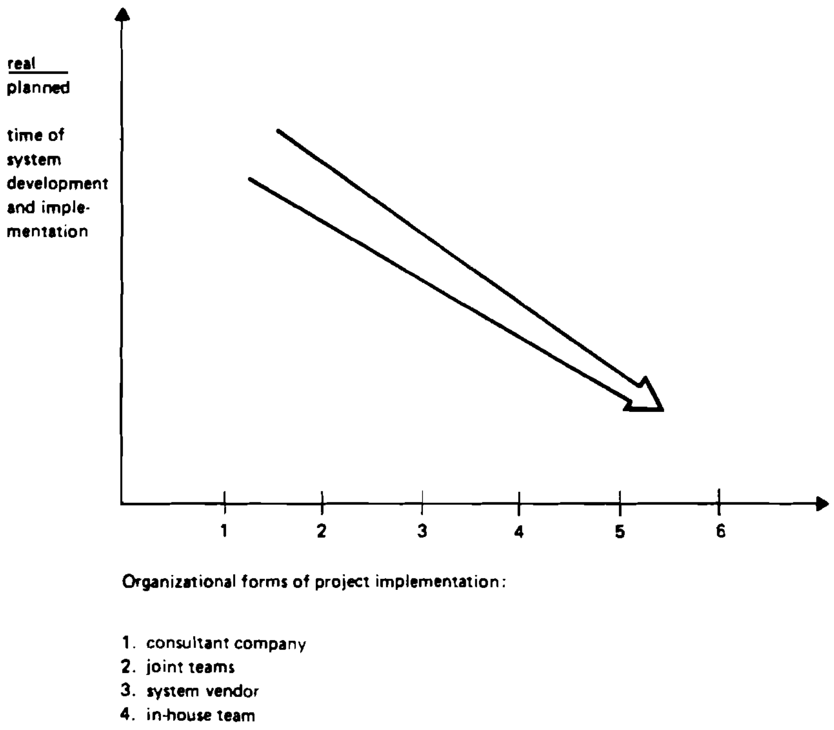


Figure 10. Organization of project implementation.

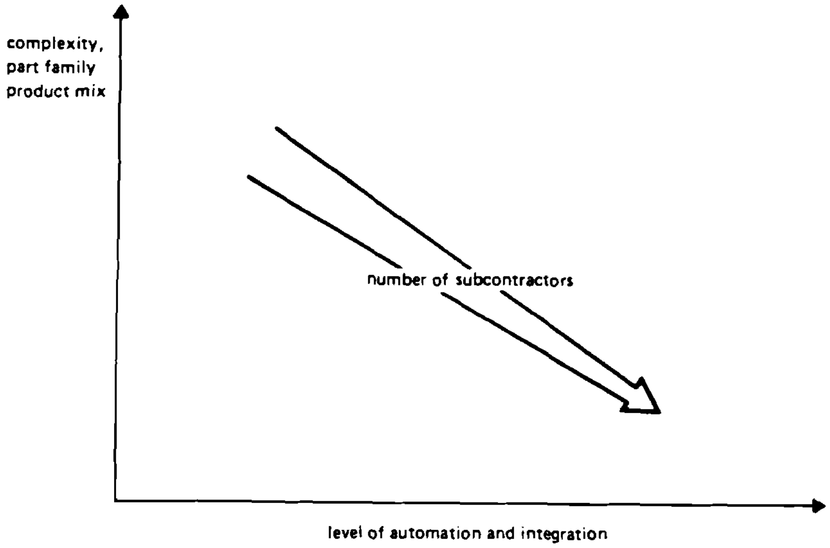


Figure 11. Level of automation and integration.

The next hypotheses have some organizational context, but they rank with a very important area whose relevance is permanently growing -- the information area. Of course we can not analyze this area in detail, and for reasons of specific problems connected with such an analysis we tried to concentrate only on some issues.

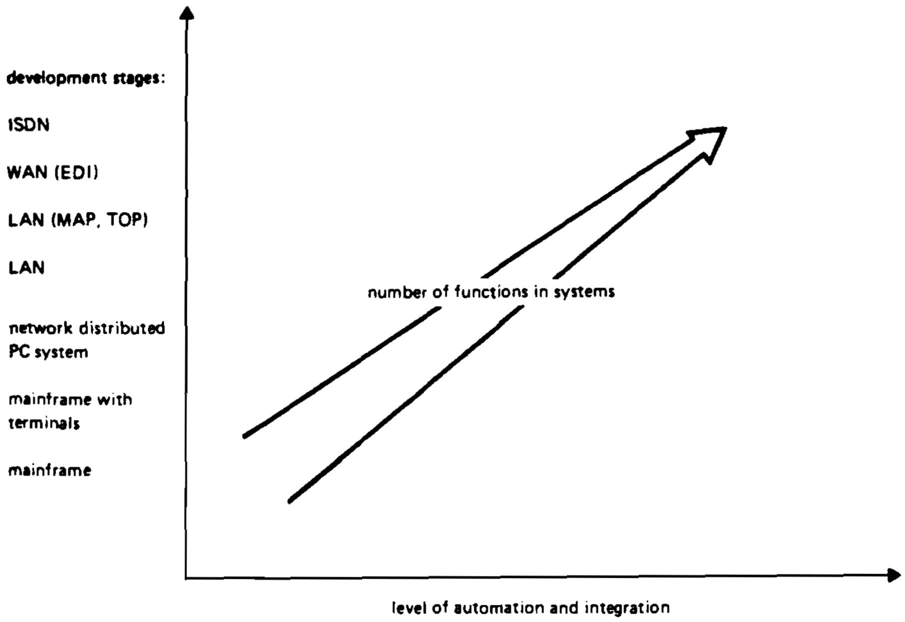
The first hypothesis shown in Figure 12 expresses the relationships between the level of automation and integration and the development stages of information exchange and processing. Higher stages of automation and integration require a higher level of integration and more sophisticated and standardized communication systems.

The results from our pilot study show that the Czechoslovak FMS use mainly mainframe systems with terminals and, surprisingly, no PCs. The Finnish FMS are oriented mainly on network-distributed PC systems. None of them have so far used LAN and communication standards and protocols.

The second hypothesis tries to show the relationship between level of automation and integration and the number of function processes in different stages of information exchange and processing. The hypothesis can also be demonstrated in Figure 12 and is formulated in the following terms: the higher the level of automation and integration, the higher the number of operation processes in higher stages of information exchange and processing.

The results from our pilot study show that in all of the analyzed systems practically all functions are computerized. Within the Finnish systems only one system uses a Minicomputer for CAD/CAM functions, the other functions are computerized by means of PCs, but in CAD/CAM the functions are not computerized.

In the Czechoslovak systems the functions such as material requirement planning, inventory control, order processing and sales monitoring are computerized by means of mainframe computers, and the others by minicomputers including CAD/CAM. Only one system uses PC for material flow control and inventory control.



Notes:
ISDN = Integrated Services Digital Network, including as well telex, telefax, etc.
WAN = Wide Area Network
LAN = Local Area Network
EDI = Electronic Data Interchange
MAP, TOP = communication standards and protocols

Figure 12. Development stages of information exchange and processing.

2.3. Socio-economic Issues and Consequences

The knowledge from theoretical studies and published case studies leads mostly to the conclusion that the development of skills of manpower goes to multi-disciplinary skilled shop floor personnel and to multi-skilled managers [Ranta, 1986; Braczyk, 1986; Schumann, 1986; Bullinger et al., 1987; Bessant & Haywood, 1985].

The division of labor in conventional systems is characterized by a very narrow specification of operators, by a division between traditional crafts and skilled workers, and by division and specialization of labor. The other groups consist of semi-skilled and unskilled workers (mainly for loading and unloading operations). The number of direct operators (handling the machine-tools and other devices directly) and mechanical maintenance-men is relatively high. This is the typical Taylor type of division and specialization of labor.

In course of the time, when a higher level of automation and integration is introduced in the production process, the nature of the process requires integration of skills; thus the number of direct operators is decreasing and, on the other hand, the number of indirect support staff is increasing. The ratio of electrical to mechanical maintenance men is going up, as well as the number of system analysts and programmers. We can examine the gradual substitution of the best qualified production personnel in a system for unskilled workers, such as loaders and unloaders.

Multi-skilled maintenance personnel combine mechanical, electronic and software knowhow.

Even today it seems that the skills of many managers, based mainly on law and economics, might not be sufficient to solve the problems of managing the new technology and they must be changed to a multi-skilled profile.

Work structuring in production tends to job enlargement, job enrichment and job rotation, as well as to an integration of skills.

The basic hypothesis drawn from the above mentioned ideas is represented in Figure 13.

The Finnish case studies [Toikka et al., 1986; Ranta, 1986] distinguish two basic strategies in this area: substitution and development strategies.

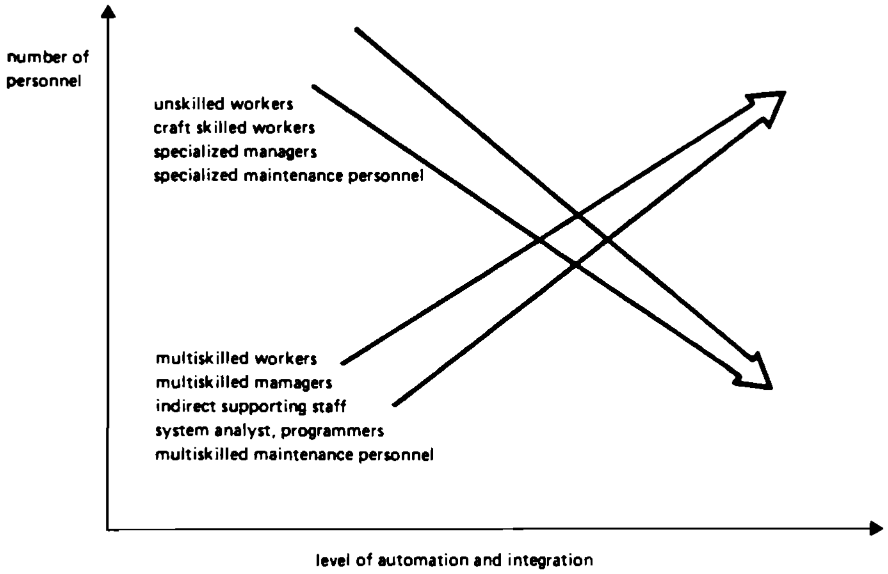


Figure 13. Skills development.

The substitution strategy corresponds to the traditional job structure, characterized by a relatively low level of personnel skills; even unskilled workers can be considered useful in this case.

The production is divided among the different groups of workers: the internal manufacturing operations that require overall planning and management are allocated to the few skilled foremen or group leaders; less qualified groups of specialized workers are placed outside of the actual production process, and unskilled auxiliary workers take care of the loading and unloading tasks; the genuine planning and preparatory operations that require high special qualifications are allocated to FMS-external partners who program and pre-set the tools and also take care of maintenance and repair.

The development strategy corresponds to the alternative job structure distinguished by the extremely homogenous, relatively highly qualified production staff. The internal manufacturing operations can be carried out by each of the workers who are rotating in different tasks. Planning and preparing of production is realized inside the system, only some programming and major repair is done outside. The time consumption for the daily production-process planning is increasing distinctly compared with a conventional system. There is discretion to regulate as much as possible on the shop floor.

The results from our pilot study show very similar outcomes in both countries. On the analyzed level of automation and integration, i.e. in FMS, there are practically no unskilled workers in the system. Compared with conventional systems or stand-alone NC-machines the number decreased from 1-2 workers to zero.

The percentage of college-educated personnel increased from 10% to 20% and the direct/indirect workers ratio changed on the average from 66/33 to 33/66 percent. Mechanical to electrical maintenance personnel changed on the average from 1:1 to 1:1.8-2.

The main changes in work content are characterized by improvement of qualifications, the rise of new professions such as automated system operators, more responsibility (wider area, not growth of task), and larger task content.

All above-mentioned tasks confirm the hypothesis shown in Figure 13. The only hypothesis not confirmed was the substantial increase of time consumption for daily production-process planning. On the contrary, this time has been decreasing in many of the analyzed systems (from 4 hours to 30 minutes).

The next hypothesis is closely related to the previous one and it is connected with the so-called technocentric or anthropocentric approach in the man-machine architecture in CIM systems, today very frequently discussed in literature. The problem has two main angles. Some of the authors stress the qualitative angle and regard the technocentric approach as "technology controlling man" and the anthropocentric approach as "man controlling technology". In the first case the technocentric approach leaves the human subordinate to the system and has no higher requirements on human qualifications. The anthropocentric approach places man in control of the system and needs the multi-skilled operator who, with a very wide, open-ended repertoire of skills, will manage the system despite unforeseen disturbances. From this angle the Finnish and Czechoslovak FMS tend towards the anthropocentric approach.

The second, quantitative angle of this problem stems from the idea that man can be replaced by machines and control devices. The role of the system operator will be to fill the gaps with the thoroughness of a designer. On this basis it is logically possible to draw the conclusion that the more expansive and complicated the system is, the fewer people will the production system need.

Figure 14 shows the results of 20 Czechoslovak and 6 Finnish FMS (in this case an extended data base from additional sources was used). The interconnection between personnel reduction (in %) and investment costs (in million US $) is presented in that figure. On the basis of these results we could come to the conclusion that, assuming only the second angle of the technocentric and the anthropocentric approach (personnel reduction), the Finnish FMS distinctly tend to the technocentric and the Czechoslovak FMS to the anthropocentric approach. However, another explanation of this phenomenon could be very prosaic, i.e. that the economic conditions in Czechoslovakia do not push so strongly for personnel reduction. The figures on the

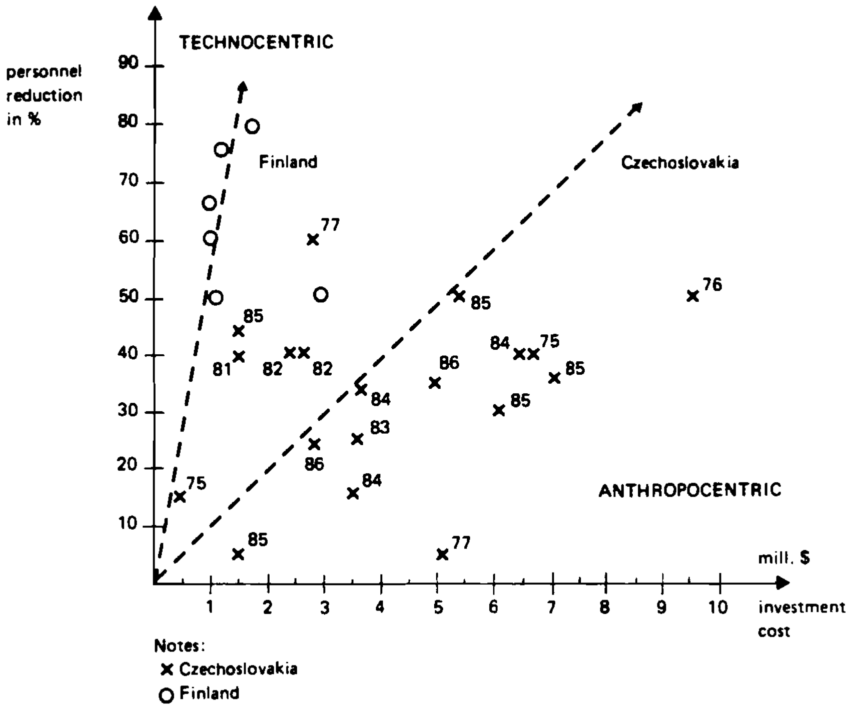


Figure 14. Personnel reduction in FMS.

graph indicate the year of installation of every system, from which it becomes clear that this factor does not have any influence on this phenomenon.

The next hypothesis expresses the notion that higher stages of automation and integration improve the working conditions such as a reduction of the hard, dangerous and monotonous work places. This fact has to have logically such a consequence as a reduction of manpower turnover (fluctuation) and sick leave ratio. The hypothesis drawn from this idea is represented in Figure 15. The results from our pilot study confirmed our hypothesis only partly. Firstly, it was stated in all systems that there are no dangerous work places. Secondly, the influence on the sick leave ratio was negligible. In all but one system no influence was indicated, i.e. the ratio remained without any change. Only in one Finnish system the ratio decreased and is now slightly lower than elsewhere in the factory. Some changes were indicated in the number of hard work places (in four systems) and the maximum decrease of that kind of work place was from 4 to zero (Finland). More distinctive changes were noted in monotonous work places, where the decrease of the number of those places compared with conventional systems was on the average 10-20%, but this applied mainly to Czechoslovak systems (only 1 case in Finnish systems).

The results for the reduction of manpower turnover (fluctuation) ratio are similar. The decrease occurred in all Czechoslovak systems and the maximum value ranges from 18% to zero, on the average from 12% to 1%. The Finnish systems do not show any changes in this respect and the value is zero.

Looking for the main reasons of the differences between the two countries, we found that the starting point of Czechoslovak systems were conventional machines and in Finland they were NC-machines. These systems were compared with FMS and we may conclude that the hypothesis (see Figure 15) is valid for the long-term perspective, assuming the stated level of automation and integration.

Further topics frequently discussed in literature are the training/retraining costs and the training/retraining and recruitment policies for CIM. The general opinion is that higher levels of automation and integration call for a longer time for training/retraining of the personnel and for higher

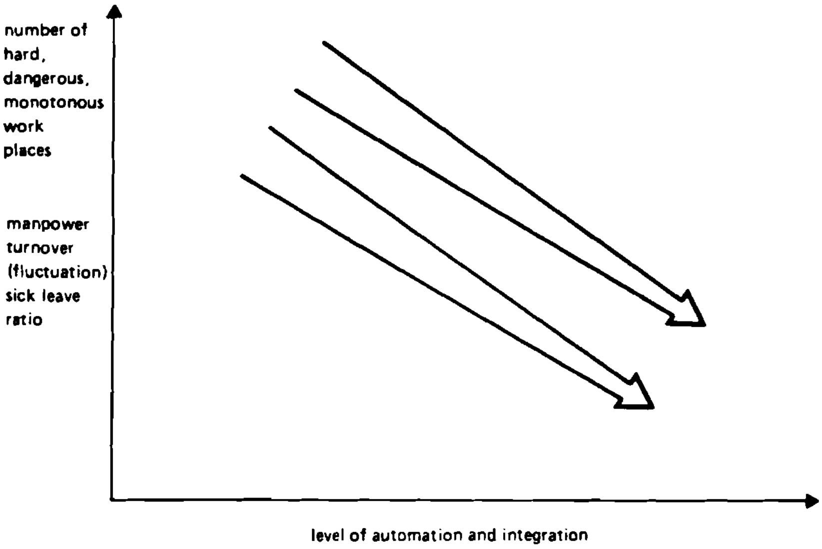


Figure 15. Changes in working conditions.

training/retraining costs. For instance Schumann [Schumann, 1986] describes a new type of multi-skilled operator as "... a man who is manually gifted and theoretically talented, able to diagnose and to act effectively, who possesses to an equal degree metal-cutting and electrical and electronic knowledge of basics. This new type of worker is not the traditional man trained on the job who gets into the position of machine operator without formal training only on the basis of years of experience. Much of the brainwork has been removed from this workplace in normal running, by steering, regulating and supervising functions taken over by computer systems. But instead, according to the new concept of use of labor, this workplace is alloted new tasks for dealing with exceptional situations. Coping with these tasks requires more than in previous times a theoretical competence to a greater extent than could be obtained only by learning by doing."

The basic tendency regarding this problem is shown in Figure 16.

The results from our pilot study contain the data regarding FMS. Unfortunately the comparable data, i.e. for conventional or stand-alone NC-machines are not available, thus it is not possible to follow up on the tendency.

However, the current data do not only show similarities, but they also show some substantial differences between countries as well as inside one country.

The average length of training/retraining ranges between 1-3 weeks in Czechoslovakia and is almost the same in all systems. There is a different situation in Finland, where the time period ranges in two systems between 6-9 months and in the other two systems it ranges between 2-4 weeks. Moreover, in systems with the longest training/retraining time the operators have an excellent background, years of experience with NC-machines and a good basic training. The total training/retraining costs per operator range between 1000-7000 US $ in Czechoslovakia and are again on a similar level in all systems.

In Finland the costs are naturally substantially higher in systems with the longer period of training/retraining: 12000 to 22000 US $. In the other systems the costs range between 1500 - 3000 US $.

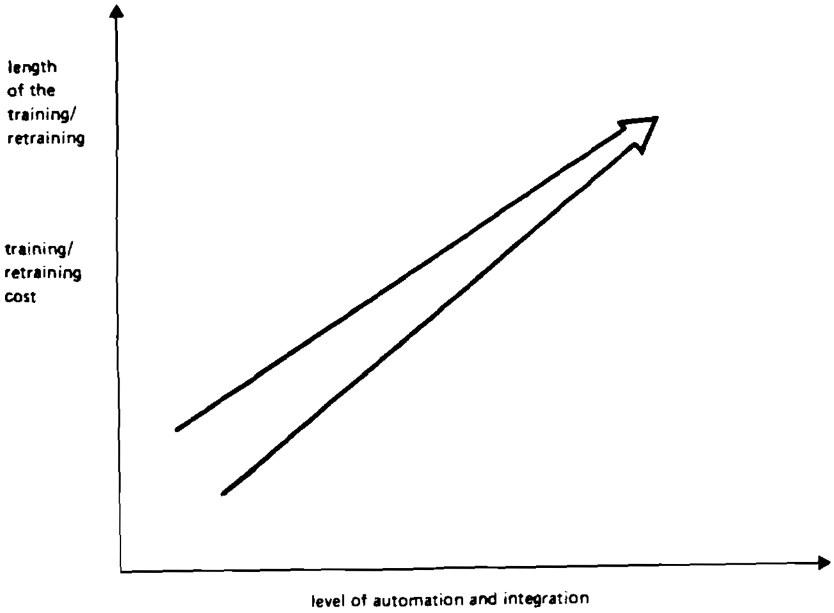


Figure 16. Training, retraining cost.

The last hypotheses in this area are again the so-called "open hypotheses"; they can be testified after gathering more statistical data.

The aim of the hypothesis is to specify more appropriate organizational forms for training/retraining. As a criterion for the assessment of such forms two factors are used, i.e. the non-adaptable operators ratio and the manpower turnover (fluctuation) ratio. The following organizational forms are taken into account:

- on-the-job training;
- off-the-job training organized by:
  training department of user company
  special training institution
  vendors.

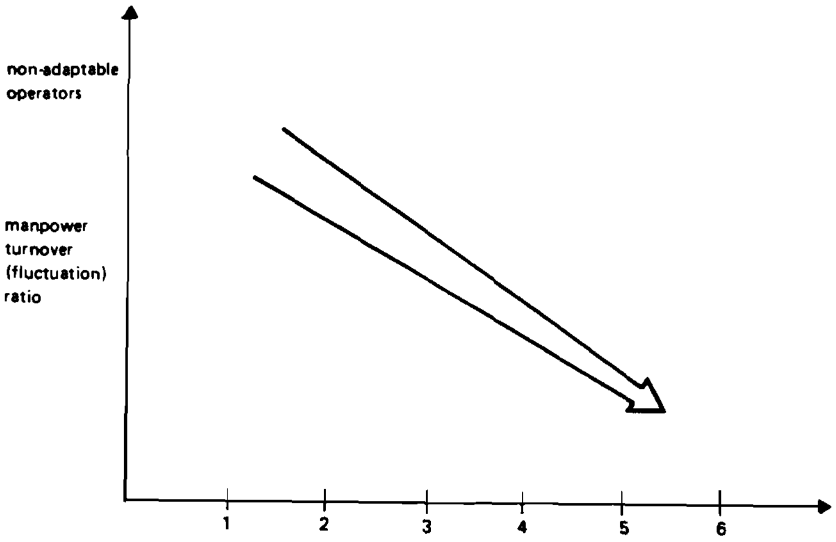
The hypothesis is represented in Figure 17.

The preliminary results from our study show that companies usually use a mix of organizational forms and that there does not yet exist a distinctive correlation between the manpower turnover (fluctuation) ratio and different organizational forms. Moreover, the other factor, i.e. the non-adaptable operators ratio could not be used at all, because no example of that kind exists so far. Maybe it would be necessary to find another factor for the correlation.

The next hypothesis demonstrates the interconnections between organizational forms of recruitment of personnel for CIM and, again, the factors manpower turnover (fluctuation) and non-adaptable operators ratio. The hypothesis stems from the idea that the better the form of recruitment, the lower will the ratio of both factors be, as shown in Figure 18. The following possible forms of recruitment are taken into account:

- recruitment from manufacturing areas closer to CIM;
- recruitees having worked with previous system (machining centers, NC-machines, conventional system);
- young recruitees;
- recruitment from the best operators (creaming-off policy).

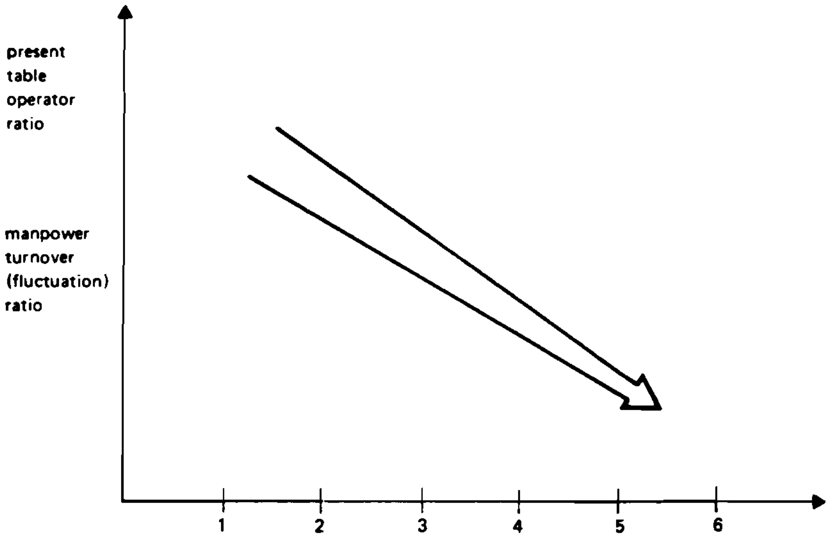
The last "open" hypothesis is connected with the reward system suitable under the changed conditions, i.e. at the higher



Organizational forms of training/retraining:

1. on-the-job training
2. off-the-job training organized by training department of user company
3. off-the-job training organized by special training institution
4. off-the-job training organized by vendors

Figure 17. Training/retraining organizational forms.



Organizational forms of recruitment:

1. from manufacturing areas closer to CIM
2. worked with previous system (machining centers, NC-machines, conventional system)
3. young recruiters
4. from the best operators (creaming-off policy)

Figure 18. Recruitment policy for CIM.

level of automation and integration. From the literature [i.e., Lasko, 1988; Krabbendam, 1986] we can draw the logical conclusion that the reward system has to reflect the global responsibility of the operators. People work as a team and have the responsibility for all the improvements in productivity. This hypothesis reflects the interconnection between the form of reward and the manpower turnover (fluctuation) ratio. The better and more appropriate the reward system, the lower will the ratio (or other indicator?) be. The following forms were taken into account:

- piecework system;
- individual wages;
- time wages;
- group wages;
- group premium payment.

This hypothesis is represented in Figure 19.

CONCLUSIONS

The main purpose of the paper was to describe and systematically classify the managerial hypotheses connected with CIM adoption.

The hypotheses embrace the strategic, organizational and socio-economic areas of managerial activities. They create an open system and will be enlarged in the second stage of our study, i.e. after gathering the data according to the refined version of our questionnaire from an expected number of 100 systems. Many of the organizational and social parts were extended in that last version.

All above-mentioned and newly created managerial hypotheses will be tested by means of the proper statistical methods and new conclusions will be drawn from special comparisons such as centrally planned vs. market economies, small vs. large countries, different branches of industry, different areas like USA vs. Japan vs. Western Europe vs. Eastern Europe, etc.

The preliminary results from the Finnish-Czechoslovakian pilot study show some interesting results. Testing the hypotheses drawn mainly from theoretical studies and published case studies, we have come to the conclusion that some of them

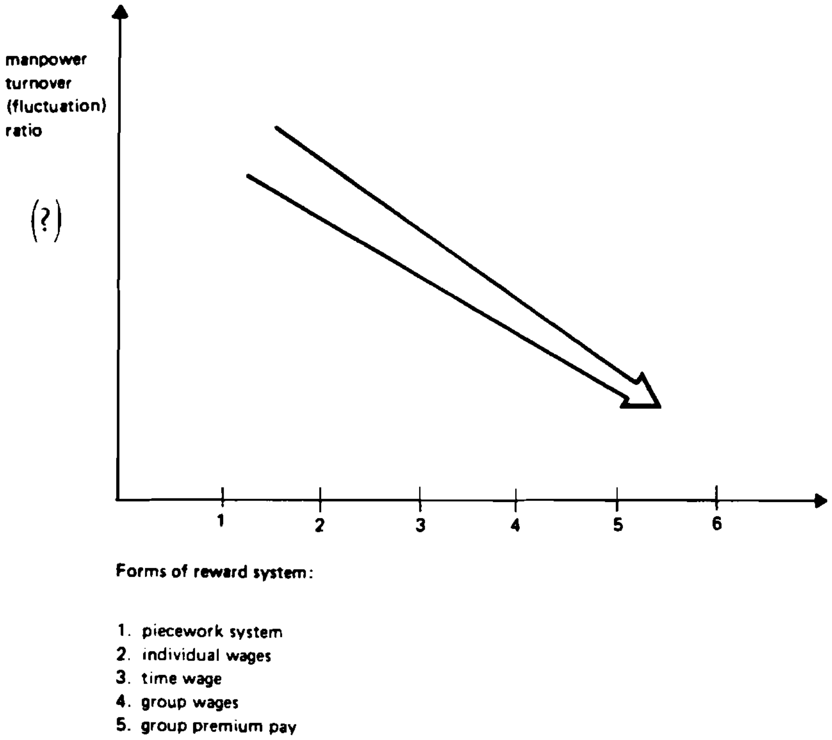


Figure 19. Reward system in CIM.

have been confirmed, some of them not. There are also some interesting differences whose reason may lie in the different economic systems. But we have to stress that it is very dangerous to draw final conclusions from the pilot study. We have to wait for a more elaborate data base, where the final conclusions will not be only reasoned conjectures, but well researched subjects. The large data base comprising 100 systems creates the desirable precondition for drawing new conclusions and generalizing the results for different environmental, economic, cultural and other conditions. In order to arrive at interesting results for the relevant decision-makers it is intended to clarify the main factors and ways by which different companies adopted CIM and to specify the pacing factors decisive for the successful adoption of these particular systems.

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IMPLEMENTING INTEGRATED TECHNOLOGY

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Abstract

This paper draws on empirical research in the implementation of a number of computer-integrated manufacturing technologies, primarily in the UK. It argues that, whilst the potential benefits available from these technologies are significant, achieving them in practice depends upon considerable organisational adaptation during the implementation phase. The paper concludes with an examination of possible organisational development strategies to support effective implementation of CIM.

IMPLEMENTING INTEGRATED TECHNOLOGY

The potential of computer-integrated manufacturing

There is widespread agreement that advanced computer-based systems have considerable potential for improving manufacturing operations. Rates of diffusion of technologies such as computer-aided design (CAD), flexible manufacturing systems (FMS) and computer-aided production management (CAPM) systems, although still slow are beginning to accelerate as firms recognise the benefits which can be obtained in terms of reduced inventories, shorter lead times, tighter production control, higher quality and overall improved responsiveness to the market. Table (1) which draws on the INSEAD manufacturing futures survey of European manufacturing executives (1) indicates the range of typical manufacturing concerns and sets these against the contributions which computer-based technologies can offer.

Table (1) CIM - a solution for the manufacturing problems of the 1990s?

Main problem issues as seen by senior manufacturing executives in Europe	**Potential contributions offered by CIM**
Producing to high quality standards	Improvements in overall quality via automated inspection and testing, better production information and more accurate control of processes
High and rising overhead costs	Improvements in production information and shorter lead times, smoother flow less need for supervision and progress chasing
High and rising material costs	Reduces inventories of raw materials, work-in progress and finished goods
Introducing new products on schedule	CAD/CAM shortens design lead time. Tighter control and flexible manufacturing smooths flow through plant and cuts door-to-door time
Poor sales forecasts	More responsive system can react quicker to information fluctuations. Longer term, integrated systems improve forecasting
Inability to deliver on time	Smoother and more predictable flow through design and possible accurate delivery
Long production lead times	Flexible manufacturing techniques reduce set-up times and other interruptions so that products flow smoothly and faster through plant

The trend in application of computer-based systems is towards computer-integrated manufacturing (CIM). That is, the convergence of the various systems associated with different aspects of manufacturing around a single database and shared communications. Such convergence continues a trend established for some time within the manufacturing process where - as Kaplinsky (2) points out - there has been growing integration, first within and then between tasks. A good example is the case of machine tools, where the various individual operations which used to be carried out by different machines and operators have gradually converged into single sophisticated machining centres and where much of the original craft skill of the operator can be embodied in the control program of a CNC device. Such machines can also be combined with robot manipulators, computer controlled tool management and parts handling, and linked together with other machines capable of different types of operation - for example, cutting, drilling or grinding. This has made it possible to create an integrated manufacturing cell, under some form of direct numerical control (DNC) by computer, and behaving in many ways as a single complex machine. The present stage of convergence is for integration between these operations and the overall production planning and scheduling systems in a flexible manufacturing system. Computer-integrated manufacturing takes the process a step further, by offering potential linkage with all elements of the manufacturing process - design, co-ordination and production.

It is also worth noting that the pattern of integration does not need to stop at the boundaries of the firm; linkages between firms - on design, purchasing, distribution, etc - are also possible via similar computer communication networks. Digital Equipment, for example, (3) in a recent report describing their Clonmel CIM facility in Eire point out that through the use of the company's world-wide computer/communication network the plan can access up to 15,000 computer systems. For a task like design this means that a vast resource of specialised knowledge - distributed geographically throughout the world - can be brought to bear on the problems of a particular plant through a single computer terminal and appropriate communications software.

Problems with CIM

From this it appears as if CIM represents a "golden key" with which manufacturers will be able to unlock their productivity and quality problems. And at first glance the diffusion of advanced automation technology appears to support this view, with market growth rates in particular sectors often in excess of 20% per year. For example, a recently published Frost and Sullivan report (4) suggests a threefold increase by 1991 in the number of industrial computer systems from its present level of around 22,000. Similarly, data on automation projects already established indicates both a rapid expansion and also a broadening out in application across the industrial spectrum. In the UK the 'Engineering Computers' survey, which uses a large - 2000 plus firms - statistically structured survey on an annual basis, growth in overall application of computer hardware and software is shown rising at around 20% per year. (5)

Evidence also supports the view that advanced manufacturing technology can bring spectacular benefits. For example, in our own work on flexible manufacturing systems we have seen lead times and work in progress inventories cut by as much as 75%. (6) The trade and technical press is regularly filled with case histories of successful implementation. But in practice, although there has been considerable publicity and strong market pressure from the supply side, a growing mood of disenchantment with CIM amongst users can be detected, with many reducing their investment intentions and seeking simpler solutions to their manufacturing problems.

A report for the British Institute of Management makes the point that although firms have made investments in AMT these have not always been successful. (New) (7) In one sample of 64 plants which had invested in some form of FMS over two thirds had so far only achieved low payback, whilst others using CAD also felt that they were not getting the best out of them. Inevitably this has led firms to revise their investment intentions downwards and in particular away from the more complex systems technologies.

Table 2 **Payoffs from advanced manufacturing technology**
(Base: 250 firms)

Technology	Zero to low payoff (%)	Moderate to high (%)
CAD	46	54
CAM	46	54
MRP	19	81
FMS	67	33
Robots	76	24

Source: New,1986

Too much should not be read into figures of this kind, but they do demonstrate that moving to integrated configurations of technology raises a number of questions. Despite optimistic market forecasts and the promise of considerable benefits, a growing sense of caution is clearly developing amongst potential users. This emerges in the apparent slowdown in investment , in comments in the trade press, and in a growing cynicism about much of the supply industry. It reflects, above all, a disenchantment with AMT's ability to deliver the benefits promised and there are several examples of costly failures or of systems which are only working at a fraction of their true potential.

Even where systems do work it may take several years to learn to use them well enough to exploit the sort of gains which the suppliers suggested were possible. For example, in research on CAD, Senker and Arnold (8) found that it took firms an average of two years to achieve "best practice" productivity gains whilst another study of CAPM by the ACME Directorate of the SERC pointed out that "...even advanced CAPM users have difficulty in understanding how best to use the numerous CAPM control variables (especially in combination)....thus they are not getting full benefit from CAPM systems".(9)

Although there are clearly several major technological problems to be overcome in achieving full integration, it is becoming clear from closer analysis of the experience of firms which have implemented partially-integrated solutions (such as CAD/CAM or FMS) that considerable organisational change is also needed in order to achieve the expected benefits. Indeed, in several cases firms report that the majority of benefits achieved derived from these organisational changes rather than the technology in which they had invested.

An illustration of this can be found in the experience of Digital Equipment in implementing a major CIM facility in Clonmel, Eire. Although this was planned as a technological innovation and, five years on, is generally regarded as having made a significant contribution to improved performance at the plant across a range of indicators, such as productivity growth, stock turn, inventory reduction, lead time reduction and quality improvement, the plant director views the major benefits as having come from organisational learning. He identifies several key lessons which the company learned including the need to ".....Simplify ways of doing things before automating. Most people who get into difficulties with investments do not realise their potential because they try to automate their existing operations".(10)

This also illustrates another key point in CIM implementation; many of the benefits which with hindsight have been of most value to the firm were not seen at the outset or included in the investment justification. In a recent survey of 106 firms which we conducted the majority of ; although most (77%) attempted to use some form of formal justification for their investments they did not feel that these took account of the many intangible benefits which new manufacturing technology offers. Examples of such intangibles include increased flexibility, better responsiveness to customers (and hence greater customer satisfaction), improved awareness of production bottlenecks and quality problems and better supplier relationships. What is emerging in some cases is a dual system whereby investment proposals are made on the basis of accepted methods and criteria - such as labour savings - but where the real justification is often ' an act of faith' backed up with a judgement about the strategic benefits which might emerge later. (11)

At root these problems reflect the fundamental nature of the challenge which CIM poses. Rather than discrete automation, which involves doing what has always been done a little better , integration opens up completely new possibilities for doing things in totally new or radically improved ways. The shift from substitution to augmentation implicit in this challenges the organisation at a fundamental level - and we should not be surprised to find that existing structures and practices are not always apprpriate to support its implementation.

Organisational adaptation to new technology

It is useful to consider how far the organisational response to technology can influence its success or failure. A good example of this is the case of CAPM systems which have been around for some time but where the experience is still - as indicated above - that many of them are being poorly used. Although such systems appear logical and relatively simple in concept, there have been significant problems in their use since the 1960s when basic Materials Requirements Planning (MRP) systems were first introduced. Early systems suffered from a number of problems which had more to do with organisational and human factors than technological. These included:

- poor quality data input (because of lack of commitment or even deliberate action). Poor data in the system renders information generated ineffective or wrong.
- poor implementation; many systems remained the province of data processing experts and were often imposed upon the rest of the organisation.
- lack of commitment from senior management
- slow in operation (runs could take several hours) and unresponsive to changes
- lack of feedback provision to take account of changes in capacity, order levels, lead times, etc
- often seen as the responsibility of one department (usually DP or stock control) rather than an organisation-wide responsibility
- weak links to other aspects of the production process such as quality control.

As a result, MRP systems worked best for those firms making with little basic variety in product range and with relatively stable patterns of orders and supply. More advanced systems, such as MRP2, were developed in the late 1970s to maintain the basic principles but also to improve the practicalities. However, although many elements - such as improved feedback and responsiveness to change - are designed into the system, much still depends on the way in which it is implemented within the organisational context.

More recent work on flexible manufacturing systems (for example, the US/Japan comparison made by Jaikumar (12)) has highlighted international differences in the way in which firms approach the use of new technologies and it is clear that considerable scope exists for different forms of organisation and implementation.

Dimensions of organisational change

The need for some degree of organisational adaptation to get the best out of technology has long been recognised - indeed, it forms the basis of the well-known "experience curve" effect identified during the 1940s. That is, that organisations learn to produce more efficiently as volume and familiarity with the process increases. Such learning involves several components including patterns of work organisation, of plant layout, of processing routing, plant loading and so on.

Where this effect applies to a single new machine or a well established process, it represents something which the firm can assimilate in incremental fashion. However, it can be argued that the novel, highly complex and integrated characteristics of present manufacturing systems makes this at best a long learning curve and one which requires considerable adaptation along the above-mentioned dimensions. In particular, the requirement appears to be for much higher levels of integration within the organisation, to match those emerging in the technology.

An example of this can be found in the skills area. As industry moves towards more integrated forms of manufacturing so it becomes clear that some new skills will be needed, such as programming, systems analysis and electronics maintenance. In addition to these there is a need for increasing breadth in the portfolio of existing skills and for increased flexibility in their deployment. Finally there is a need to blend new skills with long-term "tacit" knowledge and experience of the processes involved and the materials being used and worked on.

Combining these elements in response to the demands being posed by increasing technological integration has led to the emergence of new breeds of personnel at a variety of levels in the business. For example, the concept of "manufacturing systems engineers" - that is, engineers with a breadth of knowledge across production systems and technologies rather than the somewhat narrower traditional single discipline graduates - are increasingly to be found in the UK(13) whilst in West Germany demand for the Wirtschaftsingenieur is growing.

In the design area the traditional draughtsman is being replaced by a composite designer/draughtsman/CAD technician with close links into and experience of the actual manufacturing process. In the maintenance area - as several authors (for example Senker(14) and Fleck (15)) have pointed out - the multidisciplinary/multi-trade maintenance fitter is becoming essential to support items such as robots which involve several different technologies such as hydraulics, pneumatics, electronics and mechanical engineering.

Multiple skills are an important requirement in this connection, bringing together different engineering disciplines (hardware/software, electronics with applications, manufacturing systems engineering etc) and different craft skills (for example, in maintenance). Further, with the decreasing importance and involvement of direct workers, those who remain need to be flexible and highly trained in first-line maintenance, diagnostics, etc whilst the increasing number of indirect support staff need to be broadly skilled and able to respond in flexible fashion to a wide variety of problems right across an integrated facility.

In essence this is a process of skill convergence to match that of technological convergence in the moves towards the computer integrated factory. Nor is it confined to production-related skills alone. Similar patterns can be found in other application areas - for example, in the case of flexible manufacturing systems. In one Scandinavian example which we examined, the level of delegation to the shop floor was such that even purchasing decisions regarding the castings to be machined and the overall relationships with the supplier foundries were handled by the highly-skilled system operators. In other cases skilled operators were trained to undertake aspects of the maintenance and quality management and to contribute to the overall scheduling and planning within flexible manufacturing cells.

The move to FMS and other integrated automation technologies also poses questions about organisational structures and particularly about the traditional pattern of functional specialisation. For example, there is the need - itself facilitated by moves towards CAD/CAM linkages within firms - for the design and production departments to work closely together to develop products which are suitable for manufacture on an FMS. Such a "design for manufacture" philosophy is of particular significance in the flexible assembly automation field where small modifications to the design of an item can eliminate the need for complex manipulation or operations within an automated system.

In one FMS case which we examined, for example, redesign of the product led to a reduction in the number of operations, handling and machining- from 47 to 15 - with significant implications for cost and lead time savings. As one manager put it, " FMS is going to drive the shop - but it's also going to drive the people who design the product and the production engineering...those parts have got to be made if we are to justify this investment".

The essence of such functional integration is not to eliminate specialist skills but to bring them to bear in a co-ordinated fashion on the problems of designing, producing and selling products - creating a single system view of the process rather than one with many parochial boundaries and little interchange across them. Another good example of this can be found in the area of financial appraisal of FMS, where the integrated and strategic nature of the technology is forcing a major rethink about the traditional role and perspective amongst management accountants.

In the same way as integrating technologies require closer functional integration, so they imply shorter hierarchies and greater vertical integration in the organisation structure. In order to exploit the full benefits of a rapidly responsive and flexible system it is necessary to create a managerial decision-making structure which is closely involved with the shop floor and which has a high degree of delegated autonomy. In this connection it is clear that the pattern of devolution in the use of FMS and in the wider factory context is much more developed in Sweden than in the UK, with few levels in the operational and decision-making hierarchy and with considerable responsibility passed through to the operators themselves.

Integration also has significant implications for the pattern of work organisation. With greater reliance on a small group of workers and managers comes the need to look for models of production organisation which have less to do with task fragmentation , division of labour and control by external regulatory systems of sanctions and rewards and to evolve alternatives based on small autonomous working groups, with high flexibility and internal control. These moves which, it should be stressed were not observed in all the plants visited, can be seen as attempts to move towards more appropriate form of manufacturing organisation to support highly integrated technology. Whereas "traditional" production organisation often stresses factors like functional specialisation, division of labour, procedural control and other components of what Burns and Stalker(16) called "mechanistic" organisation, it can be argued that more "organic" forms which stress integration and more flexible controls will increasingly be required.

New forms of organisation and management?

The prescription for CIM appears to require the presence of an integrated organisation. It is important to recognise that this challenges many of the basic assumptions about the way in which manufacturing is organised and managed. The traditional model with which most industrial managers are familiar derives from the ideas of men like Frederick Taylor and Henry Ford. At the time they were working their approach - based on the principles of scientific management - was highly effective. (It is instructive to remember, in these days of discussion about lead time reduction and just-in-time production - that Ford's plants were reputed to be able to produce a complete Model T from raw iron ore in five days).

The basic pattern can be summarised in the following table, in which the Ford/Taylor approach is contrasted with the kinds of model which may be more appropriate for supporting CIM.

Table 3 **The Ford/Taylor Approach and the CIM Approach**

Ford/Taylor	**CIM**
Production in high volume, low variety	Production of small batch, customer specific products
Dedicated production process	Flexible production process
High division between skill levels leading to a *tall* vertical organisational structure	Increasing integration between skill levels, leading to a flatter vertical structure
Individual repetitions task emphasising horizontal differentiation	Increased integration horizontally, with semi autonomous work groups
Reward structure based on individual performance	Reward structure based on group performance

Tight supervision	Supervisor viewed as a resource

Mechanisms whereby integration can be achieved

The preceding discussion - and much of the research work which has so far been carried out in the area - has highlighted the need for simultaneous technological and organisational change. This requirement is not surprising since in its original definition 'technology' makes no differentiation between hardware and the organisation of production - it is defined as ' the useful; arts or science of production'. Thus we should recognise its multi-dimensional nature and ensure that implementation of change reflects this breadth.

That said, there is a challenge to identify both the nature and direction of changes required and the mechanisms whereby they can be implemented in firms moving towards CIM. As we can see from Table 3, CIM cuts across traditionally recognised and accepted functional and hierarchical organisational divides. Thus in order to gain successful results from CIM applications, some corresponding integration of the organisation needs to take place. For example, in a recent survey of CAD/CAM users, Voss found that those organisations acheiving either business or systems success had undergone some form of organisational integration .(17)

As Child(18) points out, there are a number of potential alternative mechanisms, whereby integration of the technology, strategy and structures of organisations can be acheived. Inevitably there is no one "best" solution for how to integrate an organisation, since each organisation has its own history and set of characteristics which shape the choices and constraints influencing its integration strategy.

Structural reorganisation is often seen as an essential key to the success of an integrated system. Various methods for integrating the organisational structure have been developed by both organisational development consultants and academics. One such form of organisational integration is that of Matrix Management. In a Matrix structure groups representing different functional disciplines are brought together on a team basis, usually to tackle a specific project. The physical integration of the group, that is the combination of different functions such as engineers, designers and marketing people, combined with its geographical integration (usually in the same location), fosters team spirit. That the group is also directed to acheiving one agreed goal appears to pay off in terms of tangible benefits, such as reduced lead time, design for manufacture etc. As Voss discusses, although usually a short-term, project specific approach a Matrix structure can be a permanent arrangement, enabling multi-functional teams to work.

To paint a glowing picture of the Matrix Management structure may however be misleading. Certainly it does have advantages in terms of maximising communication between functions on specific projects, but it also has drawbacks. One problem often confronted is what might be termed, the "servant of two masters" issue, ie, where an individual is part of a project team but also part of a functional department. Potential conflict exists, for example where commitment to a project may be seen to detract from career progression within the functional department. It is therefore essential to ensure clearly defined authority lines and maintenance of professional links, for example through frequent meetings or circulation of professional magazines.

Although a Matrix approach can be seen as a way of integrating the organisation, the structure means that the original functional labels are maintained. Thus the extent to which radical integration using this form of organisiation can take place is questionable. It can be argued that Matrix Management in fact only represents partial integration whereas integrating technologies are revolutionary and therefore demand more radical functional change.

Restructuring the organisation in such a radical way may work within a small, organic organisation, but as Child suggests, for larger, relatively mechanistic organisations such a change, or simplification of structure may not be as easy to acheive. Winstanley et al, in a study of CAD users found that "a number of companies in the sample were having to struggle with inappropriate and outdated organisational hierarchies which were impossible to use effectively".(19) In several cases this had led to the design functions being hived off allowing a simplification of the structure enabling the function to respond more effectively to the demands of the new system. This may also be seen as a way of defusing the political resistance to integration another point which was highlighted by Child.

The emphasis of these studies is that integrated technologies require a simplification of structure along horizontal levels, ie between functions, to enable fuller integration. The need for similar simplification of the organisational structure on the vertical axis, is given weight by a study of Swedish firms successfully employing FMS (20). It was noted that organisational structures in Sweden are considerably flatter than their equivalent in the UK (3-4 levels in Sweden compared with 6-10 levels in the UK). Haywood asserts that this structural organisation has significant implications for the organisation, increasing communication and enabling managers within the organisation to have a greater overall knowledge of the business as a whole. This increase in integration appears to reduce the progress chasing role of middle management although it represents a potential threat, in some cases by making this level of management redundant.

Research evidence also suggests that organisations may have to undertake changes in organisational roles and skills in order to acheive further integration. In a study currently being undertaken by Winstanley et al, the introduction of new integrative technology for CAD users, has implications for the role of the draughtsperson. This task can now be undertaken by a design engineer, but this often means a change from the multi-functional engineer who might operate within a matrix strucure to the multi-disciplinary engineer. Thus the engineer instead of being a development engineer or a designer may carry out both tasks and perhaps work directly on a CAD.

Interestingly, Haywood also quotes from Swedish managers who suggest that the traditional deliniation between blue collar and white collar staff may be weakening. Computer driven companies may cause white collar staff to become more involved with shopfloor work and conversly the new integrated technologies may cause shopfloor workers to do more indirect work

"*We would rather get the person with the machine or manufacturing knowledge to acquire computer or electronic skills rather than get the academically more qualified to acquire machining knowledge, since it generally takes much longer to acquire machining skills*"(21)

We have already indicated the need for higher levels and greter breadth of skills required by organisations implementing CIM applications. For example, as Haywood cites, Swedish companies adopting FMS increased their graduate level from 3% in 1981 to 10% in 1986. Moreover these graduates were spread across functions in the organisation rather than being in the traditionally accepted positions such as R&D or production engineering.

The changing skills requirements for craft skilled workers are shown in research work by both Cross(22) and Fleck(23). The latter makes the point that robotics encompass a range of different skills such as electrical, electronic, mechanical and hydraulic and programming skills which cut across traditional craft boundaries. This has implications for trade unions in terms of membership strategies which have been discussed elsewhere (for example, by Helen Rainbird (24). It also poses problems of demarcation disputes. For example, Clegg et al report on considerable delays in implementing a flexible manufacturing system arising out of a dispute between unions as to the location of responsibility for programming the system. With the increased use of CNC machines, for example, the emphasis changes for the operator from the manufacturing task to tasks associated with programming and maintaining equipment. As Burns (25) asserts, workers without relevant skills can cause expensive down time and repairs. Integrated technology is requiring employees to move beyond narrow job definitions and functional barriers. With the implication that each worker will be responsible for more jobs/ machines. The advantages to the organisation are that it should increase integration, more people will know what is going on and delays in the downtime of machinery will be reduced but such shifts in the skill profile of firms will require extensive investment in a programme of training and retraining for its employees.

However, this shift in training emphasis may prove difficult to achieve in the current climate of retrenchment, where training needs have been increasingly met by consultancies, or have been sold as part of the package for a manufacturer's explanation of how the machine works. In future internal training may well become a key mechanism for ensuring full organisational integration. For example, Senker and Beesley (26) show in their study of Computer Assisted Production Manufacturing implementation, that clearly defined organisational goals with respect to the new technology, and the users knowledge of these overall aims, made for successful systems.

Further integrating strategies for the implementation of of the technologies may come from new methods of working approaches like just-in-time and Total Quality Control. For example there is growing appreciation of their applicability within CIM systems. (27) As Schonberger (28) suggests, such approaches enable the worker to become more conscious of his/her own work and to understand the whole system of organisation and production and his/her own part within it. Thus the system is philosophically a more integrative one, although in practice it needs to be combined with the removal of restrictive practices.

So far we have discussed various strategies which potentially could be employed for increasing integration throughout the organisation. In addition we have to consider the ways in which an organisation can best introduce new technologies and work practices. Webb and Jones (29) looked at two very different approaches to the installation of CIM equipment and its associated organisational structures. In the company which successfully implemented it the technology was well discussed and explained. The technological integration and its accompanying organisational changes were accepted and built upon and the ownership of the system had extended across the the organisation. Participation in the introduction and implementation of the system has been evident at each stage, and consistent with participative design approaches of the kind championed by Mumford. (30)

It would appear vital when implementing integrated technologies of any form, that the organisation has an understanding of the process and reasons behind the integration thrust. This understanding will perhaps more readily allow organisations to adapt their structure, create an atmosphere of functional change and skill change, which should in turn lead to better use being made of the systems employed by the organisation.

Conclusions

Concern is growing that despite the availability of powerful advanced manufacturing technologies, productivity growth is slowing down in many advanced industrial nations. One possibility which may help to account for this is that the problem lies not so much in the level of investment as in the way in which that investment is used. This places emphasis on issues of implementation rather than simply of adoption and diffusion of technology.

This brief review of literature and recent empirical research suggests that getting the best out of advanced manufacturing technology may require extensive organisational adaptation. The basic thrust of such change is towards higher levels of integration - although it is important not to neglect the increased opportunities for differentiation within such a framework which provide considerable flexibility to organisational structures and functions.

We would argue that the discussion and research agenda now needs to move on from describing the problem and its symptoms to exploring mechanisms for for solving them. It is unlikely thast there will be a single 'best' solution for all firms but rather a range of approaches for roganisational change and development. Important blueprints can be found in the philosophies of 'just-in-time' manufacturing and in 'total quality control', both of which emphasise mobilising the entire workforce within a non-traditional framework of structure and operation. But other options remain to be identified and/or developed if the full benefits of integrated manufacturing are to be realised.

Acknowledgements

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Problems and Prospects for Effective Plant Modernization in U.S. Manufacturing@

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@This paper is to be presented at the Second Annual International Institute for Applied Systems Analysis (IIASA) Workshop on Computer Integrated Manufacturing at the Frauenhofer Institute for Production Technology and Automation, Stuttgart, The Federal Republic of Germany, July 18-20, 1988. Work in this area was supported by the National Science Foundation, DePaul University, The Industrial Technology Institute, and The University of Michigan. The opinions herein are those of the author and do not necessarily reflect the official position of the National Science Foundation.

Problems and Prospects for Effective Plant Modernization in U.S. Manufacturing

Recently Caterpillar, Inc. announced a seven year Plant with a Future (PWAF) program that will cost the company $1 Billion that could payback $1.58 Billion by 1991 (Giesen, 1988, p. 4). The program focuses on upgrading 88 of the most critical manufacturing operations within Caterpillar, and was originally planned for five years.

Caterpillar is not alone in its quest for viable manufacturing capacity. Caterpillar plans to hire 600 engineering and other technical professionals this year in order to implement the program, and at least one estimate indicates that 40,000 new manufacturing engineers will be required nationwide to satisfy the human resource needs for modernization in the United States.

Managing this extraordinary investment in manufacturing technology is no small challenge. A number of investigators have begun to add to our knowledge about manufacturing innovation uniquely, in the same way that there was a surge of interest in R&D management in the 1960's and 1970's. Most have concluded that it is the management of these new, integrated manufacturing technologies that will make the difference, not the new technologies per se. Technology is a business. It is a business to those that supply the new processes and computer-driven technologies and it is a business to those that apply it. These technologies would not be successfully sold or installed if they did not make a difference.

Effective management of new plant modernization programs is not something that can be taken off-the-shelf and applied piecemeal to these advanced manufacturing technologies. In this paper, we summarize some of the problems and prospects of managing this new generation of technologies in U.S. manufacturing plants based on a four-year study of modernization.

Plant Modernization Study

During the period 1983-1987 we conducted a two-part study of domestic plant modernization. The first phase of this project was a retrospective examination of 41 cases of robotic and FMS supply and implementation which we used to focus the second, more intensive study of plant modernization. This second phase involved random sample data collection in a total of 51 plants upgrading their production processes to become more flexible and integrated. A summary of the results of the second phase of the project is presented here and the final report on the project (Ettlie, 1988a) is available from the author.

Significant Problems During Modernization

We asked respondents installing significant new processing technologies in the durable goods manufacturing industries what their most significant problem was. The results for the first and third panel data collection are presented in Table 1 below. Note that there is remarkable consistency over this two year period and three data collection panels. Respondents continue to name manufacturing software and programming as the most significant problem during implementation of advanced, flexible integrated, manufacturing technology. We have devoted an entire chapter to this problem in our final report and have started a research program on this issue as a result of these findings. In general, we have data that suggests that modernization teams have great difficulty translating their needs into the specific system and therefore, software requirements in manufacturing. Often, significant development tasks are delayed into the software maintenance period on these large modernization projects.

TABLE 1: Significant Problems During Modernization

Which of the following have been major (show stopper) problems?

Most Important Problems

	N (%) 1984-85	1986-87	
a.	2 (5.1)	2 (5.1)	Assignment of personnel
b.	13 (33.3)	10 (25.6)	Software, programming
c.	--	1 (2.6)	Employee participation lacking
d.	3 (7.7)	1 (2.6)	Integration of parts of the system
e.	--	1 (2.6)	Training
f.	1 (2.6)	1 (2.0)	Integration with plant workflow
g.	--	--	Goal not understood
h.	--	--	Measurement
i.	2 (5.1)	2 (5.1)	Design flaws
j.	--	--	Lack of management support (specify mgmt. level ______________)
k.	--	--	Insufficient in-process sensing
l.	--	--	Parts planned for system no longer needed
m.	2 (5.1)	2 (5.1)	Design Engineering, new product development and manufacturing don't coordinate
n.	1 (2.6)	1 (2.6)	We expected a turnkey system
o.	11 (28.2)	13 (33.3)	Other (Please name ______________)
	4 (10.2) missing	5 (12.9) missing	
Total	39	39	

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*Third panel data collection includes 12 replacement cases for attrition.

Synchronous Innovation

Our most significant findings on the project support the general thesis that in order to be successful, modernizing firms must match their new products and processing technologies with innovative administrative practices. These administrative experiments tend to fall into one of four categories:

1. Changes in Organization Structure. Most involve significant delegation of authority and power sharing with lower organizational levels, including blue collar employees.

2. Closer coordination between design and manufacturing. The most important new behaviors here involve adoption of design for manufacture techniques and movement of personnel across this organizational boundary. In earlier panels of data collection, we also found that compatible CAD systems for design and manufacturing engineering were essential predictors of success.

3. Integration with components suppliers. We found that modernization programs that included JIT purchasing and manufacturing as well as new supplier arrangements were best.

4. Closer coordination with customers during modernization. As might be expected, firms that take customers into account by integrating new processes with JIT delivery, and marketing strategy were more successful. However, this area remains the most significant, persistent challenge for modernization, and timing of customer involvement is crucial.

Unique Outcomes of Integration Efforts

As one might expect, no one firm does everything right when modernizing. However, good practices, defined as having a positive impact on some measurable outcome, do correlate with performance measures uniquely, when viewed from the administrative innovative perspective on integrating dimensions.

In Table 2, we summarize these unique outcomes of novel administrative practice for modernization. In general, those novel integrating practices used for new technology deployment and targeted on internal functions, i.e., changing structure and design-manufacturing relationships, impact system focused performance measures. This included throughput time reduction and two-shift utilization, respectively. Those practices targeted at context--suppliers and customers tend to impact measures at the boundary of the business unit, i.e., achieved cycle times, scrap and rework reduction for supplied parts, and changeover time for customers. However, we found plants reported longer implementation times when customers were more involved. Overall, firms reported more than 30% quality improvement over existing plant levels with these new technology systems.

Perhaps the most important finding we have to report is that the more challenging the new technology to a business unit, the more creative it must be in adopting administrative experiments to successfully install, utilize, and learn from the modernization experience.

Prospects for Effective Plant Modernization

Where does the U.S. stand in manufacturing and modernization? It is fair to say that we have made significant progress in the last five years, but we have a substantial challenge yet to face in this area. Utilization rates have generally increased by about 1% per year since 1969 to average about 72% (two-shift). Systems generally run about 65% utilization untended, yet many firms here and abroad achieve 85% utilization rates.

Quality perceptions and internal measures for many significant product groups still favor foreign competitors. Market share and job losses continue to be a persistent concern of American manufacturing managers. Downsizing operations by as much as 35% in some industries is an unfortunate

Table 2.

PERFORMANCE CORRELATES OF ADMINISTRATIVE INNOVATIONS

	Performance Measures				
Dimensions of Integration	**Throughput Time Reduction**	**Utilization**	**% Cycle time Achieved**	**Scrap & Rework**	**Changeover Time**
Hierarchy	√				
Design-Mfg.		√			
Suppliers			√	√	
Customers*					√

*** Takes longer to install**

preoccupation. Yet, part of being successful is to learn from experience, and this experience base is growing. U.S. manufacturing organizations that emerge from this experience will no doubt look quite different and have much different philosophies if they survive into the next century. We are just beginning to see the emergence of these philosophies.

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Heinz-Dieter Haustein

Automation and a New Organizational Mode of Production

Contribution to the international discussion on the factory of tomorrow

Berlin, 1988

Further progress in automation requires to answer two economic questions.

Which will be the saving potential of flexible automation in relation to the labor force engaged in national economy?

Which degrees of automation will probably be achieved by the various fractions of labor force under the conditions of the new historical type of automation?

Our estimates are presented in Table 1 and Fig. 1. Another estimate of the saving potential by CIM technologies in industry for all production workers according to 16 different functional groups resulted in a saving potential of 32 per cent in the USA and Japan (Ayres, Brautzsch, Mori, S. A. 2-6). Our estimates for the GDR show a saving potential of about 2.5 million persons employed. When assuming a compensation of this saving by an absolute growth in the manpower employed in science, the systems of public health and social care, education, culture and art, the number of employees in these fields would have to increase 2.35fold. This will be an average growth rate of 2.9 per cent per year in these areas in the next thirty years.

Fig. 2 shows a forecast of flexible automation measured by the production of automation devices in the GDR. The maximum of this development is to be expected in 2012, that is about 30 years after the maximum of classical single-purpose automation.

Fig. 3. shows the development of the automation coefficient of labor (share of persons employed, engaged in control and supervising at automatic machines, in the total manpower in production). Tendencies are calculated with a logistic function

Table 1

Employment structure of the GDR national economy in 1986 and automation potential

	Total of persons employed		automation degree of labour (in per cent)		savings potential of FA	
	in 1,000	per cent	actual stock	FA potential	column 1 in per cent	in 1,000
	(1)	(2)	(3)	(4)	(5)	(6)
1. material production without maintenance and production preparation	2,796	33	13	40	32	875
2. maintenance	699	8	1	10	10	70
3. science and production preparation	512	6	4	20	38	195
4. trade and services	1,119	13	5	30	36	403
5. administration	2,104	25	6	25	40	842
6. public health and social services	543	6	1	5	5	27
7. education	574	7	1	5	5	29
8. culture and art	91	1	0	0	0	0
9. other fields	101	1	0	0	0	0
Total	8,539	100	9	24	29	2,460

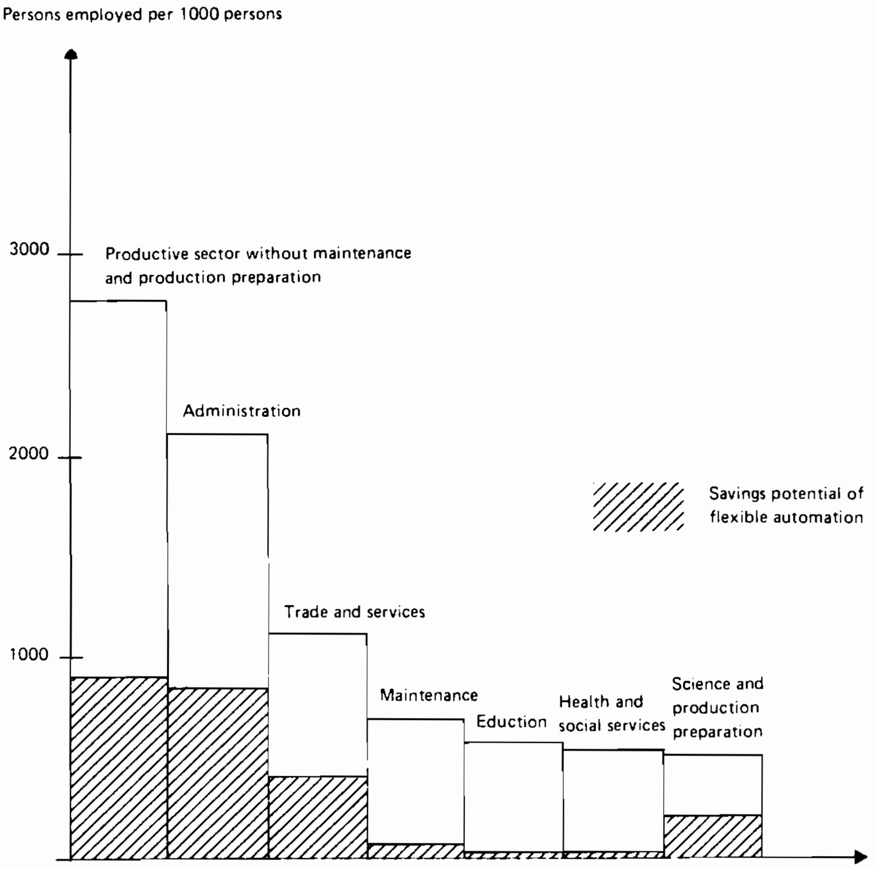

Figure 1. Employment structure of the GDR national economy in 1985 and the saving potential of automation

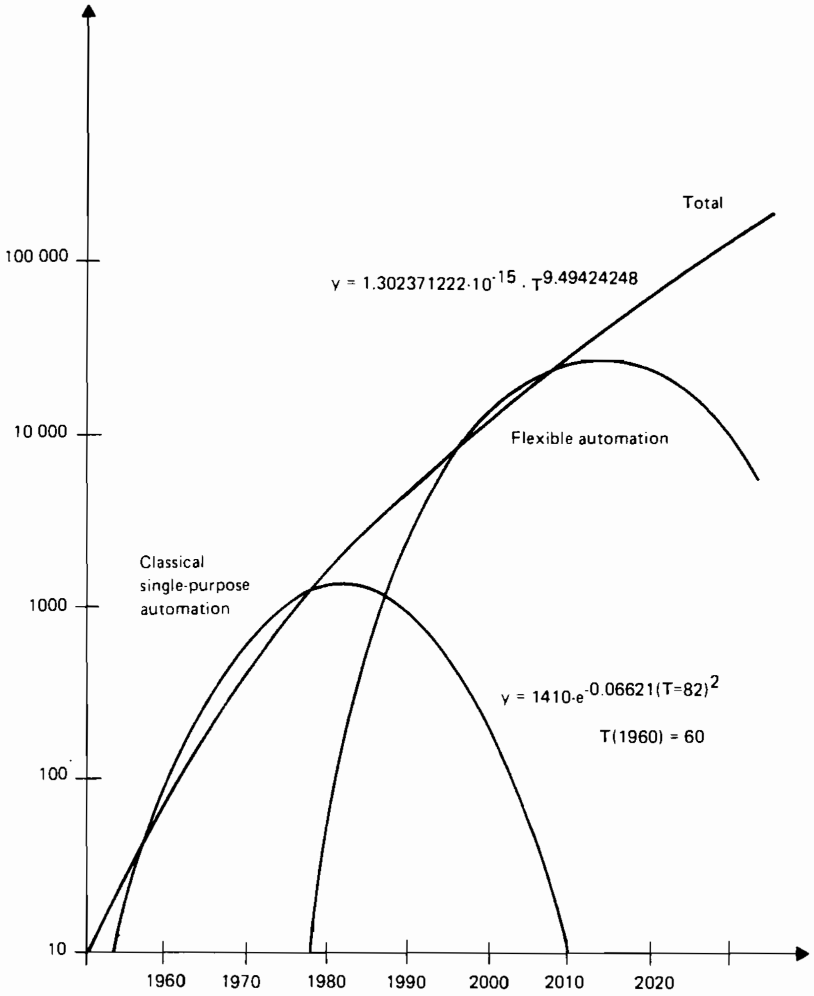

Figure 2. Devices and equipment for the control and regulation of production in mio Mark (prices of 1980) in the GDR

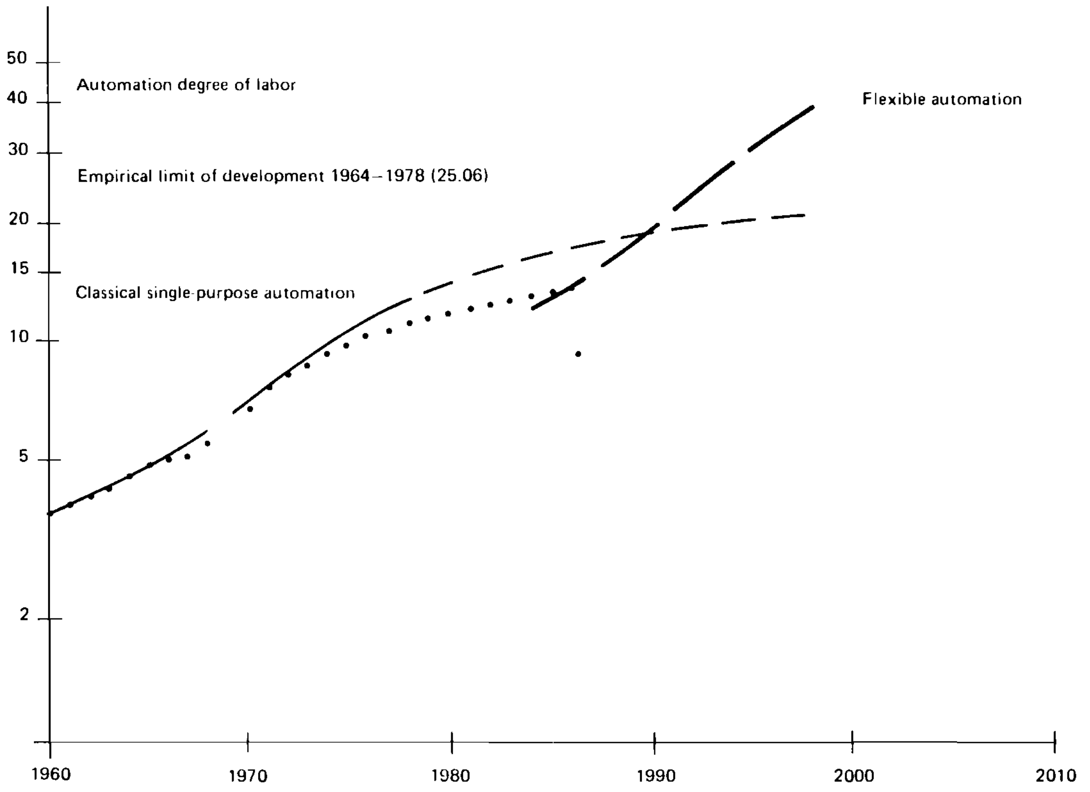

Figure 3. Development of the degree of automation in GDR industry

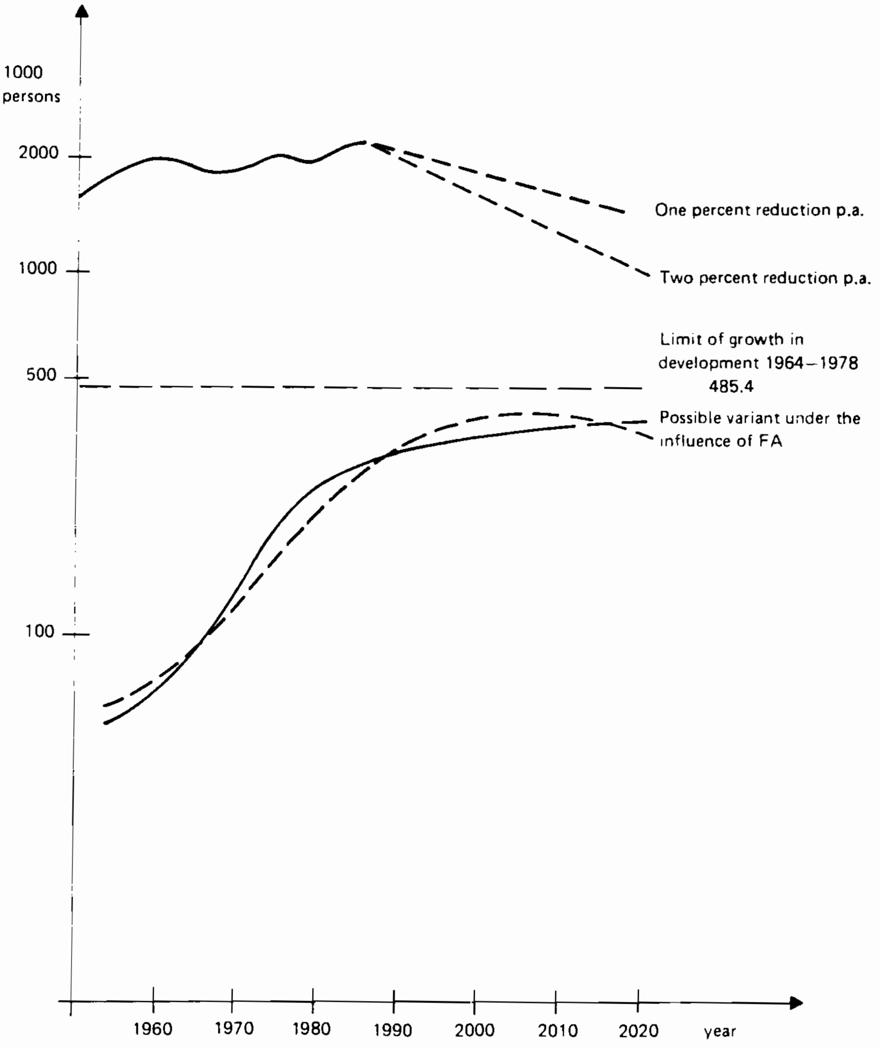

Figure 4. Growth of the number of production workers and workers performing the function of control and checking at automats in GDR industry.

$y = k / (1 + m \cdot e^{-ax})$, and the result is an empirical limit of $k = 25.06$ per cent with the parametres $m = 4.9565$ and $a = 0.1039067$. The actual development after 1978 shows an even stronger saturation. When the same procedure is applied to absolute values, the result is a limit of 435.400 persons with the parametres $m = 5.4235$ and $a = 0.114529$. The results are presented in Fig. 4.

Flexible automation is hopefully to overcome these tendencies of saturation. A new and larger potential of automation will be created which, according to cautious estimates, will be about 30 to 40 per cent.

The compensation effect is the main reason for the slow growth of the automation coefficient of labor in the last years.

The compensation effect and the new organizational mode of production

From 1981 to 1985, 35.500 workers became involved in automated work. In this basis, 201.000 production workers could be substituted according to higher productivity of automated labor as compared with non-automated labor. In the non-automated field, came up remaining functions which required an additional amount of 125.000 production workers for a production growth of 22 per cent. Together with other opposite factors, this results in a considerable compensation effect which in 1985, compared with 1980, brought an additional demand of 43.000 production workers. In the whole productive sector in 1985, the compensation effect was 285.000 persons, that is 36 per cent of the relative reduction of manpower.

What is the reason for compensation effect which we will have to take into account also in the future in connection with the introduction of new key technologies and which is especially high in periods of the use of new technology on a wider scale?

One decisive reason is that organization fails to follow revolutionary changes in the means of labor, and this impedes the change of the social functions of labor in comparison with the change in its technological functions.

Every basic innovation, every new technological mode of production creates a certain potential of efficiency and usage. The utilization of this potential depends on changes in the whole economic and social enviroment.

The technological mode of production is the type of using tools and production instruments, which is the result of a technical revolution and a point of departure for a new type of the operational and social organization of labor and production. Marx used the term "gesellschaftliche Betriebsweise" or simply "Betriebsweise".

The organizational mode of production is the historically determined form of the organization of enterprises, which results from the technological mode of production and whose type is determined by production relations.

The point is that every new historical combination of technological means can fully use its potential only when the organizational mode of production is changed in a revolutionary way. At present we know four organizational modes of production:

1. Handicraft
2. Manufacture
3. Factory with central power drive and workshop principle in manufacturing

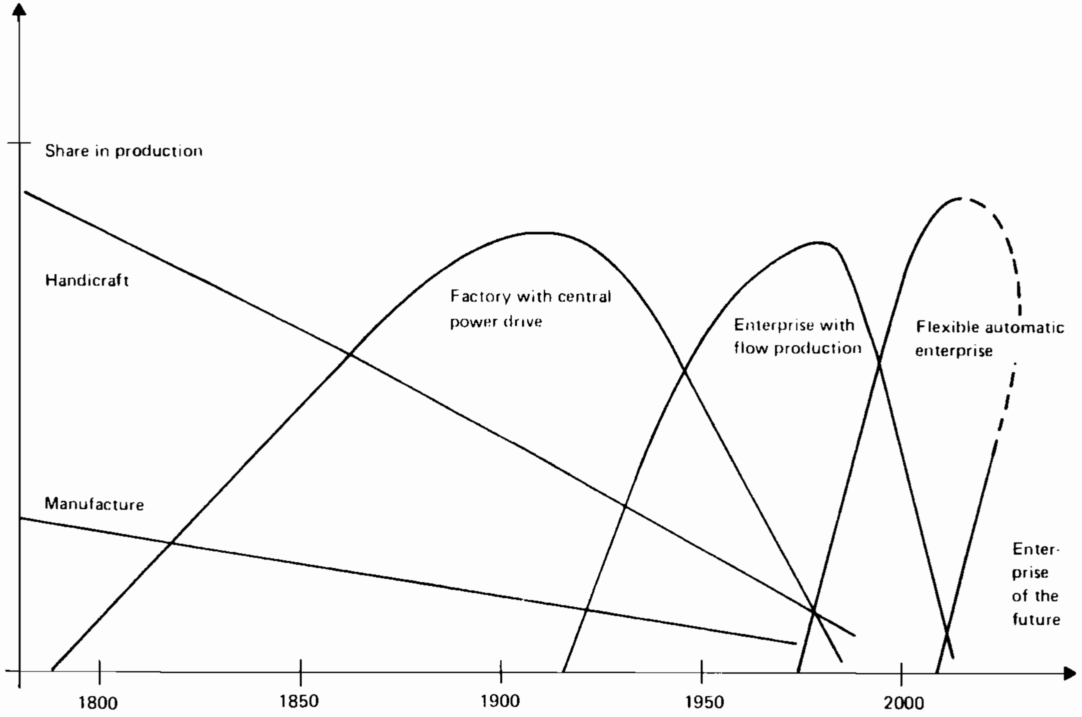

Figure 5. The historical development of the organizational mode of production.

4. Enterprise of object-specialized conveyer belt manufacturing with decentral power drive.

Fig. 5 shows that these organizational modes of production are co-existing even today.

At present we are facing the transition to a new organizational mode of production, to flexible production. The enormous potencial of efficiency of the technological revolution of information processing on the basis of microprocessors can be fully used only when profound changes are made in the traditional organization of production in enterprises and the society as a whole.

<u>New organizational paradigms of production</u>

Historical development of production is connected with ~~stability and for~~ a change in organizational paradigms. An organizational paradigm is a certain pattern in the combination of labor functions with the means of production, which depends on a given technological mode of production.

In Table 2 we tried to summarize some essential characteristics of various historical modes of production. These are as follows:

- the characteristics of technology or the system of the means of labor;
- the dominating type of replacing technological labor functions;
- the type of automation;
- the general agent;
- the main dynamic component of costs DCC;
- the law of cost of the organizational mode of production;
- the type of compensation effect;
- the organization principle of manufacturing in enterprises;

Table 2

Characteristics of various historical types of the mode of production

mode of production	characteristics of technology or the system of the means of labor	prevailing form of replacing technological functions of labour	type of automation
1. handicraft	manual	-	sporadic use of machinery
2. manufacture	manual; differentiation of the instruments of labor	-	sporadic use of machinery
3. factory	machinery with central power drive	energetic function	single automats
4. enterprise of flow production	machinery with decentralized power drive	operating function	transfer lines; means of single-purpose automation
5. enterprise with flexible automation	developed system of machinery (material-changing machinery and information processing machinery)	controlling and logic function	flexible automation (CIM technology, machine intelligence, highly developed software of FA)
6. enterprise of the future	self-renewing systems	elementary processing of knowledge	binary automation; highly developed AI technology

general agent GFA	main dynamic component of expenditure	bottleneck and effect of compensation
skilfulness of craftsman	-	-
virtuosity of detail worker	decreasing costs of learning; decreasing value of manpower	increasing transport cost in the workshop
steam engine	low-cost coal, railway transportation, steel and driving energy	increase wage cost and increasing expenditure of living labour outside the main processes
electric motor	low-cost oil and energy-intensive materials	increasing transport cost and fixed cost especially with regard to management and administration
microprocessor	low-cost microelectronics	increasing software expenditure, increasing cost of information
software tools of AI	low-cost information	-

law of expenditure	principle of enterprise manufacturing organisation	type of the social organisation of production
specialization of trades with limited competition	variable within the frame of guild laws	division of labour among guilds
learning curve of unit costs	hegerogeneous and organic manual division of labour; simplification of operations of labour	division of labour in the manufacture; combination and specialization
substitution of living labour by materialized labour in the field of main processes	workshop principle (procedure-oriented); gradual transition to serial production of exchangeable components; transition from customer-oriented manufacture to stock manufacture	vertical and horizontal division of labour; competition of production
economy of scale (law of mass production); increasing share of costs of material and decreasing wages	operational principle functional division of labour (Taylorism)	increased vertical division of labour; more intensive use of science
decreasing cost of change over with increasing variety of production	combination of functions; transition from stock manufacture to customer-oriented manufacture	increased combination of production and reproduction processes (diversification)
-	elimination of division of labour between disposition and operation	elimination of traditional branch-based division of production

- the type of social organization of production.

The organizational mode of production as a type of productive organization is not determined by the new ensemble of technological means directly but by the relationship between the dynamics of expenditures and benefits or dynamics of costs and profits, which are constituted by this ensemble. There exists a correlation between technology and economy, and the respective technological revolution is driven by revolutions in demand and costs tremendously. This correlation occurs in the concrete historical agents of the productive forces, which are brought into movement in industry as a result of the application of scientific achievements'. The potential of efficiency of these agents is not proportional to the direct labor time used for this purpose. But it depends on the general state of science and the progress in technology, or the application of this science on production (ibid.). These agents are of a concrete technological-historical character. They represent the technological implementation of certain scientific principles of action PA. For example , the agent of the dynamo and later the electric motor (1879, Siemens) results from the principle of the dynamoelectric effect (1866, Siemens). Out of the large number of agents, those are of special importance which are of the character of general agents GA.

The electric motor is the GA of the fourth organizational mode of production, the microprocessor is GA of the fifth organizational mode of production, and software tools of artificial intelligence may be the GA of the following organizational mode of production.

A general agent GA is to apply principle or a scientific effect in a new technical and economic resource which has the characteristics of universal availability, unlimited expansion and dynamizing the structure of the overall expenditure (see Perez, p. 60). Let us deal with the characteristics of the GA more in detail:

First, the GA determines the main dynamic component of costs DCC directly. In the third organizational mode of production, this is coal, steam as drive energy, later also low-cost railway transport and steel.

In the fourth organizational mode of production, oil and energy-intensive low-cost materials occupy the position of DCC, and in the fifth organizational mode of production, this is the whole hardware-based microelectronics with its enormous price deceleration.

Second, the DCC influences the cost dynamics not only as a special kind of cost with regard to the emergence of costs but the GA as its basis also becomes a key factor with regard to the cost effect, that is, it changes the whole structure and dynamics of costs and provides a decisive impetus to cost reduction on the scale of the society. For example, the present-day use of microcomputers in the preparation of production is an important factor of effect as to reducing the cost of materials.

Third, the GA is available in a practically unlimited manner. It brings qualitatively new progress with regard to resources which are available without limits. Steam power is accessible more universally than water power. The electric motor brings a new stage of availability as compared to steam power. The microprocessor overcomes the limits of traditional electromechanical expensive and voluminous control technology and classical data processing. Hardware and the software environment of artificial intelligence will eliminate the limits of the expenditure of programming.

However, the above three characteristics do not explain sufficiently the extreme economic drive of the GA with regard to implementing a new organizational mode of production.

The fourth characteristic is the almost unlimited potential of extensive and intensive expansion. The GFA brings about a superexponential growth of the number of applications and basically new possibilities to create additional new values by new products for new or known fields of needs.

It determines the main dynamic component of expenditure and, together with the whole constellation of needs and resources, brings about the constitution of the law of cost for the respective organizational mode of production.

To say it briefly, there exist historical laws of cost of the respective organizational modes of production. Processes of devaluation, which occur as a result of tendencies of saturation in the old organizational mode of production, and which suddenly accelerate like an avalanche in the form of the transition from quantity to quality, require the transition to new dynamics of costs.

Every technological revolution solves basic trade-offs of the system of productive forces by means of a main dynamic component of expenditure. This component of costs DCC develops into a vehicle of intensification, it has an effect on all elements of costs and creates a new potential to reduce socially necessary costs in three directions:

First, through the creation of new possibilities to create additional new values.

Second, through the constitution of new or changed causal relations of costs.

Third, through the acceleration of the circulation and turnover of capital.

Oil and energy-intensive new low-cost materials were the dynamic factors of cost of the fourth organizational mode of production (see Perez, p. 63). Conveyor belt manufacture and increased vertical division of labour with relatively small costs of transport brought about a further reduction of the share of wage costs. The economies of scale were connected with considerable savings. However, by means of its upswing, the old organizational mode of production brings about its decay at the same time. In this case, the compensation effect appear as the gradual growth of costs of transport, the cost of production preparation, management and administration as well as lay-off and waiting times of the information processes LTIP and the lay-off and waiting time of the reproduction process LTPR.

Characteristics of the new organizational mode of production

Main characteristics are presented in Table 3. The new mode of production cannot come into existence before the wide application of new technologies.

It is possible to say something about the new, the fifth organizational mode of production because its characteristics are already visible at the front line of industrial development in the world. The actual organizational mode of production of the future, the sixth stage, however, is still rather vague. It may happen that it will question the principle of product specializa-

Table 3

Characteristics of the old and new types of the organizational mode of production

No.	Characteristics	old mode of production at its saturation stage	new mode of production at its stage of upswing
1	stocks	are considered to be a resource	are considered to be losses
2	order processing time	months	days
3	time of change-over	days	minutes up to disappearance
4	quality	80 - 90 per cent	100 per cent
5	development of assortment	unification, prevailing standardization	growing variety
6	date of delivery	right to the week	right to the day and time of the day
7	size of order	increasing	decreasing
8	deliveries	month-related demand	hour-related demand
9	product innovation	10 - 20 per cent	30 - 40 per cent
10	curve of learning in case of introducing new products	steep and long	flat and short up to disappearance
11	economic analysis	traditional patterns of costs, time factor is taken into account to a small extent	new pattern of cost structure, time factor is taken into account more strongly

No.	Characteristics	old mode of production at its saturation stage	new mode of production at its stage of upswing
12	division of labour	prevailing vertical specialization	increasing combination and diversification
13	information processing	manual; mechanized and increasing division of labour	microcomputer and networks
14	flow of information	slowing down	for acceleration
15	equipment	increasing size unit	increasing efficiency of smaller standard units
16	reaction of production systems on changing market demands	increasing inflexibility	flexibility; closer contacts to the customer
17	order control	by means of mean values (funnel principle)	order-concrete control
18	prevailing type of automation	single-purpose automation	flexible automation
19	managerial system	increasing number of managerial levels and functional bodies	increasing integration of managerial levels and functional bodies; increasing importance of horizontal relations
20	degree of integration	increased complexity; that is, automation of non-integrated sections of manufacture	computer-aided integration of phases and functions of the reproduction process

tion and return to a principle of procedure-specialized manufacturing at a higher level. This would have a serious affect on the whole system of division of industrial labor.

Let us deal with the fifth organizational mode of production which is gaining in importance today although its share in manufacturing is still lees than one per cent.

The share of workshop manufacturing (process-specialized manufacturing), which was more than 90 per cent in piece goods production at the turn of the century, has been reduced to 30 per cent in developed industrialized countries. Respectively, the share of product- specialized conveyer belt or group manufacturing has already increased to 70 per cent. In the fifth organizational mode of production, the principle of group manufacturing will grow further. This principle was developed theoretically by Mitrofanov in the 1950s.

Table 4 shows the situation and development trends in the organization of manufacturing in the GDR metal-working industry.

The fifth organizational mode of production, with an increasing share of serial production, brings about a fast growth of flexible computer-integrated group and low production. This new type of manufacturing organization according to the principle of alternative production has the following characteristics:

1. It is based von computer integration of manufacturing.
2. It is connected with an increased autonomy and extended competences of the departments of manufacturing which assume functions of work preparation to some extend. Thus the time of reaction are shortened and departmental barriers are eliminated. On the other hand, certain functions can be centra-

Table 4

Kinds of manufacture and principles of the organisation of manufacture in the metal-processing industry of the GDR in 1986 (share in per cent - (+) is increasing and (-) is decreasing)

organisation of manufacture kind of manufacture	Total	workshop principle	flow line principle	group principle
single manufacture	15 (-)	12 (-)	-	3 (+)
serial manufacture	65 (+)	20 (-)	10 (-)	35 (+)
mass manufacture	20 (-)	2 (-)	9 (+)	9 (-)
total	100	34 (-)	19 (+)	47 (+)

Calculated according to date from the Statistical Yearbooks of the GDR.

lized in a purposeful manner. A new combination of centralized and decentralized functions will emerge.

3. It offers more possibilities for the change of labor and labor functions, which Marx considered as a law of production in a future organizational mode of production (see Karl Marx , Capital, Volume I). This will make it possible to accelerate combination instead of division of labor.

4. It connects the degree of continuity of low production with the potential of flexibility of workshop manufacturing. The working process of a flexible production section can be more permanent than the working process of a conveyer belt.

5. It brings about the transition from single workplaces to collective workplaces of the system of flexible manufacturing, where various operations are carried out for the manufacturing of a certain group of products. At a higher level, organization comes back to the complexity of handicraft production.

6. The principle of alternative production uses the advantages of all preceding organizational principles of manufacturing, and it is applicable to all kinds of manufacturing. It makes it possible to change from one kind of manufacturing to the other rapidly and according to the demand of the market.

Economic concept of flexibility

Economically seen, flexibility is the ratio between variety V(t) and expenditure on change-over U (t)

$$F(t) = \frac{V(t)}{U(t)} \qquad (1)$$

Variety is determined by the product of its range (number of different products) and depth (degree of differentiation).

Its purpose is to promote the production of new customer-adapted products with the creation of a higher additional new value also in relatively small commissions, and to minimize losses resulting from stocks of standardized mass products which cannot be sold.

Flexibility can be measured by terms of manufacturing technology, various international concepts of measurement exist for this purpose (see Gerwin, Buzacott). When the term 'flexible automation' is being used, this means an extremely limited kind of variety in present-day practice. It applies to a very limited spectrum of product variants. The respective technology can only master changes in a certain limited range of variety. Every serious qualitative change in the demand, however, touches the range of variety and results in a [illegible] and high increase in the change-over costs. It happens rather often that this brings about a very rapid moral depreciation of existing systems of flexible manufacturing.

In fields with rapid changes of demand, a difference has to be made between short-term flexibility with a small range of variety or no range of varienty at all, and long-term flexibility with a larger range of variety.

An economic concept of flexibility is of a more comprehensive character than the appreanches mentioned above. It measures variety throught the increase of profit from flexible production, and the expense on change-overs throught the costs.

Thus economic flexibility is

$$F^{x}(t) = \frac{GV(t)}{UK(t)} \qquad (2)$$

GV(t) is the additional profit from flexible production as a result of the higher level of product innovation and reduced losses from unsaleable stocks of finished products.

UK(t) = costs of change-over.

An economic concept of flexibility means that flexible automation is not always the ultimate solution. Under certain conditions, rigid solutions or sub-solutions of automation may continue to be the most efficient methods.

Actual flexibility in the economic life is not a mere function of technological systems. The flexibility of an organizational mode of production depends on certain characteristics of technology, organisation, manpower and the economic mechanism in their interdependences. The new, fifth, organizational mode of production results from the necessity to considerably advance flexibility because of a higher speed in product innovation, aggravated competition, a long-term slowing down of the reproduction process in the late period of the fourth organizational mode of production and the potential of flexibility in microelectronics.

When analysing the lawful relations of expenditure of the flexible mode of production, the following facts have to be taken into account:

- chances to make extra profits from higher degrees of product innovation;
- economy of quantity-fixed costs;
- economy of the change-over costs;
- reduktion of losses by stocks of unsaleable products;
- possibility to increase sales by flexible prodction;
- price movements of flexible and non-flexible production.

For this purpose, a computer simulation model MUFLE was developed.

Further empirical studies will have to be made in future. Data of international comparisons show that the maximum range of variety of flexible manufacturing systems grows rapidly on an international scale. The average range of variety, however, develops only very slowly. 32 per cent of existing flexible manufacturing systems are only able to produce not more than ten product variants. The actual utilization of the range of variety, is even smaller (see Chegrin, Tochijow, S. 15).

This is caused by the fact that the change-over cost would not only depend on the flexibility of equipment but also on the flexibility of the production or orientation which changes more slowly than technical and technological conditions.

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THE DEVELOPMENT OF INFORMATION-INTEGRATION:

BEYOND CIM?

by

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THE DEVELOPMENT OF INFORMATION-INTEGRATION: BEYOND CIM?

1: INTRODUCTION

In this paper I essentially want to examine conceptual issues relating to the dynamics of development of CIM, rather than presenting yet more empirical statistics which chart progress. A critical examination of some of the concepts involved in the analysis of CIM and associated developments will help in relating these developments to broader theoretical frameworks, in identifying the underlying forces driving and influencing current developments, and in perhaps identifying areas which deserve further empirical research attention.

This analysis will also serve to situate and motivate various studies[*] carried out at Edinburgh by myself and colleagues.

In a nutshell, these Edinburgh studies are concerned with the underlying dynamics of development of technical change; ie. with the processes whereby these new technical forms come into being. We have adopted the label "social shaping" to identify our approach and to distinguish it from other approaches. These include (a) studies of social impacts or implications, which take the technology as given and are concerned with the working out of its effects; (b) technological determinists, who would argue that there exists an internal technically-hermetic dynamic of change, ie. new technologies stem purely from previous technologies, so that human actors become reduced to facilitating or inhibiting supporting roles; and (c) those neo-classical economists, who, although agreeing with us that technological change is not purely technically determined, would argue that it is economically-endogenous, ie. that it is essentially economically determined, and would not necessarily go along with our emphasis on the social, which we view as including the economic (much to the irritation of many economists, I might add!).

In line with my discussion below on technological components, one can regard the various Edinburgh projects as basically concentrating on the development of particular components. These include previous studies of missile navigation technology, numerical control, my own studies on industrial robots, and studies of a technologally (or instrumentally) based scientific specialty, radio astronomy. Current studies include an analysis of development in artificial intelligence (and expert systems), a real-time tracking of development of parallel computers with especial attention being paid to the Transputer, and, the project of most relevance to this meeting and one I will say a little more about below, a study of the emergence of company-wide configurations (again more on this below) of information-integrated automation (IIA), and including as a major focus the role and deployment of models of work organisation, which feed into the future development of IIA as a crucial causal variable. Closely related to this project, (which is entitled the "Organisational Shaping of Integrated Automation"), is a study focussing on the role of computer personnel and their interactions with top-level "strategic " management, in bringing about significant innovations in the financial services sector. This we see as looking at a broad equivalent of CIM, but in the service sector, hence our use of the term "information-integrated automation". A new project is also about to commence, which will focus on the customer-supplier

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[*] See: Report of Research Progress to PICT Steering Committee, RCSS, Edinburgh University, 1988, for further details

relationship in technological development.

In addition, there is a planned project on the comparative role in the UK and Japan of "national systems", ie. the institutional and organisational arrangements (eg. including user-supplier infrastructures), within which specific developments, especially in R&D take place. In this project, we will cross-link with the other projects, eg. by comparing development of the transputer and the tron chip.

A final project is intended to examine developments in software aimed at "proving" correctness of particular programs, and thereby avoiding expensive errors and maintenance, to help overcome the "software crisis", currently seen as constituting a bottleneck in technical progress in information technology in general.

The core of the argument of this paper is that the information-integration (and hence CIM) development process is extremely complex: lines of technical development are not anything like as clear or straightforward as is often thought; patterns of development across different industries and organisations are highly variable and contingent to those organisations and industries; the implementation process of information-integrated automation is relatively intractable, and the resolutions of difficulties during implementation are a major source of innovation and novelty; and finally the context and process of developments demand detailed longitudinal case-study analysis in order to help identify the qualitative issues involved and in order to help us to clarify our understanding of how new operating systems actually come out of pre-existing technical, social, organisational, and economic complexes.

Given the complexity of the information-integrated development process, therefore,it becomes crucial that we do not foreclose on what we think the "factory of the future" will look like; we must be circumspect when we go acquiring and interpreting statistics which purport to indicate development, as the very process of abstraction necessary for generating statistics can obscure fundamental qualitative shifts; and we need real-time studies of the emergence of new forms of operating system.

2: WHY INFORMATION-INTEGRATION RATHER THAN CIM?

It is perhaps appropriate at this point to comment on the focus on information-integration rather than CIM. There are several reasons.

One is that , as Ayres points out (1), the current wave of technical changes are based on fundamental developments in microelectronics rather than computers *per se*. Further, there is little doubt that a drive to integration is the key dynamic of development, even though, as we discuss below, this is certainly not unproblematic (4). Moreover, this drive to integration is proceeding on a far wider scale than just within the factory: in various different forms (telecommunications, the just-in-time supply revolution, revised global strategies on the part of major multi-national corporations, etc.), integration is occurring between office and plant, between design, production, and markets, and along the supply-chain. Perez calls this trend "systemation" and identifies it as one of three key elements which together constitute an emerging techno-economic paradigm which is taking shape around microelectronics (12). The other elements are (a) a relative shift of emphasis from economies of scale to economies of scope, ie. the increased importance of flexibility; and (b) a move towards an economy which is based on information-intensive rather than energy or materials intensive products and processes.

As regards (a), there is little doubt that such a tendency does exist in reality, although claims for increased flexibility are more often than not over-exaggerated (xx). It is very instructive in this respect to to compare the present situation with that described in Bright's classic 1958 study, Automation and Management. Many of Bright's observations are still highly relevant today (indeed, some are further discussed below); the major discrepancy is that the major drawback to automation as it was then, was identified by Bright to be the attendant loss of flexibility. However, once again, it has to be noted that many of the claims about flexibility of robotic systems and FMS's have to be strictly qualified.

As regards (b), the move towards information-intensity, there is ample supporting experiential and empirical evidence (xx). The interesting thing to note here is that in fact developments concerning pure information aspects are moving far faster than those involving any interface with material reality, ie. the specifically manufacturing aspect. Such developments as value added data services (VADS) and electronic data intechange (EDI) seem set to transform the nature of the manufacturing organisation more rapidly and radically than CAM or CIM. For instance, in the course of 1988-89, IBM, Greenock in Scotland aim to have their 50 major suppliers on line, thereby eliminating traditional paper exchange, documentation, and authorisation. At the same time, despite extensive use of robots etc, they still have significant manual involvement. Indeed, certain of their high-tech developments have already been superceded by more recent approaches to flexibility in manufacturing (see below).

For these various reasons, then, it would seem that the natural unit of reference is indeed information-integration. The question-marked clause "beyond CIM?" in the title , as well as inviting consideration of this point is also intended as an ironic gesture towards the academic game of jumping on the band-wagon of the latest trendy buzzword.

3: ANALYSING THE DEVELOPMENT OF INFORMATION-INTEGRATION AND CIM

While in the longer term, progress towards a greater degree of automation in manufacturing and other sectors appears inexorable, so that the numbers of people employed in manufacturing will decline in much the same way as has happened in agriculture, technical progress is not a simple straightforward matter that can be unproblematically extrapolated from current trends.

The uncertainty of technical development

There is a high degree of uncertainty about technical developments. Although there seems to be a very clear example of the working out of a technical trajectory in the developments of basic microelectronics technology, as indicated by the continuous and apparantly guaranteed improvements in memory capacity and processing power (1), this progress is achieved via a highly volatile process of technical experimentation and economic competition with different alternatives. Currently, for example, there is activity with laser-based circuits as well as electronics, and even more speculative efforts with forms of biotechnological computation. In the area of computational architecture development, there are something like 50 different approaches to attempting to achieve parallel processing (xx), and at present it is extremely difficult to identify the winners, or accurately forecast what specific domains of application are likely to benefit most from these development. Moreover, as analysis of the transputer case indicates, success is not just a matter of the pure hardware technical performance parameters, but also depends on the development of an effective software support infrastructure: the use of the new language OCCAM for instance has led to some difficulties on account of a small user base for the language.

With respect to factory automation, the range of possibilities is even wider. We can share Diebold's 1952 doubts (quoted by Freeman, 9) about whether the workerless factory or paperless office of popular prognostication will ever emerge.

(the "workerless factory" absorbed as a subcomponent of new structures)
(Simons beanbrick economic arguments xx)

The problem of interpretation

These issues of uncertainty are compounded by the question of the interpretation of these technical developments and their causes and consequences. For instance, why has there been a general decline in productivity accompanying the widespread and (some would argue) unprecedented diffusion of the new microelectronics technologies? -what Freeman calls the "productivity paradox".

Clearly part of the answer lies in the fact that productivity and profitablility are not simply determined by the technical components, but rather by the overall operating system as a whole, where the operating system may be defined in standard operations management terms as the configuration of resources - financial, human, and technical - which work together to achieve the organisations overall objectives. We can usefully extend this conventional notion of an organisationally-based operating system to an industry-based system, which would include issues concerning the efficient allocation of tasks and resources among the various members of the vertical supply chains, and the horizontal product complementarities. The increasing importance of such issues is reflected in growing interest in business logistics, just-in-time supply philosophies, etc. The important point to note here, of course, is that the hardware and software technical components play only one part in the overall organisation or industry operating systems. It proves remarkably difficult in practice to translate machine performance into business performance, even with such well-established technologies as numerically control machine tools (xx).

The effective exploitation of the new technological opportunities thus requires considerable organisational adaptation at the level of the company, and considerable restructuring at the level of the industry. Freeman and

Perez (9) recognise these changes and argue they should be placed in the context of long waves of industrial development (10). At present, they argue, we are in the midst of the crystallisation of a new techno-economic paradigm, incorporating a Shumpeterian revolution based on combinations of innovations associated with microelectronics and computers. As Freeman argues: "the current developments in FMS and computer-integrated manufacture (CIM) are part of a worldwide trial and error search for the most effective forms of development and application of the new techno-economic paradigm". (1987, p13). The relative success of the Japanese in industrial economic terms stems essentially, on this view, from their having already made progress towards this restructuring. The basic dynamic then, is one in which widespread experimentation is taking place in order to find out how to best exploit the new opportunities opened up by the the new ICT paradigm.

In somewhat of a contrast to this view, is the argument put forward by J.R. Beniger (3). Beniger suggests that the current revolution is not so much a response to new opportunities arising out of microelectronics and computer echnologies as much as a resolution of problems of control and communication which have arisen and accumulated as a result of changes in transport and communication structures which started as long ago as the mid 19th century. By the turn of the century, the increase in the speed of social and economic intercourse had brought about a crisis of control, as traditional methods of managing these activities proved inadequate. Advances in technology from the 1850s onwards, primarily the railroad, telegraph, and steam-driven printing press, had resulted in a speed up first in distribution, then in production, and finally in consumption, whilst the ability to manage and control the flow of goods, raw material, and information simply did not keep pace, and thus created strong pressures for innovations to resolve the crisis, culminating in the present microelectronics developments.

The need for analytical concepts

Given these difficulties over the uncertainty and interpetation of developments, there is a need for reviewing and clarifying concepts which might help analyses at more immediate and pragmatic levels. The analyses in which I am interested concern the specific paths and processes of development, the particular opportunities and threats confronting practitioners at the sharp edge at any one time, the options and alternatives which exist, and the capacity of particular organisational and infrastructural arrangements for exploiting or accommodating them. For these purposes we need concepts which go beyond a categorical description of the technical elements, and which offer some purchase on the dynamic relationship of these elements to the domains and contexts of their use.

In exploring developments at this level, it is not sufficient to work with a single unilinear scale of automation progress. A more articulated set of concepts is required to enable us to map out the structured and interrelated patterns of develpment that are taking place. Bright's identification of 17 levels of automation are a useful starting point in this respect (see fig. 1) and indeed Ayres utilises an updated variant (2). Bright's notions of scope and penetration of automation are also quite useful, and indeed are further discussed in the next section on patterns of development.

However, some means of relating different types of developments across different areas and capturing the notion of integration are also required.

SEVENTEEN LEVELS OF MECHANIZATION AND THEIR RELATIONSHIP TO POWER AND CONTROL SOURCES

Initiating Control Source	Type of Machine Response		Power Source	Level Number	LEVEL OF MECHANIZATION
From a variable in the environment	Responds with action	Modifies own action over a wide range of variation	Mechanical (Nonmanual)	17	Anticipates action required and adjusts to provide it.
				16	Corrects performance while operating.
				15	Corrects performance after operating.
		Selects from a limited range of possible pre-fixed actions		14	Identifies and selects appropriate set of actions.
				13	Segregates or rejects according to measurement.
				12	Changes speed, position, direction according to measurement signal.
	Responds with signal			11	Records performance.
				10	Signals preselected values of measurement. (Includes error detection)
				9	Measures characteristic of work.
From a control mechanism that directs a predetermined pattern of action	Fixed within the machine			8	Actuated by introduction of work piece or material.
				7	Power Tool System, Remote Controlled
				6	Power Tool, Program Control (sequence of fixed functions).
				5	Power Tool, Fixed Cycle (single function).
From man	Variable			4	Power Tool, Hand Control.
				3	Powered Hand Tool.
			Manual	2	Hand Tool.
				1	Hand.

Figure 1 Source: Bright (ref.6)

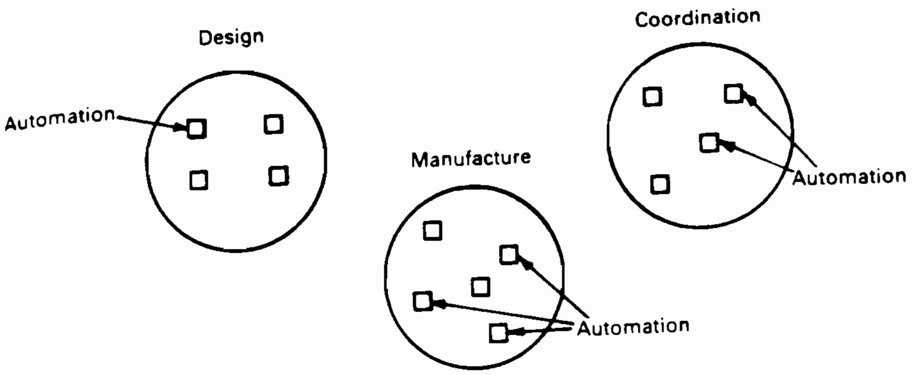
As kaplinsky (11) points out, Bell's 1972 distinction between the separate key components of control, transformation, and transfer can help in analysing automation within a process. This allows for various heirarchical degrees of automation (following Bright), but also allows for the fact that a high level in one area need not necessarily be associated with a high level in the other two. The distinctions are particularly pertinent in respect of modern factory automation, with microelectronics directly accelerating developments in control and indirectly, through robotics, in transfer. Transformation, on the other hand, being more intimately connected with the nature of the physical processing, has been more subject to developments outside microelectronics - such as spark erosion, laser cutting, and materials innovations in general, for example. This has meant that automation in transformation has been very uneven, contingent as it is upon these particular developments. Nevertheless, there is a high degree of interaction between the three components, as witness developments in numerical control in metal machining.

Kaplinsky's own analysis is useful for considering processes of integration. He distinguishes between three spheres of automation, namely design, manufacture, and coordination: these are distinctions which rest essentially upon the broad functional division of labour conventionally found in reasonably differentiated organisations, ie. organisations of any size other than the very smallest. At the same time he distinguishes between three different types of automation: (a) intra-activity automation, which is restricted to a particular activity, ie. island automation; (b) intra-sphere automation, which refers to technologies which have links with other activities within the same sphere, eg. line automation, and (c) inter-sphere automation, which involves coordination between activities in different spheres, eg. CAD/CAM linking design and manufacture (see fig.2).

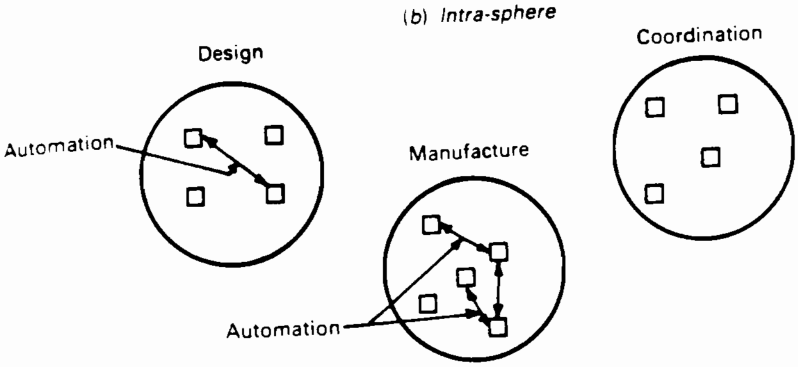
However, even Kaplinsky's 1984 typology is not fully adequate for developments in the broader context. It has become clear, for example that automation in non manufacturing sectors ("office automation") is developing in parallel with "factory automation". Some developments are also occurring in the area of very high level strategic decision making (eg. management information systems, expert systems etc.), which are not really adequately describable as office automation, and perhaps deserve the separate label "administrative automation". These further terms are based on the industrial-organisational context rather than the nature of the activity (Bright and Bell), or the organisational function (Kaplinsky), being automated. In the light of these terms, an immediate extension to Kaplinsky's typology offers itself, namely "inter-organisational automation". This clearly is relevant for such developments as VANS and VADS etc., and for describing developments which fit in with the wider ramifications of Perez' notion of systemation.

The above terms provide a convenient conceptual grid for analysing and mapping automation in as much as the nature of the application domain is concerned. But it would also be useful to develop terms that refer more directly to the intrinsic characteristics of the technologies employed, and that enable us to relate these characteristics to the nature of the development process, and in particular to the degree of user involvement necessary for their effective exploitation. In this connection, we can make useful distinctions between discrete technologies, component technologies, system technologies, and what I shall call configurational technologies.

(a) *Intra-activity*



(b) *Intra-sphere*



(c) *Inter-sphere*

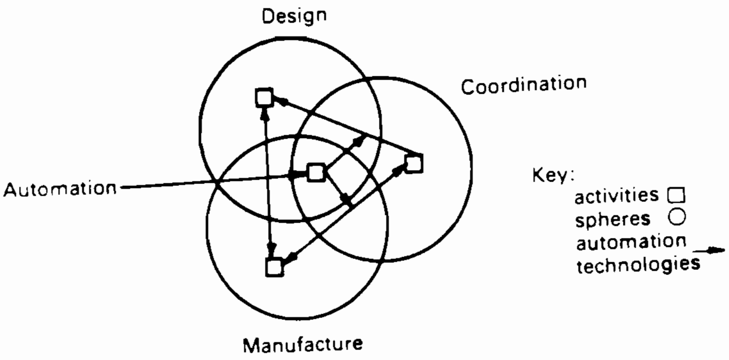


Figure 2 Source: Kaplinsky (ref.11)

Discrete technologies refer to those products (and to a lesser extent processes), which the ultimate user or consumer can make use of in a direct and immediate manner, as a self contained package, independent of other such packages, requiring no learning or interfacing with other elements, and hence discrete in its implications. Such a characterisation is of course an idealisation, but nevertheless captures the nature of many consumer products, and even some processes, where, for example, new innovations are embodied in the technology to substitute for existing elements without changing the basic functions of the process, so that from the point of the user, there is no significant learning or adaptation: the only perceivable differences are perhaps in price, or in improvements along the existing dimensions of performance. Clearly discrete technologies do not require the active participation of users, beyond their selection decisions in the market place to transmit patterns of preferences and the scale of demand to the suppliers. And so teams of autonomous R & D researchers may well come up with appropriate innovations.

System technologies refer to complexes of elements or component technologies which mutually condition and constrain one another, so that the whole complex works together, and the implications of certain innovations have to be worked through the overall system, in all likelihood necessitating changes in several components, as well as involving changes at the level of the system as a whole. For instance, in aircraft design, attempts to gain the benefits of reduced air friction at high altitudes, necessitate pressurisation of the cabin, and the development of engines able to perform efficiently at the range of altitudes envisaged. With component technologies, it is often possible to make innovations within relatively stable design specifications set by the functional requirements of the overall system, and thus improve overall system performance; the substitution of lighter plastic materials for metal in the construction of car bodies, or improvements in the power/weight ratio characteristics of the engines used , are examples here.

Clearly, various different communities and groups of knowledge carriers, each commanding relevant components of knowledge, have to cooperate closely together for innovation in such cases. One would also expect a new body of expertise to emerge at the systems level, concerned with the overall operation of the system rather than the workings of particular components. According to the extent to which systems are stabilised and standardised and therefore require little in the way of customisation, there will be a correspondingly lesser or greater need for active user involvement. The more standardised, the more conditions will approximate to those for discrete technologies, but with a greater level of complexity in terms of the number of different groups involved on the supply side. With component technologies, similar considerations obtain, except that the users/consumers in this case consist of the system suppliers. Again, with highly standardised, readily specifiable components, the participation of the users will be relatively minimal and probably highly formal (as, for example, in automobile component production).

By configurational technologies I mean to refer to situations similar to system technologies, in that the whole complex works together, and is made up of component technologies. In contrast, however, there is no clear system level dynamic: configurations of component technologies may be made up in a very wide (if not arbitrary) range of patterns; the mutually interacting (but not necessarily mutually constraining) components may be deployed in a very wide, possibly arbitrary, range of ways in order to match externally set requirements. Configurational technologies thus have characteristics similar to *open systems*.

The crucial point about configurational technologies, therefore, is the lack of any *internal* standardisation or stability in the overall system performance requirements. These need to be decided by the users, and hence the active involvement of the users is necessarily called for: it will rarely be possible for the users to simply play a merely formal role by setting specifications. However, *external* or interface standardisation will certainly be important and indeed the extent of such standardisation is a factor which positively affects the scope for constructing a wide range of configurations: the greater the degree of interface standardisation, the wider the scope for different configurations. In the absence of any such interface standardisation, configurations have necessarily to rely on human interfaces, as direct connection between technical subsytems or components is usually extremely difficult.

Even with 'proven' configurational technologies, extensive user participation is demanded, due to the characteristic penetration of the configuration into the users activities (as is found, for instance, with company-wide computer systems, which are good examples of configurational technology). With newer configurational systems, user participation will be demanded to an even greater extent, as relatively few of the configurational possibilities will have been fully understood or even previously identified, and therefore the users will have to be consulted in order to ascertain whether the new possibilities that come to light are what they want.

The notion of configurational technologies and the associated components out of which the configurations are built up, is a generalisation of the process through which particular computer systems configurations are made up according to customer specifications in the computer industry. I have discussed elsewhere its utility in helping to adequately analyse and describe development in robotics, a specific evolutionary developmental process I have termed "innofusion" (17). The work of P. Saviotti on developing metrics of technological change provides an independent empirical basis for suggesting that the distinction between systems and configurations is valid (xx).

(More on Saviotti's work)

I would argue that different theories of innovation and technological development are appropriate for the different types of technology as defined above. Straightforward linear models of an initial innovation stage followed by a quite separate stage of diffusion are certainly adequate for discrete technologies, and may be adequate for certain, probably the more mature, component technologies. With system technologies the innovation process is far more complex, with extensive iterative interactions between all the various agents - component suppliers, system integrators, and users - involved, as mature systems evolve out of mutual adaptation and processes of incremental innovation. The development of particular species of aircraft is the archetypical example here, and the notions of "technological trajectories" developed by Nelson and Winter (11), and "technological paradigms" suggested by Dosi (16), are certainly appropriate. For configurational technologies a more thoroughgoing evolutionary theoretical framework would appear to be necessary, and as discussed in section 5 below, there is considerable work being carried out from a variety of perspectives towards this end.

In some cases, there may exist a long-term developmental relation between system and configurational technologies, in that stable systems can emerge within configurational technologies, following the development of knowledge about the ranges of possibility open to the configuration, and the eventual identification of subsets of those possibilities which exhibit a degree of internal consistency. This process perhaps mirrors the crystallisation of "technological regimes" out of the innovation-diffusion or "innofusion" (17) process, and involves the emergence of a standardised body of knowledge resources out of a more open and uncertain process of experimentation and discovery. Thus, for example, while robotics as a whole is still in rapid process of development, with many configurational opportunities still to be explored, several clear examples of robotic systems appear to be emerging, such as robot arc-welding or paint-spraying cells.

(paragraph on the set of concepts we now have as being adequate, along with the terms for particular technical entities, for thorough analyses of the development of automation.)

The components of CIM

(CIM components and reference to Ayres 1987 and the IIASA CIM questionnaire)

4: ISSUES IN DEVELOPMENT: REVERSALS, COMPLEXITIES AND PROBLEM AREAS

Robotics example

On detailed scrutiny did not find uniform progress - success in certain areas and failure in others, with innovations arising during diffusion via an evolutionary trial and error process: innofusion.
Prevalence of vision push
Differentiation of technology not convergence
Transient technology - the robotic component vanishing into systems and configurations.

Expert system example

Situation very similar to robotics:
vision push: expert system infrastructure growing but selling primarily to other dev
researchers;
Prospector not important; 1st practical application in use as late as 1987?
Shells very trivial - another transient technology, used for learning and development.
Computer scientists claim they can do it with conventional techniques: AI and ES components vanishing into larger systems.

Office automation example

In the office, the nature of use of word processors is currently determined more by the pre-existing divisions of labour and work organisation, than by the technical exigencies/capabilities of the technology (Webster, 15). This illustrates an apparently fundamental characteristic of the way in which new technology is deployed and new configurations are built up: existing models of work organisation have a causal influence on system design via the design process and the educational backgrounds of those responsible for design (18)+(23).

MRP example

MRP systems always slow to mature into economic payoff. Accumulating examples of failure (eg. Raleigh) and some have even been ripped out or dramatically modified in the the light of adoption of JIT approach.

Quality control example

TQC is reversing the economies of specialisation with respect to quality control and demonstrates the economies of integration. In comparision with overall JIT approach, replacement of responsibility with craft worker shortens feedback loops to identify errors, reinforces potential for learning and minimises possible rejection-batch size.

Automated warehouse example

JIT also impinging on the automated warehouse revolution, that hardly got going in the early 1980s. No sooner constructed eg. in IBM Greenock Scotland, than being demolished to make space for productive work areas. Massive rational-automation conveyors are also being ripped out (cf. Schonberger).

JIT impact on CIM

JIT not just an organisational innovation as many social scientists with relieved glee have claimed. Includes necessary technological correlates such as modular small-scale flexible technology developed or adapted and supported in-house, although firms such as Hewlett Packard (Queensferry, Scotland) manage to gain considerable benefits despite previous large scale investment in automatic insertion, as do IBM (Greenock, Scotland) with their continuous flow manufacturing (CFM) variant of JIT. IBM are retreating from the 1st generation heavily robotised FMS which conventional wisdom would have it should be run with unmanned 3rd shift to maximise utilisation and improve capital productivity. This they now run in strict JIT mode, with rate determined not by the automatic control system, but by the human work cells (which were necessary to assemble floppy wiring subassemblies, impossible to automate), in response to pull-through from demand.

CIM example

The high tech approach to automation aimed at eliminating entirely the human worker and automating everything seems to be faltering, even in its heartland of application, the auto industry. Saturn Project reversal under fierce competition from the Japanese transplants.

If we look in close detail at a particular implementation of CIM, Avon Rubber(England), we find a complex time-consuming process of discovery and innovation (more below).

The drive for integration

There is a drive to integration, at many levels. Individual machines on the shop floor have become directly linked together into cells eg. a robot unloading a diecaster fitted with automatic metal delivery, and offering the part to inspection, quench, and trim facilities.

With machining cells, the production process may be explicitly controlled and set up in terms of certain product groups in group technology - a degree of integration between product and process.

At the overall shop floor level cells or "islands of automation" are being linked into overall systems producing a particular variety of flexible manufacturing system, integrated physically by means of handling devices - gantry robots in early FMSs, AGUs in later FMSs, conveyors in less high tech systems - and linked in terms of information by computer-aided production and control systems.

Parallel developments have also occurred in the office. The analogue of cells via computers, filing systems, printers, word processors. The central accounts and payroll functions here often forms the backbone for a more integrated overall system. In some non-manufacturing instances, a form of physical material processing - handling if not transformation - occurs, notably in Banks via ATMs.

At a higher level, a measure of integration between office and shop floor is achieved with production and stock control being linked via CAPM such as MRP I and II. This essentially represents an integration of the warehouse and production processes with certain routine office activities. Also, at this higher level an integration of the very different functions of design and manufacture are CAD/CAM systems.

At an even higher level, integration via purely information channels LANS, VADS etc and EDI is linking separate plants or offices both within organisations but also across organisations, often along supply chains, in a form of quasi-vertical integration.

interface problems

Interface problems have been a major source of difficulties which are still far from being resolved. They have occured in three broad areas: (a) between machines and material reality - error recovery, tool monitoring, vision systems for part detection and positive identification; (b) between machines - protocols and standardisation; and (c) between machines and people - the human computer interface.

The first area particularly in the case of intelligent robots has proven extremely intractable, and has forcibly demonstrated that "interpretation", a semantic or knowledge-based element, as exemplified in scene analysis,is required unless it is designed out at earlier stages of factory and product development: indeed the latter approach looks to be the easier and more economic.

The second area is far more tractable in a straightforward technical sense; it is in principal certainly possible to interface machinery and systems in all the different areas of activity, especially where information exchange alone is involved. Moreover, most of the linkages have been demonstrated as feasible already and are doubtless in successful operation somewhere, albeit in piecemeal fashion. The problems faced here are largely due to the multitude of different actors involved and machines developed on the basis of hitherto distinct bodies of expertise which inevitably leads to different forms. As well as this accidental differentiation there is also active game playing and political mobilisation in order to gain economic advantage, which has led to explicit strategies of exclusion by some in order to "lock-in" customers, and generalisation by others in order to gain a wide base of users. Thus the processes of standardisation and protocol determination, while couched in terms of technical specifications, are subject to extended negotiation and power politics; eg. GM and MAP, and the international discussions over ISDN.

The third area, the human computer interface, is like the first fundamentally difficult, particularly in terms of matching the technical features and characteristics to human perceptual, physical, and cognitive ergonomics. The latter is particularly difficult and perceived as crucial to wider diffusion and trouble free operation. The human window (Michie); AI techniques; language understanding and speech recognition; hand writing understanding; the WIMP environment, etc.

These interface problems can be seen as arising fundamentally from system requirements; ie. the need to articulate component technologies so they can work together as a coherent system: the middle one is a pure information transformation, while the others deal with information to human understanding and information to physical action, both of which lie outside the direct scope of microelectronics and computation.

5: PATTERNS OF DEVELOPMENT

While at one level it makes good sense to talk about general trends, there is a great danger that the discussions arising become totally detached from the reality, and thus of little importance either for describing what is actually going on, or getting a grip on policy issues, far less providing any practical help to the management and technical practioners at the sharp end.

Let us consider some examples:

1) Robotics statistics and diffusion of robots. West Midlands survey and developmental dynamics;

2) Overemphasis on leading edge technology, at expense of centre of gravity;

3) Volume/variety/flexibility issues. There may be an overall shift towards flexibility, but this does not mean that all production units will be going for economies of scope. Indeed, economies of scale and scope can be clearly interrelated, by identifying core components, the combination of which can produce arbitrary variety to match demand (Nippondenso example). Group technology can be interpreted as a means gaining flexibility explicitly by going for economies of scale in terms of similar product

groups at a cellular level. The rise of product/process integration is important here. There will always exist a spread of companies addressing different market segments with differing degrees of flexibility (xx). Moreover, this is not just a static process but a dynamic one (xx), relating to product life cycles, and consequently there will always be scope for the relatively large scale production of products at the appropriate mature phase. Moreover, given that production processes also have a life cycle (consider the rapid obsolescence of the first generation FMS), flexibility across product changes will not be necessary in those cases where the life cycles of the products and processes are the same.

And for different sizes of companies, different forms (configurations) of technology are going to be appropriate. For example, Avon Rubber, of England, a medium sized organisation producing tyres and a wide range of rubber products, have recently embarked on a CIM programme (13). Because of their relatively small size compared with the tyre manufacturing giants Michelin, Firestone, etc., they had to seek independently a smaller scale solution to the tricky process control problems associated with rubber products manufacturing; they simply could not afford the already developed solutions available, and in any case it is unlikely that these, despite their claimed flexibility, would in fact prove appropriate to the Avon market.

Avon's specialist OEM market necessitated very short runs (eg 20 mins) at infrequent intervals and in relatively small accumulated volumes. MAP was ruled out at the outset on grounds of cost: the basic backbone necessary just to get started, cost £40K, which was about the total cost of their initial phase of shopfloor implementation, the integration of a new cross head extruder via a supervisory PC to a local plant mini and the head office mainframe-based MRP system.

The above discussions serve to illustrate that there is a need for analyses of IT and CIM development which are sensitive to the contingencies arising from particular industries and organisations. This was an issue usefully addressed by Bright in his study of Automation. As well as 17 levels of automation, where level referred to "the degree of mechanical accomplishment of a required activity", Bright suggested two other dimensions, namely span "the spread of mechanisation across a given production system and penetration, the "degree to which secondary and tertiary supporting activities (adjustments, inspection, maintenance) are mechanised". It is worth noting that even the latest developments are far from full penetration in Bright's terms. These three dimensions (level, span, and penetration) together could give an approximate indication of the overall degree of automation within a particular production sequence. Even then, insight into the structure of automation within a particular plant was being lost, and so Bright suggested the notion of a "mechanisation profile" (figs.3,4), which attempted to indicate more clearly the span and penetration of automation by indicating the level at each distinct stage of process flow. If the same approach were to be used on an advanced modern example, a similar pattern of uneven application would be evident. In the IBM show factory at Greenock, for instance, there are still distinct stages where manual intervention is required, along with fully automated robotisation. {I intend to construct an analogue for the Greenock line, for comparison}.

(Suggestion for representing flexibility dimensions along similar lines,

MECHANIZATION PROFILE FOR INTEGRATED OIL REFINERY, NORTHLAND OIL REFINERY, 1955

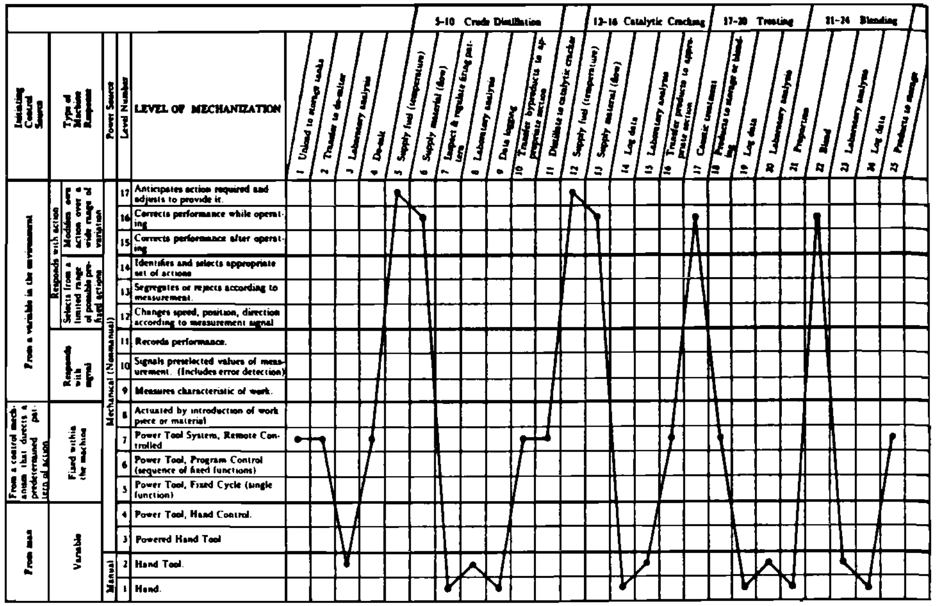
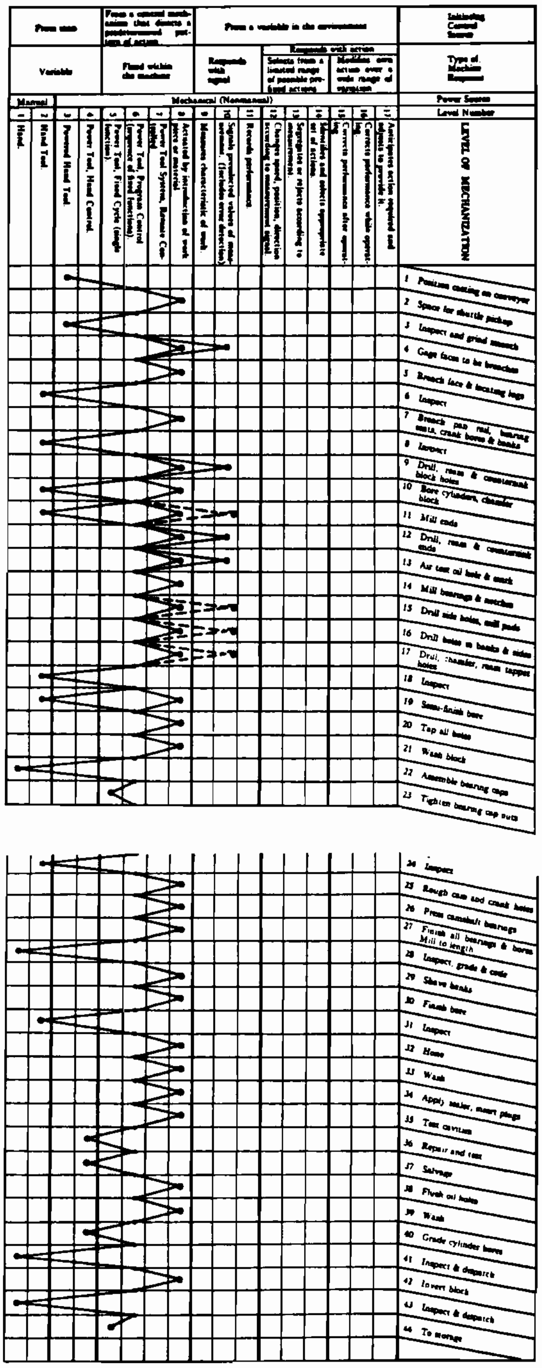


Figure 3   Source: Bright (ref.6,



MECHANIZATION PROFILE FOR CYLINDER BLOCK LINE (MERCURY), CLEVELAND ENGINE PLANT, FORD MOTOR COMPANY, EARLY 1955

Figure 4 Source: Bright (ref.6)

and for extending the analysis to cover the whole of the organisation in terms of office and administration automation as well as factory automation. It would also be interesting to carry out a modified analysis at the industry level.)

(Discussion of statistical information from questionnaires and surveys, eg. the IIASA project. Will be invaluable for identifying and tracing trends, but may not be able to capture or preserve the structural information about the range and variation to be found in specific configurations.)

(Will also develop here:
catalysation effect and integration rationalisation;
before / after analysis;
Drayson's robotic study.)

6. THE IMPLEMENTATION OF IT AND CIM

In the introduction to this paper, I suggested first that the implementation process of information-integrated automation is relatively intractable, and secondly that the resolutions of difficulties during implementation are a major source of innovation and novelty.

The implementation process

Implementation may be defined in this connection as the process whereby technical, material, human, and financial resources are configured together to produce an effectively functioning operating system. Note the emphasis (a) on the assemblage of resources and (b) on the achievement of a normally operating factory system. The existence of a new (or for that matter, old) technology does not, in itself, guarantee success. Many studies indicate that considerable effort is required to implement the new technologies in order to get them working effectively in real life production processes. There is rather a large gap between idealised demonstrations in what usually amounts to little more than a showroom, and successful functioning of the technology in a production process in a specific factory within a particular attendant organisation. Not only technical adjustments, adaptations, debugging, interfacing, etc., are required, but managerial and organisational adjustments, negotiations, choices, decisions, allocations of responsibilities, coordination between different groups and departments, justification, planning etc., are also necessary. In particular, the changes associated with the way in which human workers intersct with the system are of crucial importance.

In the last five years, the implementation process has been increasingly recognised as a key phase in the adoption and diffusion of technology, especially computer-based technology (21), and indeed is becoming a standard course within the management of technology and the management of change more generally (20), both at the level of experienced managers education (5) and the postgraduate and undergrsduate levels (xx). Evidence on the intrinsic difficulty of the implementation process has been usefully summarised by Bessant (4), who identifies the major barrier as being due to problems over integration. Swanson's metaphor of a jigsaw puzzle is particularly compelling here (fig.5). I would further observe, however, that Swanson's depiction is somewhat over-idealised: in reality the shapes of the jigsaw pieces are highly indeterminate and many different fits are

The Implementation Puzzle

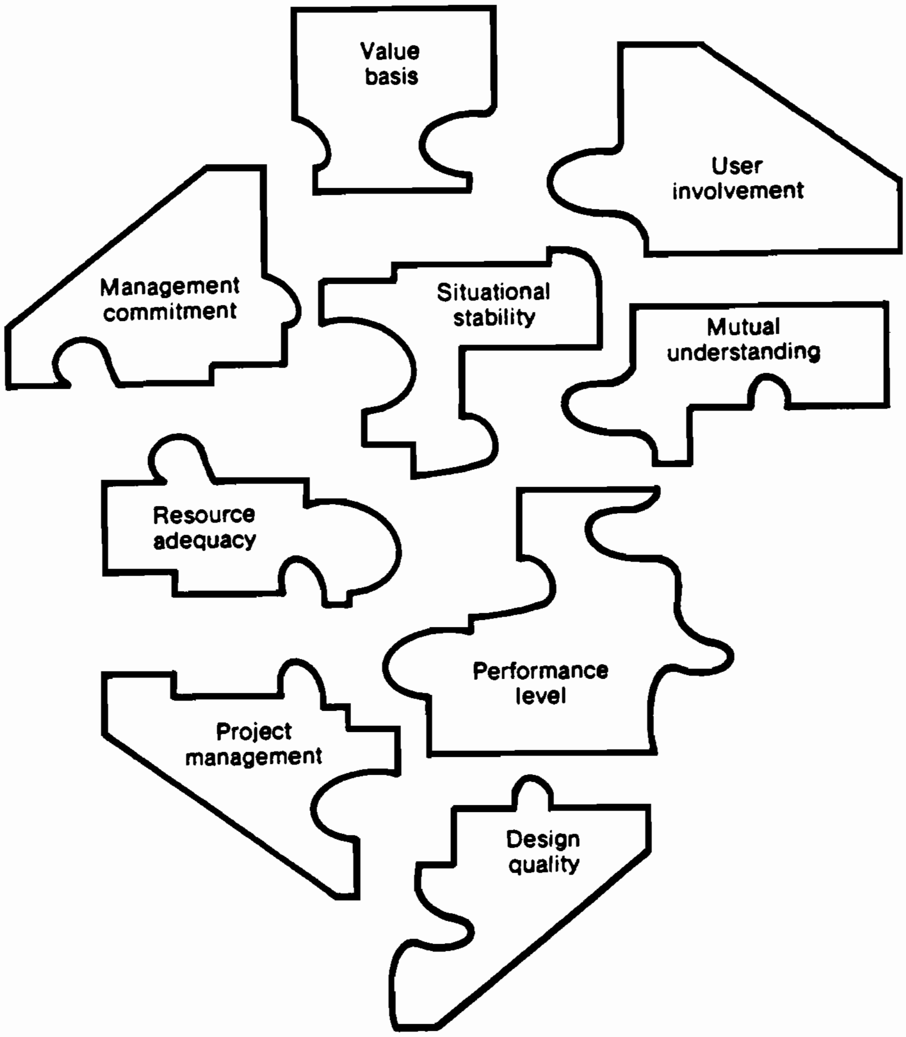


Figure 5 Source: Swanson (ref.22)

equally possible, but may not be best suited to the overall contingencies of the particular organisation and industry as discussed above.

The reversals suffered by the advanced high tech approach at the hands of the Japanese JIT approach are a case in point. Sophisticated high tech robots can be fitted in Flexible Manufacturing Systems and large scale assembly lines such as automobile spot-welding lines, or they can be exploited within relatively low-tech contexts as modular, flexible and therefore short set-up time components in a JIT system as described by Schonberger (21). In the first case there will be a drive for high machine utilisation in order to recoup the high capital costs, and thus under certain market conditions could lead to the flexibility advantages not being taken full advantage of, as often happens with robot installations.

While this recognition and the widespread use of the term implementation is relatively recent, the basic problems have long been observed. Bright, for instance, comments in respect of automation:

> "The negative aspects of automation seem to arise in four areas; (1) problems in designing, procuring, and building automatic production systems, (2) trouble during installation and debugging period, (3) operational difficulties that are inherent in the system even after it is working with mechanical perfection, and (4) conceptual difficulties in relating the automatic system to the requirements of the business." (6)

Typically, however, these problems were seen as primarily technical; Bright comments on the need for successful planning of automation to fit the technical and economic structure of the business, but places less emphasis on the need for fitting the organisational structure of the business - despite his very perceptive observations on the skill requirements of automation. A major effect of the JIT revolution has been to focus attention with a vengenance onto the organisational side of the business, to such an extent that as Freeman points out (9) there is a real danger that some consultants will cease to give due consideration to the technical issues.

Implementation arises essentially because of the need for practical operating systems to respond to the particular internal organisation and market exigencies of the business. It is more or less difficult depending (assuming all the other factors are equal) on the scope of the innovation, ie. the extent of the interfaces of the technology with the rest of the operating system. Discrete technologies such as consumer durables are easy to implement: they require plugging in, elementary training on the part of the user, and appropriate tasks to carry out. Systems technologies will necessarily require more work, more adaptation to the overall system, and more adaptation of the system to the components. The organisational location of the system becomes an important variable, ie. the relation of the technical system to different departments within the organisation. Essentially, the more departments and outside agents that are involved, the more difficult the task of implementation.

The toughest case for implementation is with configurational technologies, especially when they are at a stage before component interfaces have become standardised. Information and communication technologies, especially when they involve real world interfaces such as the human computer interaction and material transformation are very much the archetypical examples of configurational technologies at present. Again the organisational location becomes crucial, especially since, by virtue of their nature, ICTs are involved primarily across functional departmental and even organisational barriers.

Implementation as a source of innovation

But the difficulties of the implementation process, are also the source of innovation and significant novelty. Typically implementation improvements are what have been termed incremental innovation. But as Sahal (14) observes, there is much empirical evidence to support the contention that incremental innovations accumulate to yield major qualitative changes over the longer term;furthermore, Sahal argues that most of fundamental change is of this nature, rather than the more exciting and flashy radical innovations. I would agree with Sahal here and would argue that many apparently radical supply-side innovations can, on closer examination and analysis, be interpreted in terms of feedback from a previous implementation phase (eg. Hollerith's invention of the ATM from an involvment in the census data handling). Elsewhere, I have tried to produce a critique of

The importance of an evolutionary process of innovation, epecially for process development, of innovation diffusion, (or of innofusion), is increasingly recognised and discussed. An emerging corollary is the realisation of the importance of the intangible knowledge assets of an organisation (cf. the knowledge base concept of Metcalfe and Gibbons, 19), and of the distribution of expertise. Both these notions are implicitly consonant with the JIT approach which takes as a basic tenet the decentralisation of responsibility, and the redistribution of knowledge to a wider base of personnel within the company (cf. the widespread diffusion of knowledge about statistical process control in Japan, which is underpinned by a journal for foremen, with a circulation of some 50,000, 11).
Consider also the role of skills and work organisation at the level of the workforce, and the division of knowledge and expertise at mangerial and technical levels, which includes knowledge about job design, work study, and industrial engineering, which have a direct causal effect on the technological configuration which is built.

A second corollary is the increasing integration of the user of the innovation in the implementation innovation process itself (xx). Again, information-integration and CIM, because they are essentially configurational technologies, maximally require the active participation of the users in the process. In this connection, Freeman comments on Baba's observation that industry is being used as a laboratory (9). Rooney observed in the case of Avon Rubber's CIM that the suppliers of the cross head extruder started coming to the company precisely because the facility was fully monitored and was the only such case (13). This gave them the opportunity to observe the parameters of real production performance. Due to the non-Newtonian behaviour of rubber, it is not possible to experimentally derive performance characteristics from pilot or small scale operation.

Kaplinsky, in his account of the history of manufacturing organisations commented that much prior development has been in terms of progressive specialisation and increasing differentiation, in particular with R&D and production becoming completely seperated (11). We may explain these developments in terms of economies of specialisation. With information-integration, however, such activities are becoming reintegrated, and once again, real life production is where it is at. It is not possible to experimentally study the large-scale, highly variable processes characteristic of technological configurations separate from actual production running.

This underpins the need for real-time longitudinal case studies analyses.

(Concluding paragraphs)

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