WORKING PAPER

FMS WORLD DATA BANK

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May 1989
WP-89-33

IIASA
International Institute
for Applied Systems Analysis

NOT FOR QUOTATION
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OF THE AUTHOR

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FOREWORD

The present paper consists of the first results and conclusions from the third version of the IIASA FMS database. This version of the database includes more than 750 systems from 26 countries. The accuracy and completeness of the data has improved since the second version. Now it is time to look for solid regular patterns of impacts and draw statistical conclusions. This paper confirms that the preliminary conclusions made in the earlier papers were basically correct and gives a deeper insight into the costs and benefits of FM-systems.

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1. Introduction

The assessment of FMS diffusion in the world industry requires statistical support. At the time being there are practically no official statistical publications covering the FMS installed; there are some occasional articles containing either partial banks or detailed descriptions of several systems.

To analyze the state of the art, the competitive positions and the future expansion of these sophisticated technological systems, we needed several sets of data as a minimum. The first set was to describe the costs of FMS and the cost elements. The second one was to represent different economic advantages of the systems (labor and capital saving, etc.). The third one had to reflect operational modes and technical features of the object. Finally, to avoid duplication, we had to identify different systems by industries and areas of their application, types of production, etc.

As a starting point the UN information [35] on approximately 220 FMS installed in 17 countries was chosen in 1987. Then the data were checked and sometimes corrected by the use of the description of some cases from [9]. The first analysis of the FMS data bank was published in [38].

Dealing with the first version of the bank, we came across problems connected with low statistical reliability of distribution and correlation studies for some variables. For example, the inventory reduction was reported only in 6 cases, lead-time reduction in 9 cases, productivity increase in 7 cases and pay-back time only in 18 cases. The number of the cases with coinciding information (different variables for the same cases) for obtaining statistically reliable correlations was sometimes even smaller. This was significant with regard to the efficiency data and relative FMS advantages.

In order to overcome the data shortage, the second version of the bank was developed in 1988. We were additionally supplied by data from the national research institutions and experts. Thus we got a detailed description of the FMS installed in the Finnish industry (from the Finnish national TES Program), and for the Czechoslovak FMS from VUSTE (Research Institute of Technology and Economy in Mechanical Engineering). A very fruitful information on the British FMS was obtained from Brighton Polytechnic, on French systems from Lyon University, on the Japanese FMS from the Science University of Tokyo, etc.

Naturally a lot of additional cases and figures were retrieved from scientific journals, occasional papers, etc.

By using new sources we extended the second version of the bank to approximately 400 cases and added some significant information to the existing cases. As a result the number of data in each column went up considerably. This provided a higher level of statistical reliability of the correlation results. For instance, the number of cases where there was some information on inventory reduction increased up to 23, for lead-time reduction it increased up 45, for productivity it increased up to 33 and for pay-back time up to 44.

The analysis of the data collected in the second version of the bank as well as their correlation study were published in [39] and [40], respectively. However, the experience of the study demonstrated that for some variables we could not retrieve reliable and obvious patterns of the relationships, in spite of the data expansion.

The main reason was, as we understood, the mixing of different types of FMS in the bank. For example, metal-forming systems usually have a very high product variation and lead-time reduction and a relatively small number of NC-machines. FMS used in electronics production have very high batch sizes and product variation in comparison with the systems installed in machine-building or transportation equipment industry. Assembling FMS are usually based on many robots and they do not often include machining centers or other NC-machines.

As a result, assembling FMS have a much higher personnel reduction, a rather limited number of product variants, and so on. There is even a difference between the FMS producing rotational and FMS producing prismatic parts, even though they are installed on similar shop floors. As was reported by Japanese specialists, the pay-back time was usually two times longer for FMS of the rotational type than of the prismatic type.

Finally, we observed some significant differences between FMS used for the same production, but in different countries. For instance, the US FMS costs are much higher than those of similar systems in Japan or in Europe. One of the reasons is the difference in systems of cost calculation. National peculiarities also influence such FMS features as batch size and a product variation (both of them are unusually high in the GDR machine-building industry), pay-back time and inventory reduction (in the CSSR 7 years pay-back time is considered to be acceptable, but Japanese firms try to keep it below 5 years), etc.

In order to take these differences into consideration when purifying general tendencies and interrelationships, it was necessary to cluster the data from the bank by industries, types of product, areas of application, and countries. It was a fruitful approach for some studies, but sometimes we did not have enough observations for specific clusters.

This is why the third version of the bank with approximately 750 cases was developed at the end of 1988. All the sources we used are mentioned in the references. There are 4 types of sources:

- international data banks [3, 7, 8, 9, 12, 19, 20, 30, 35, 37];
- national data banks [2, 5, 17, 21, 23, 24, 25, 28, 43, 44];
- occasional descriptions of cases [1, 4, 6, 11, 13, 14, 15, 16, 18, 27, 29, 31, 33, 26, 41, 42];

- expert data collections prepared for IIASA by national experts [10, 22, 26, 32, 34, 45].

We did not include FMS mentioned in the sources if there was no information on them except user/vendor names, or FMS installed in research institutes or universities and not used in real industrial production.

To provide enough data for a cluster analysis we asked national experts from IIASA's external collaborative network to check the data, to add new cases and to fill the empty cells in the bank matrix, especially with data on effects and advantages. We received many valuable comments and additional data from the colleagues and we should like to express our appreciation for the support provided by Y. Bouchut, V. Ganovsky, B. Haywood, H.-D. Haustein, R. Jaikumar, Z. Kozar, P. Lindberg, J. Mieskonen, S. Mori, M. Ollus, G. Tondl and H.-J. Warnecke in the development of the FMS data bank.

2. Description of Indicators

The main purpose of this section is to show the definition, estimation methods and interpretation aspects of the FMS indicators collected in the bank.

In order to avoid a mixing of flexible manufacturing systems, cells and units, we have chosen the following rather wide definition of an FMS. It is a production system consisting of more than one NC-machines and/or industrial robots, interconnected by a flexible or fixed transportation system, used for providing the whole production cycle under computerized control. Such a system can be supported by material and tool handling subsystems, storage and inspection subsystems, which are integrated with the production system.

Due to the lack of information on the mode of computer control we can not exclude a certain probability of hidden FMC existence in the bank. According to our own estimate there are probably 30-50 systems (or 5% of the total) which do not correspond to the above-mentioned definition.

Not all the cases include the full set of the variables, but the number of data for each variable grew significantly in the third version of the bank (see Table 1). However, if we collected a lot of cases for some indicators (number of machines, product variants, investments and batch size), we could not find more than 50 cases for some others (set-up time, inventories, machining time reductions).

In comparison with the second version [39] we enlarged the list of the indicators by adding "type of product" and "unit cost reduction" as new indicators and by calculating NC and TC. Now the bank includes 32 positions (see Appendix 1).

The first four indicators serve for FMS identification. They include abbreviated country names (COUN), names of company users including their allocation (COMP), names of main vendors of

Table 1. Number of cases with the main FMS indicators

Indicators	Version 2	Version 3	Share in total %
1 Technical complexity	310	675	89
2 Product variants	229	417	55
3 Bach size	89	209	28
4 Investments	188	279	37
5 Pay-back time	44	76	10
6 Lead time reduction	45	98	13
7 Set-up time reduction	26	40	5
8 In-process time reduction	33	59	8
9 Machining time reduction	26	37	5
10 Inventories reduction	23	44	6
11 Work-in-progress reduction	36	64	8
12 Personnel reduction	74	137	18
13 Number of MT reduction	12	84	11
14 Productivity increase	33	61	8
15 Capacity utilization increase	24	76	10
16 Unit cost reduction	0	55	7

the systems (VEN) and years of installation (YEAR). Everything is clear only for the first indicator. Unfortunately some cases have no information on the vendor and there are 47 unidentified cases without a user's name in the bank.

The description of these unidentified FMS usually resulted from studies carried out anonymously. This is why the studies' authors had to publish the detailed information without mentioning company names. Sometimes we were obliged not to disclose company names when we got some specific data. The use of the unidentified cases provided by external experts suggests a risk of case duplication.

Another problem arises from the field of linguistics. For example, sometimes we are not sure that similar company names are not identical. The difference could result from multi-step spelling. The names of the departments or daughter companies are in some cases mentioned in different sources, and we are not sure if we either deal with different FMS or with different descriptions of the same systems. Several companies have been renamed during the last decade and we tried to use the latest name.

Some difficulties arose when we dealt with companies which used several similar FMS, like Volvo or MBB. To recognize the systems we had to add a plant allocation or specific product orientation of such FMS. In spite of these efforts we admit that 10-15 duplications could be hidden in the bank.

Almost the same problems were met with regard to vendor identification, and, besides, it was difficult to choose the main vendor when the system was supplied by several companies.

The "year of installation" is a relatively flexible parameter, due to its different interpretation in different sources. There were few sources where the year of investment, the year of first installation, the year of final installation and the year of productive implementation were mentioned. Such details were not usually reported. As we used "year of installation" as an identification indicator, a difference of 1 or 2 years in the indicator was important.

The installation process usually takes from half a year to 2 years, but some FMS were installed in a step-wise way. Additional units or subsystems were added several years after the first installation and after some experience had been acquired. When we had detailed information we chose the year of final installation as the "year of installation".

The second group of indicators describes the technical complexity of FMS and includes: the number of machining centers (MC), the number of other NC-machines (NC), the total number of NC-machines (NCMT), the number of industrial robots (ROB), types of transportation (TRT), storage (STOR) and inspection (INSP) systems as well as a synthetic indicator of technical complexity (TC).

In spite of the apparent clarity of the first four indicators some misinterpretations are given in the sources. In [35] horizontal milling NC-machines are sometimes treated as machining centers, and as milling machines in more technical reports. Supplementary machines like washing or drying machines are sometimes included in NCMT and sometimes excluded. When we had detailed information we excluded them from NC and NCMT, and treated machining centers as multi-functional units. The definition of industrial robots is not accurate in some national reports. The most primitive manipulators with fixed functions and routes, which are not flexible by nature, should not be treated as industrial robots, but we suspect that in some sources they were.

The bilateral figures (1 or 2) for typization of the transportation, storage and inspection systems are rather conditional. The first type covers the systems based on conventional equipment with inflexible control. In the case of transportation this type covers conventional conveyors, cranes, etc. AGV (wire- or rail-guided), transportation robots were treated as transportation of the second type. Automated storage and retrieval systems as well as computer-controlled warehousing systems were treated as type two of the STOR indicators. Automated maintenance and monitoring systems based on in-process measurement and final inspection were considered as belonging to the second type of INSP.

Due to the different architectures of FMS and the different areas of application we needed a general, weighted indicator of the technical complexity of the system. The method of its estimation has already been described in [40] and the weighted formula is as follows:

$$TC = 0.35\ NC + 0.7\ MC + 0.3\ ROB + 0.3\ TRT$$

There are three types of data in the "Economic and operational data" section; investments and pay-back time (INV, PBT), total number of shifts and number of unmanned shifts a day (OPR, UNM), number of products and average batch size (flexibility indicators) (PV, BS).

We accepted a three-shift day standard, 8 hours each, and recalculated the information on OPR and UNM in terms of shifts. In Japan many companies use an alternative operation mode for FMS: two shifts (10 hours each) and 4 hours of unmanned night shifts. In these cases we considered OPR = 3 and UNM = 0.5.

Some sources reported the number of products, taking all variations into consideration, other sources gave only the number of part families, and all of them usually indicated either average figures for different years or the latest figures. We tried to use data on averaged numbers of products whenever possible, but when the system was reconstructed or rearranged for the production of new parts we used the latest figures. The PV indicator is rather reliable for those systems producing several types of parts, but the reliability decreases when the system is incorporated into the production of hundreds or thousands of types, and especially when the "potential" maximum was reported.

The batch size information is not very stable by nature. Normally each FMS produces different types of parts by different batches. For example, part N1 with BS = 3-5, part N2 with BS = 20-25, part N3 with BS = 100-200, etc. It is clear that the averaging procedure is connected with some problems, because the relation between N1, N2 and N3 is unstable.

One problem is due to demand instability, another to the necessity to increase capacity utilization, or to decrease work-in-progress, the third one is due to the changes in the production structure, etc. The "best" sources indicated weighted average figures, but sometimes minimal, or minimal and maximal figures were reported. For instance, the batch size for some systems was reported as: "BS_{min} = 1, BS_{max} = 1000". For such cases we used 50% of the maximum value as an average.

Investment figures have two hidden inaccuracies. The first one is connected with a different coverage of real spendings. Some companies have bought FMS as turn-key systems, others developed some parts of the systems (i.e. software) themselves, and there were companies which shared the costs with governmental donators. The real expenses were, in such cases, not indicated in the investment costs. The second inaccuracy is connected with the recalculation of investments reported in national currencies into US dollars. For this purpose we used the official exchange rate of the installation year.

Pay-back time (sometimes reported as return on investment) was usually measured in years, starting from the year of installation, but, if the system was installed step-by-step during several years, it was difficult to define the final figure. For the most recent FMS we applied the forecasted estimates.

The relative advantages of FMS in comparison with previous modes of production (conventional machines, stand-alone NC-machines, or FMC) were measured in terms of unit cost reduction (UCR), or labor saving (PER, PROD), fixed capital elements saving (FLS, NOM, CAP), current expenditures saving (INR, WIP), time saving (LTR, SUT, IPT, MT).

The total production time can be divided into several sub-periods, namely:

- set-up time (SUT), which is necessary for setting up equipment to prepare a system for new part production;
- in-process time (IPT), which is spent for part production from a first operation up to final operation;
- machining time (MT), in which equipment is used for part production;
- lead time (LTR) is the period from the order to the delivery to a customer.

When throughput time reduction was reported in the sources we treated it as ITP. In several cases, where FMS were used (with CAD) in experimental production for the development of new products, the lead time was interpreted by the sources as the period from the design to the production of the experimental item.

There were several misinterpretations of inventory reduction (INR) in the original sources. Sometimes INR included not only raw material and final goods inventories, but work-in-progress as well, and in some cases the figure reflected only final product inventories. But the share of such exclusions was small.

Personnel reduction (PER) usually shows the decrease of production workers, engineers and supporting personnel directly connected with the technological line. The indirect effects, such as personnel reduction in general administration, book-keeping and purchasing departments, were not taken into consideration as a rule.

Productivity increase (PROD) is directly connected with personnel reduction if there is no change in production volume. For the majority of the cases we found either PER, or PROD, but, knowing nothing about production changes, we could not combine them into one indicator.

The capacity utilization increase (CAP) was measured as an increase of the share of productive time in total potential time. For example, if the share of cutting time for stand-alone NC-machines was 3 hours a day, and it reached 6 hours within an FMS, this means that the CAP has doubled. It is clear that, if conventional equipment was used during two shifts a day and an FMS is used in 3 shifts a day, it will increase the CAP, ceteris paribus, by a factor of 1.5. This is why this indicator was usually calculated for a two-shift standard.

We have mentioned all these information and estimation problems to show the content of the indicators and our attempts to collect reliable and comparable data, but sometimes the lack of information or different interpretations became obstacles we could not overcome.

3. FMS Diffusion

There are several directions of FMS diffusion -- geographical distribution, in-time diffusion, allocation by industries and application areas. Of course, the geographical distribution in the bank (see Table 2) is not an exact copy of the real diffusion, which is due to a difference of availability of information from the respective countries. But the figures in the third version of the bank should be much closer to reality than in the second one.

It is obvious from the table that there are two leaders among the countries -- Japan and the USA (22% and 18% of the total FMS population, respectively). The second group includes those countries with a share from 9 to 12% -- France, the FRG and the UK. The CSSR, the GDR, Italy, Sweden and the USSR own 3-5% of the total FMS population each. The share of the USSR is

Table 2. Geographical distribution of FMS installations

Country	Number of FMS installed		Share, %
	Version 2	Version 3	Version 3
1 Austria	3	4	0.5
2 Belgium	3	6	0.8
3 Bulgaria	3	14	1.8
4 Canada	3	3	0.4
5 CSSR	20	23	3.0
6 Finland	9	13	1.7
7 France	48	66	8.7
8 FRG	25	74	9.8
9 GDR	12	23	3.0
10 Hungary	0	7	0.9
11 Ireland	0	1	0.1
12 Israel	0	1	0.1
13 Italy	15	37	4.9
14 Japan	73	165	21.8
15 Netherlands	8	8	1.1
16 Norway	1	1	0.1
17 Poland	0	5	0.7
18 Romania	0	1	0.1
19 S. Korea	0	2	0.3
20 Spain	0	2	0.3
21 Sweden	17	35	4.6
22 Switzerland	4	6	0.8
23 Taiwan	0	5	0.7
24 UK	67	93	12.3
25 USA	83	135	17.8
26 USSR	0	28	3.7
TOTAL	394	758	100.0

underestimated due to the lack of published data. The share of all other 16 countries is 10% of the total.

Figure 1 shows a correlation between the number of FMS installed (N) and the gross national product (GNP), measured in billions of US dollars.

As is shown in Figures 2 and 3, 80% of the systems were installed after 1979. In reality this share is even higher as the main sources we used were published in 1986-1987 and the information on the systems installed in 1986-1988 is incomplete. According to our estimate more than 75% of all FMS in the world are now younger than 5 years, and the average annual growth rate of FMS population exceeded 15% during last years.

The normal life-cycle of an FMS is considered to be 8-10 years, but there are several "veterans" serving 16-18 years, some of them with renovated hardware. We did not exclude the FMS of the first generation from the bank to use their data for the dynamic analysis of the FMS development.

The FMS distribution by industries shows that about half of the systems are used in transportation equipment industry (mainly in car and tractor production and in aerospace). The second main user is non-electrical machinery (mainly machine building), and the third one is electrical machinery. The smallest user among the metalworking industries is instrument production. The technological processes in car parts, big electrical machines, and machine-tool production are very similar. This is why there are only two aggregated industrial sectors shown in the bank:

1 - transportation equipment, non-electrical machinery, big electrical machines;
2 - electronics and instruments.

Approximately 700 FMS are allocated in the first sector and only 50 in the second. 82% of the systems are involved in machining processes, 8% in manufacturing (non-machining processes, like plating, combination of different processes like machining and assembling). 5% of FMS form metal sheets and the other 5% are involved in welding and assembling.

Among the machining and manufacturing FMS 64% develop prismatic parts, 24% rotational parts and 12% both types of parts.

As the list of FMS contains a combination of different types of systems with different architectures and performance characteristics, we clustered the data bank into several groups and compared the average figures for the basic version and for the compressed one. The latter includes only machining-type FMS (and a part of manufacturing FMS where machining processes dominate). The comparison of the average figures for these two versions of the bank is provided in Table 3.

The average number of robots in a system decreased from 6 to 2.5 because the excluded assembling systems were usually based on several tens of robots. The average number of product variants

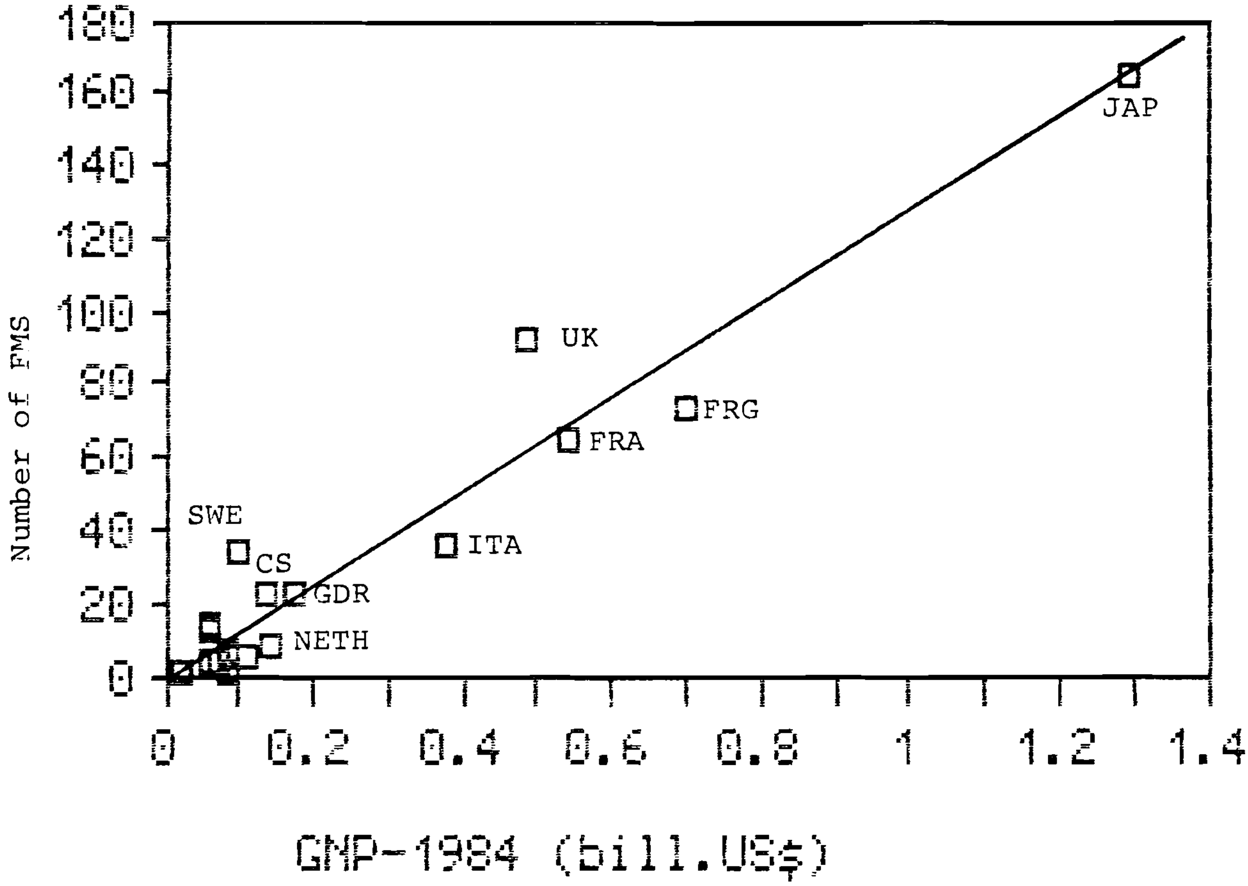


Figure 1. Number of FMS over GNP (the USA and the USSR are excluded).

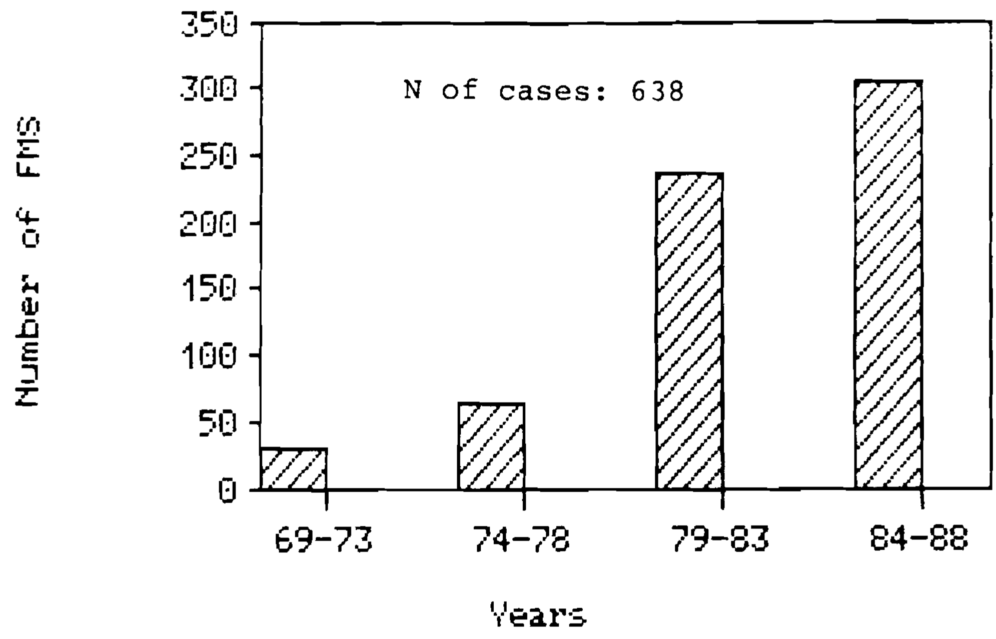


Figure 2. FMS installations by 5-year periods.

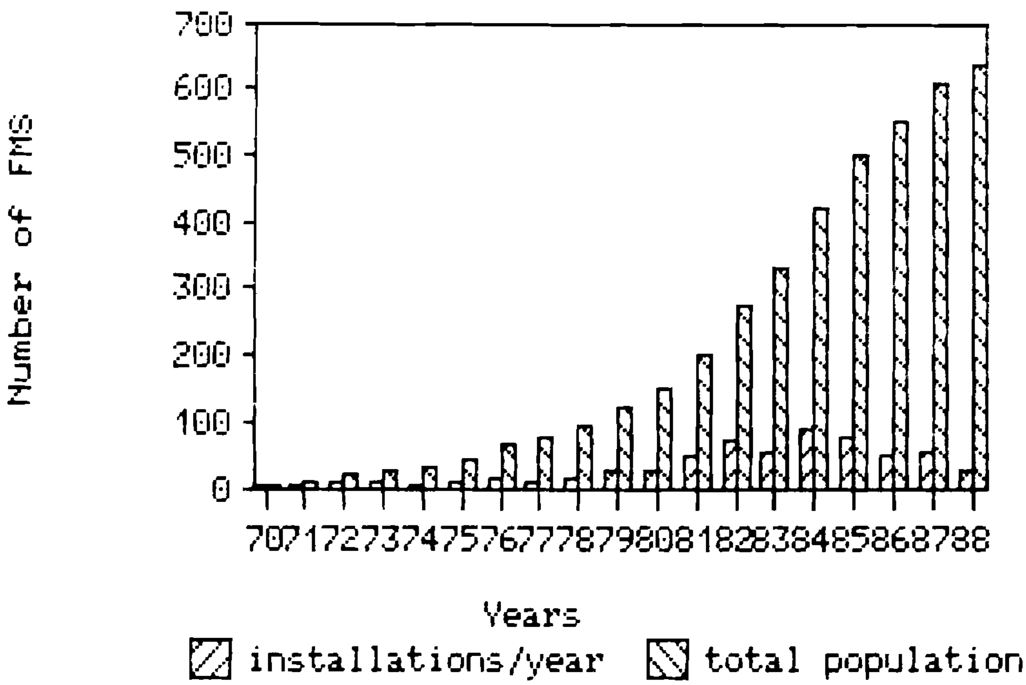


Figure 3. FMS installations by years and trend in FMS population.

Table 3. The comparison of average figures for basic and compressed versions of the data bank

Indicator	Basic version (758 cases)	Compressed version 3 (675 cases)	Indicator	Basic version (758 cases)	Compressed version 3 (675 cases)
MC	4.7	4.6	LTR	5.6	5.0
NCMT	7.4	6.7	SUT	10.1	11.0
ROB	6.1	2.5	IPT	6.8	7.3
TC	4.5	4.1	INR	6.0	5.1
INV	5.6	5.3	VIP	4.4	3.7
PBT	3.9	3.9	PER	4.3	4.6
DPR	2.7	2.7	NOM	4.5	4.0
UNM	1.0	1.0	PROD	5.9	6.6
PV	206	159	CAP	1.8	1.7
BS	213	208	UCR	1.6	1.6

went down from 206 to 159 due to the exclusion of metal-forming FMS, which are usually able to produce thousands of different parts from a metal sheet. The exclusion of the latter systems decreased the average reduction of lead time, inventories and work-in-progress. Machining-type FMS have a higher personnel reduction and productivity increase than on average.

4. Technical Complexity

The technical complexity is described by the number of NC-machine tools, machining centers, industrial robots, type of transportation and other systems. The FMS distribution over a number of NCMT, shown in Figure 4, demonstrates that 46% of all FMS, for which the information was available (655 cases), include 2-4 NCMT, but only 67 systems (or 10%) could be treated as simplest systems, as they were based on 2-4 machines with one function. The other included machining centers. The systems with medium complexity in terms of NC-machine number (from 5 to 10) have a 39% share, and only 15% of the systems include more than 10 NC-machines.

One fourth of the FMS population is based on NC-machines with one function (usually NC-turning, milling or drilling machines), 40% are based on the use of multi-functional machining centers and only 35% have mixed architectures.

Approximately 60% of the FMS include 2-4 MC (see Figure 5), though there are 7 FMS with 20 and more centers. 65 systems (or 13%) based on MC include 2 machining centers without any NC-machines. Naturally they should be considered to be the simplest.

There were only 188 FMS (or 25% of the total) where the use of robots was reported. They are used in different types of systems: for loading/unloading, transportation, in manufacturing, assembling, solding, testing, painting, coating, etc.

Machining FMS use (if they have robots) 2.5 robots per system on the average, machining, manufacturing and metal-forming FMS use 3.1 robots on the average. The robots are, however, the main component of welding and assembling FMS, which include 28 robots on the average, and some of these systems use even more than 50 robots.

As is shown in Figure 6, the FMS of the first three types of application areas usually include 1-3 robots (more than 80% of the total number of FMS of these types), and 42% of them use only one robot. On the other hand, 57% of the welding and assembling FMS have more than 10 robots and 43% of them more than 20 robots. This is why there is a certain shift in the average number of robots (6.1) for all the systems due to their large number in several welding/assembling FMS.

Approximately 57% of the 614 FMS, for which the TRT data were reported, use conventional types of transportation systems (conveyors, cranes, etc.), and 43% use automated (wire, rail, wireless) guided vehicles and robots. There is a suspicion that

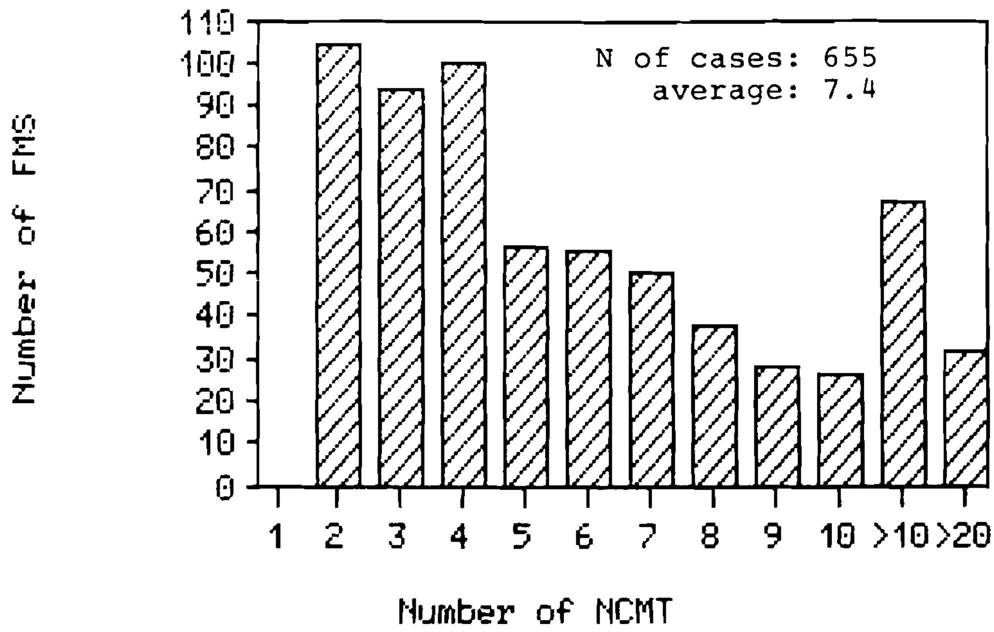


Figure 4. FMS distribution over number of NC-machine tools in a system.

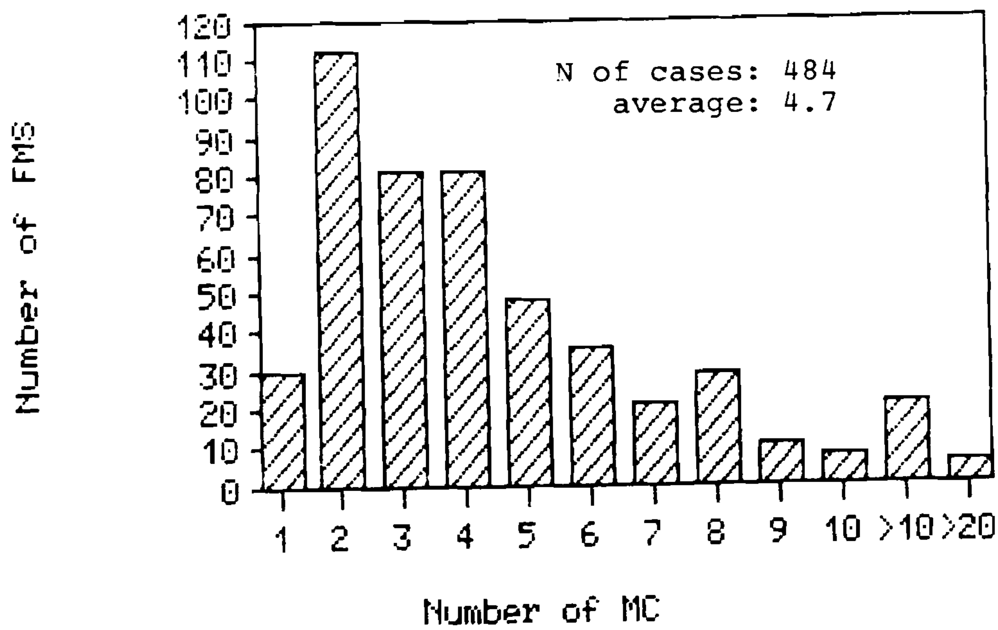


Figure 5. FMS distribution over number of machining centers in a system.

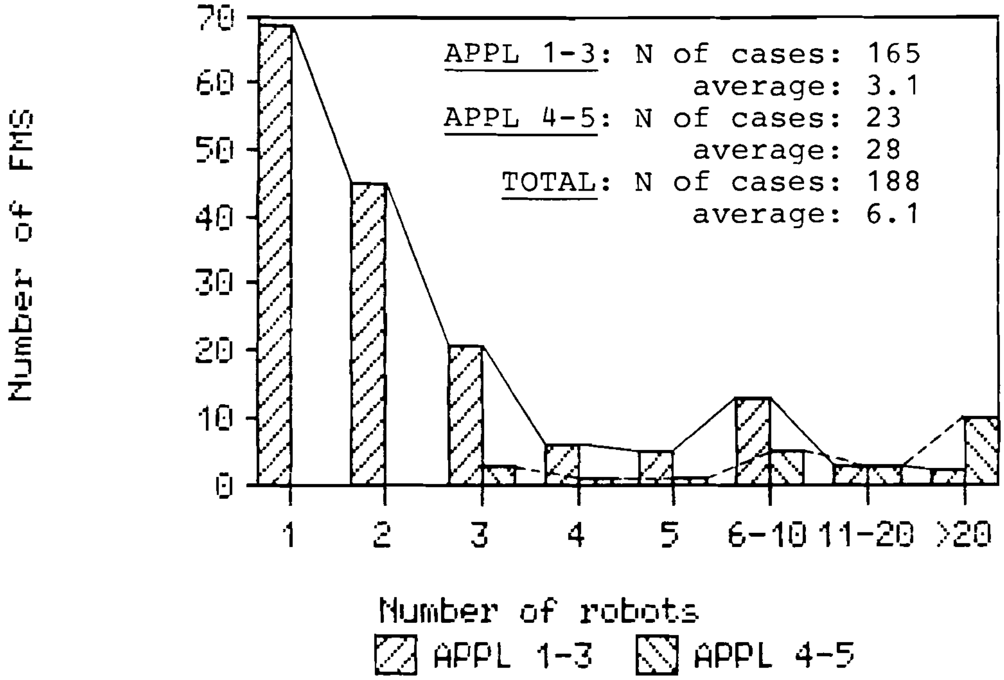


Figure 6. FMS distribution over number of robots in a system (1-3: manufacturing, machining, metal-forming; 4-5: welding and assembling).

the majority of cases with unreported data has the first type of transportation system.

The clustering of the storage and inspection system is rather flexible and it was difficult to divide the real, manifold systems into two classes. This is why we just state that in the bank two thirds of 279 FMS have conventional storage systems, and 53% of 321 FMS also have conventional inspection systems.

The technical complexity, measured as a weighted combination of NC, MC, ROB and TRT, is distributed as shown in Figure 7. About 100 FMS, or 15% of 675 systems, where the data were reported, are the simplest. Their TC does not exceed 2. The systems with a technical complexity from 2 to 4 present 25% of the total amount and they may also be treated as simple systems.

At the same time 33 systems have a TC from 10 to 20 and 11 FMS of more than 20. Among these 11 super-complex systems 6 were installed in Japanese companies, 3 in the USA, and all of them have been in use since 1982 or later.

5. Economic and Operational Data

The analysis of the data from the third version of the bank shows the FMS distribution over their costs, which is rather close to the distribution we obtained by using the second version of the bank [39]. About 65% (in comparison to 66% in the second version) of all FMS, where investments were reported, are not more expensive than 5 million US $. Moreover, 50% of the FMS costs are not higher than 3 million $, and 24% are between 1 and 2 million $, see Figure 8.

In reality the share of relatively cheap FMS is supposed to be slightly lower, because there are several hidden FMC and partly donated FMS in the bank. But such a shift is not big enough to be taken into consideration, and the coincidence of the distributions retrieved from the two versions of the bank proves this fact.

The share of expensive FMS (more than 10 million $) is 11% and among the expensive systems there are 7 FMS which cost more than 20 million $: 4 in Japan, 2 in the USA, and 1 in the FRG.

The FMS distribution over their pay-back time (see Figure 9) is close to normal, with the peak allocated around 3 years. The share of "super-profitable" systems with PBT less than 2.5 years is 22%. Japan, the UK and Finland own 3 such FMS each. On the other hand, there are 12 FMS (or 16%) with a pay-back time longer than 6 years. Among them there are 9 Czechoslovak systems, 1 belongs to the FRG, 1 to Japan and 1 to South Korea.

There is a linear proportionality between INV and PBT (higher cost means longer pay-back time) for the systems cheaper than 4 million $, and there is no significant influence of investments on PBT for the more expensive FMS, see Figure 10.

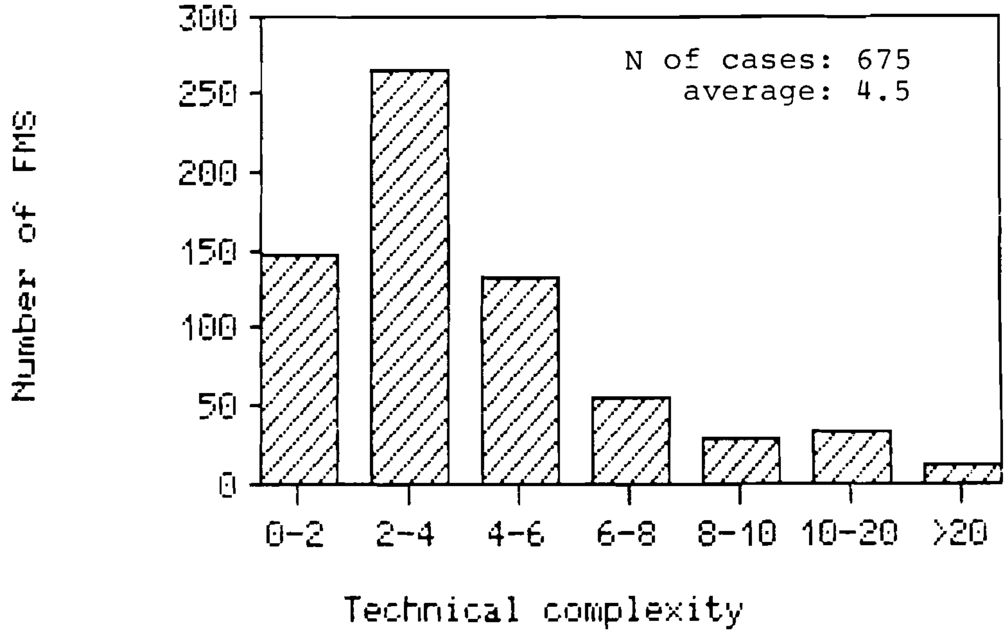


Figure 7. FMS distribution over their technical complexity.

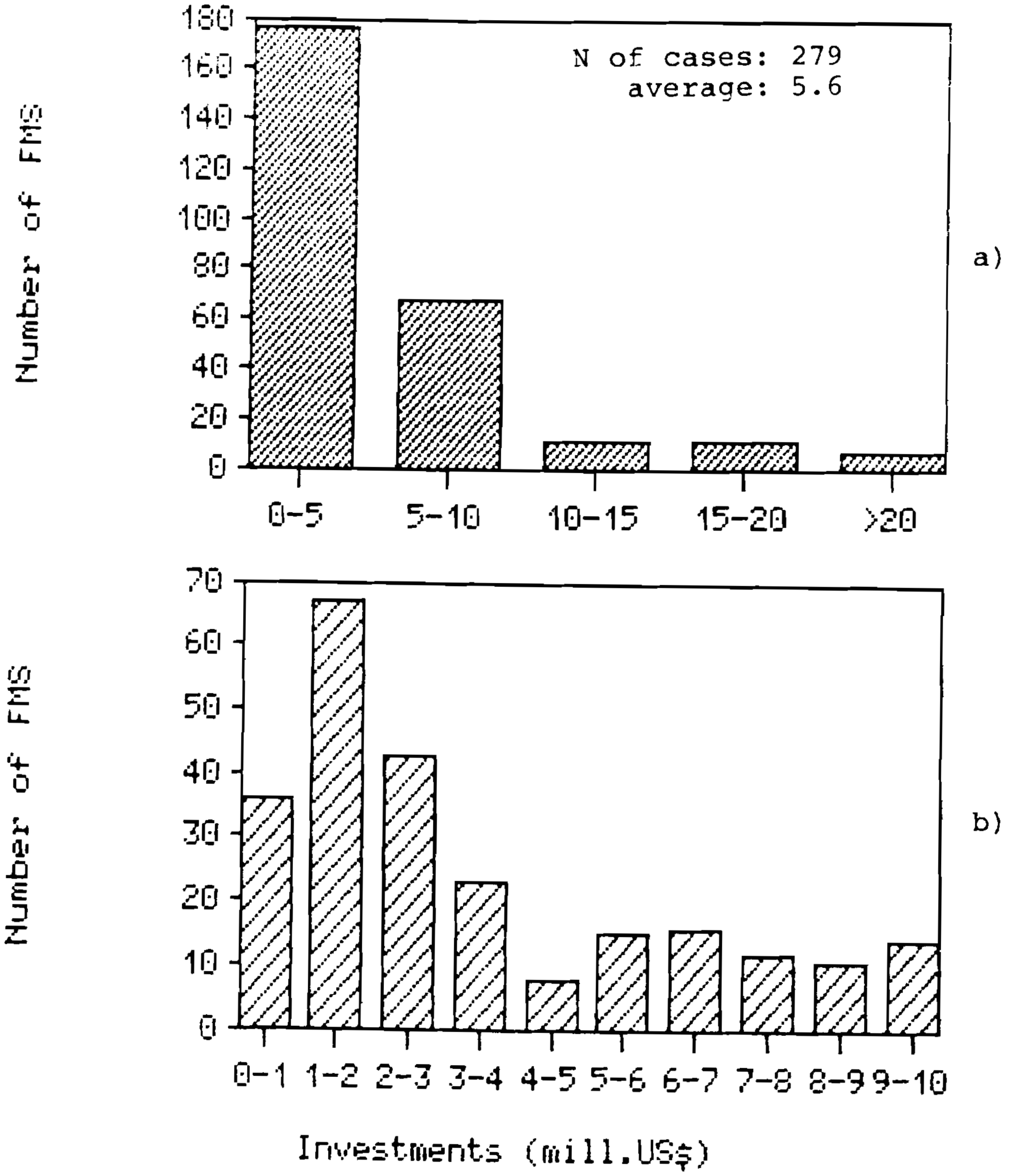


Figure 8. FMS distribution over their costs.

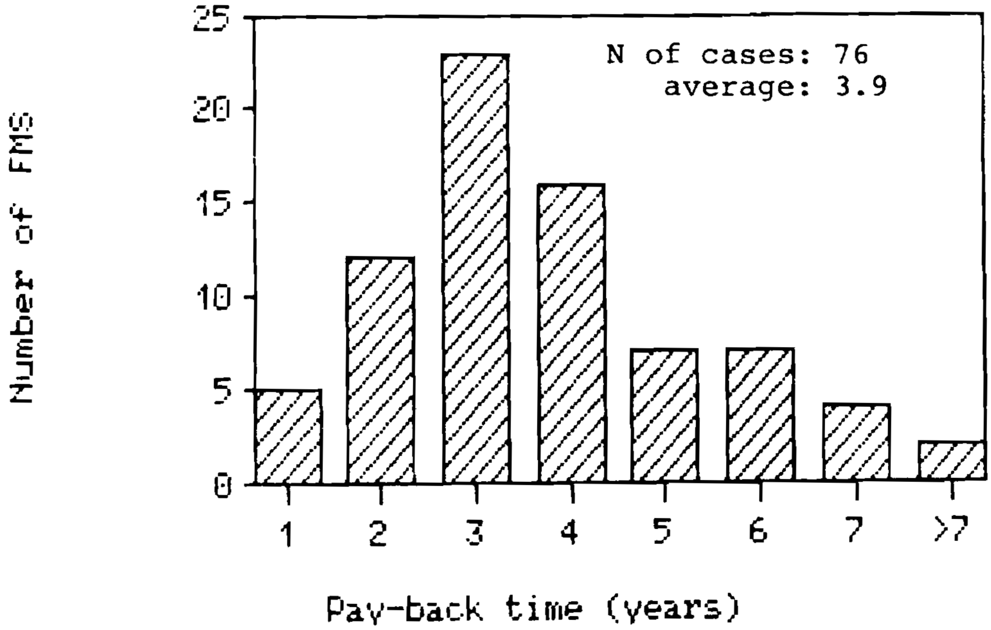


Figure 9. FMS distribution over pay-back time.

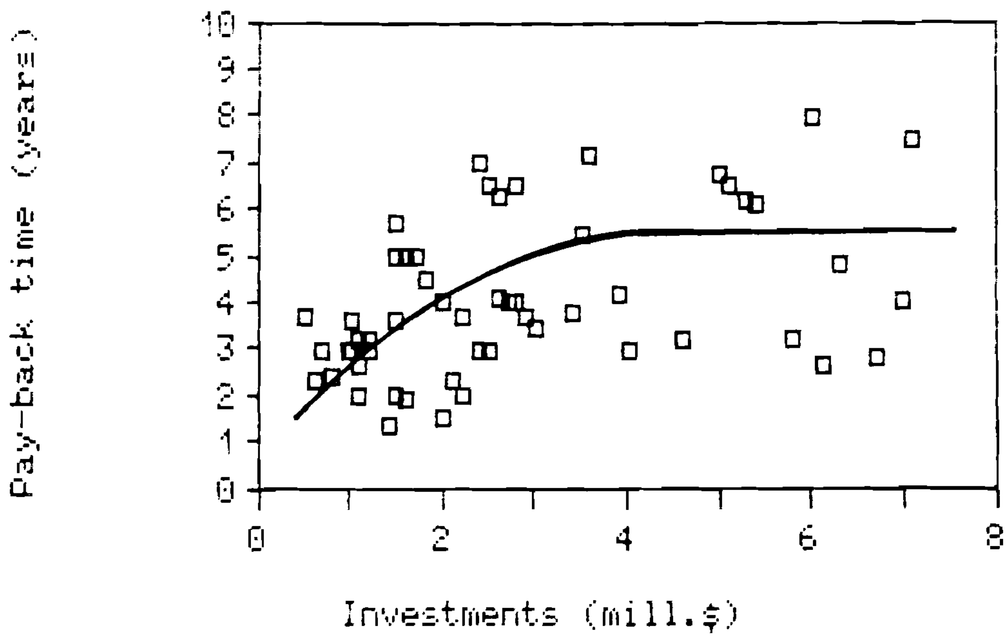


Figure 10. Pay-back time versus investments.

The most typical operation mode of FMS (see Figure 11) is as follows: 3 shifts a day, including 1 unmanned night shift. Two thirds of 232 FMS, where the information is available, are used during 3 shifts a day, 28% between 2 and 3 shifts and only 9 FMS are used during 1 shift a day.

Two thirds of 118 FMS are autonomous enough to be used during 1 shift in an unmanned mode, 15% during half a shift (4 hours) and 6% longer than 2 shifts. Naturally, the flexibility of an FMS is lower when it is used in an unmanned regime.

FMS flexibility is one of the most important features and advantages of a system. It is usually measured by two indicators: average batch size and number of product variants. The distribution of the batch sizes, displayed in Figure 12, shows that the majority of FMS are really used for small batch production. Three fourth of the FMS produce parts by batches, which do not exceed 100 units a batch, and one third by batches of no more than 10 units a batch. At the same time 9 FMS (or 4.3%) are used for big batch production. They produce parts by a batch of more than 1000 units.

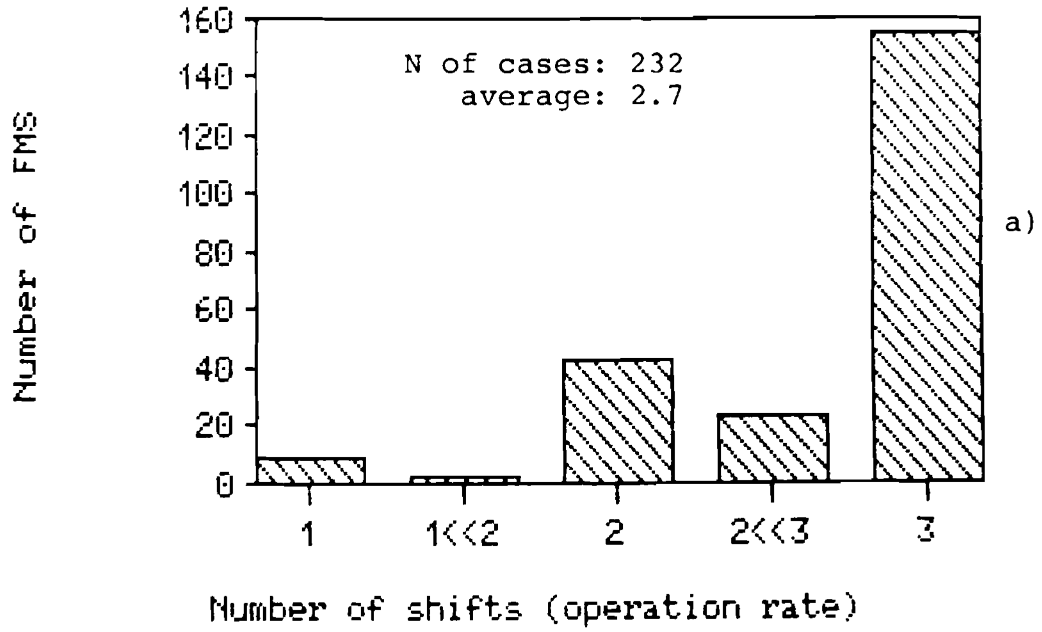
Another indicator of flexibility -- number of product variants -- shows (see Figure 13) a rather moderate flexibility of 30% of the FMS. Practically they produce no more than 10 different parts. About 44% of the systems produce from 11 to 100 parts, and the "super-flexible" FMS (4% of the total) are used for the production of more than 1000 parts.

Due to a very high variation of both indicators it is impossible to represent their correlation by one graph. Clustering the cloud of points we found that there were several distinct stripes where BS versus PV points were allocated, see Figure 14. All the stripes show negative slopes. The interpretation of the figure allows to conclude that there are several clusters of the FMS from the flexibility viewpoint. The drawing of the stripes was naturally based on a visual impression, but looking through the cases allocated within each stripe we found that the main factor of such clustering could be the technical complexity of the parts produced by the FMS.

As we have no direct indicator of the part complexity, we have chosen the MC/NCMT relation as a substitute for the indicator. The higher share of multifunctional machining centers, usually developing a lot of surfaces, in the total number of NC-machine tools corresponds to a higher part complexity.

The estimates of the average shares (MS) for each stripe showed a very strong gradient (see the window in Figure 14), proving the assumption statistically.

The left lower corner includes the cases where the moderate batch size is explained by the demand structure and the low number of products is connected with a very high complexity of the parts (number of surfaces developed, accuracy of development, etc.). The left upper corner of the graph demonstrates the FMS replacing production lines for mass production of a rather



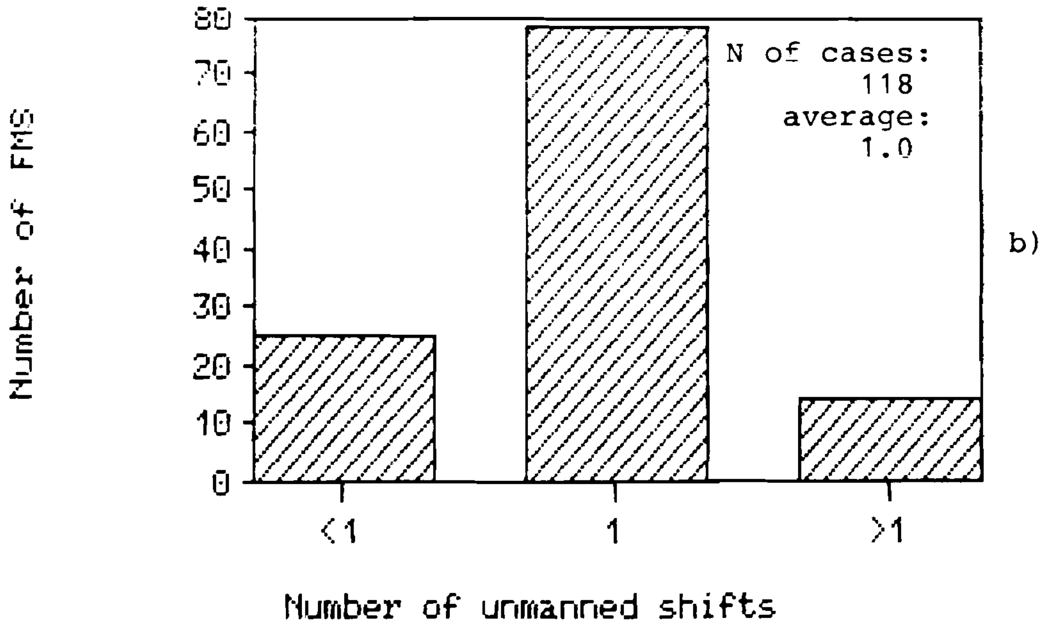


Figure 11. FMS distribution over operation mode.

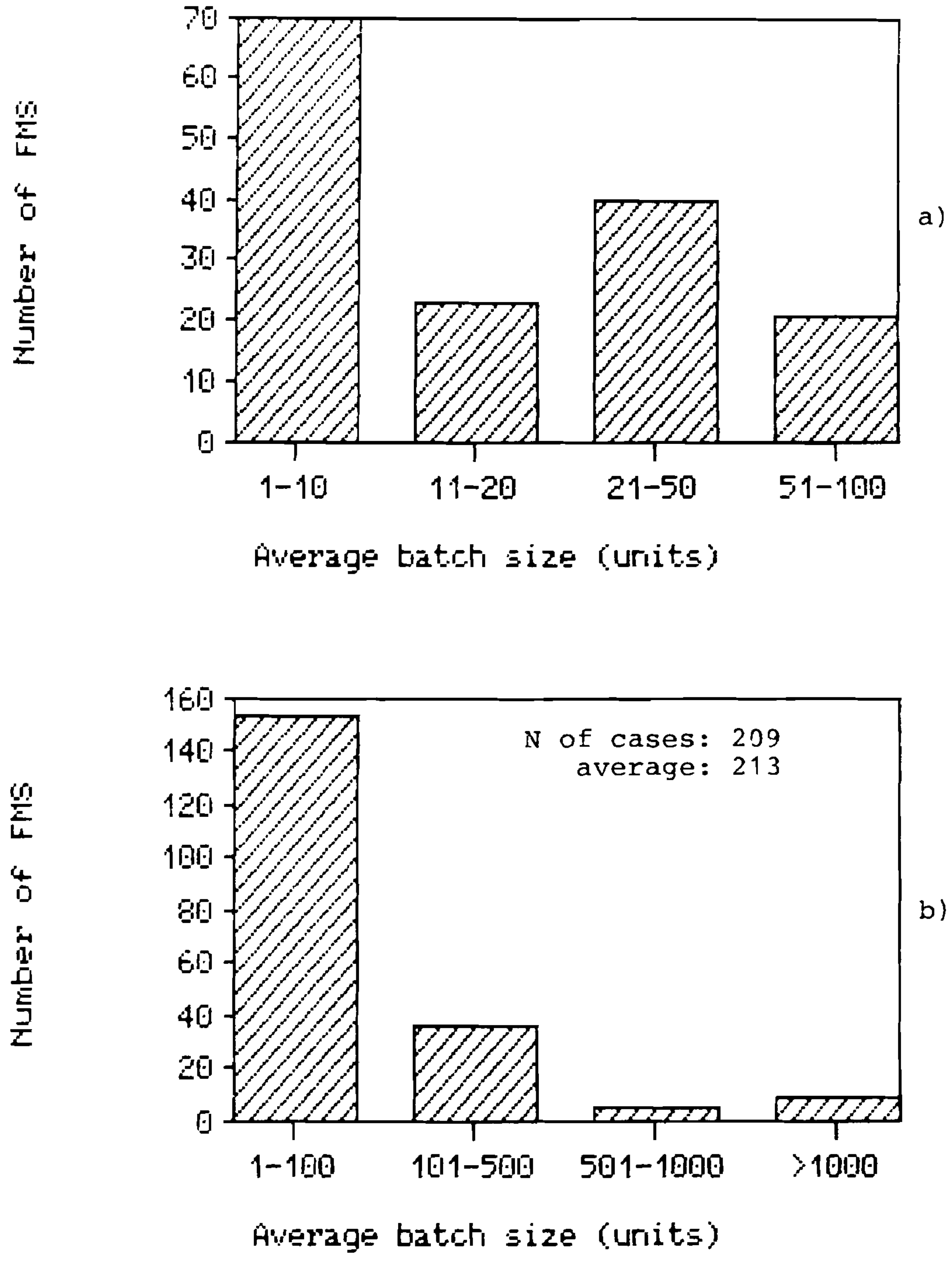


Figure 12. FMS distribution over average batches of production.

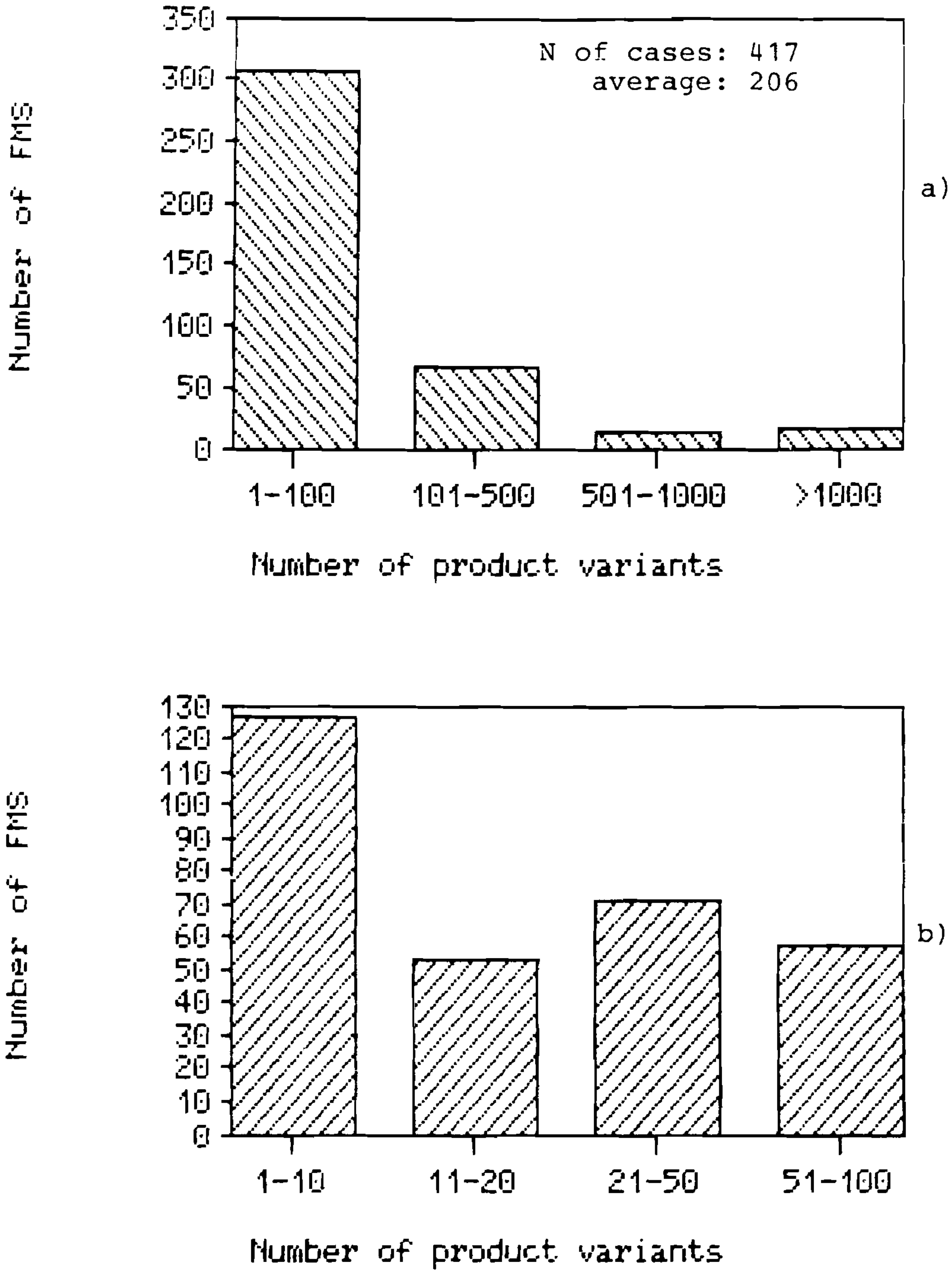


Figure 13. FMS distribution over number of product variants produced.

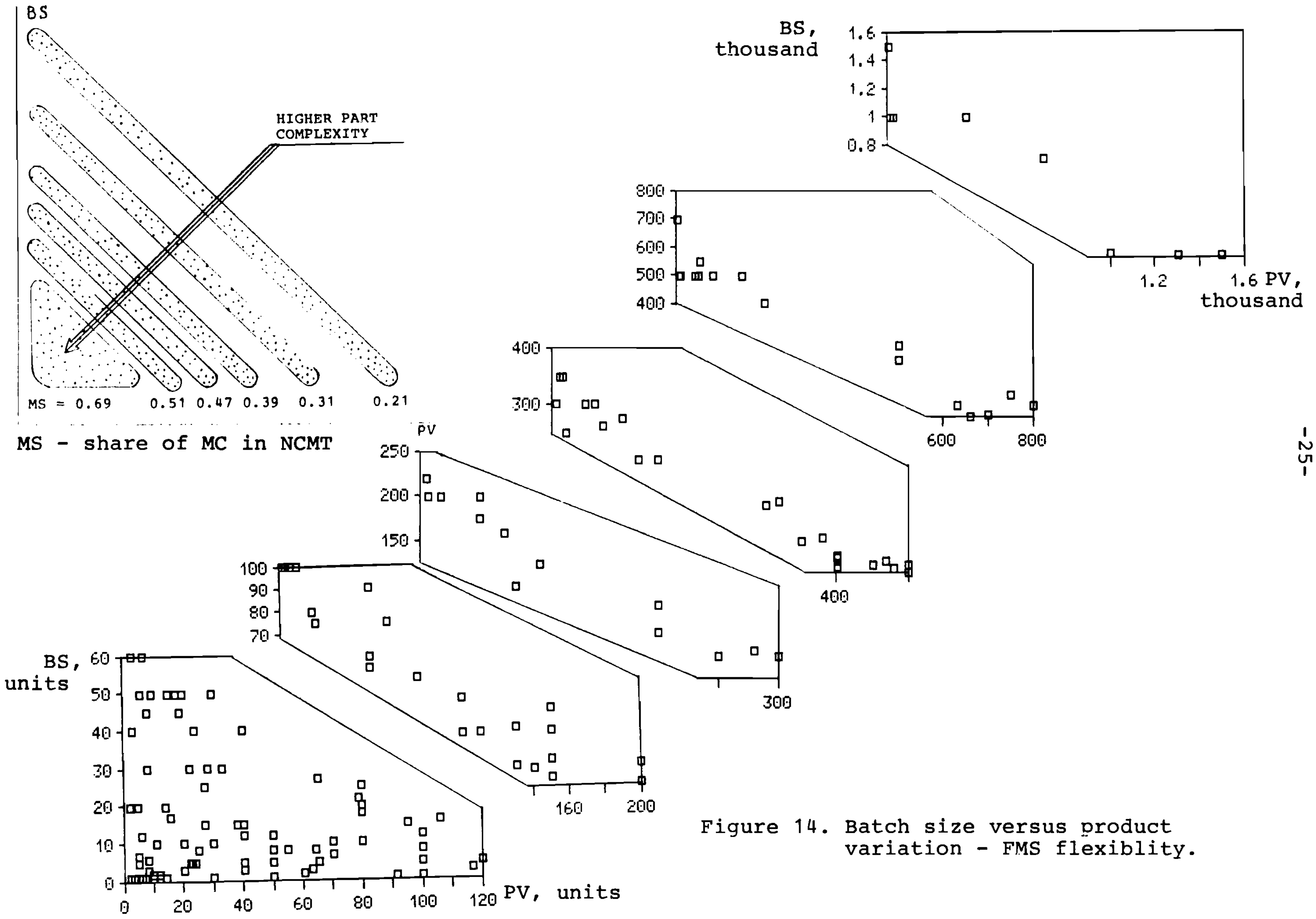


Figure 14. Batch size versus product variation - FMS flexiblity.

limited number of parts, e.g., when an FMS is installed instead of several lines to produce 4-6 variants of diesel cylinder heads. The right lower corner is that area, where FMS for simple parts production are allocated.

Naturally, the interrelation between PV and BS is influenced by industry-specific features or the general mode of production (the average batch size in Eastern countries is, ceteris paribus, bigger than in Western companies). But we agree with some specialists who consider the potential flexibility to be much higher for the existing FMS than the real one. The misapplication (i.e. the planned PV seemed to be much higher than it was in reality) can be explained by a shortage of experience, software and inadequate pre-installation planning.

6. Relative Economic Advantages

All the FMS advantages collected in the bank are measured in relative terms of increase or decrease in comparison with substituted conventional technologies. They reflect different aspects of fixed capital, current expenditures and labor savings.

The advantage indicators are interrelated by nature. For example, shorter set-up time or/and shorter in-process-time result in a shorter lead time. This, in turn, allows to produce different types of products requiring less raw materials, final goods inventories and work-in-progress. At the same time a shorter set-up or lead time increases the capacity utilization rate and provides the same production by a lower number of machines. The lower number of machines with a computerized control are served by less personnel and the labor productivity increases. Higher investment costs of NC-machines and supporting subsystems within an FMS are partly compensated by saving through a lower number of machines, less floor space, as well as economy on storage and sales departments.

The current expenditures are a second way of saving. The lower volumes of inventories and work-in-progress provide a significant part of the saving. There is also lower electricity consumption (during unmanned shifts). The labor cost saving is due to less personnel, even if the average wage rate goes up.

As a result of the partial compensation of high investments through savings in different elements of fixed capital, as well as lower current expenditures and labor costs, the unit costs are usually lower, but, unfortunately, the latter was only reported in 55 cases.

Lead time reduction was reported for 98 cases and the FMS distribution over different sizes of LTR is shown in Figure 15. About two thirds of 98 FMS displayed a lead time reduction by a factor of 2-4. The average reduction has shifted to 5.6 due to 16 successive FMS, where the reduction was by a factor of 10 and even more. The exclusion of 2 metal-forming FMS with an extremely high LTR decreases the average figure from 5.6 to 4.9.

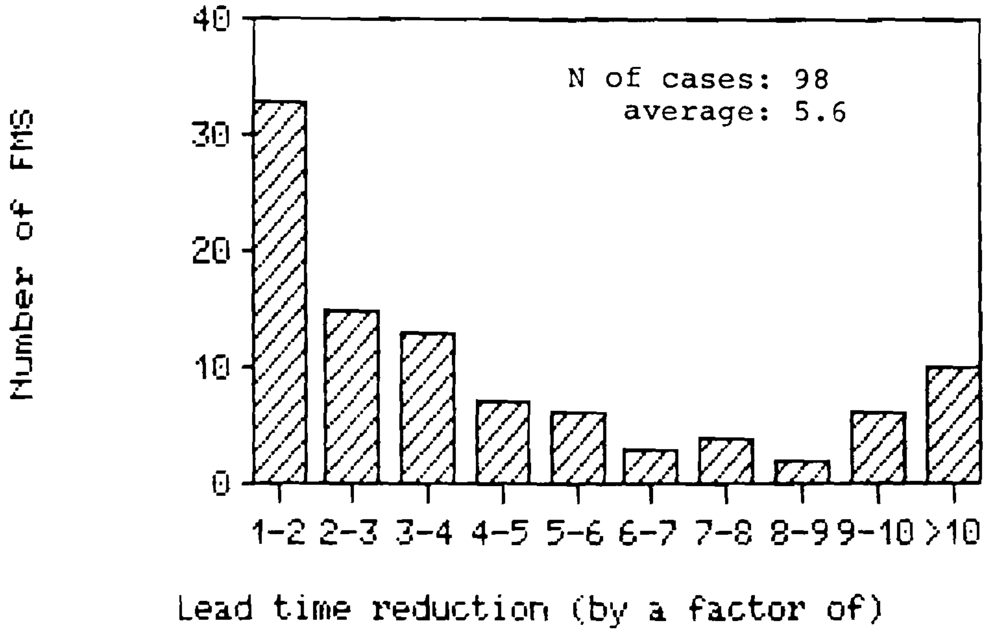


Figure 15. FMS distribution over lead time reduction.

There are similar distributions for set-up time and in-process time reductions, see Figures 16 and 17, respectively. Two thirds of 40 FMS showed a set-up time reduction by a factor of 2-4, and in the implementation of 5 systems the SUT decreased almost to zero. The exclusion of the latter pushed the average figure from 10 to 4.4, which looks more reasonable.

With regard to the in-process time reduction, two thirds of 55 systems reduced the IPT again by a factor of 2-4, and 14 FMS by a factor of 10 and more. The machining time reduction is more moderate: 73% of the FMS had an MT reduction by a factor of 1-2. This is understandable as the machining time reduction is provided only through a combination of different cutting procedures and is not influenced by any organizational factors.

There is a strong correlation between lead time reduction and set-up reduction, see Figure 18. The correlation between LTR and IPT is weaker (see Figure 19) and there is no LTR correlation with the machining time reduction. This confirms the fact that the lead time reduction is provided, first of all, by the reduction of the set-up time and, secondly, by the decrease of the in-process time.

The logistic advantages of FMS could be represented by the reduction of raw materials and final goods inventories, as well as by a relative decrease of the work-in-progress. The inventory reduction is not only connected with FMS performance, but also with the activity of the supply and distribution systems. About half of the FMS display a rather moderate decrease of INR and WIP, see Figure 20. Among the systems there are 3 FMS which provided practically zero inventories and the other 3 FMS provided almost zero work-in-progress. The exclusion of these peculiar systems decreases the average INR from 6.0 to 2.8 and the average WIP from 4.4 to 2.8.

As has already been discussed above, the personnel reduction and the productivity increase are interrelated, as shown in Figure 21. This is why the similarity of the FMS distribution over these two indicators (see Figure 22) is no surprise. About 60% of the FMS showed a personnel reduction up to a factor of 3, the share of the FMS with a corresponding productivity increase was about 70%.

At the same time the share of "super labor-saver" -- FMS, which reduced personnel by a factor of 5 and more, was considerably higher (18%) than the share of FMS which increased the productivity at the same rate (8%).

The major source of fixed capital savings is the lower number of machines used within the FMS in comparison to conventional technologies. This is reached due to the multi-functionalism of machining centers, the more efficient use of numerically controlled machines and their higher utilization rate. The FMS distribution over the number of reduced machines is shown in Figure 23. The average reduction was by a factor of 4.5, which compensated approximately 40-50% of the machine cost increase.

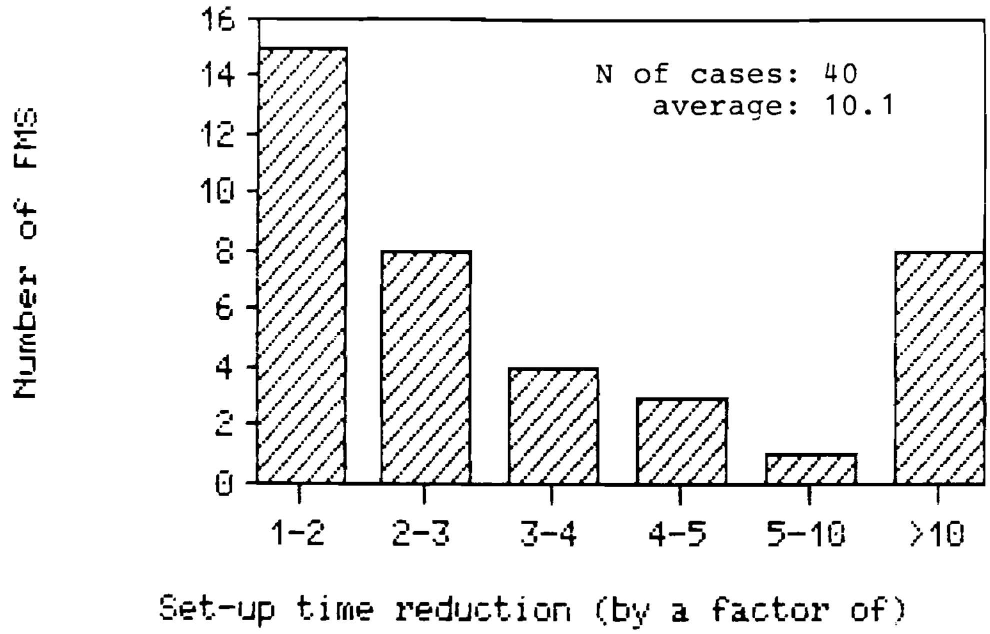


Figure 16. FMS distribution over set-up time reduction.

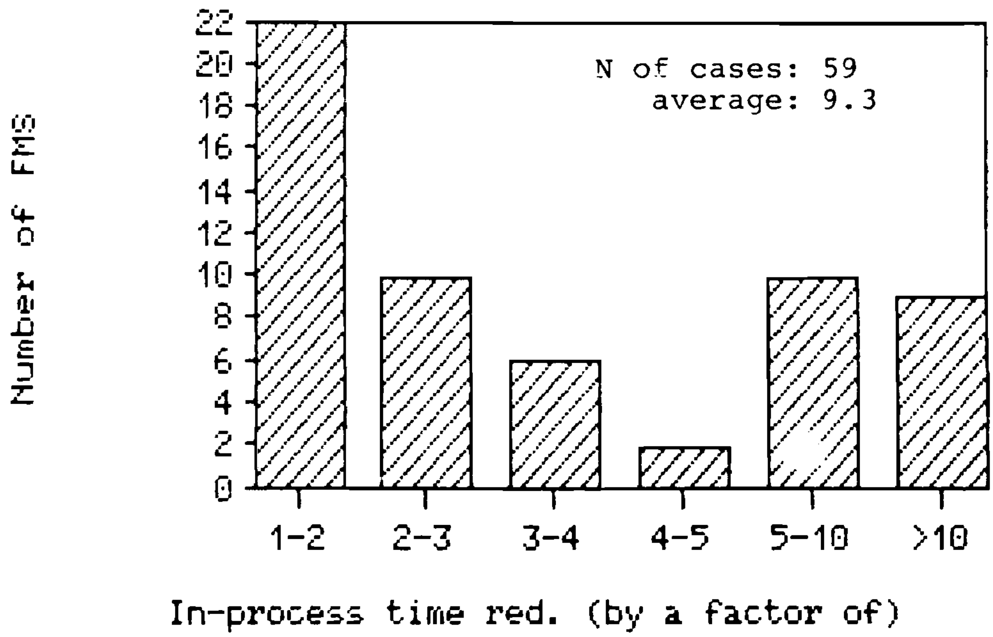


Figure 17. FMS distribution over in-process time reduction.

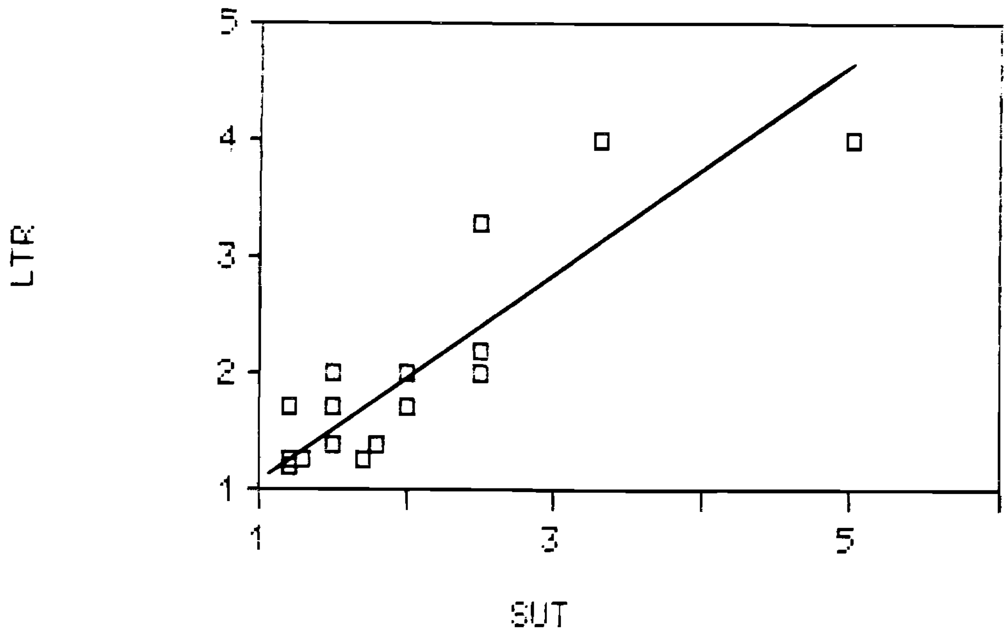


Figure 18. Lead time reduction versus set-up time reduction (by a factor of).

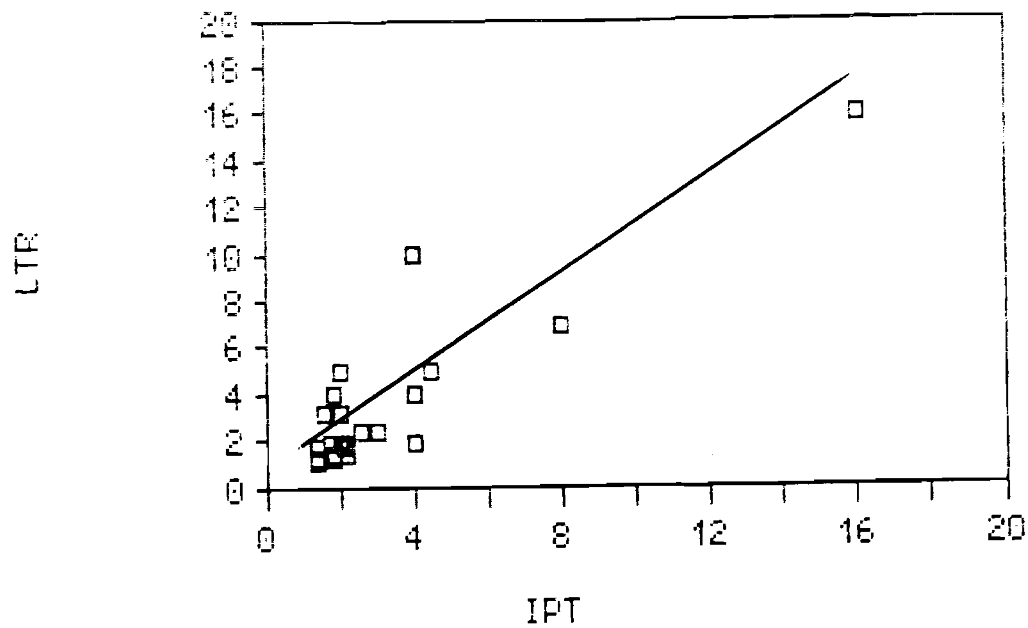


Figure 19. Lead time reduction verus in-process time reduction (by a factor of).

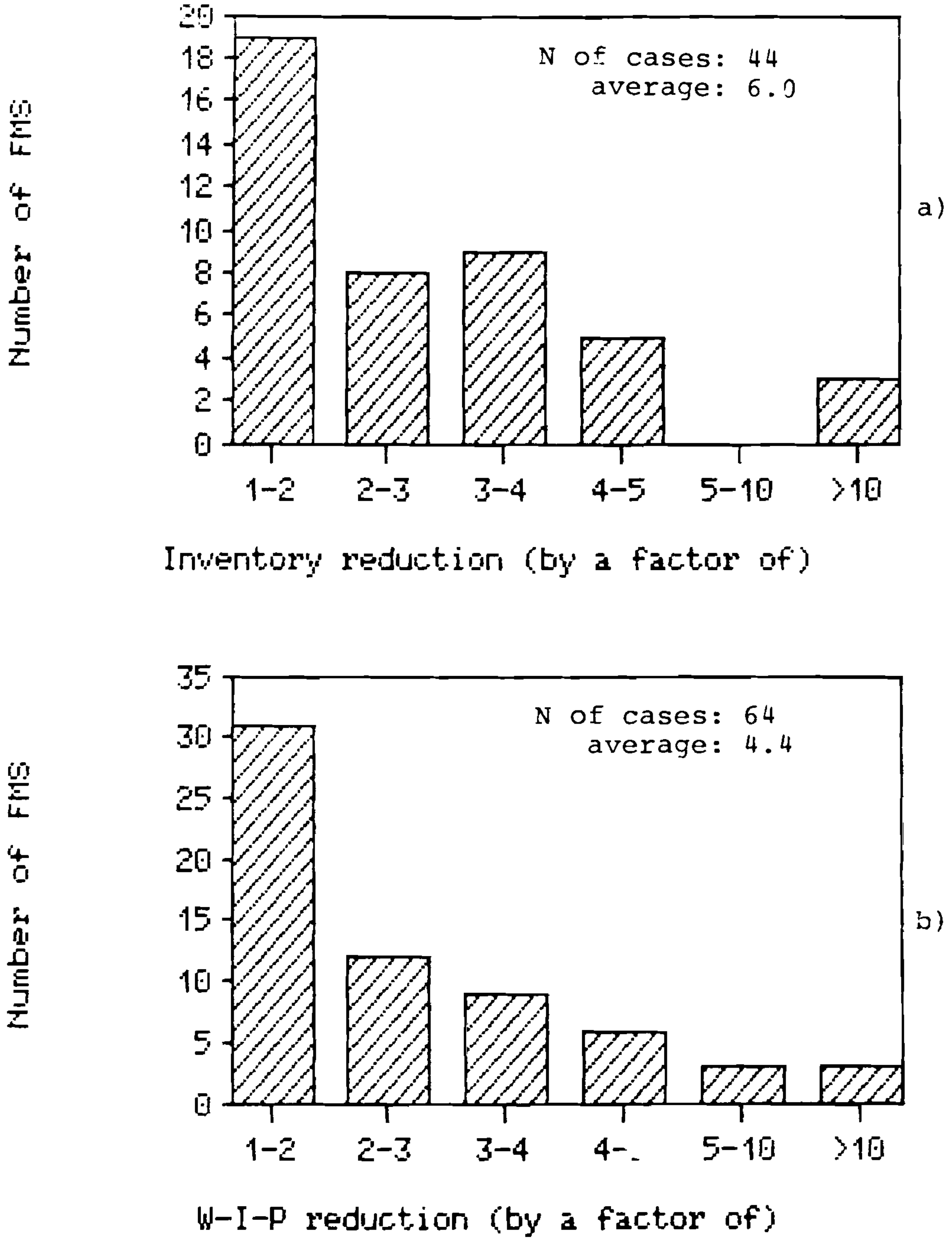


Figure 20. FMS distribution over inventory (a) and work-in-progress (b) reduction.

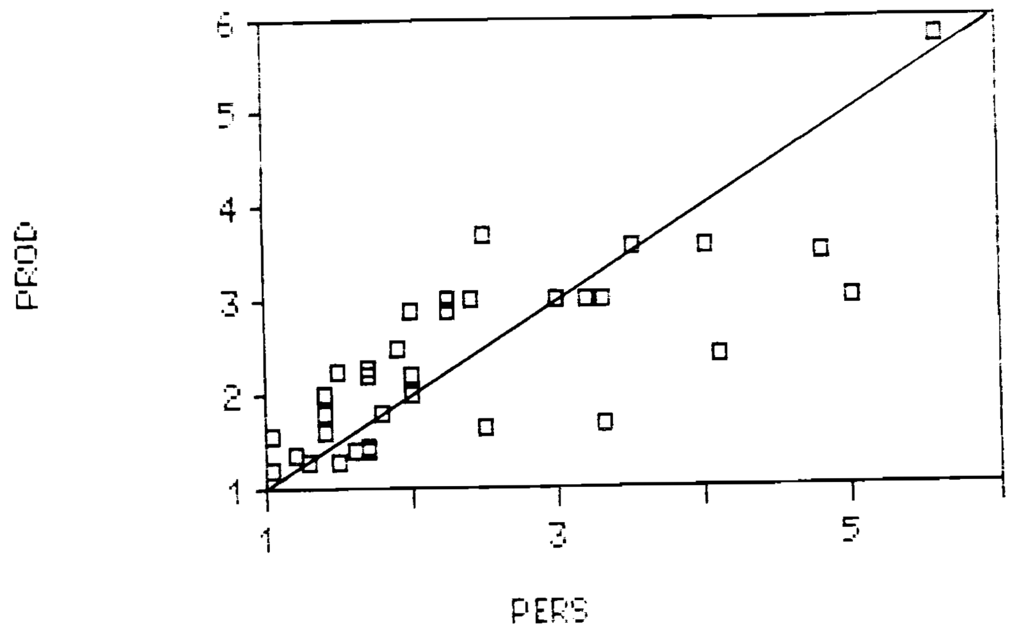
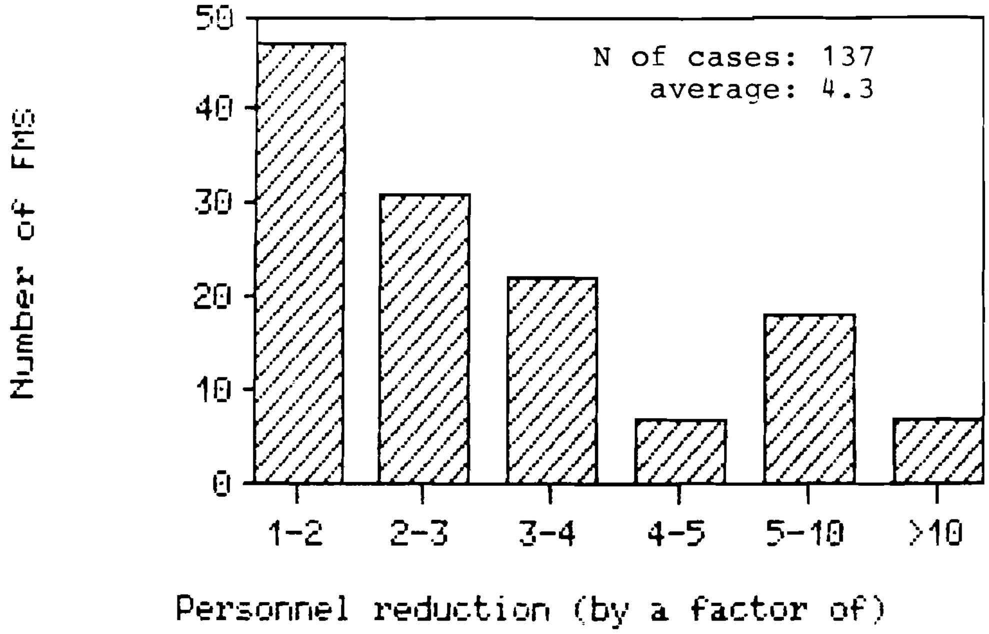
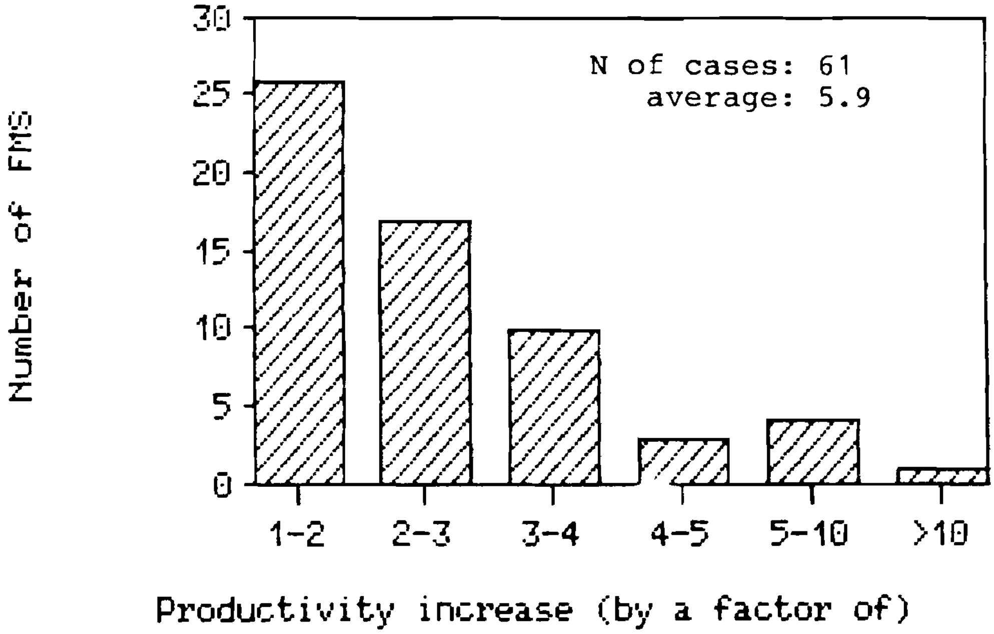


Figure 21. Productivity increase (PROD) versus personnel reduction (PERS), by a factor of.



a)



b)

Figure 22. FMS distribution over personnel reduction (a) and productivity increase (b).

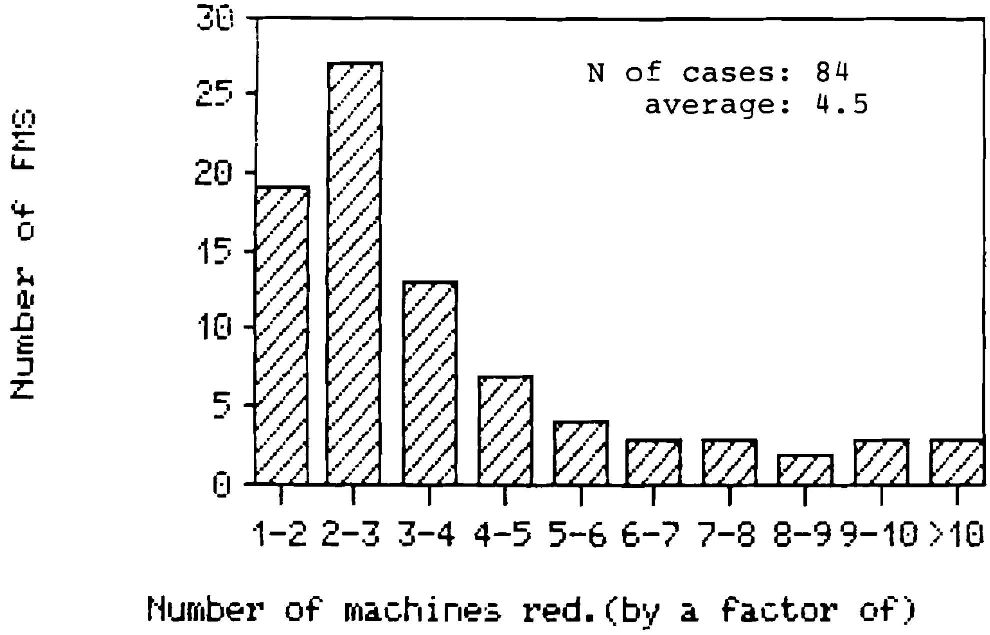


Figure 23. FMS distribution over number of machines reduction.

The highest share (32%) belongs to those FMS, whose usage led to an NOM reduction by a factor of 2-3. More than one fifth of the FMS have 5-10 times less machines than their conventional predecessors.

The capacity utilization rate, measured as the share of machining time in total disposable time (24 hours a day and every day) increased by a factor of 1.8 on the average. If 6-8% is the normal share of machining time for conventional metal cutting machines, such an increase means that much more expensive NC-machines are used within FMS about 3 hours a day. If we exclude vacations, week-ends and other unavoidable losses, this figure will reach 6-8 hours per working day.

For the majority (80%) of the FMS where the CAP was reported, the increase was by a factor of 1-2, see Figure 24, and only 13 FMS reached a higher increase of the utilization rate.

Another way of fixed capital saving is a reduction of floor space and, consequently, construction costs. Due to the lower number of machines and the more compact storage and retrieval systems, the average floor space reduction of an FMS substituting for a conventional technology, is by about a factor of 2.

As a result of savings in different cost elements -- fixed capital, labor and operational expenses -- there were noticeable unit cost reductions for the parts produced by 55 FMS. The majority of the cases (60%) demonstrated UCR from 10 to 30% (see Figure 25). 50% and higher reductions were reported in 11 cases, mainly for the systems where this advantage was mentioned as a main target of the FMS implementation.

In some cases a significant cost reduction was reported in the case of product changes, i.e. when the FMS began to produce new parts.

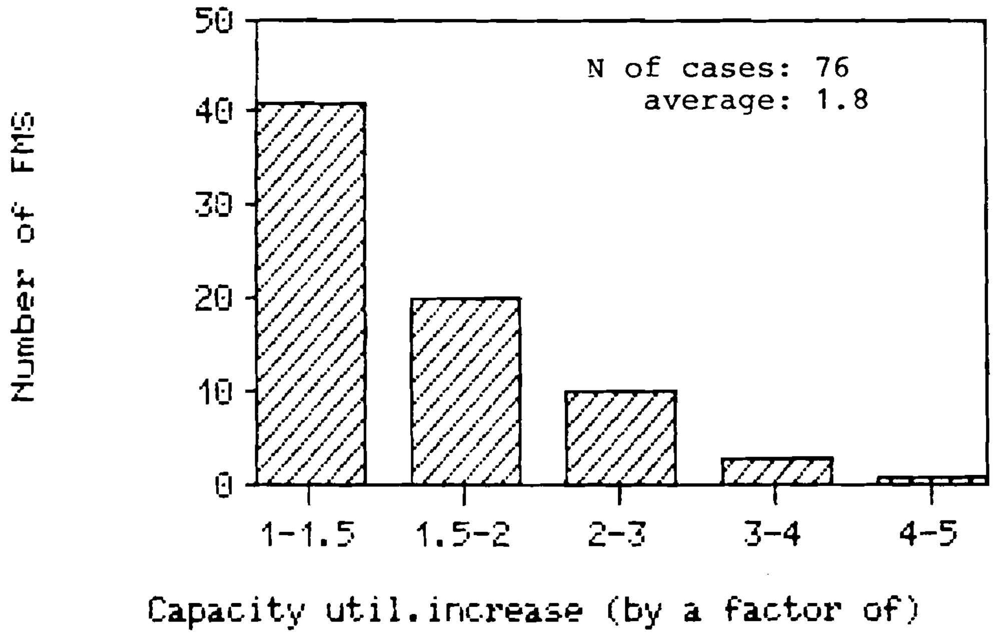


Figure 24. FMS distribution over capacity utilization increase.

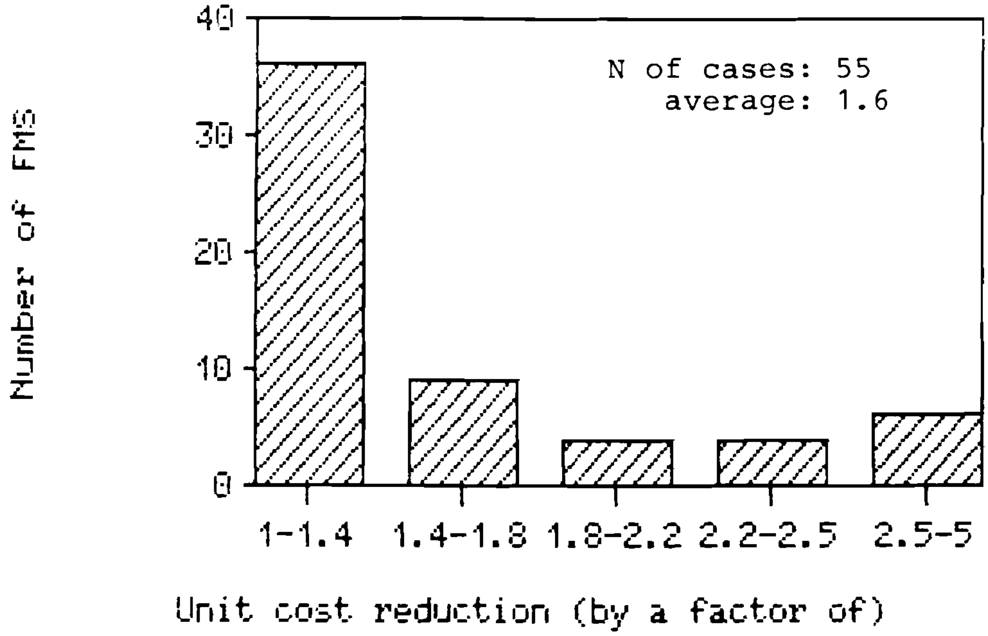


Figure 25. FMS distribution over unit cost reduction.

Appendix 1.

List of Indicators

I. System Identification:

1. "COUN" - name of country where FMS is allocated.
2. "COMP" - name of user.
3. "VEN" - name of main producer.
4. "YEAR" - year of installation.

II. Application:

5. "IND" - industry of application (1 - final metal products + non-electrical machinery + part of electrical machinery (large machine building) + transportation equipment; 2 - other part of electrical machinery and electronics + instruments).
6. "APPL" - application area (1 - manufacturing, 2 - machining, 3 - metal forming, 4 - welding, 5 - assembling).
7. "TOP" - type of product (1- prismatic, 2 - rotational, 3 -both).

III. Technical Complexity:

8. "MC" - number of machining centers.
9. "NCMT" - total number of numerically controlled machine tools (including MC).
10. "NC" - number of NC-machines (excluding MC).
11. "ROB" - number of robots.
12. "TRT" - type of transportation system (1 - conventional conveyor or crane; 2 - automated guided vehicles or computer-controlled carts).
13. "TC" - technical complexity = 0.35 NC + 0.7 MC + 0.3 TRT + 0.3 ROB.
14. "STOR" - type of storage system (1 - conventional systems; 2 - computer-controlled warehousing system and automated storage and retrieval system).
15. "INSP" - type of inspection (1 - manual inspection; 2 - automated maintenance and monitoring system).

IV. Economic and Operation Data:

16. "OPR" - operation rate (number of shifts a day).
17. "UNM" - number of shifts of unmanned operation.
18. "BS" - average batch size.
19. "PV" - product variation or part family (number of products produced by FMS).
20. "INV" - investment cost in million US $ (converted according to the exchange rate for the year of installation).
21. "PBT" - pay-back time (years).

V. Relative Advantages:

Reduction of, by a factor of:

22.	"LTR"	-	lead time.
23.	"SUT"	-	set-up time.
24.	"IPT"	-	in-process time.
25.	"WIP"	-	work-in-progress.
26.	"MT"	-	machining time.
27.	"INR"	-	inventory.
28.	"PER"	-	personnel.
29.	"NOM"	-	number of machines.
30.	"FLS"	-	floor space.
31.	"UCR"	-	unit cost reduction.

Increase in, by a factor of:

32.	"PROD"	-	productivity.
33.	"CAP"	-	capacity utilization.

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