WORKING PAPER

FLEXIBLE MANUFACTURING SYSTEMS (FMS): MAIN ECONOMIC FEATURES (Part II)

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September 1988
WP-88-83

IIASA
International Institute
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FOREWORD

The IIASA CIM Project has collected a world-wide database of FM-systems. This paper is the second one (for the first paper, see [2]) analyzing the properties, benefits and trends of FM-systems based on version 2 of the database (comprising about 400 systems). The paper focuses on the main economic features and impacts of FM-systems. It clusters and correlates different indicators trying to explain the factors behind the achieved benefits. The paper presents new results and features of FM-systems.

Prof. J. Ranta Project Leader Computer Integrated Manufacturing	Prof. F. Schmidt-Bleek Program Leader Technology, Economy, Society

CONTENT

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:

$$LTR = 6.0 - 1.01\ Invest$$

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:

$$LTR = -0.6 + 0.46\ Invest$$

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:

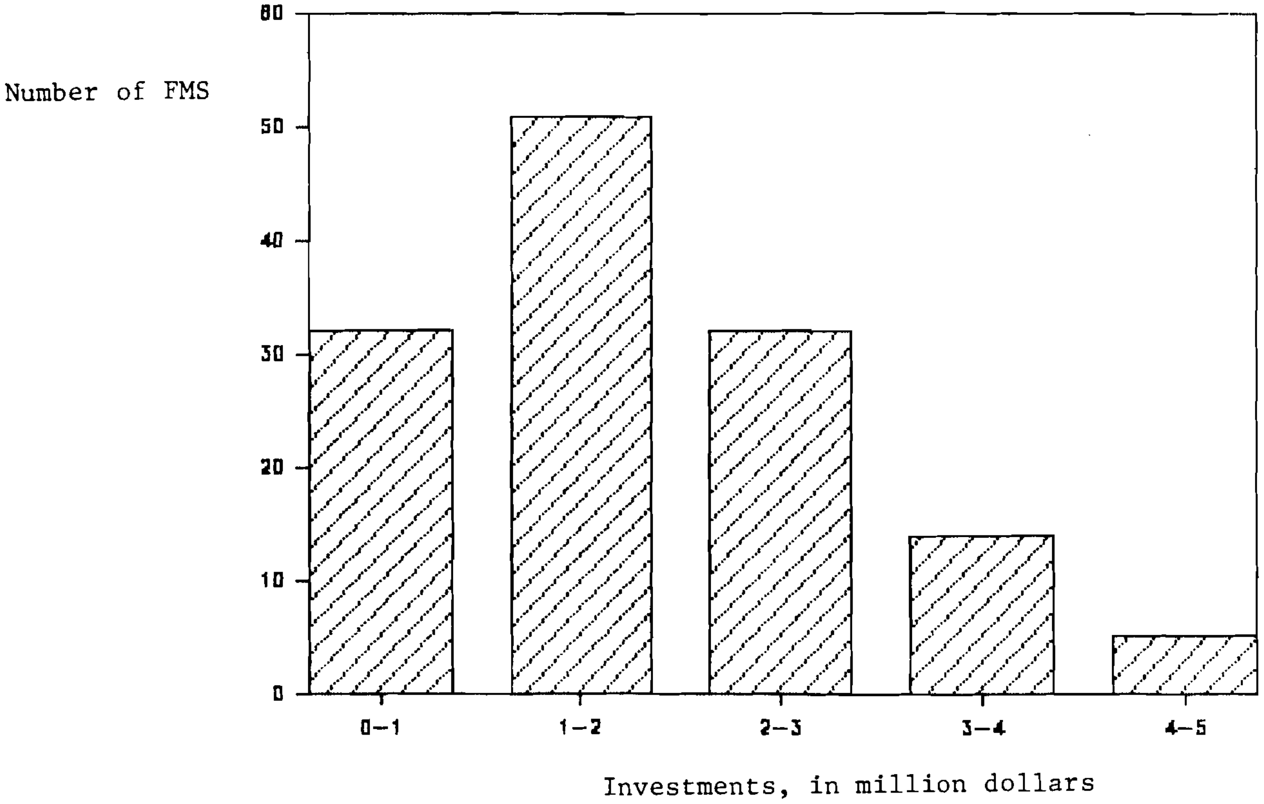
$$\text{PER} = 0.61 + 0.18 \text{ Invest}$$

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.



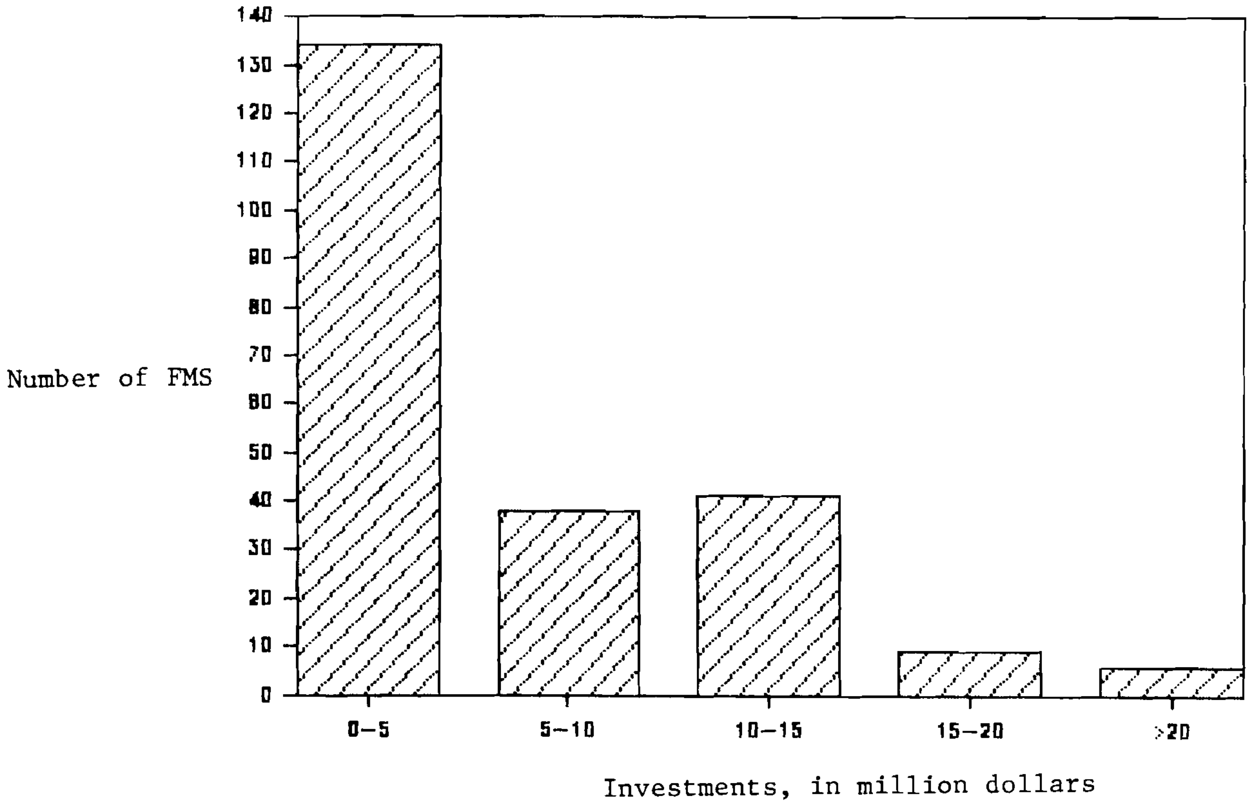


Figure 1: FMS distribution over investments

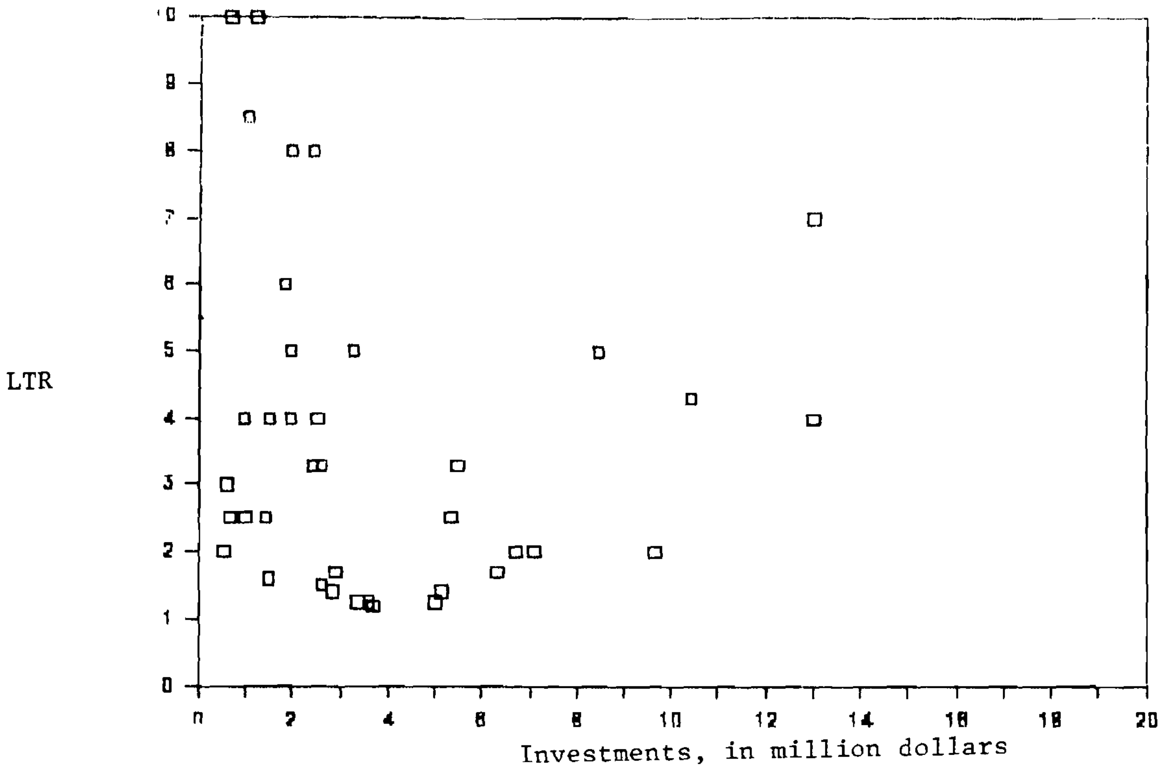


Figure 2. Lead-time reduction (LTR) over FMS cost.

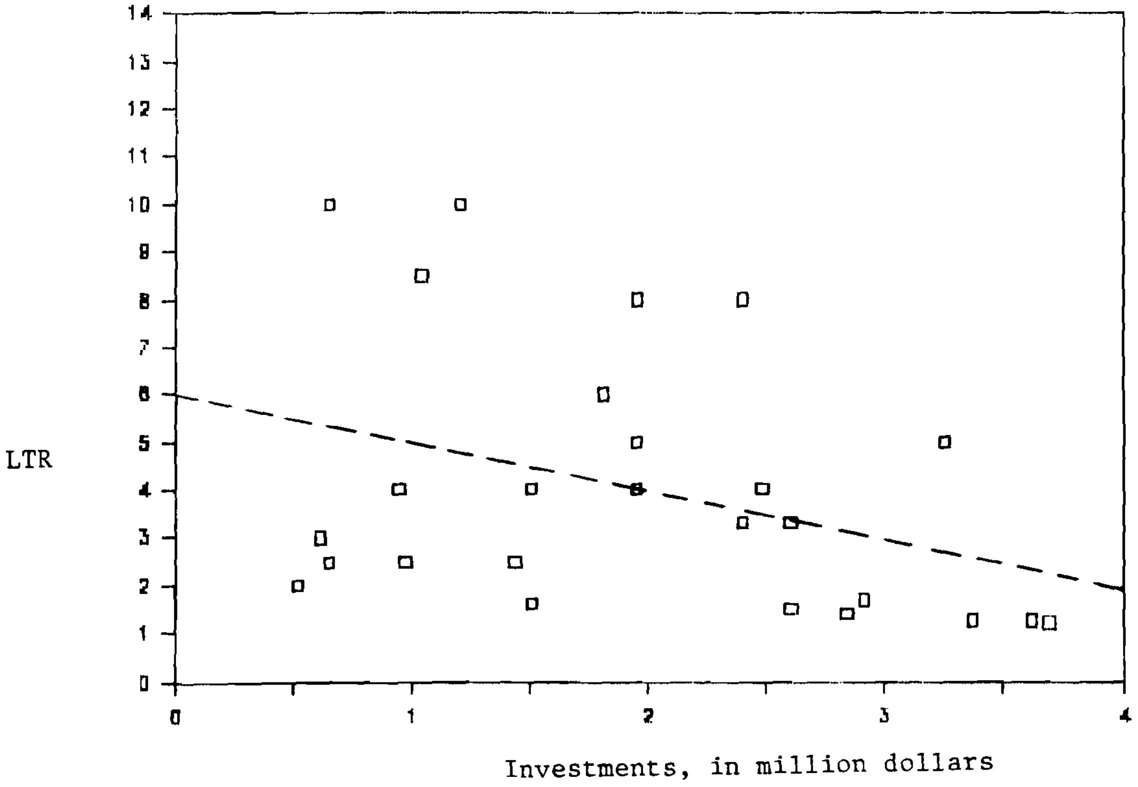


Figure 3. Lead-time reduction (LTR) over FMS cost.

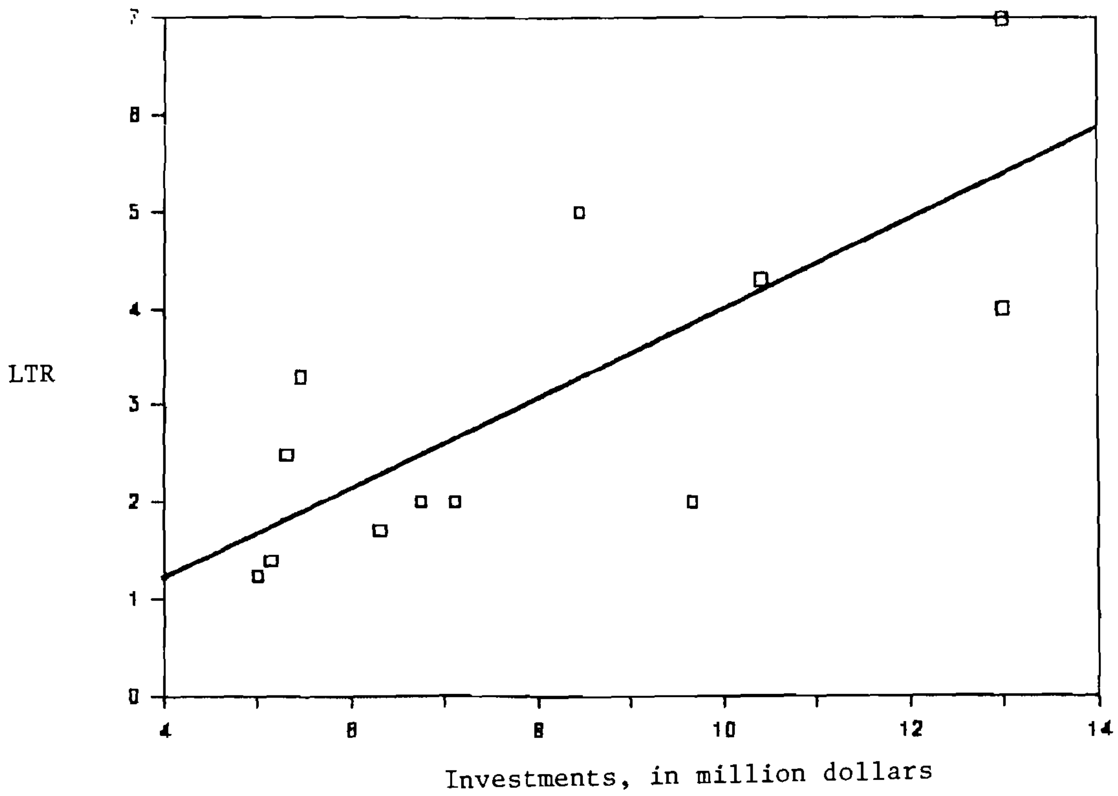


Figure 4. Lead-time reduction (LTR) over FMS cost.

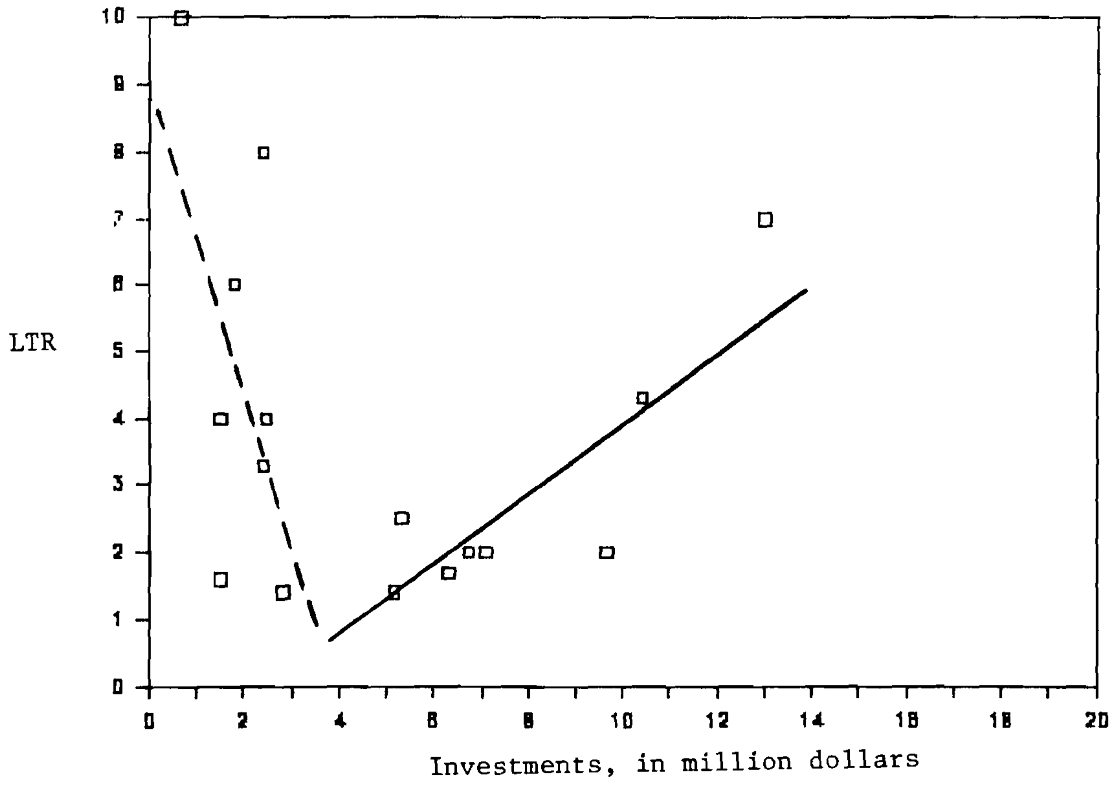


Figure 5. Lead-time reduction (LTR) over FMS cost for machinery and transportation equipment industries.

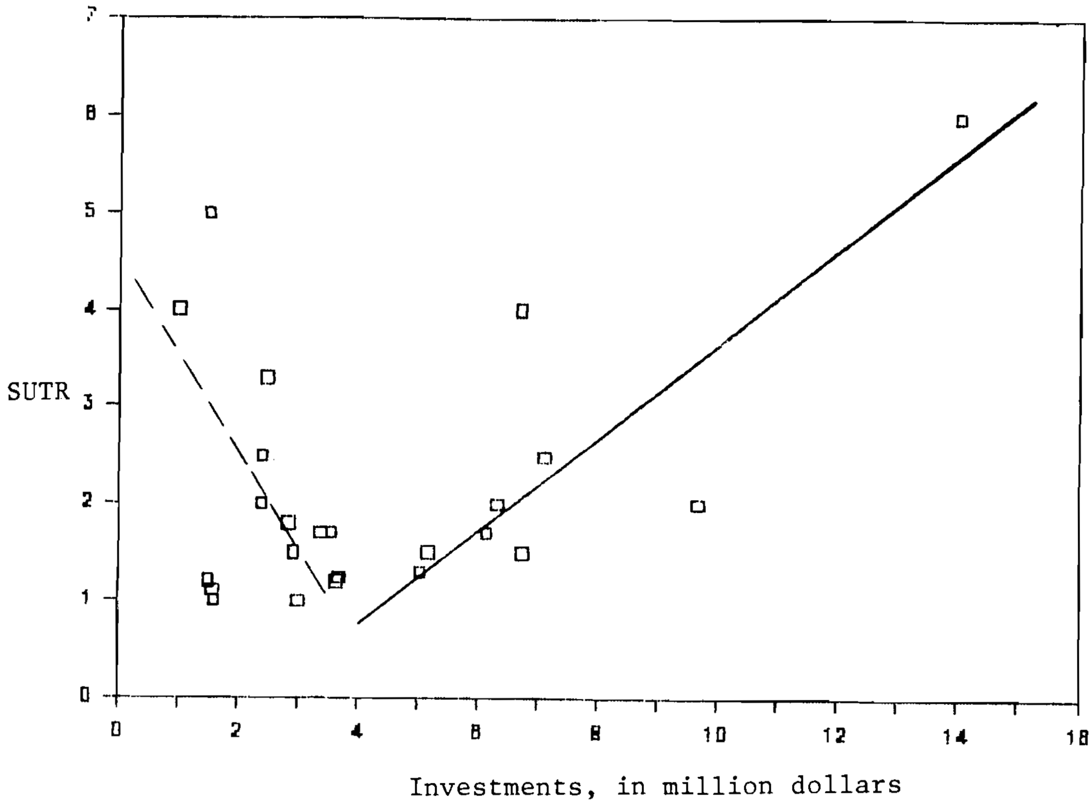


Figure 6. Set-up time reduction (SUTR) over FMS cost.

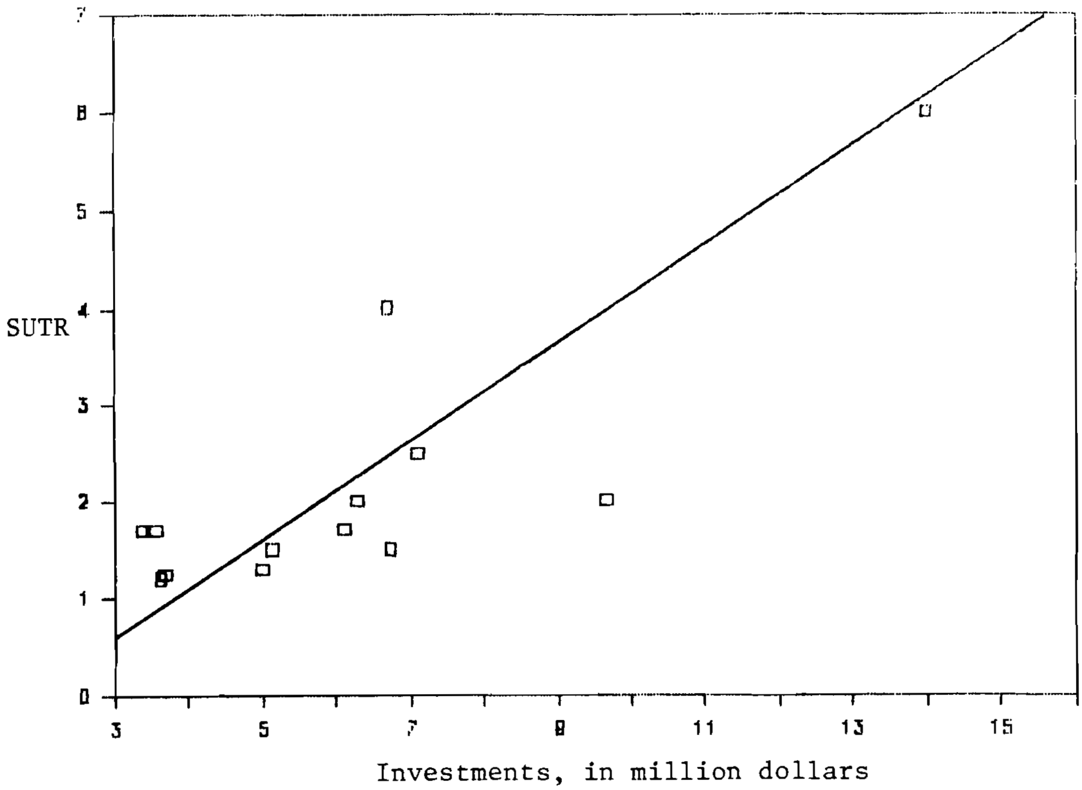


Figure 7. Set-up time reduction (SUTR) over FMS cost.

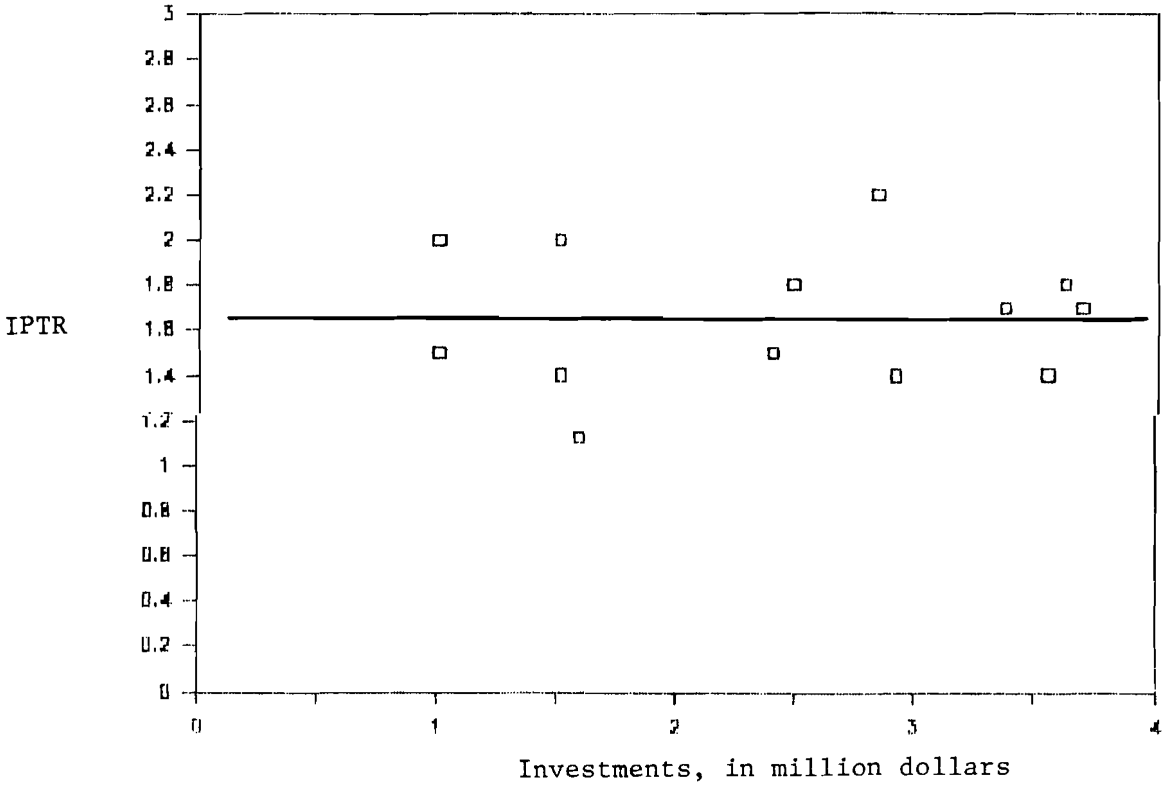


Figure 8. In-process time reduction (IPTR) over FMS cost.

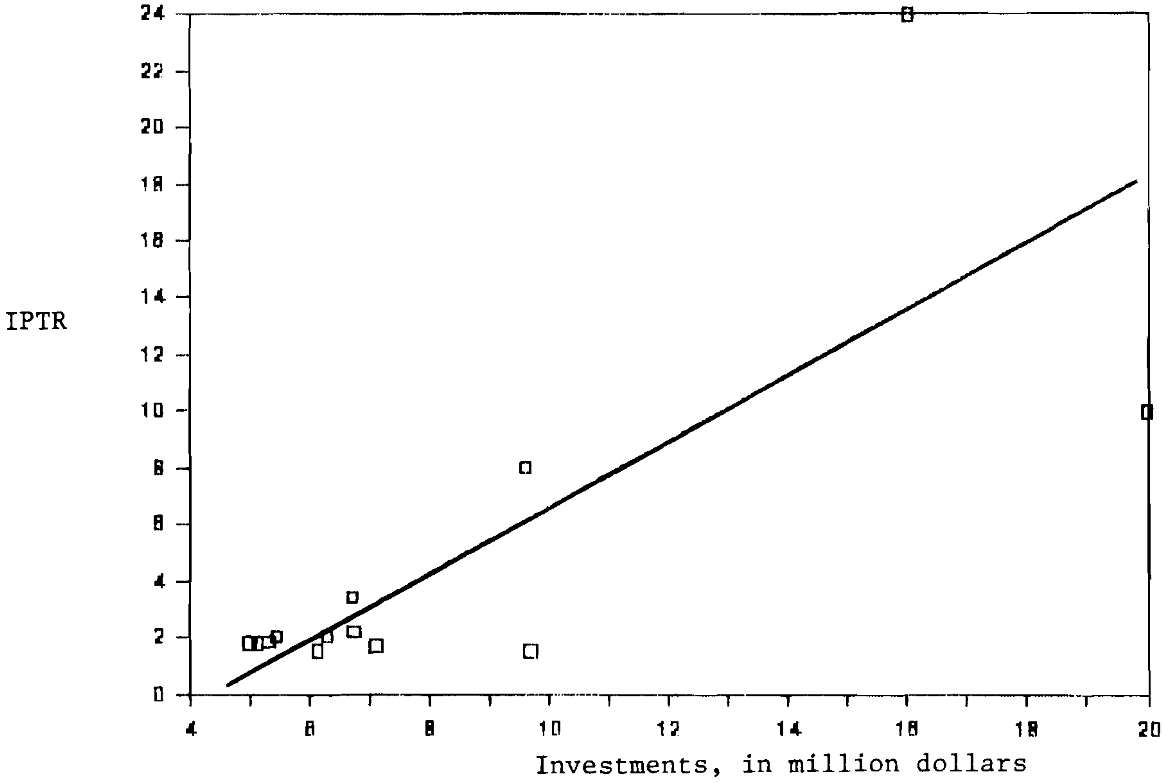


Figure 9. In-process time reduction (IPTR) over FMS cost.

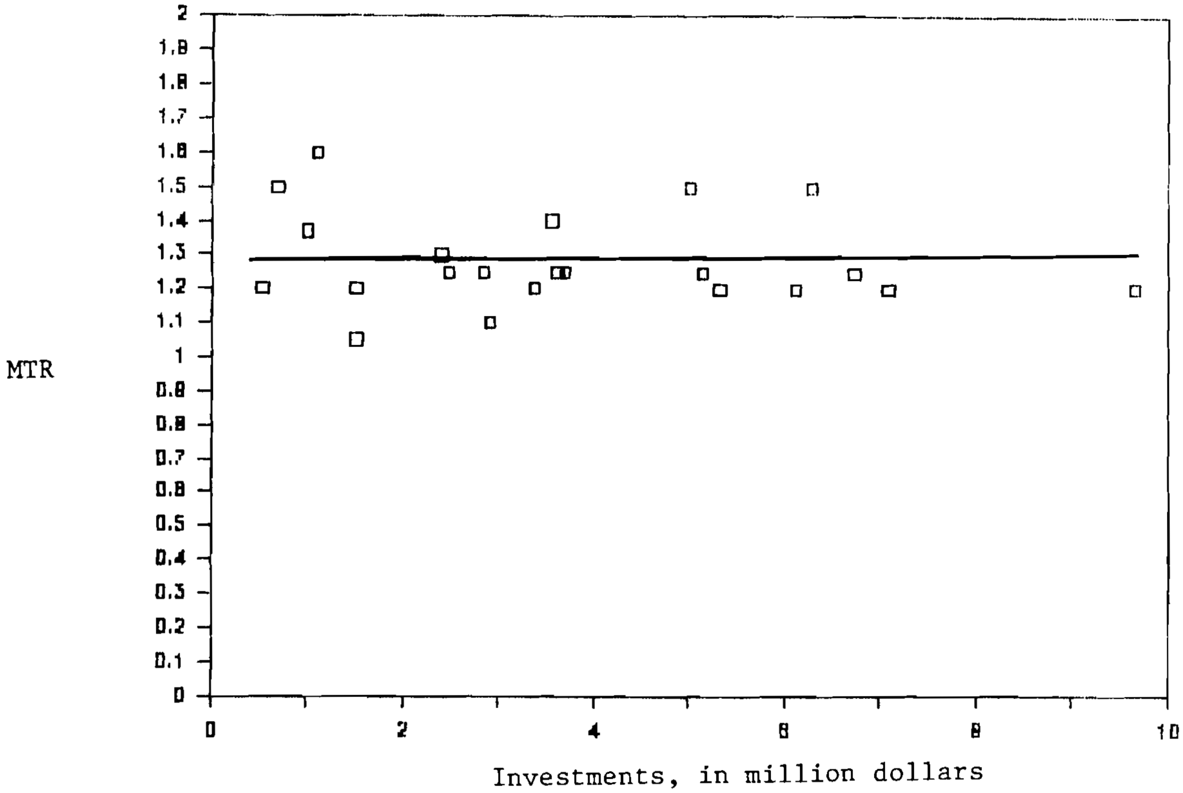


Figure 10. Machining time reduction (MTR) over FMS cost.

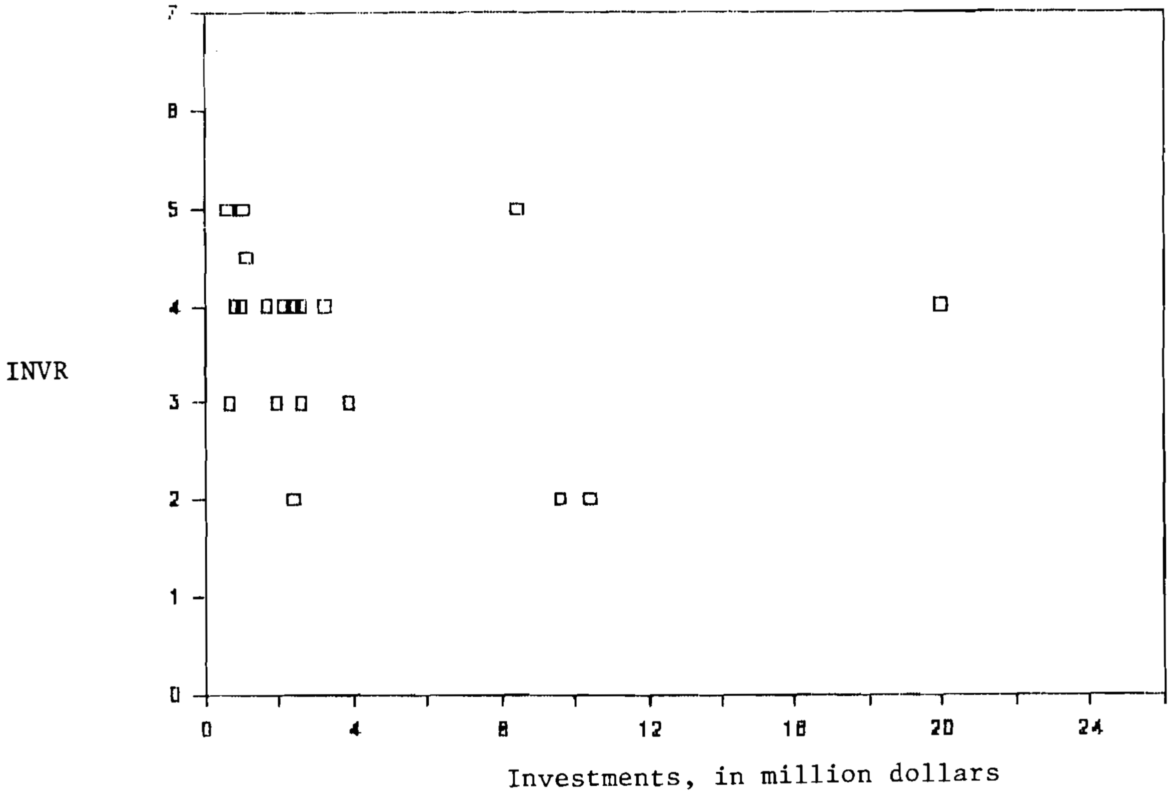


Figure 11. Inventories reduction (INVR) over FMS cost.

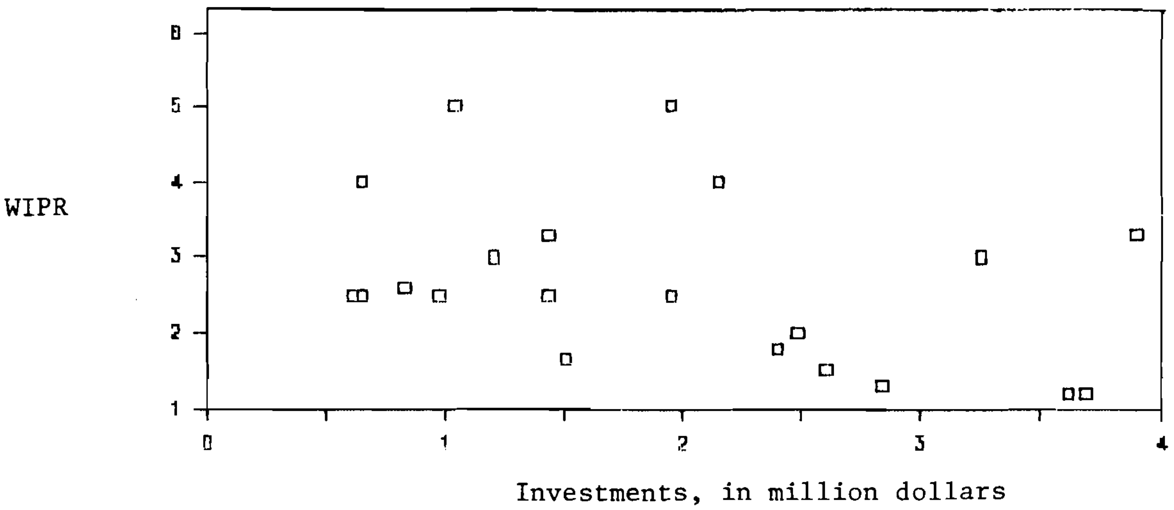


Figure 12. Work-in-progress reduction (WIPR) over FMS cost.

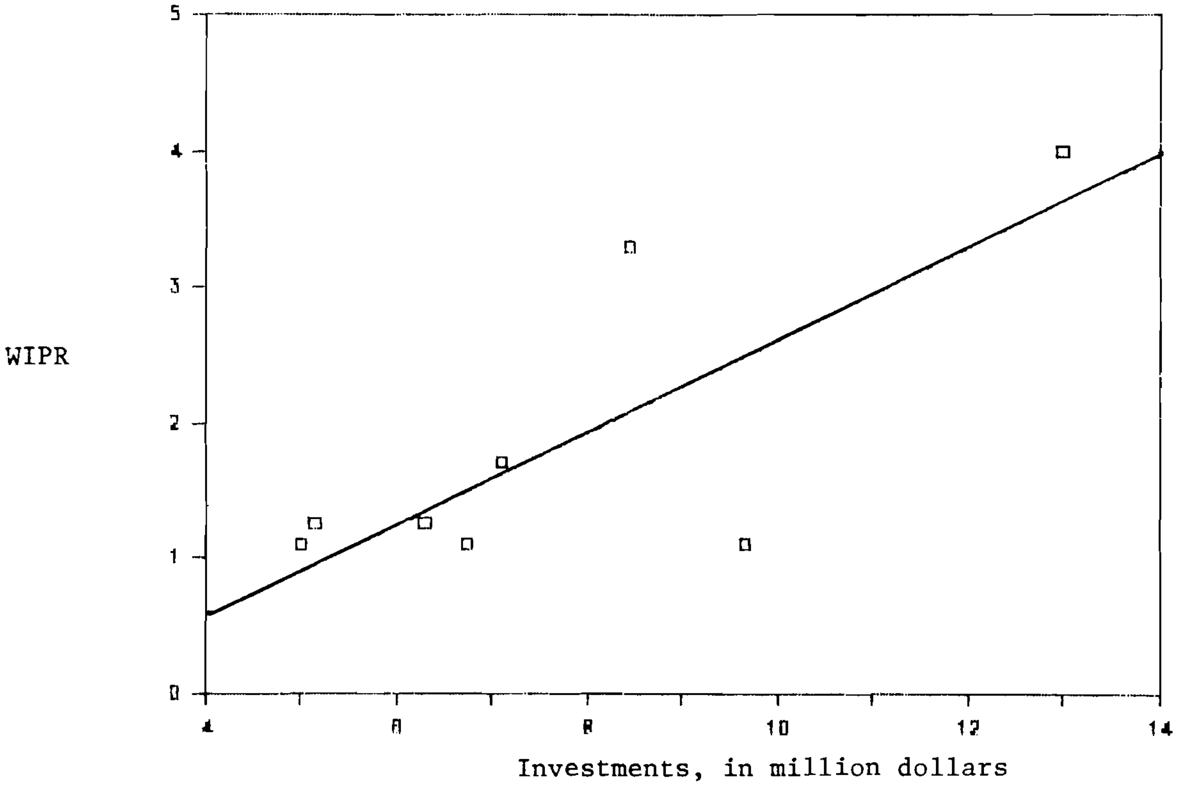


Figure 13. Work-in-progress reduction (WIPR) over FMS cost.

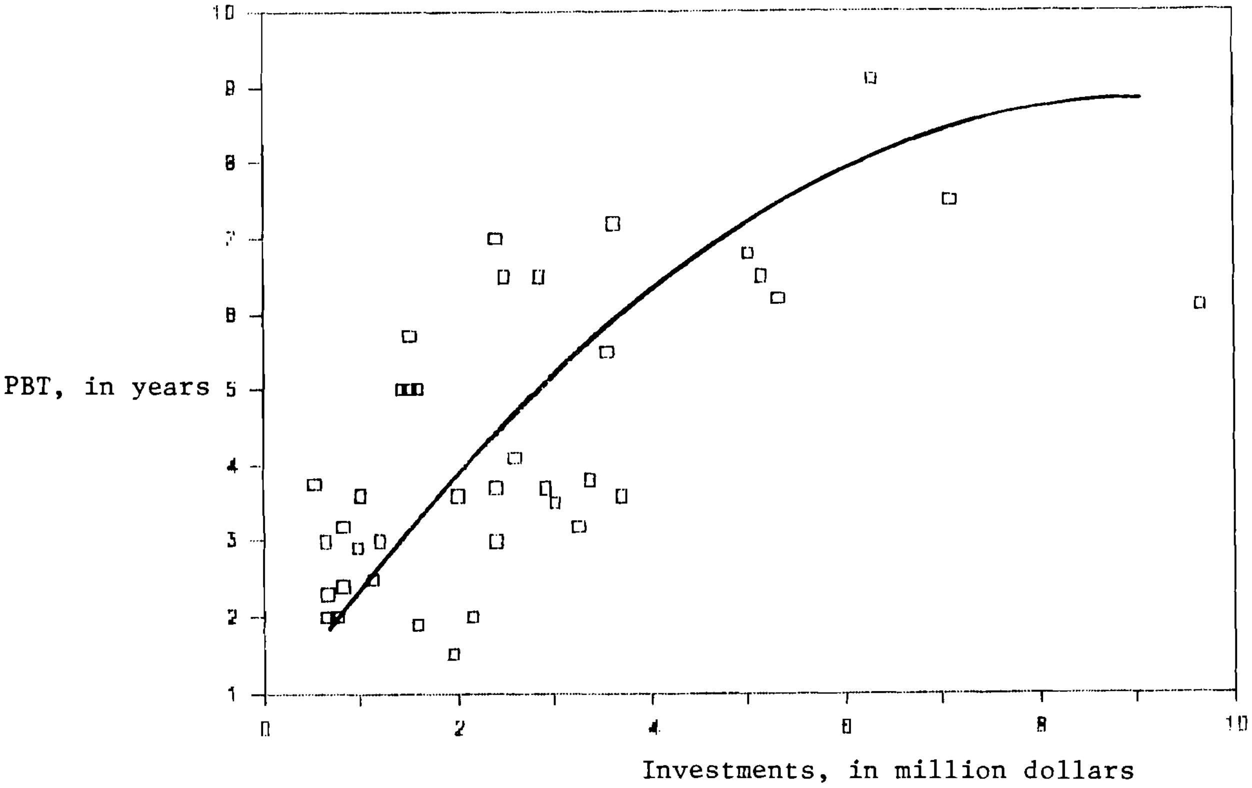


Figure 14. Pay-back time (PBT) over FMS cost.

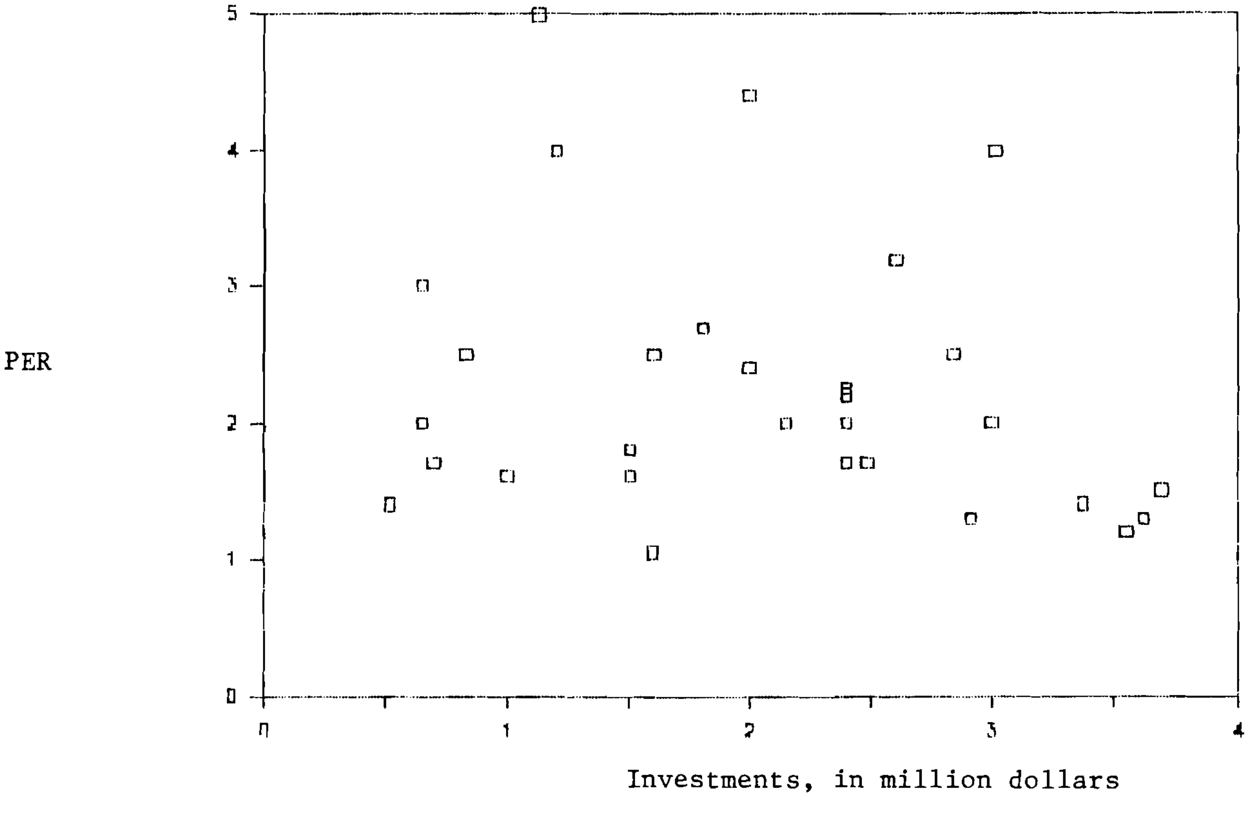


Figure 15. Personnel reduction (PER) over FMS cost.

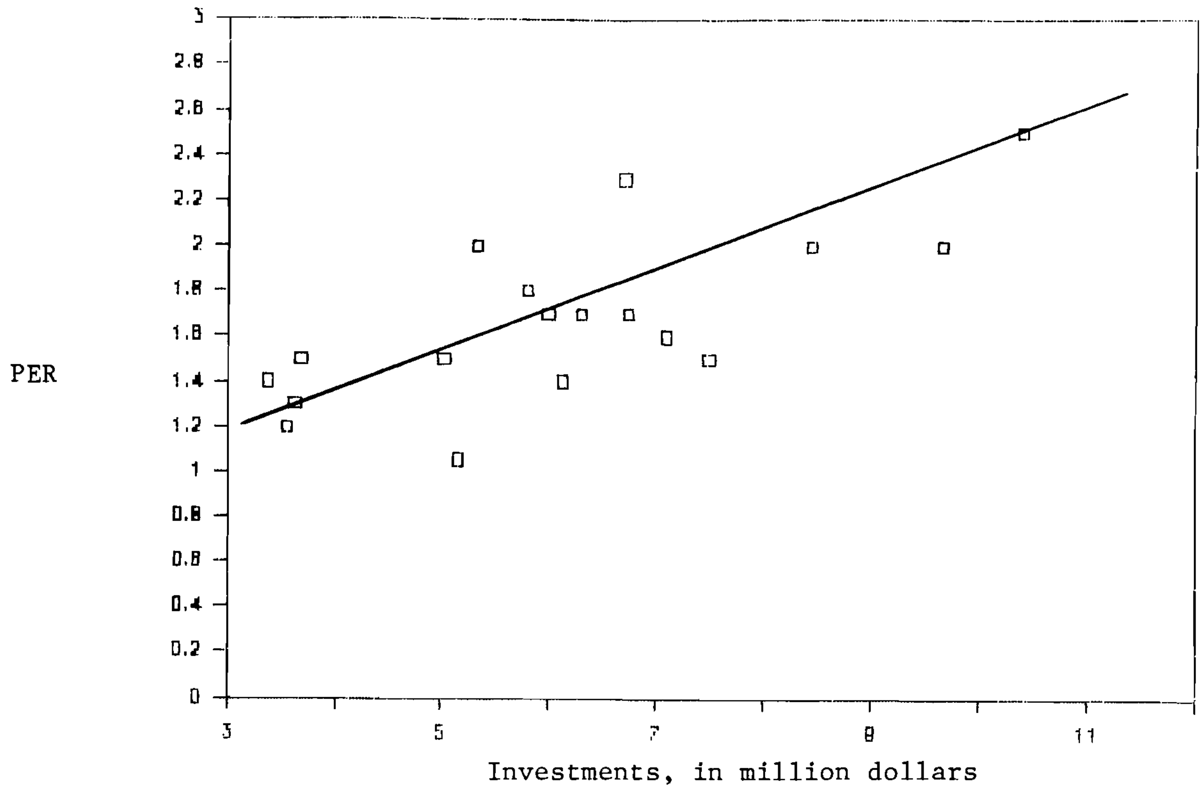


Figure 16. Personnel reduction (PER) over FMS cost.

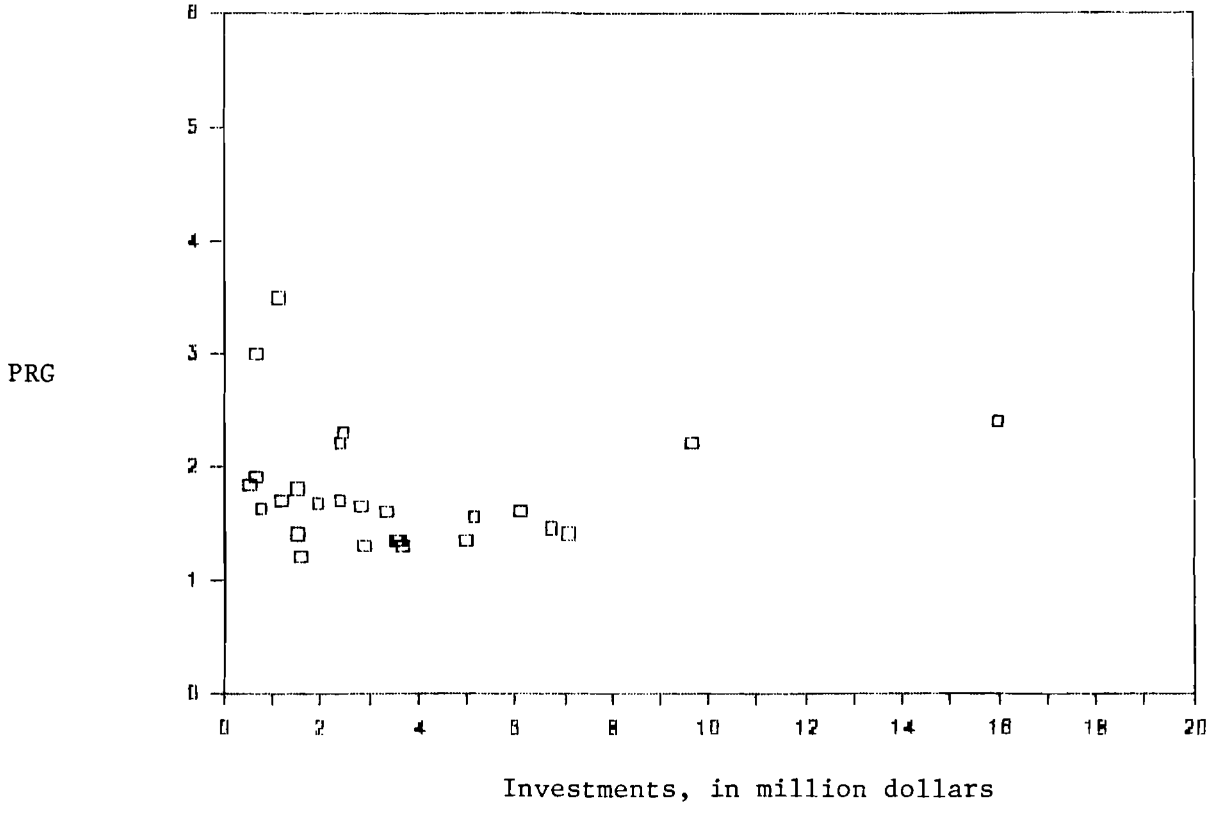


Figure 17. Productivity growth (PRG) over FMS cost.

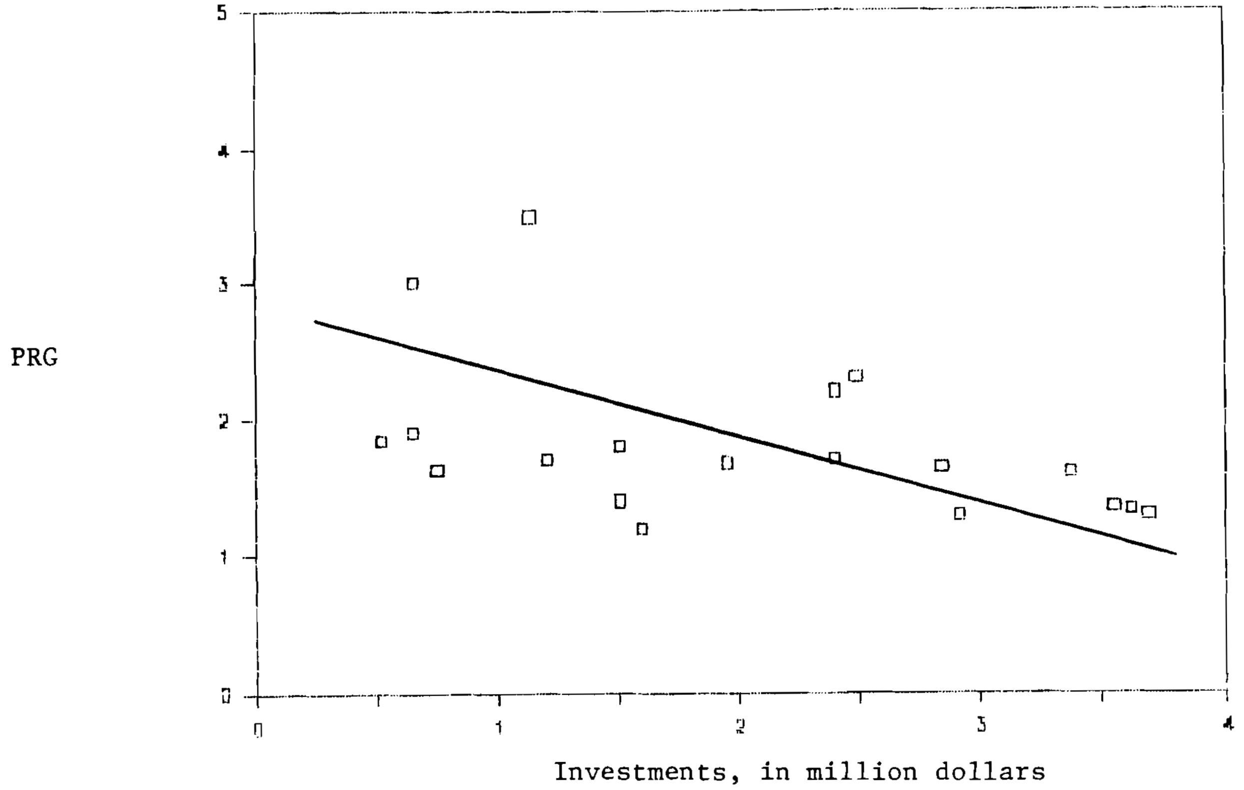


Figure 18. Productivity growth (PRG) over FMS cost.

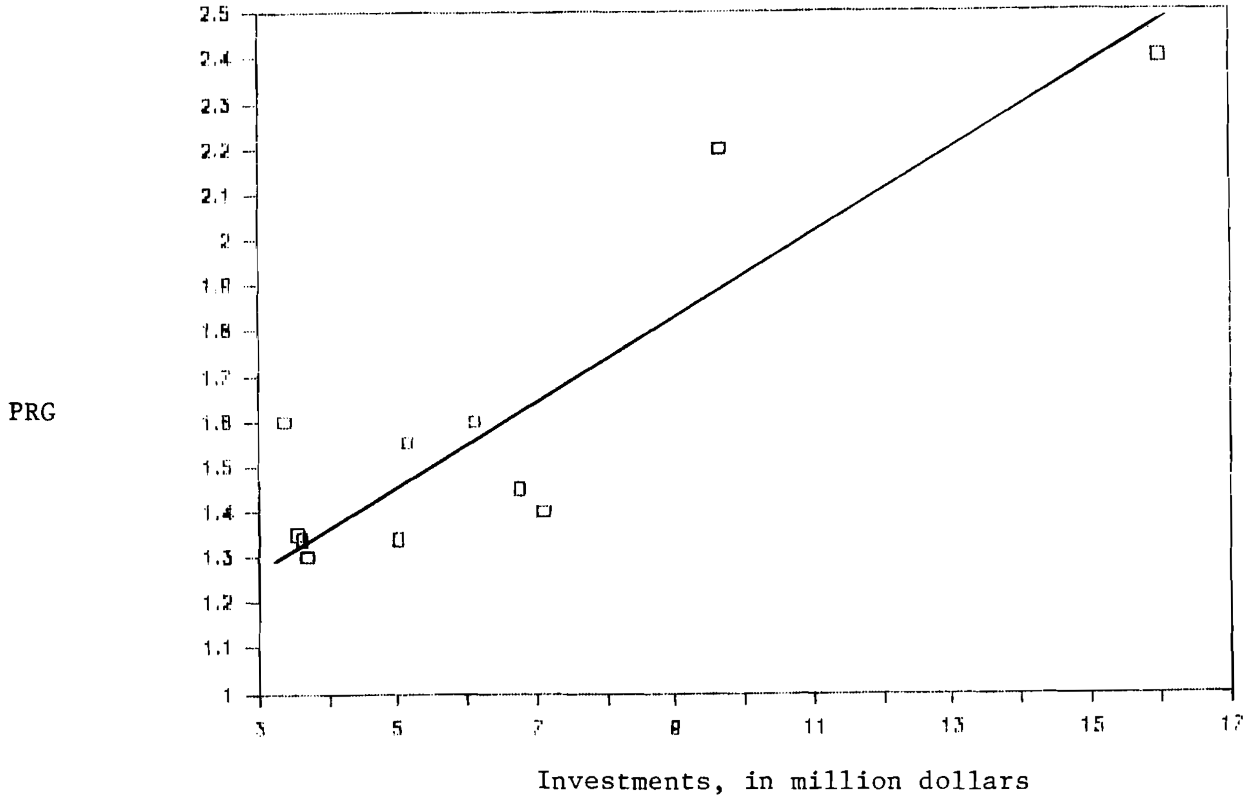


Figure 19. Productivity growth (PRG) over FMS cost.

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.

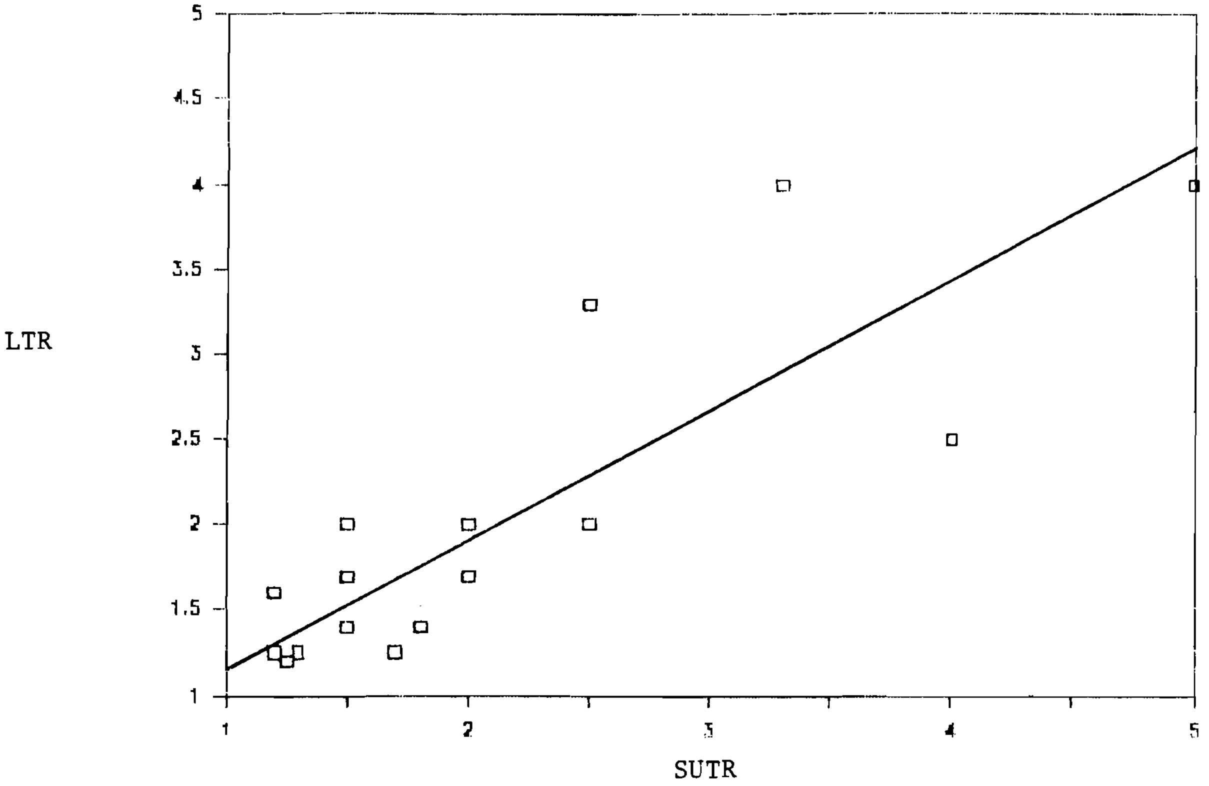


Figure 21. Lead-time reduction (LTR) over set-up-time reduction (SUTR).

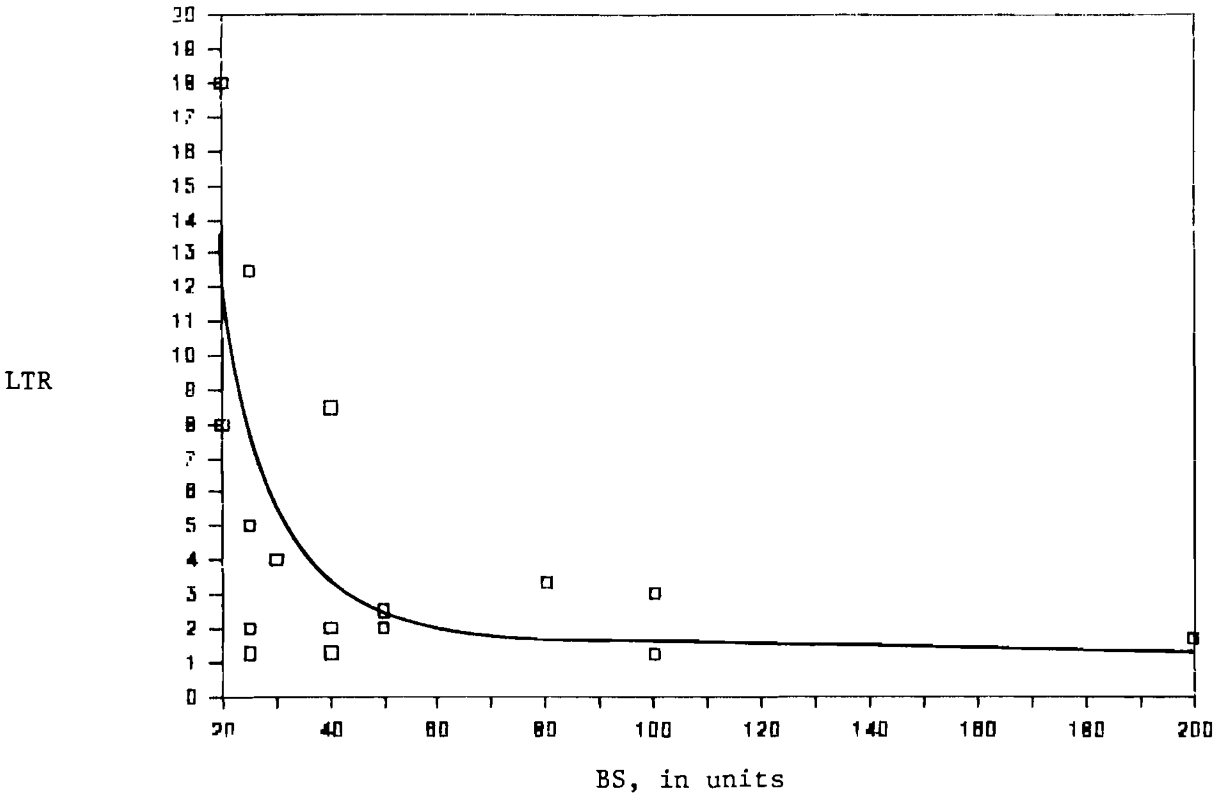
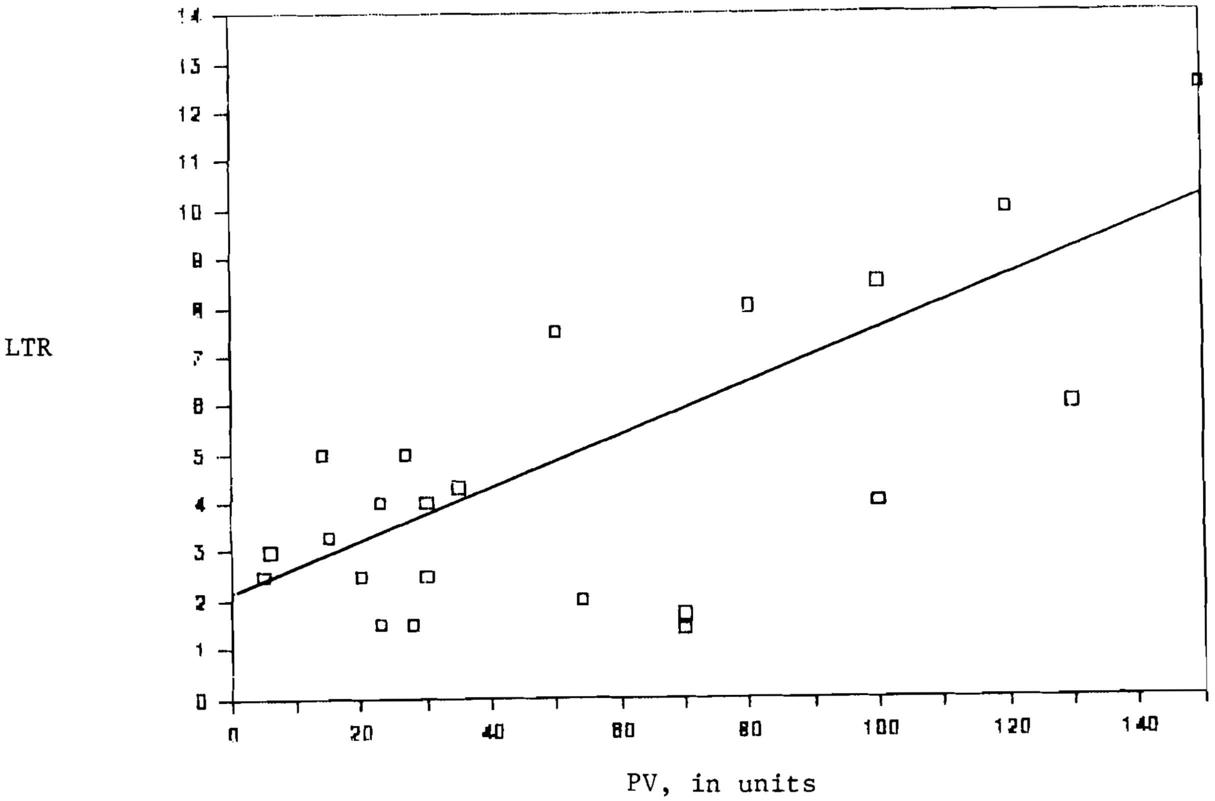


Figure 22. Lead-time reduction (LTR) over batch size (BS).



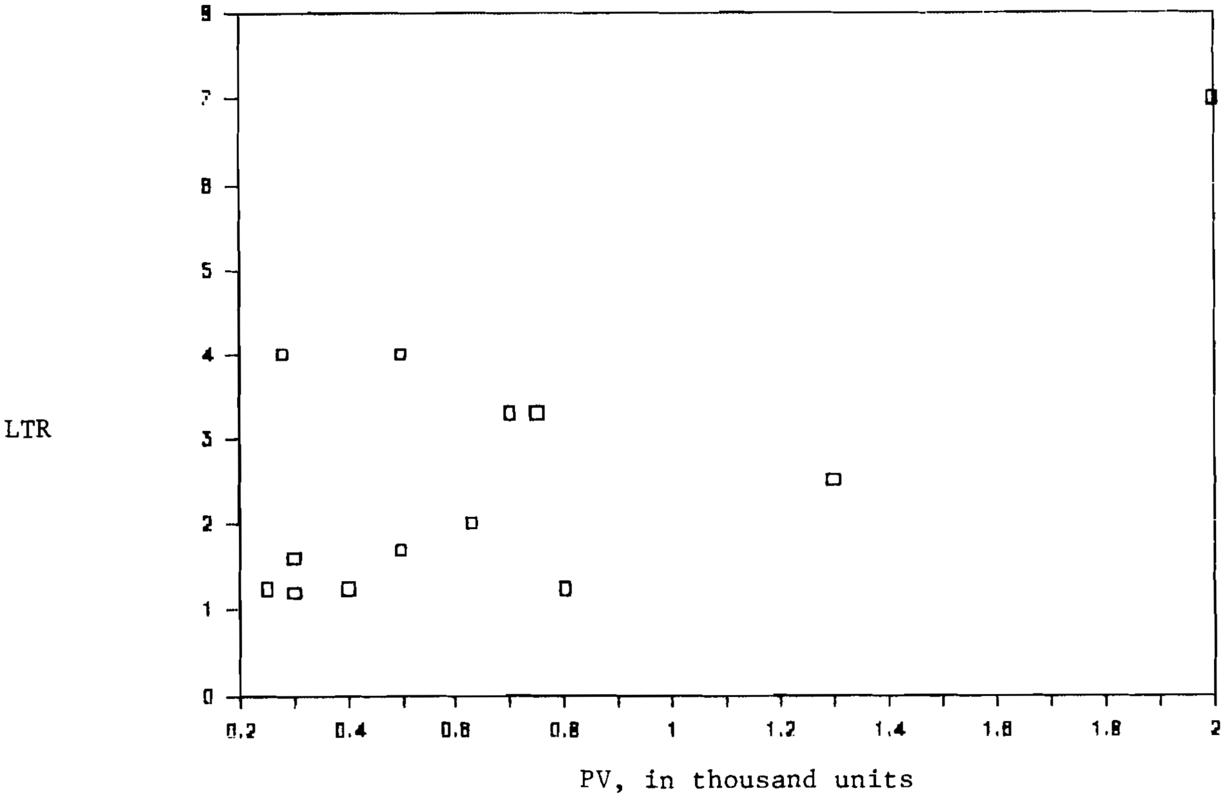


Figure 23. Lead-time reduction (LTR) over product variants (PV).

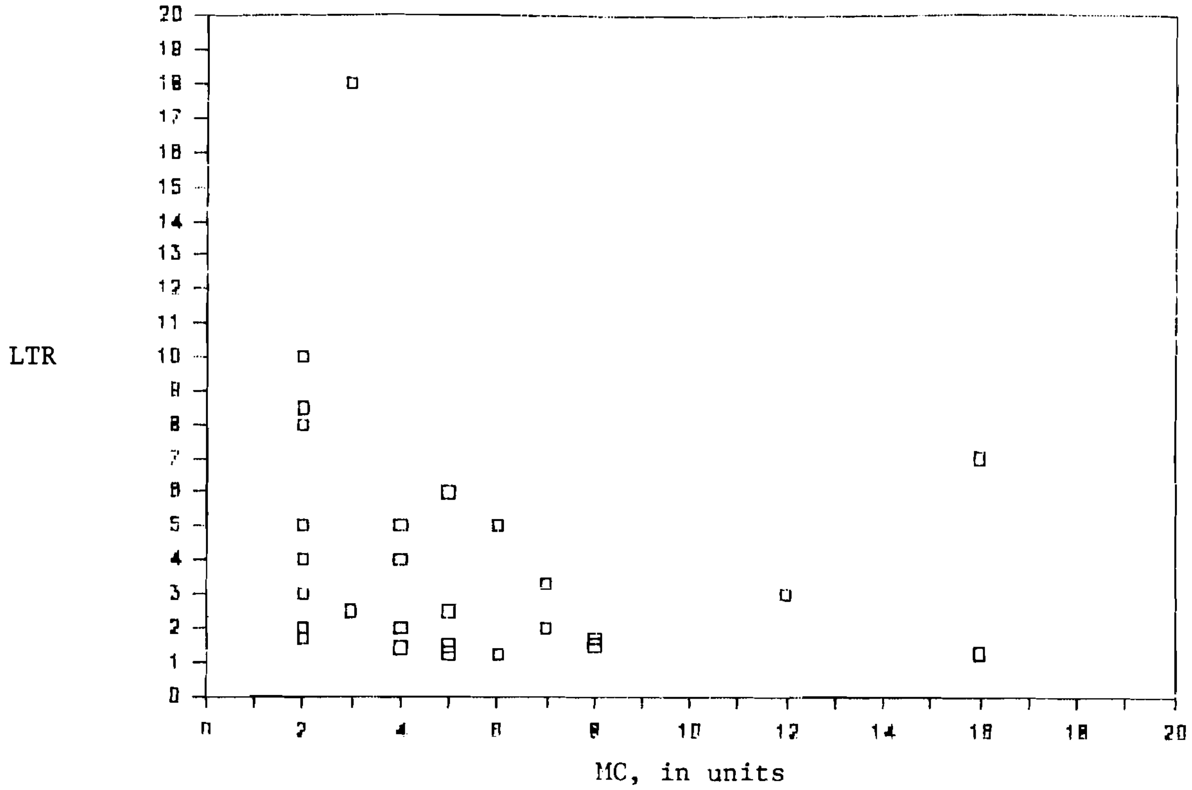


Figure 24. Lead-time reduction (LTR) over number of machining centers (MC).

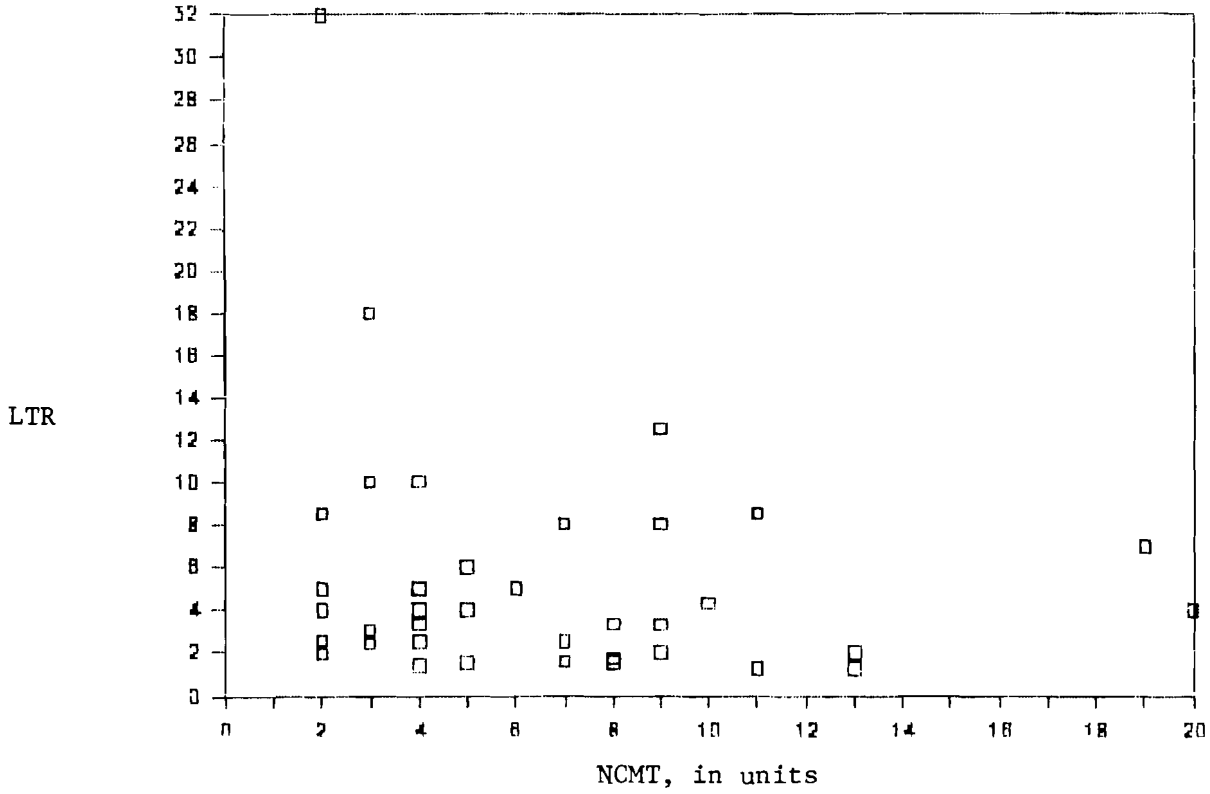


Figure 25. Lead-time reduction (LTR) over number of NC machine tools (NCMT).

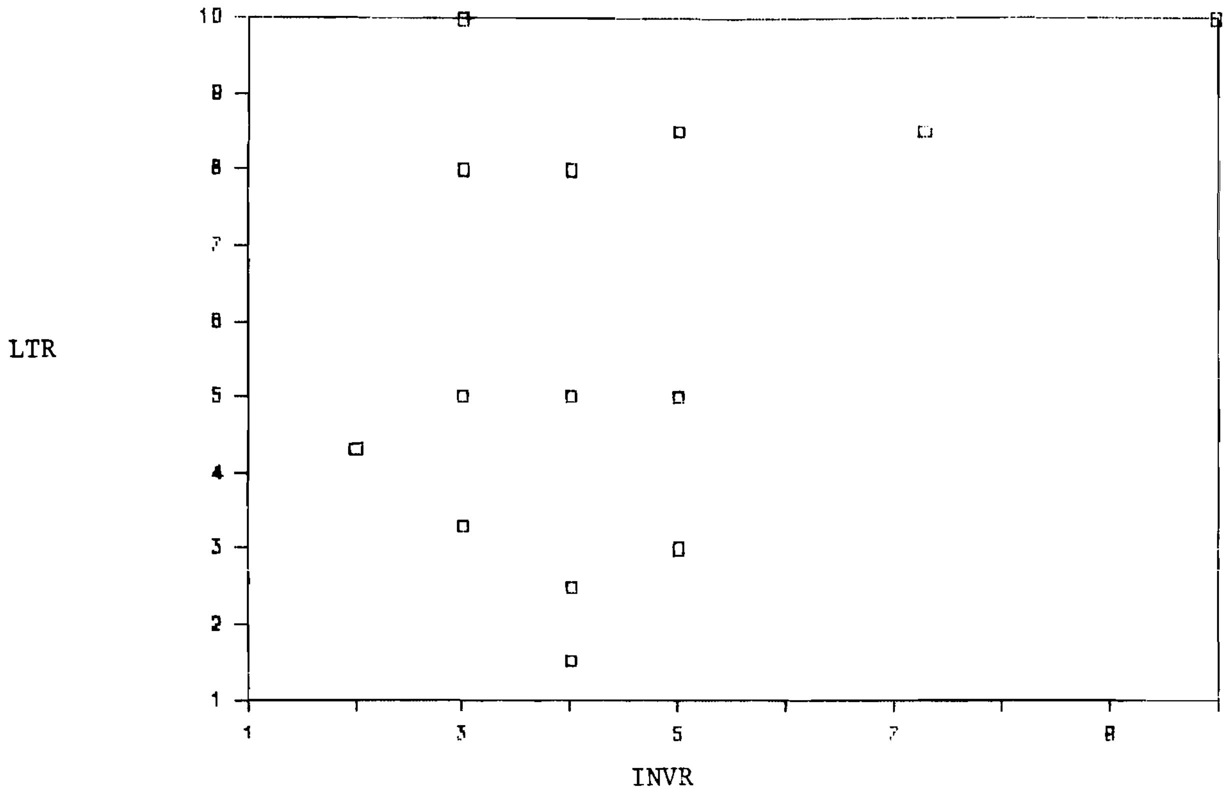


Figure 26. Lead-time reduction (LTR) over inventories reduction (INVR).

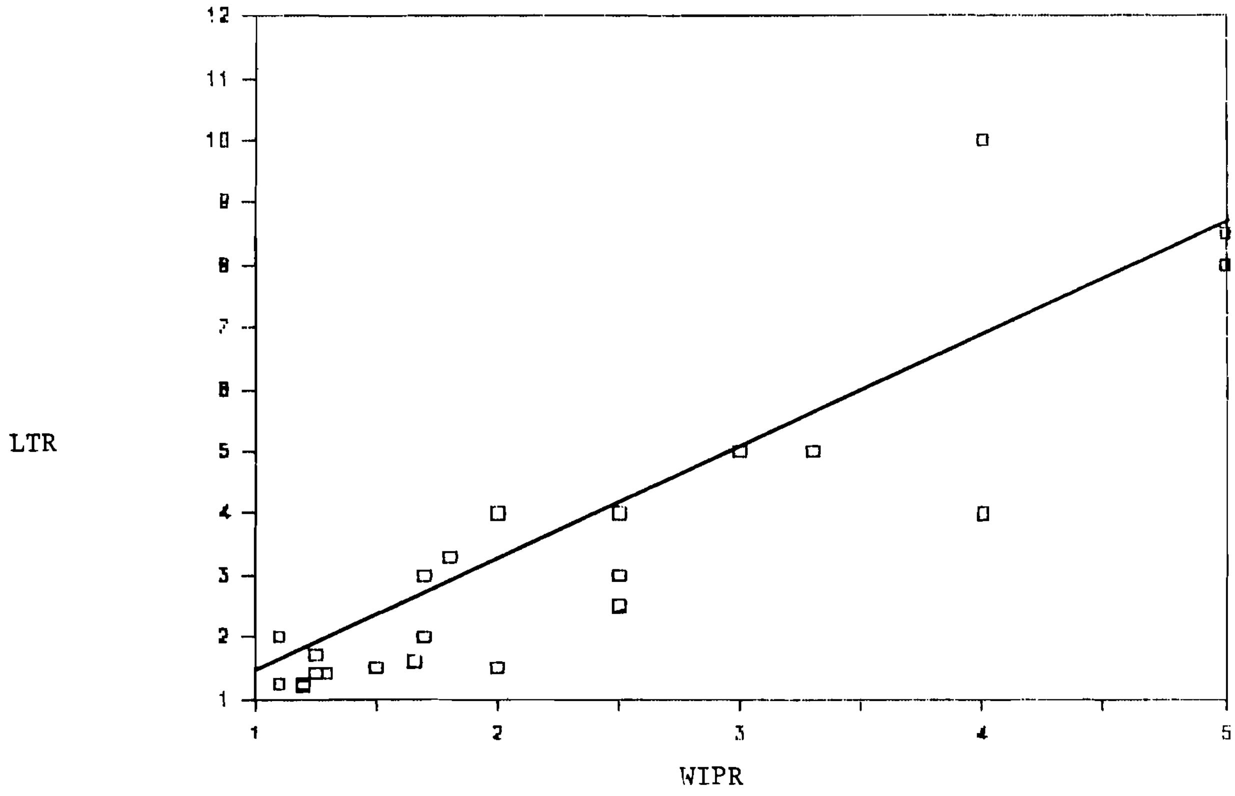


Figure 27. Lead-time reduction (LTR) over work-in-progress reduction (WIPR).

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).

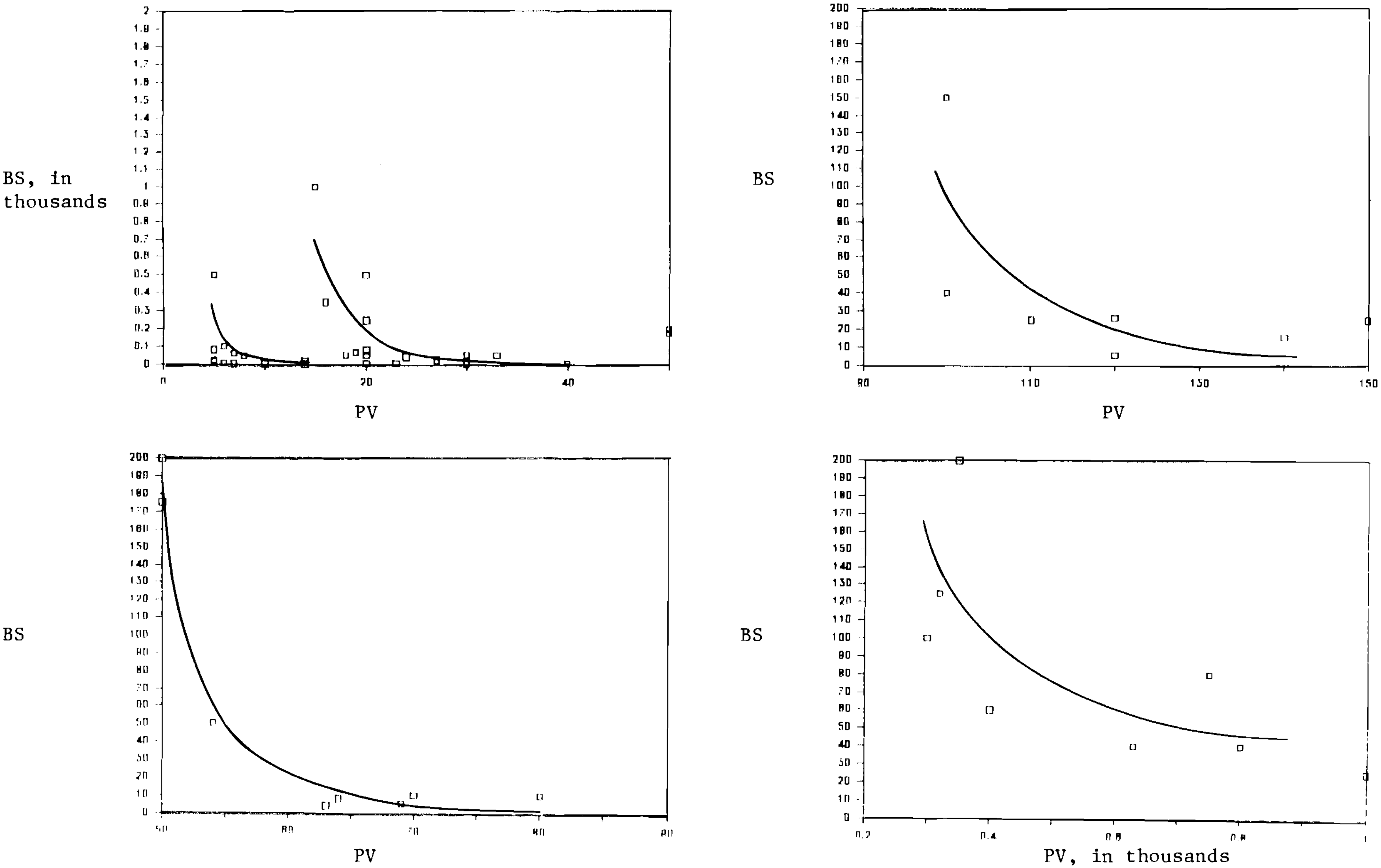


Figure 28: Batch size (BS) over product variation (PV), all in units.

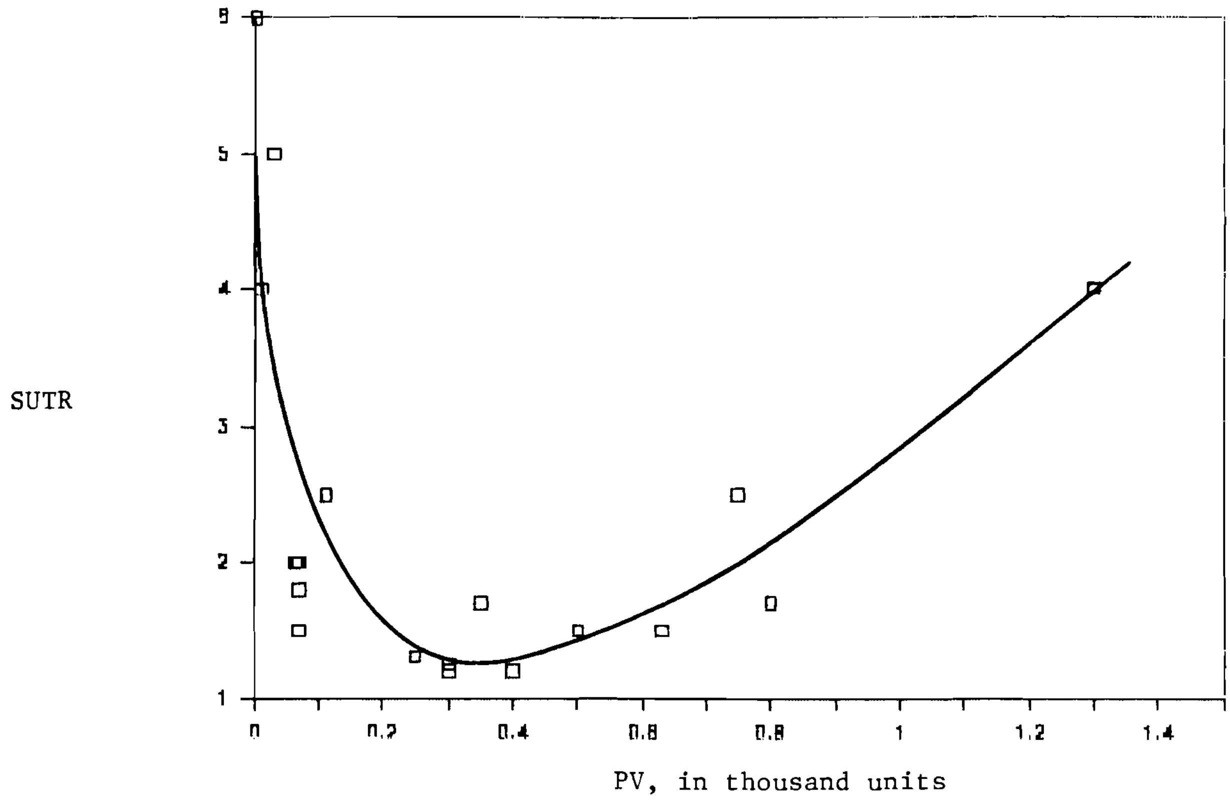


Figure 29: Set-up time reduction (SUTR) over product variations (PV)

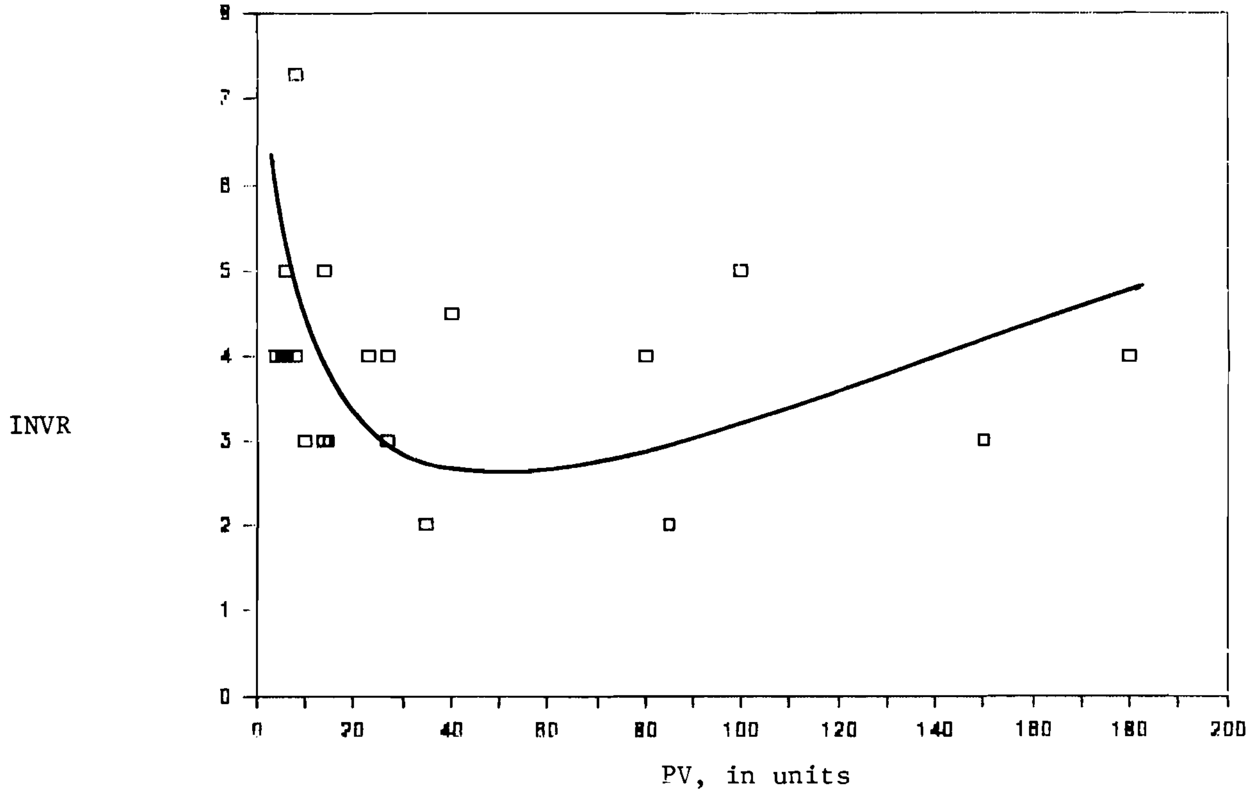


Figure 30: Inventories reduction (INVR) over product variation (PV)

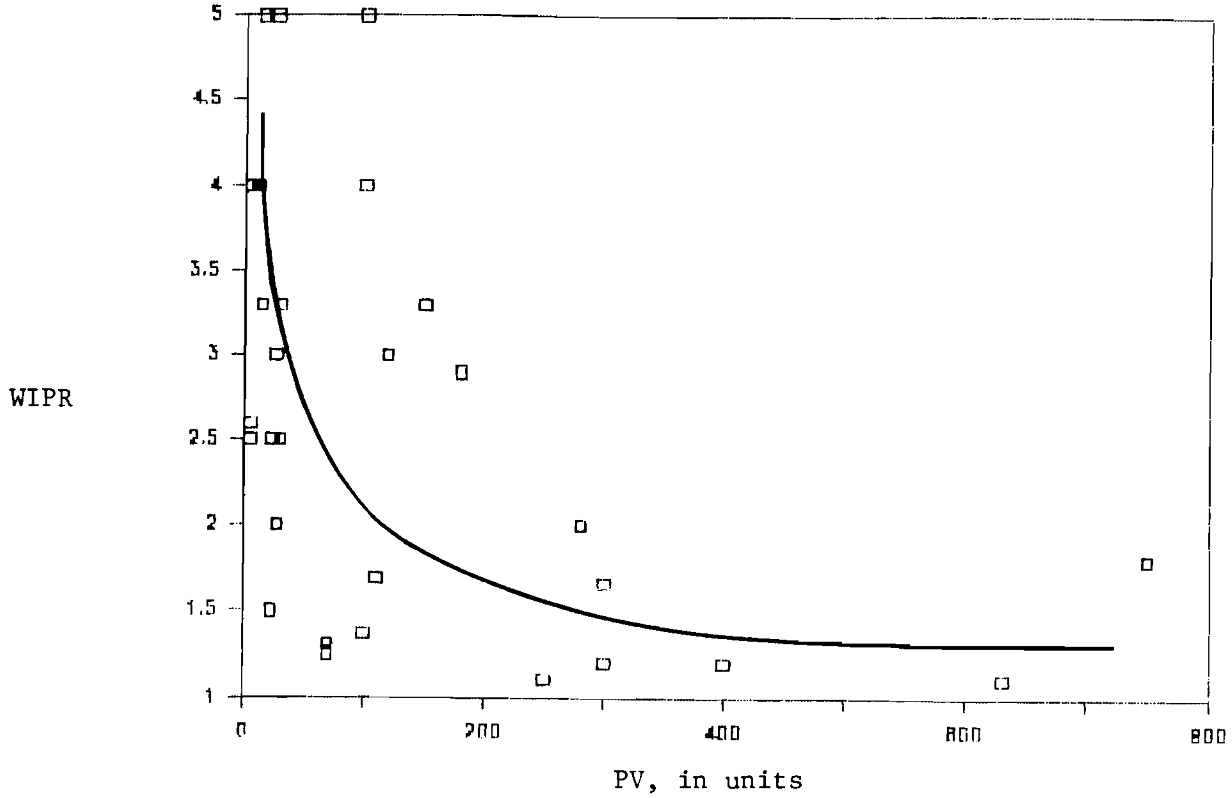


Figure 31: Work-in-progress reduction (WIPR) over product variation

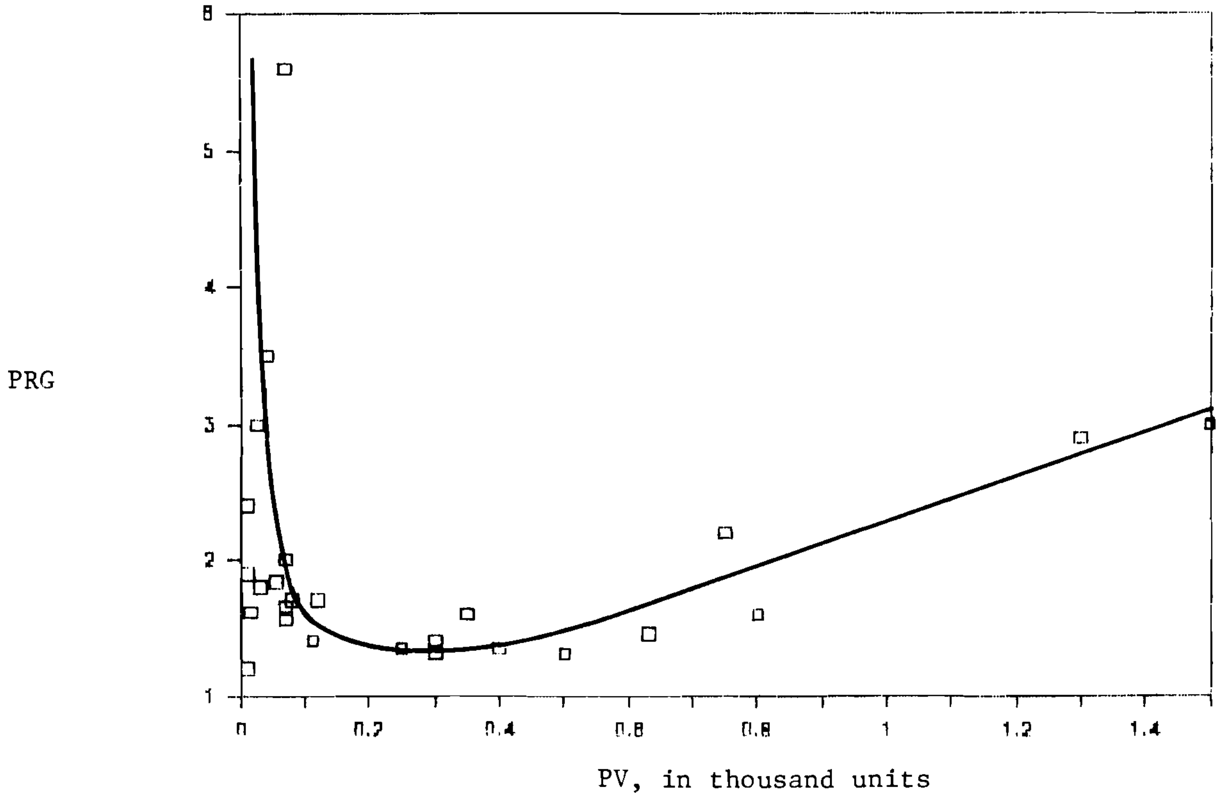


Figure 32: Productivity growth (PRG) over product variation

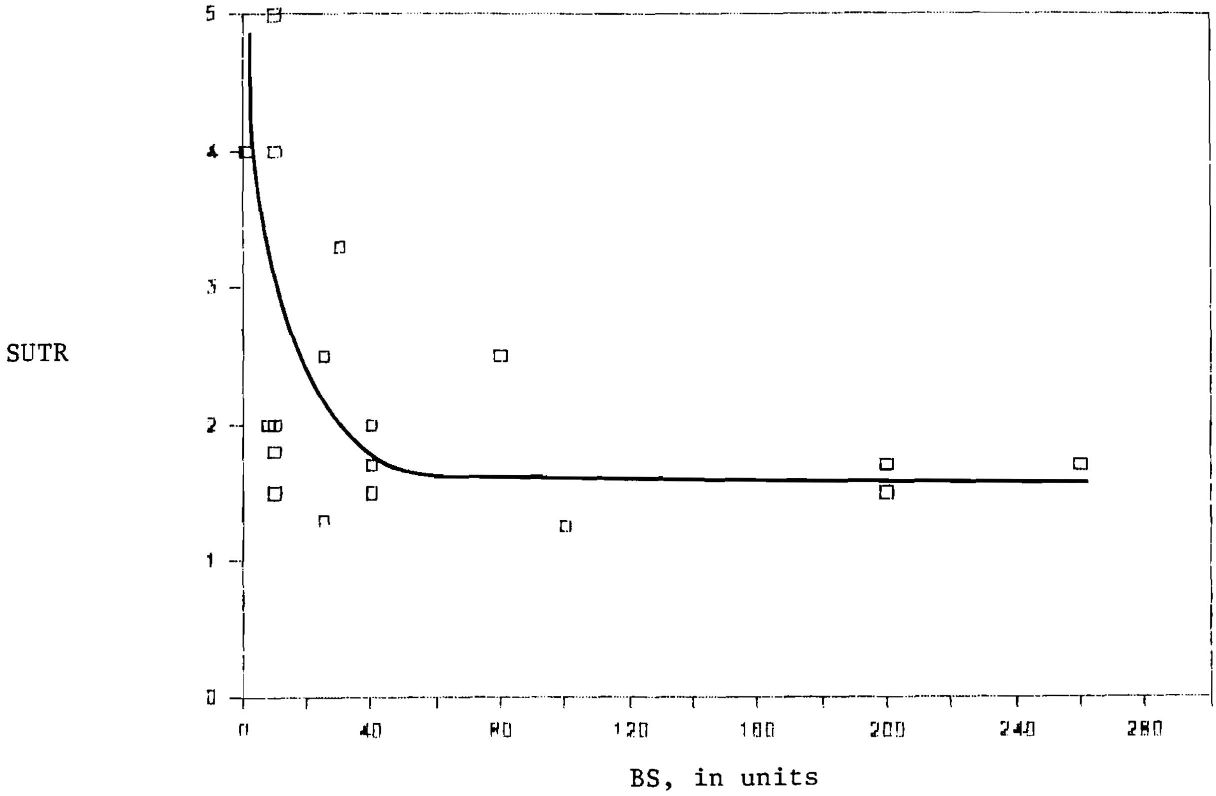


Figure 33: Set-up time reduction (SUTR) over batch size (BS).

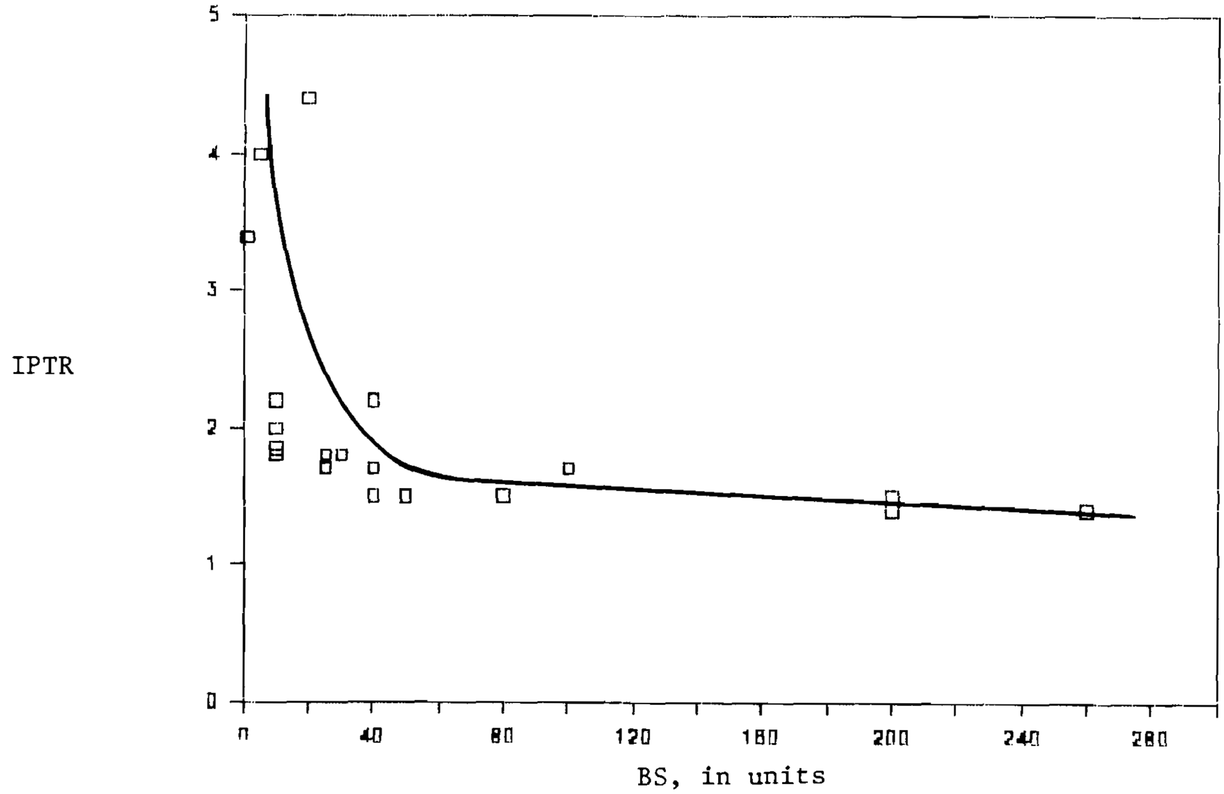


Figure 34: In-process-time reduction (IPTR) over batch size (BS)

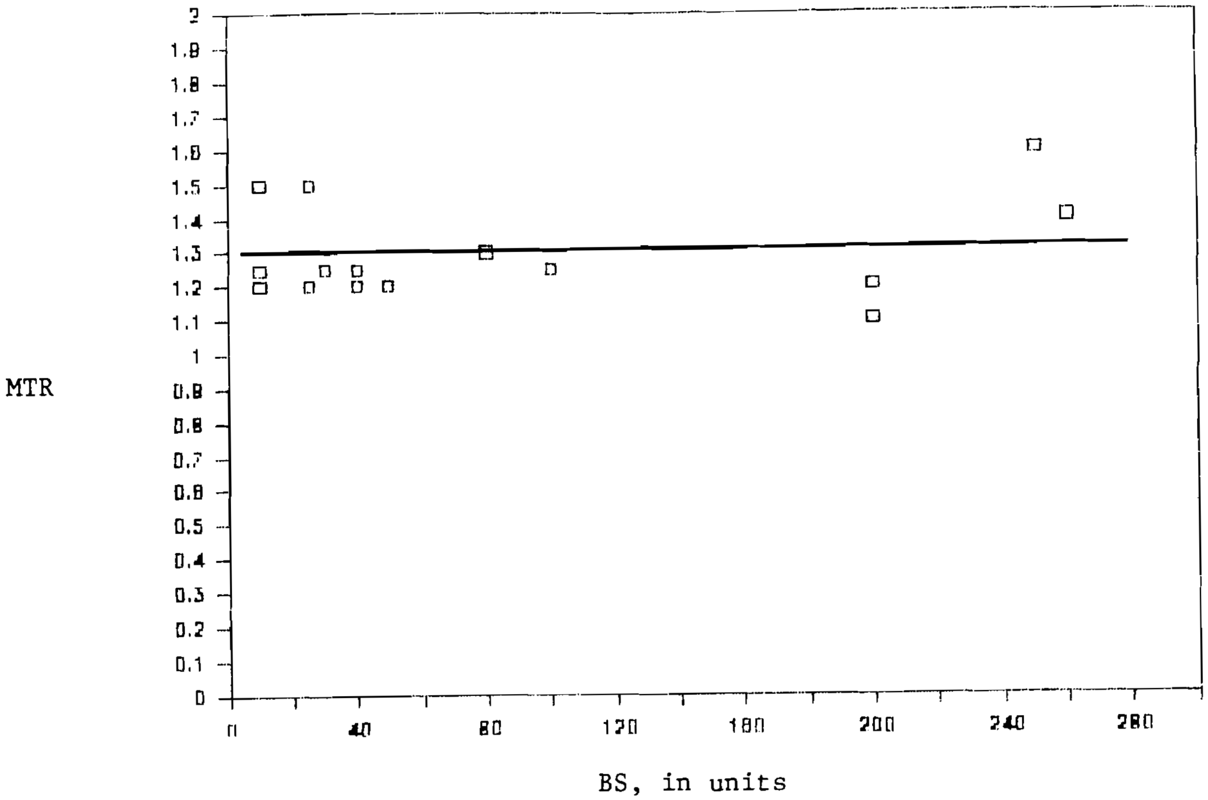


Figure 35: Machining time reduction (MTR) over Batch size (BS)

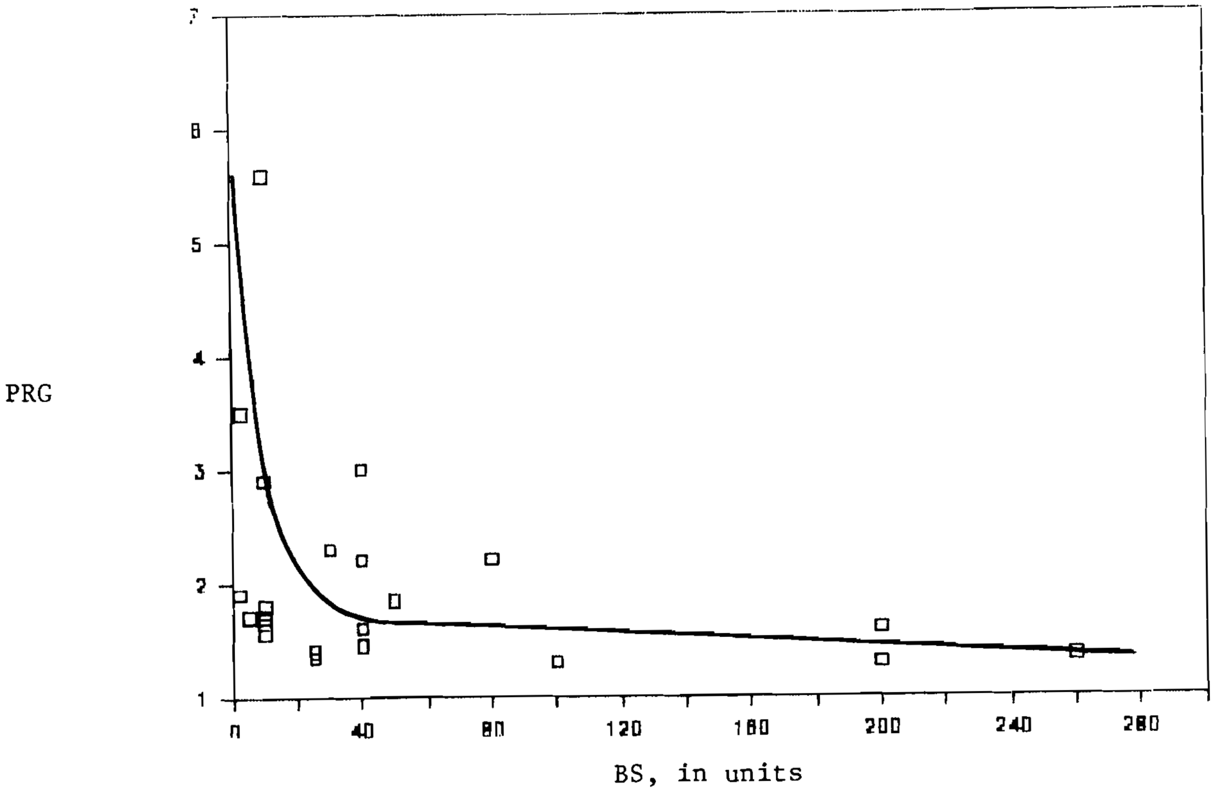


Figure 36: Productivity growth (PRG) over batch size (BS)

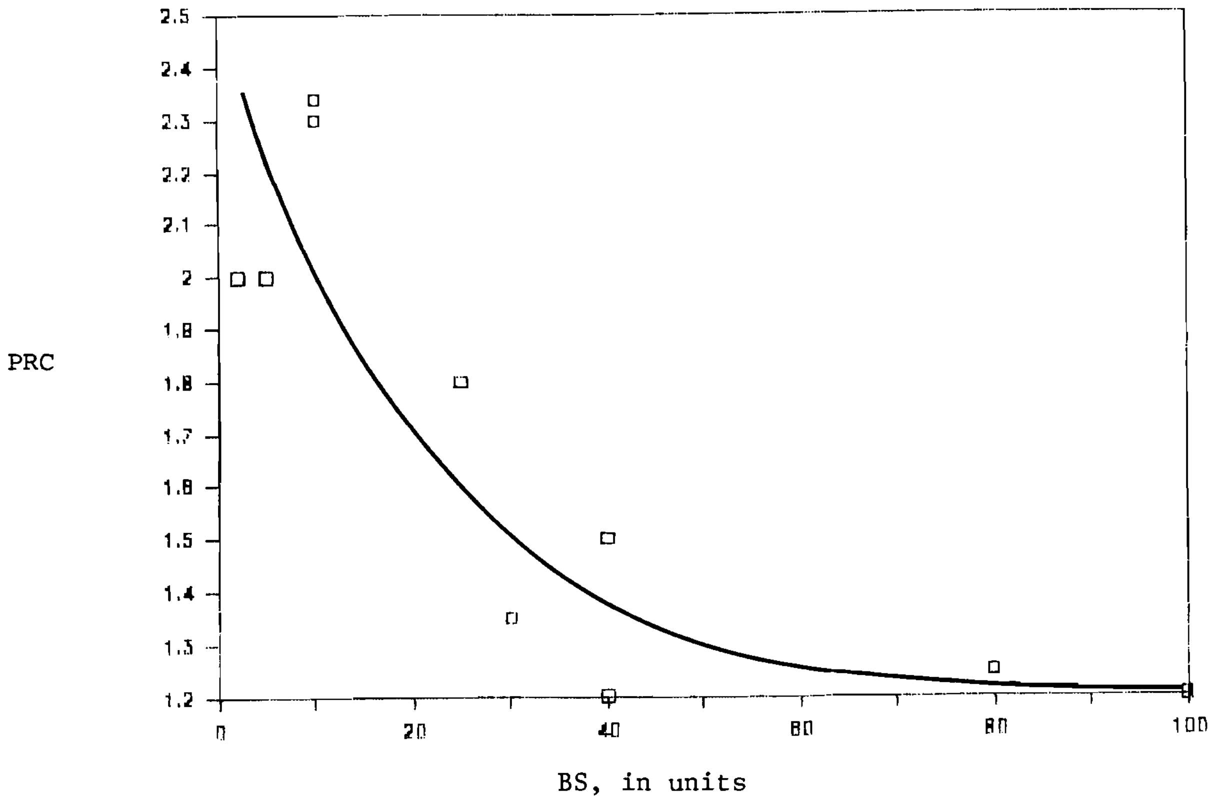


Figure 37. Production capacity (PRC) over batch size (BS)

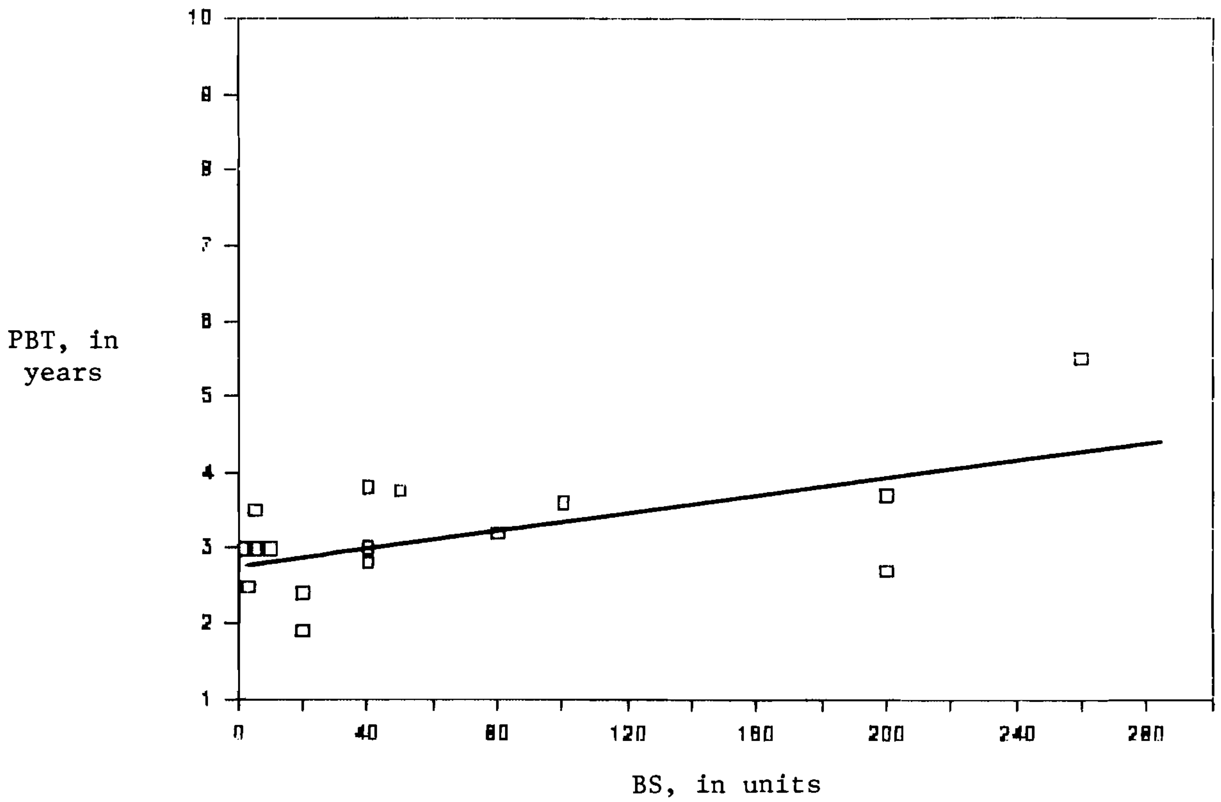


Figure 38: Pay-back time (PBT) over batch size (BS)

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.

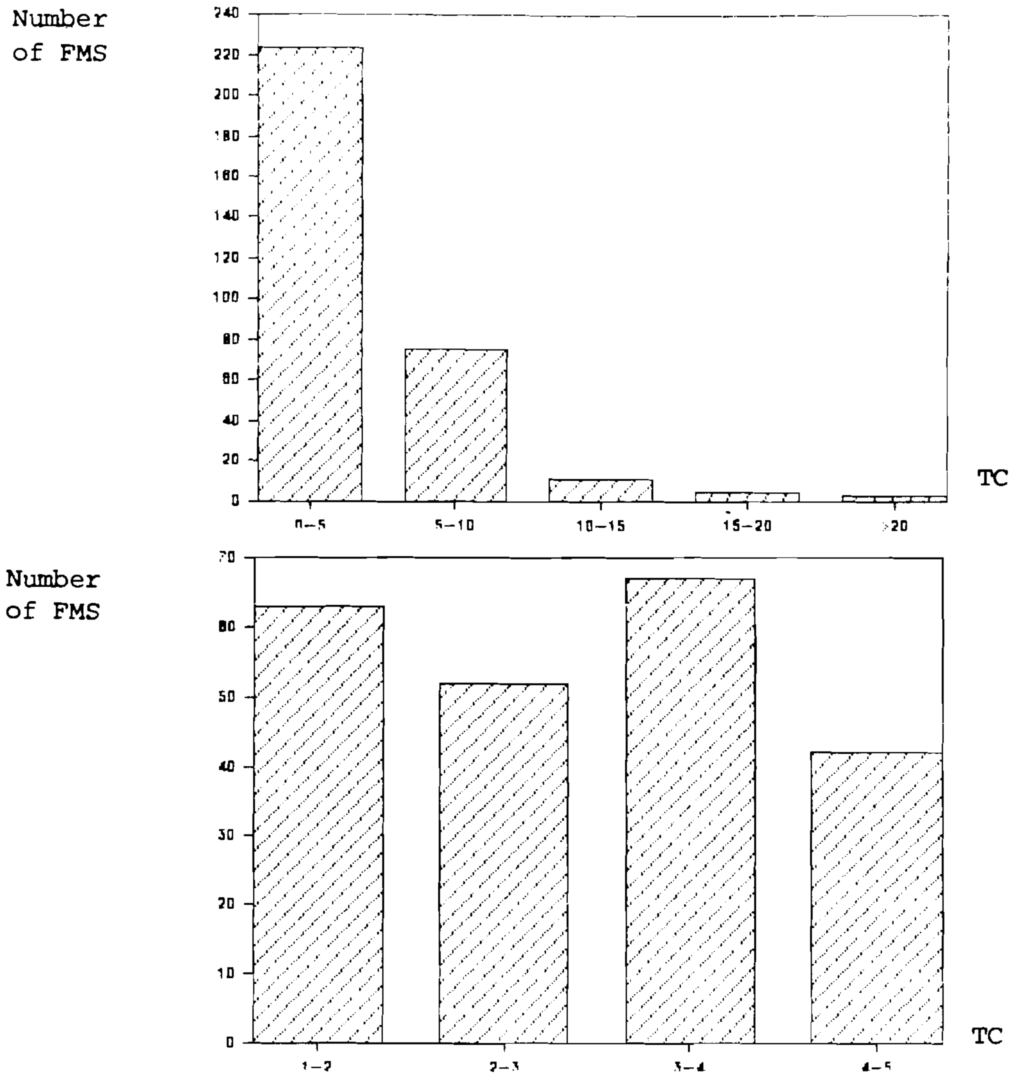


Figure 39. FMS distribution over technical complexity (TC).

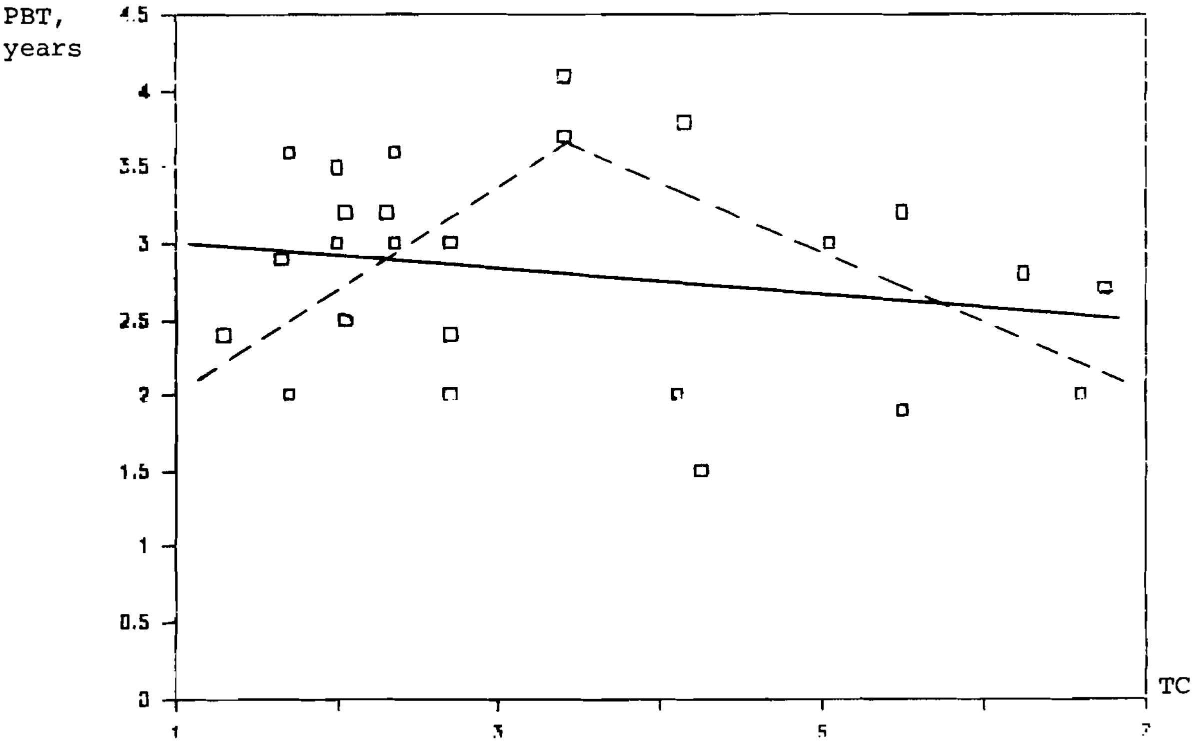


Figure 40. Pay-back time (PBT) over technical complexity (TC).

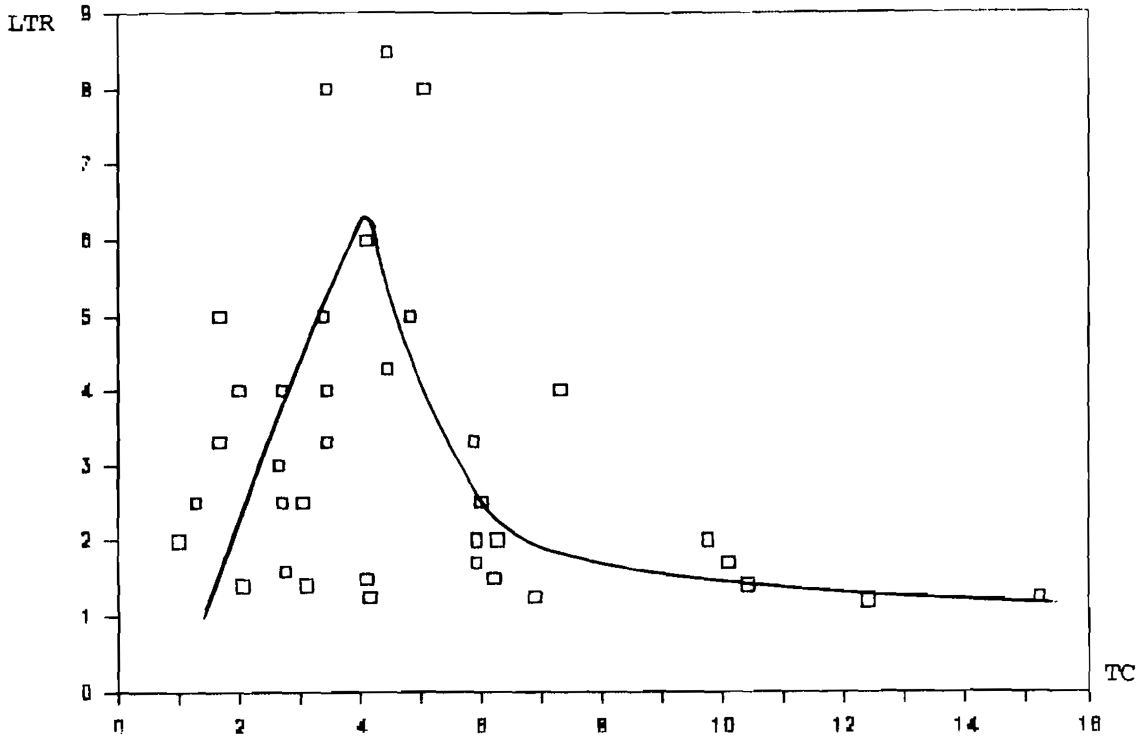


Figure 41. Lead-time reduction (LTR) over technical complexity (TC).

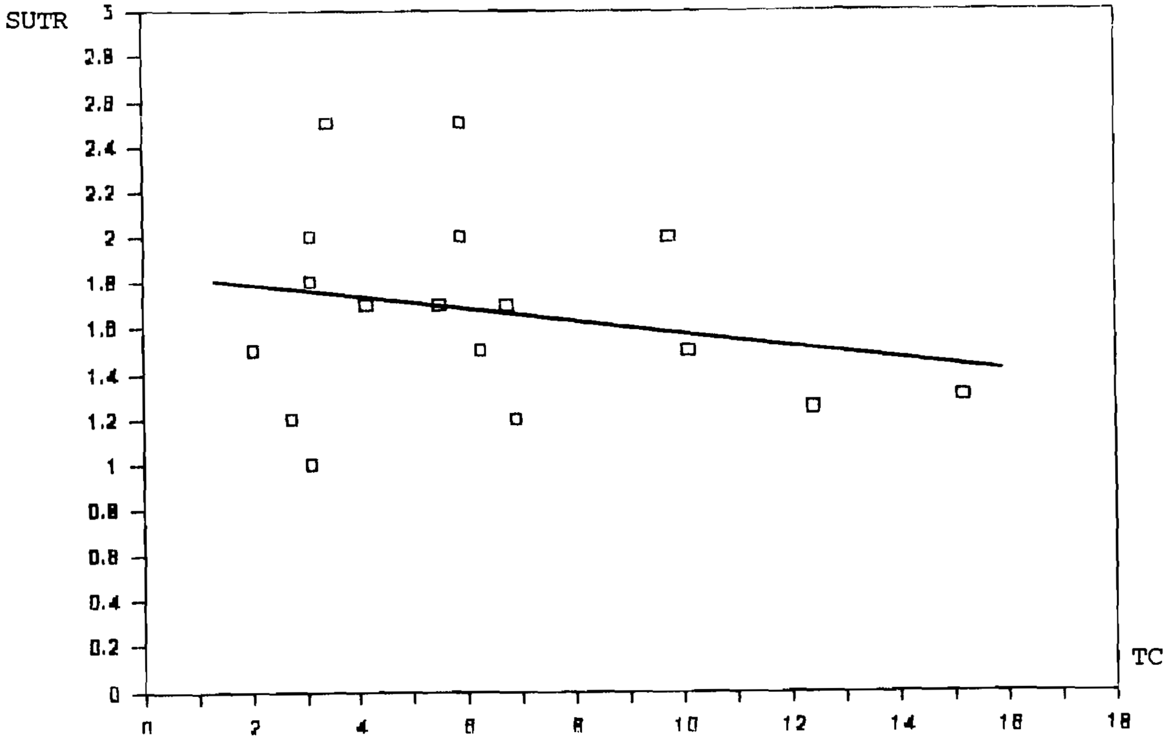


Figure 42. Set-up-time reduction (SUTR) over technical complexity (TC).

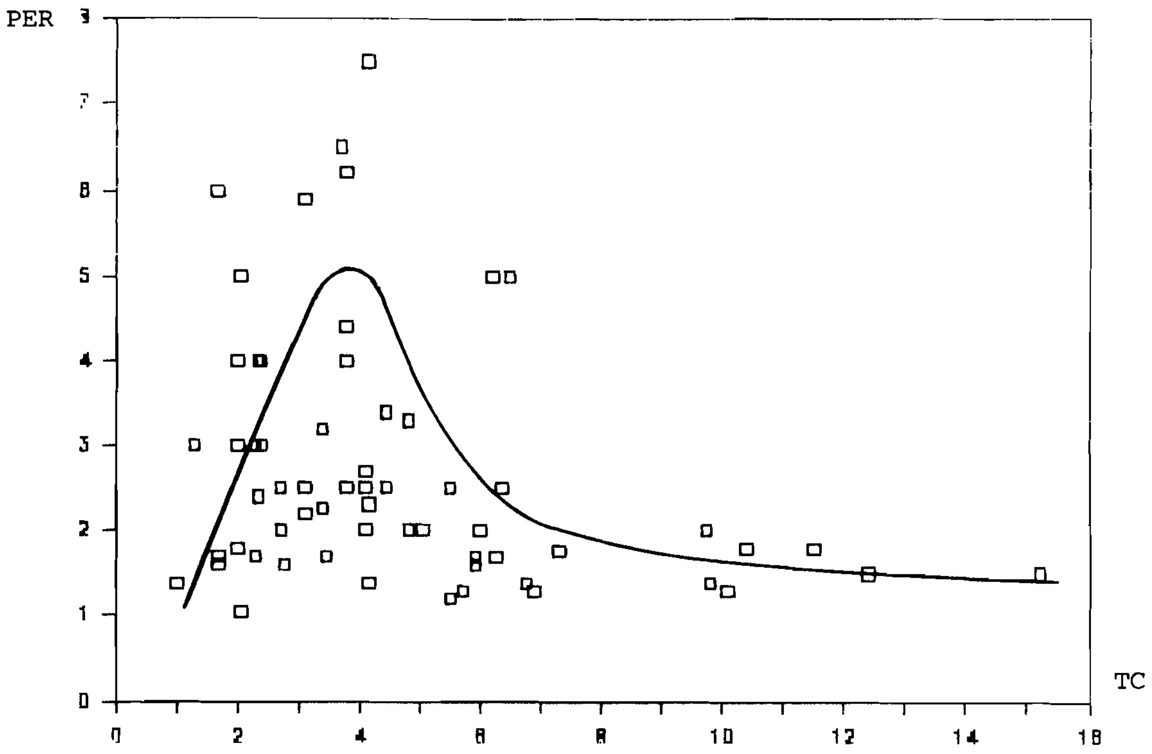


Figure 43. Personnel reduction (PER) over technical complexity (TC).

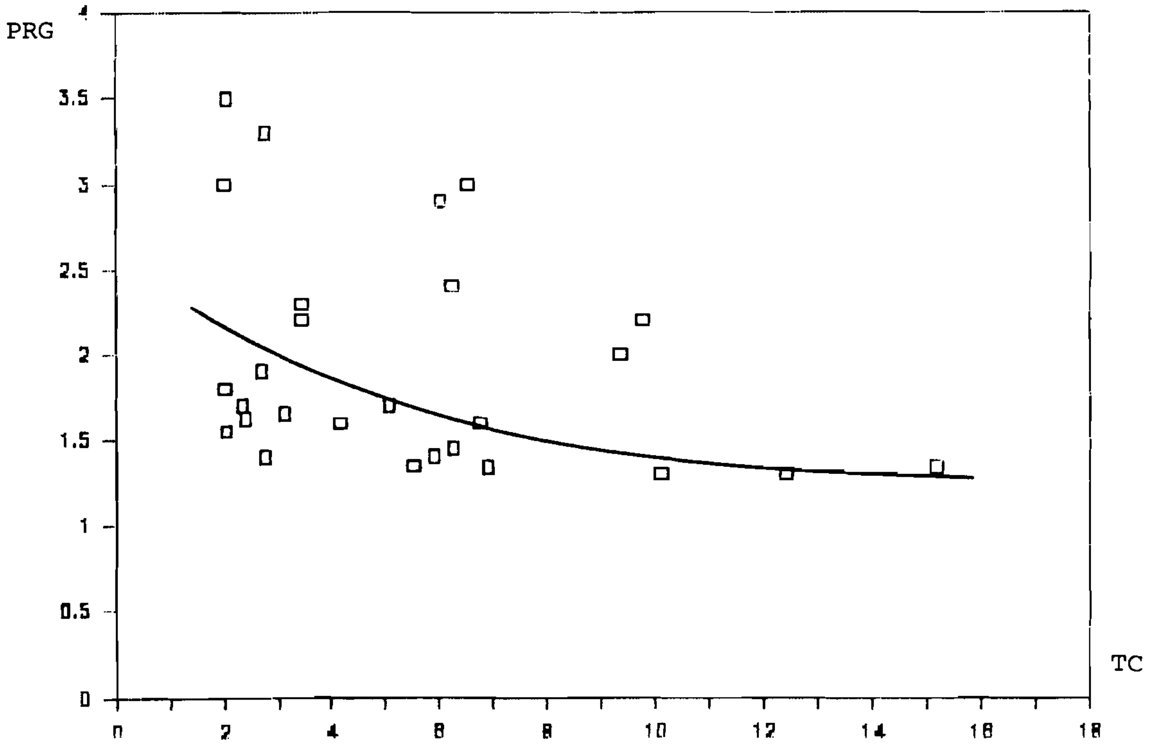


Figure 44. Productivity growth (PRG) over technical complexity (TC).

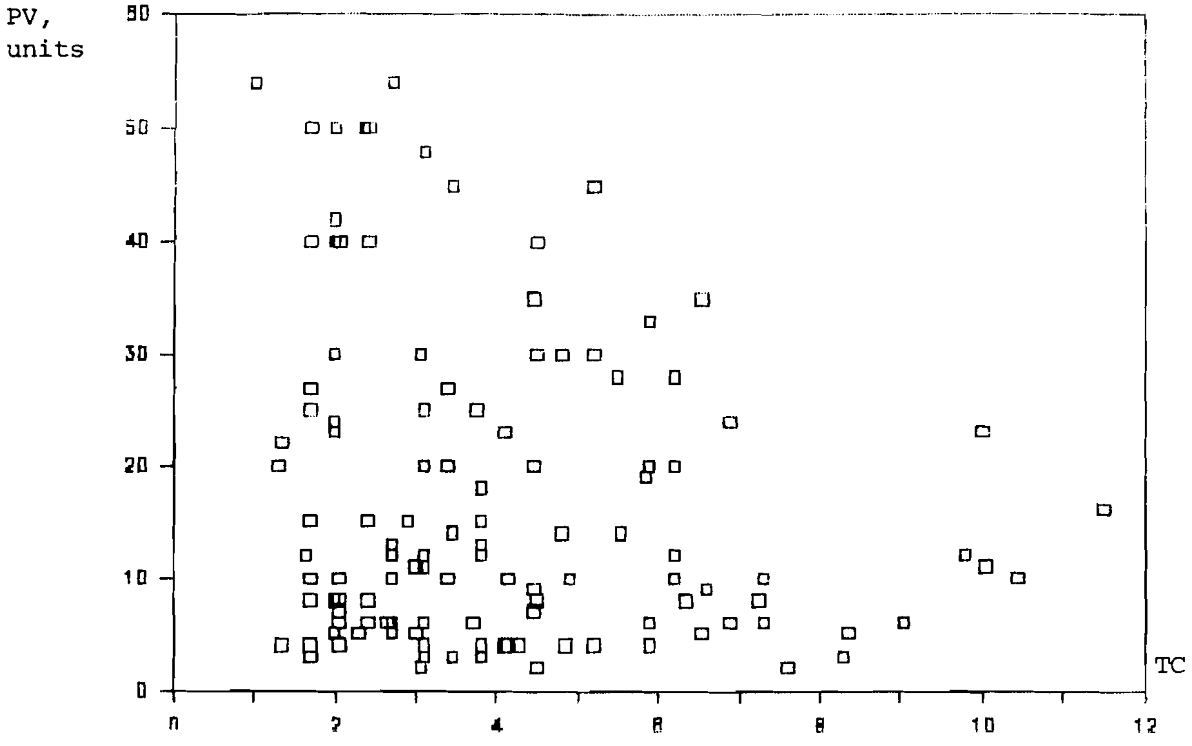


Figure 45. Product variation (PV) over technical complexity (TC).

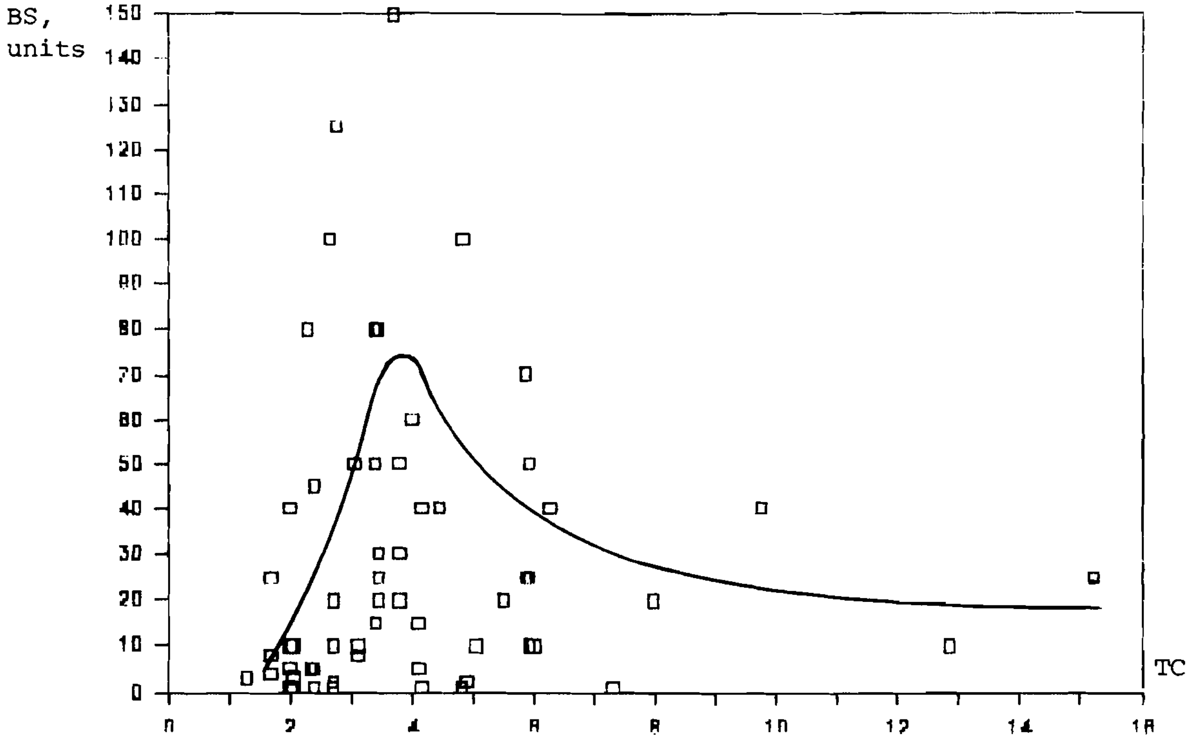


Figure 46. Batch size (BS) over technical complexity (TC).

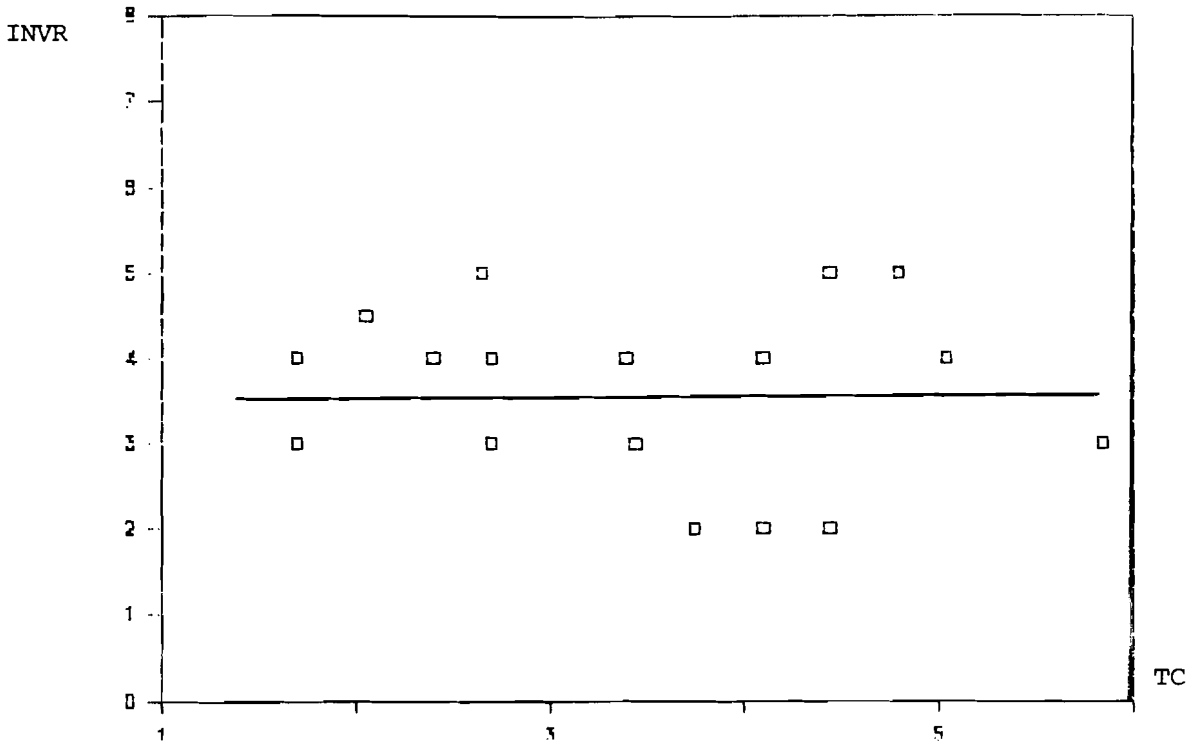


Figure 47. Inventory reduction (INVR) over technical complexity (TC).

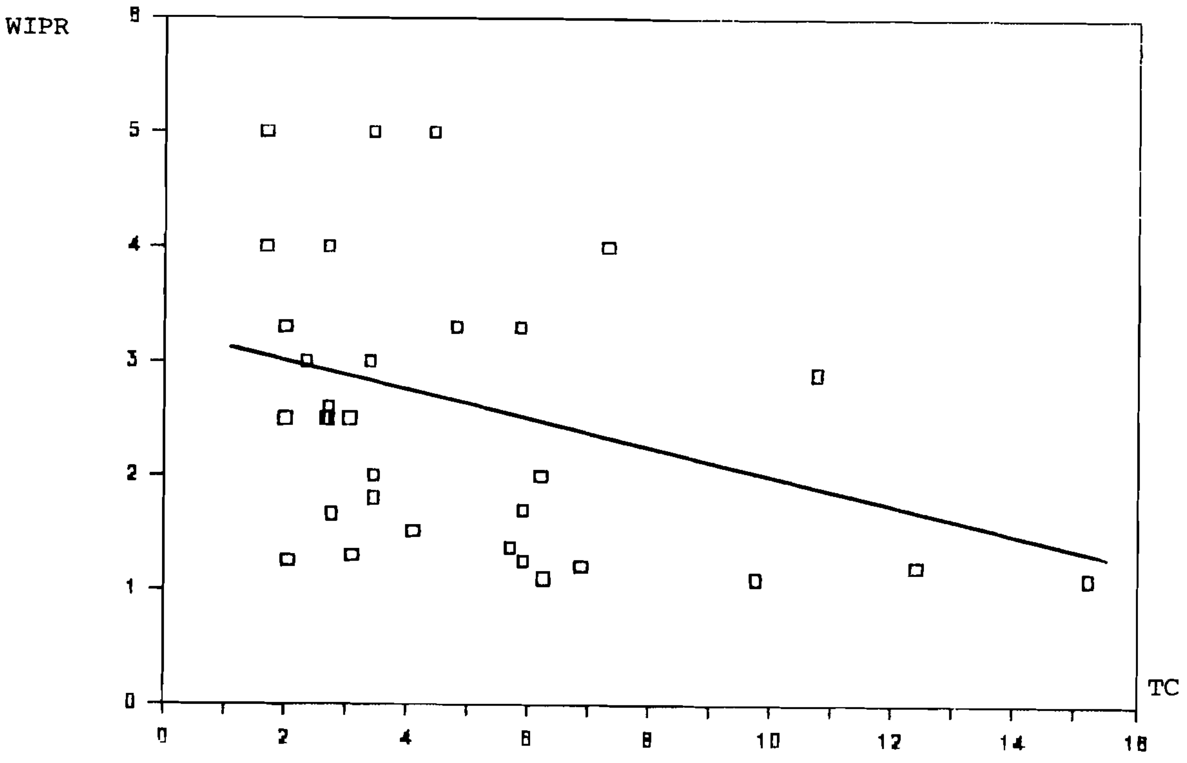


Figure 48. Work-in-progress reduction (WIPR) over technical complexity (TC).

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):

$$\mathrm{PRG} = 0.8 + 0.5\ \mathrm{PER}$$

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.

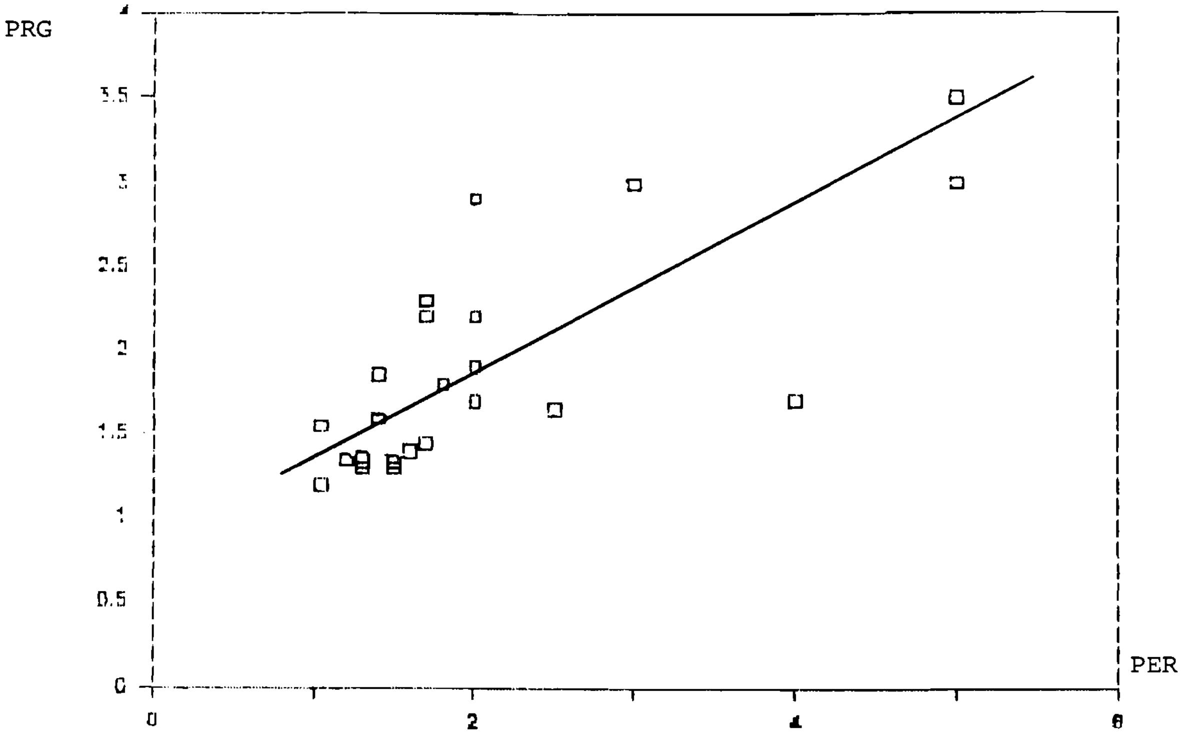


Figure 49. Productivity growth (PRG) over personnel reduction (PER).

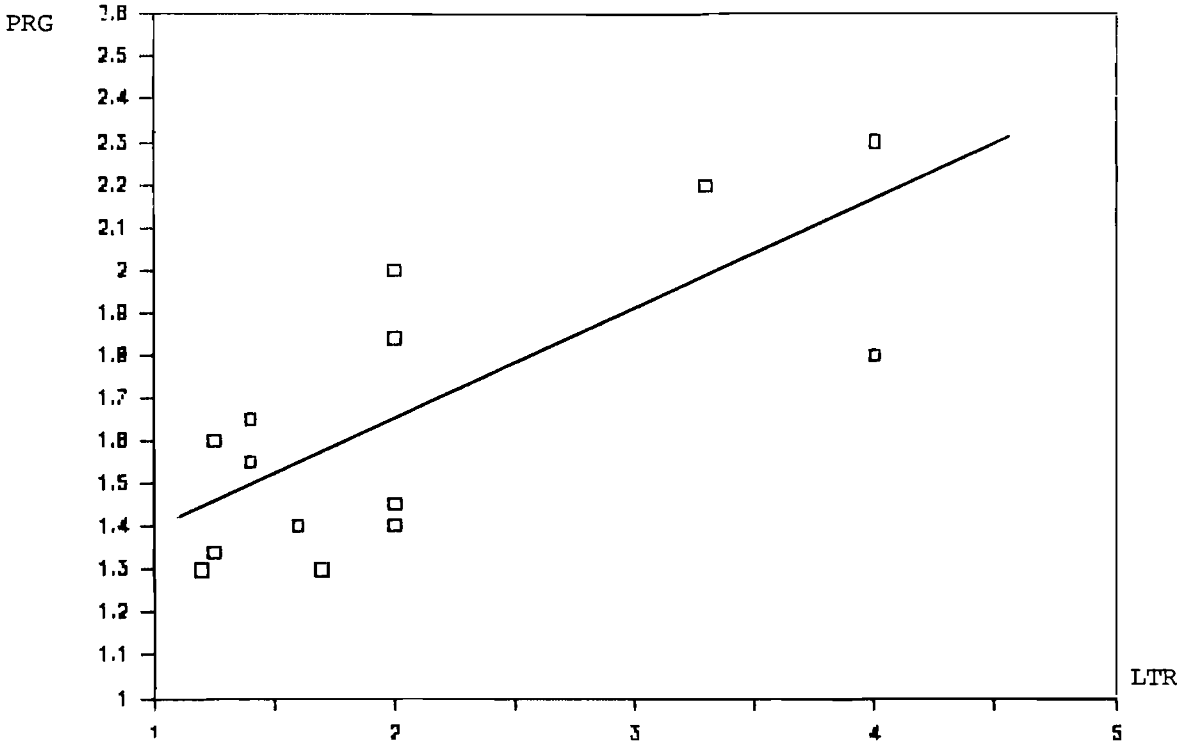


Figure 50. Productivity growth (PRG) over lead-time reduction (LTR).

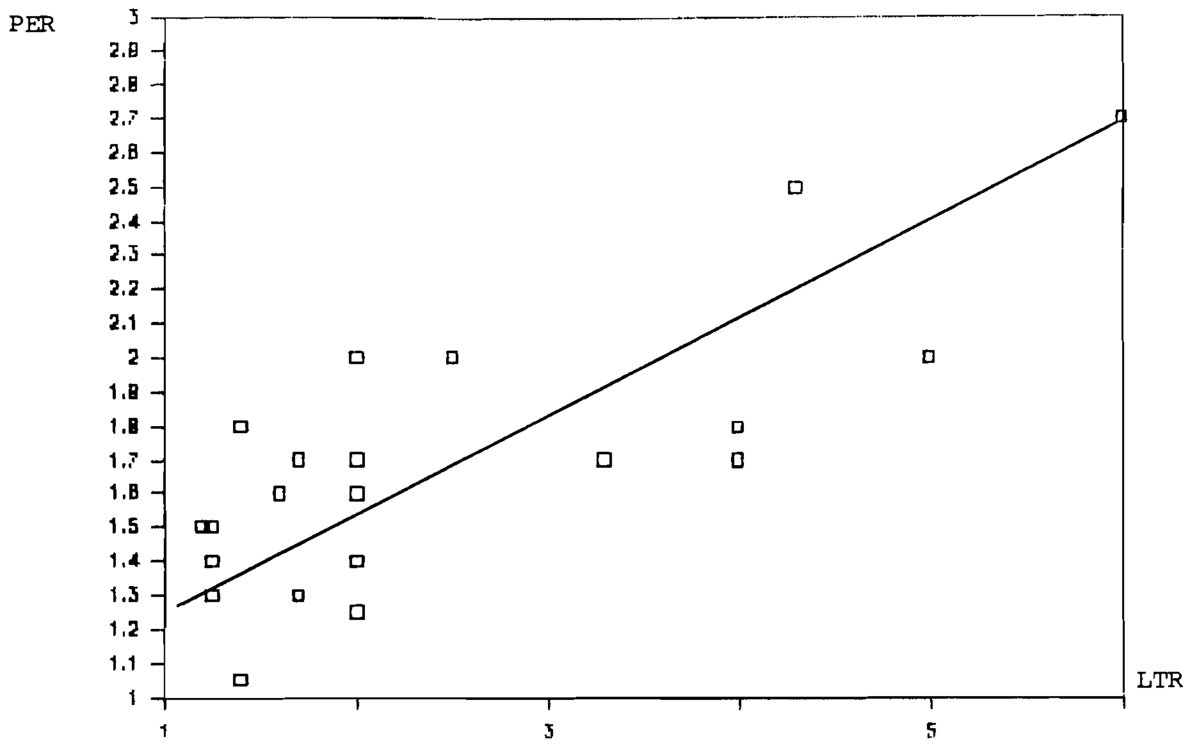


Figure 51. Personnel reduction (PER) over lead-time reduction (LTR).

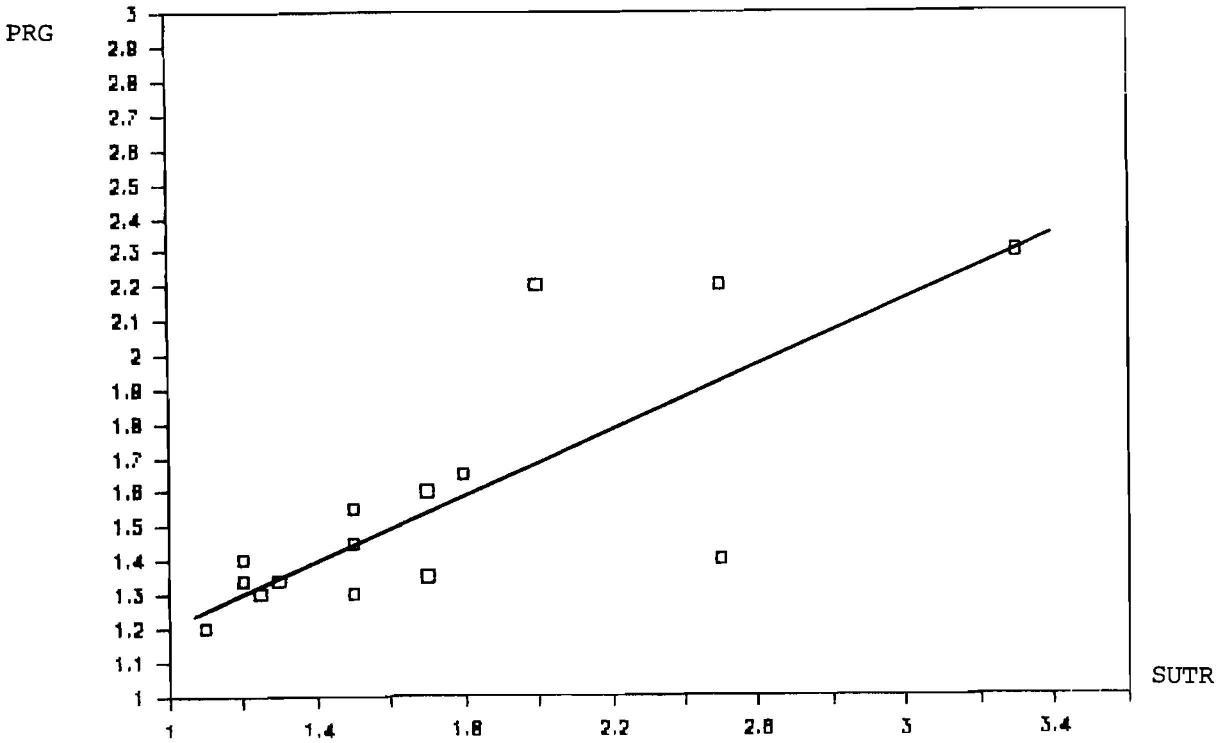


Figure 52. Productivity growth (PRG) over set-up-time reduction (SUTR).

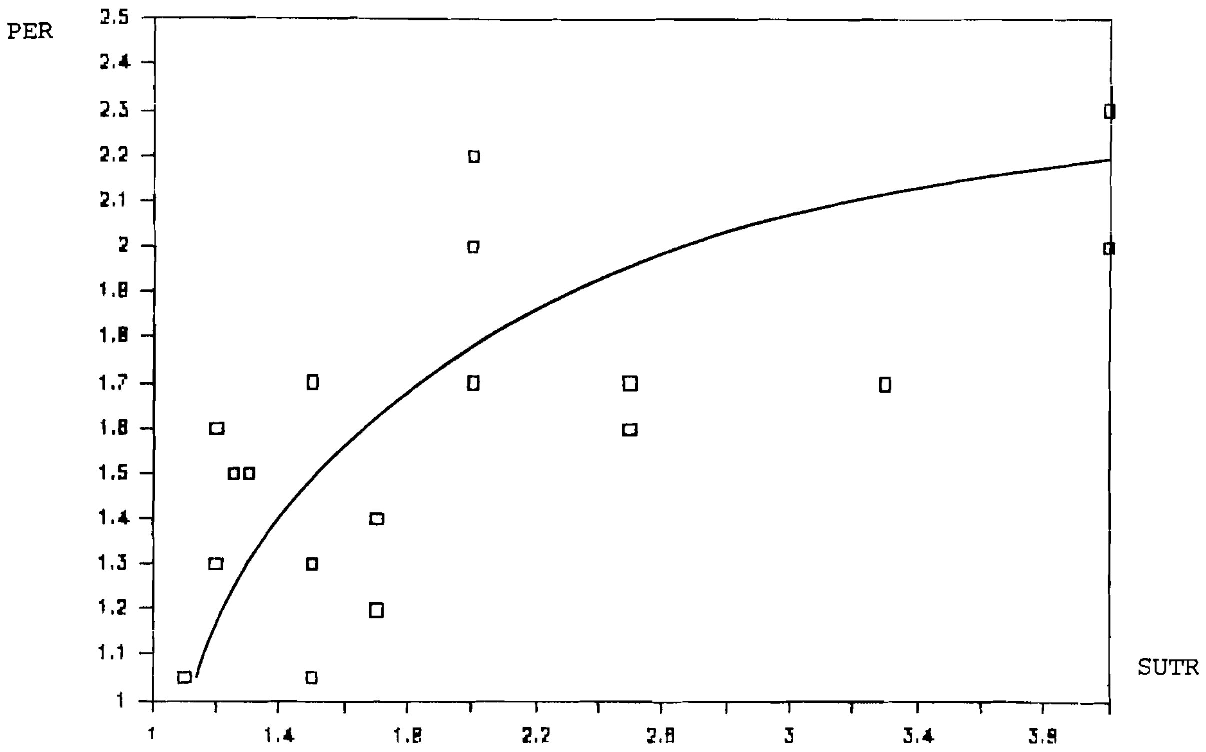


Figure 53. Personnel reduction (PER) over set-up-time reduction (SUTR)

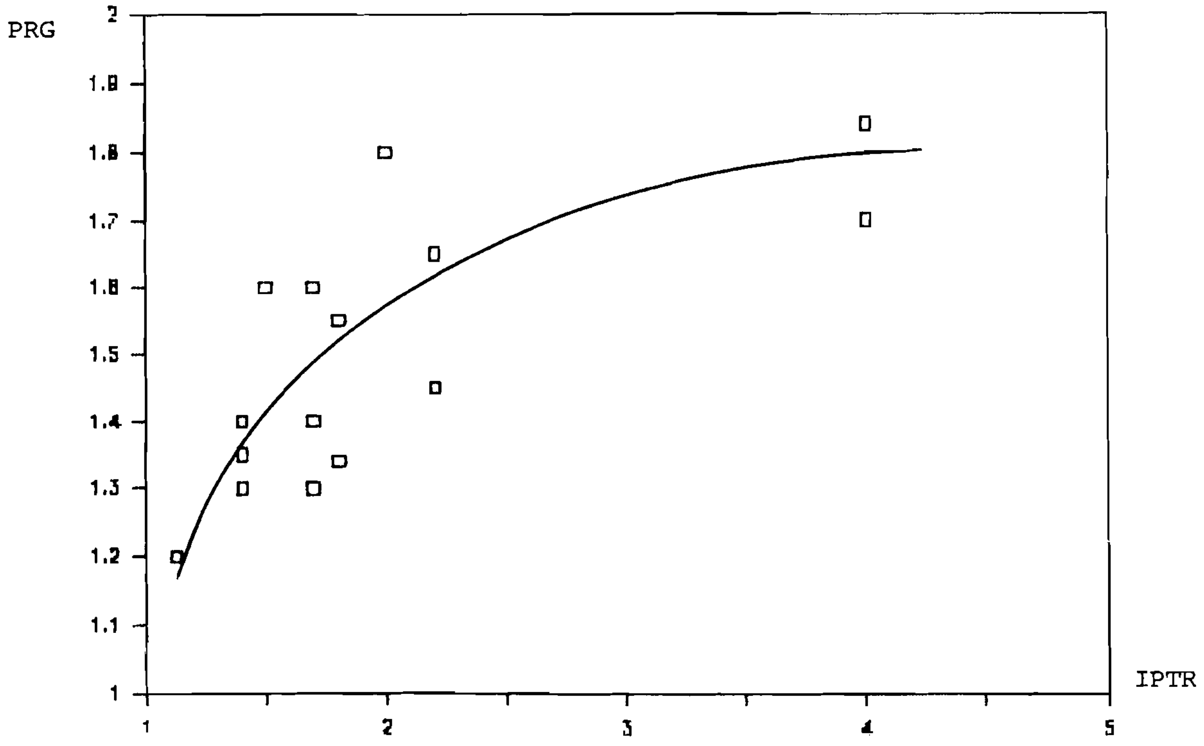


Figure 54. Productivity growth (PRG) over in-process-time reduction (IPTR)

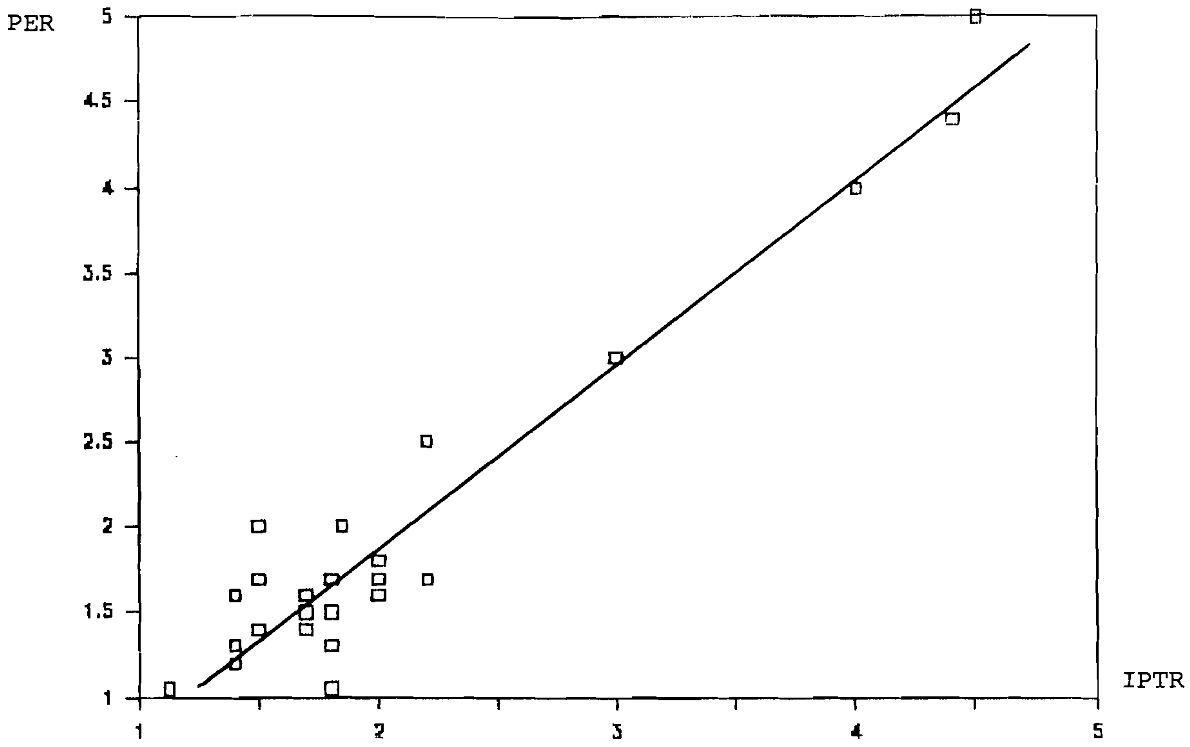


Figure 55. Personnel reduction (PER) over in-process-time reduction (IPTR).

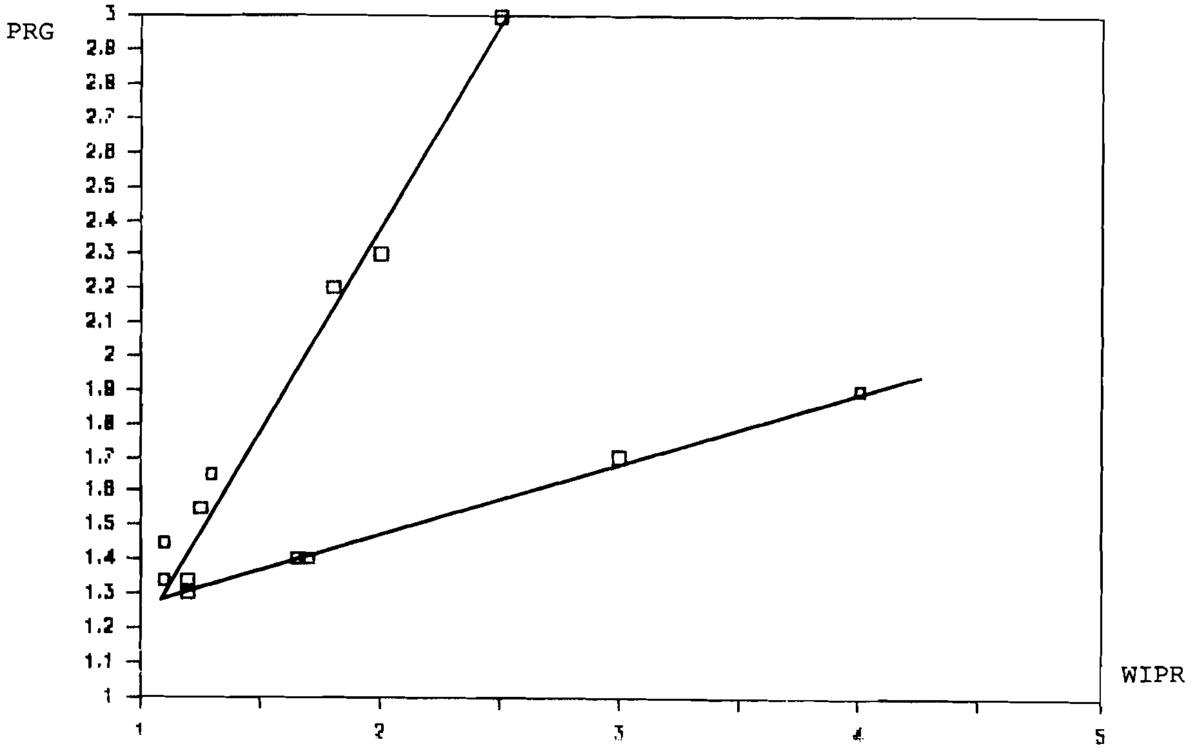


Figure 56. Productivity growth (PRG) over work-in-progress reduction (WIPR).

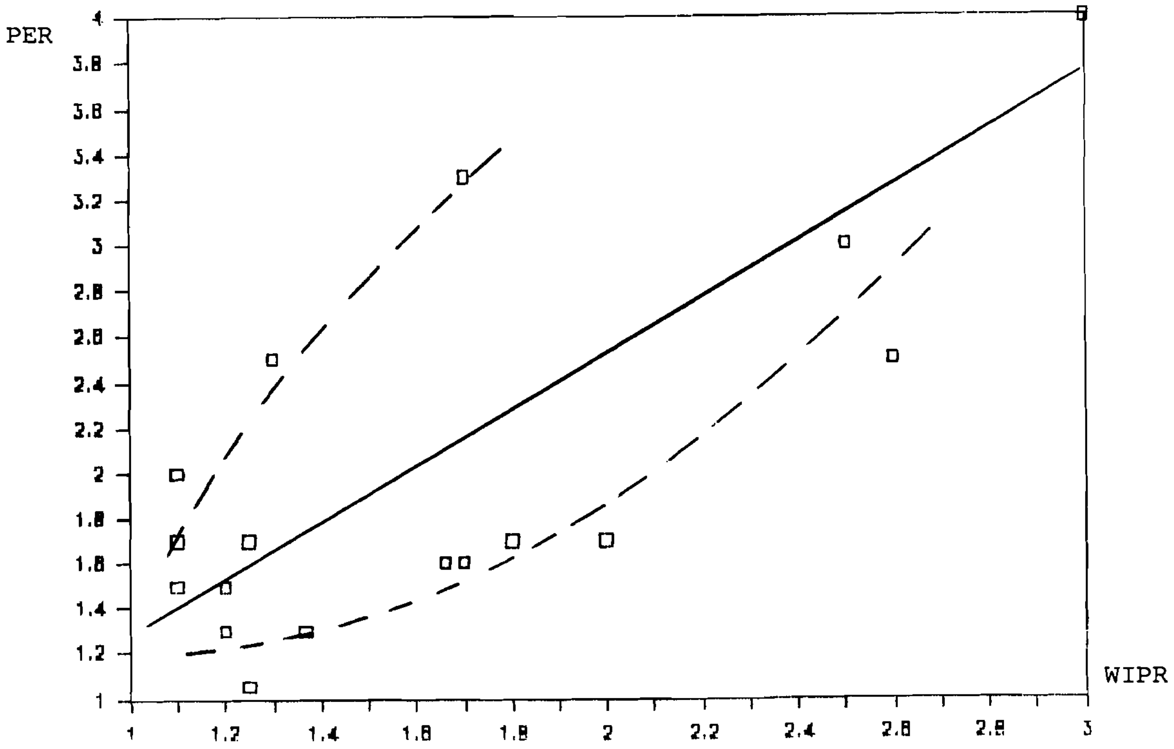


Figure 57. Personnel reduction (PER) over work-in-progress reduction (WIPR).

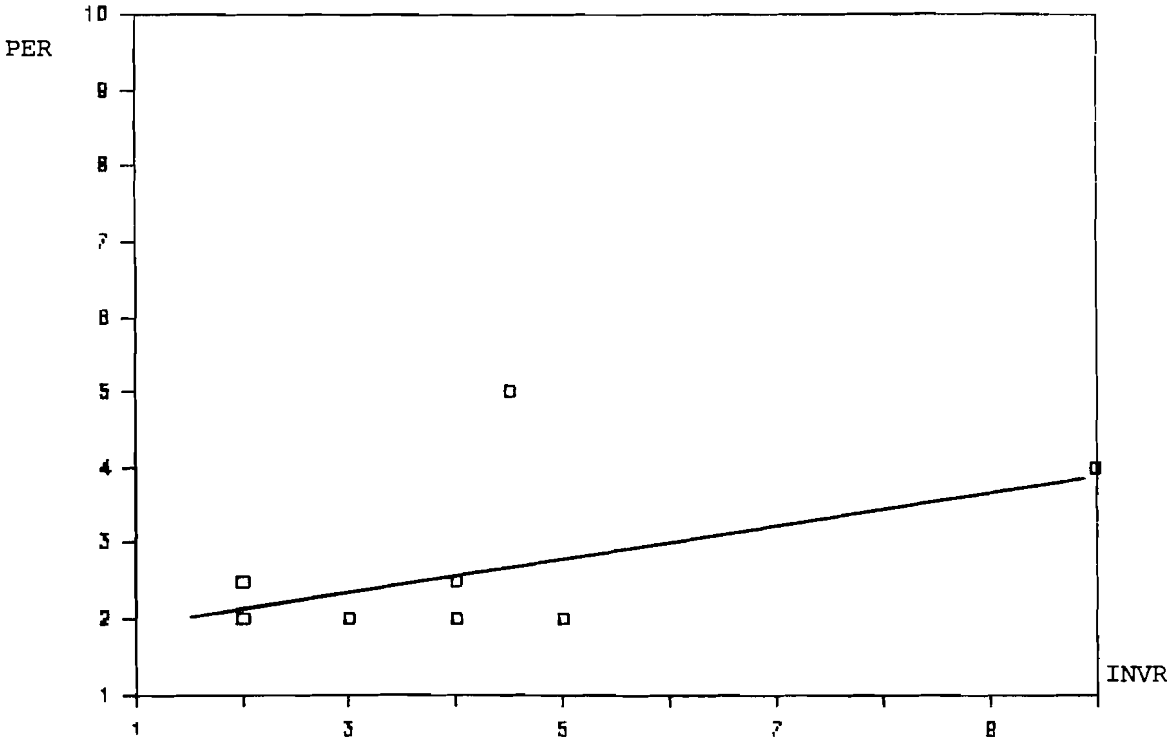


Figure 58. Personnel reduction (PER) over inventory reduction (INVR).

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.

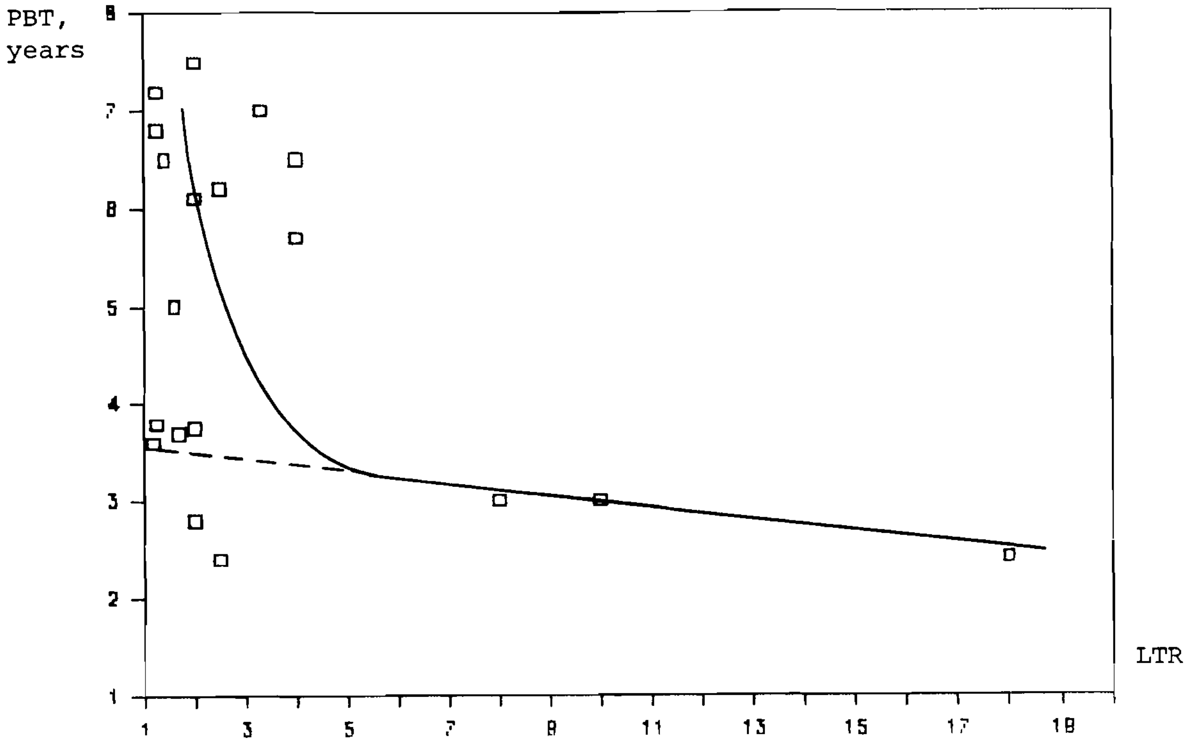


Figure 59. Pay-back time (PBT) over lead-time reduction (LTR).

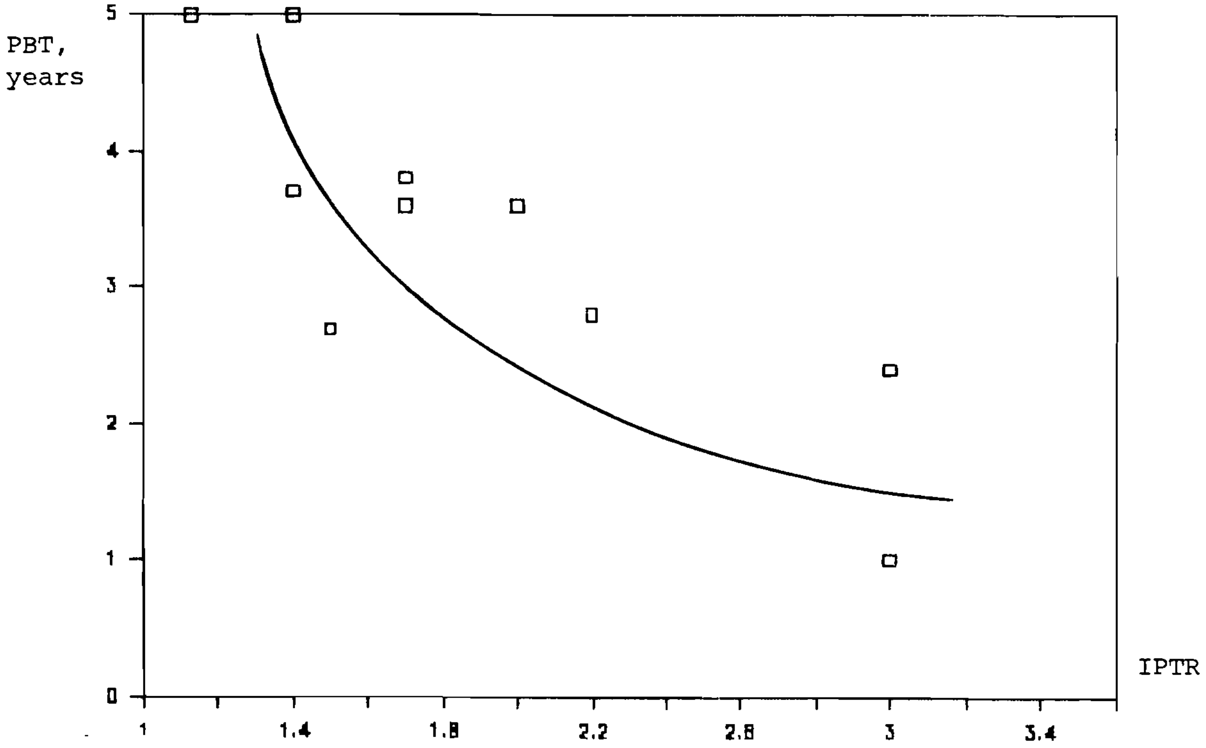


Figure 60. Pay-back time (PBT) over in-process-time reduction (IPTR)

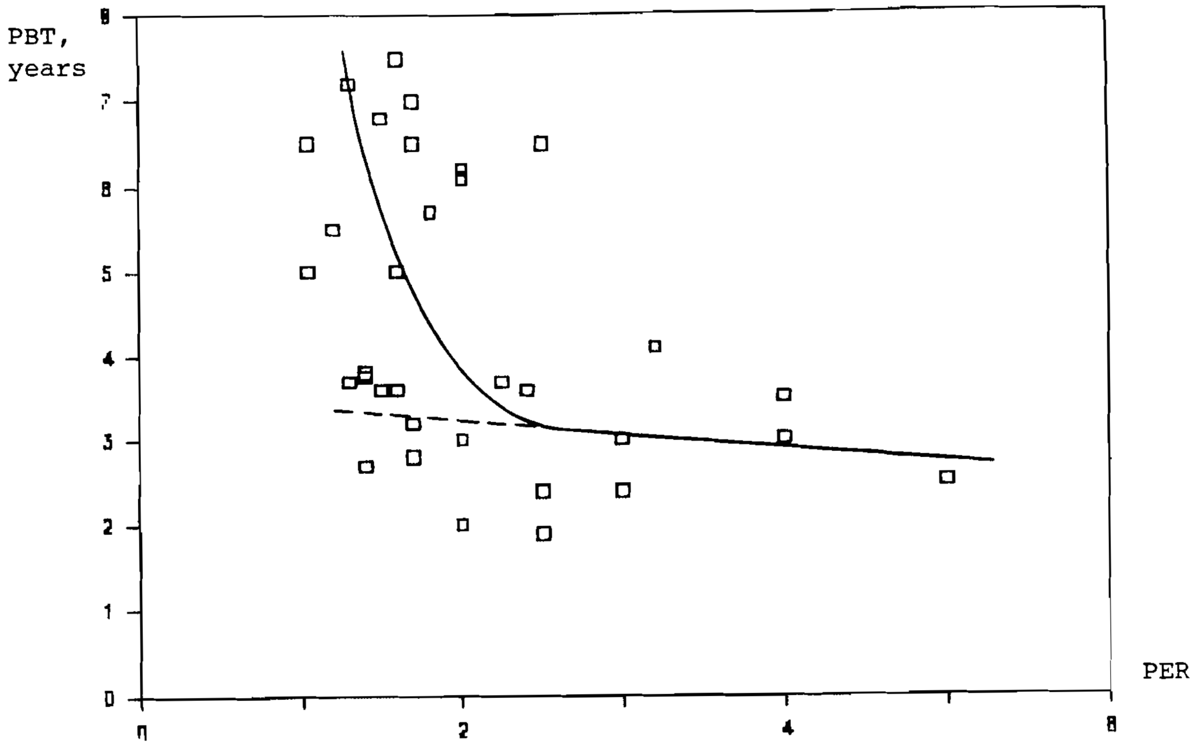


Figure 61. Pay-back time (PBT) over personnel reduction (PER)

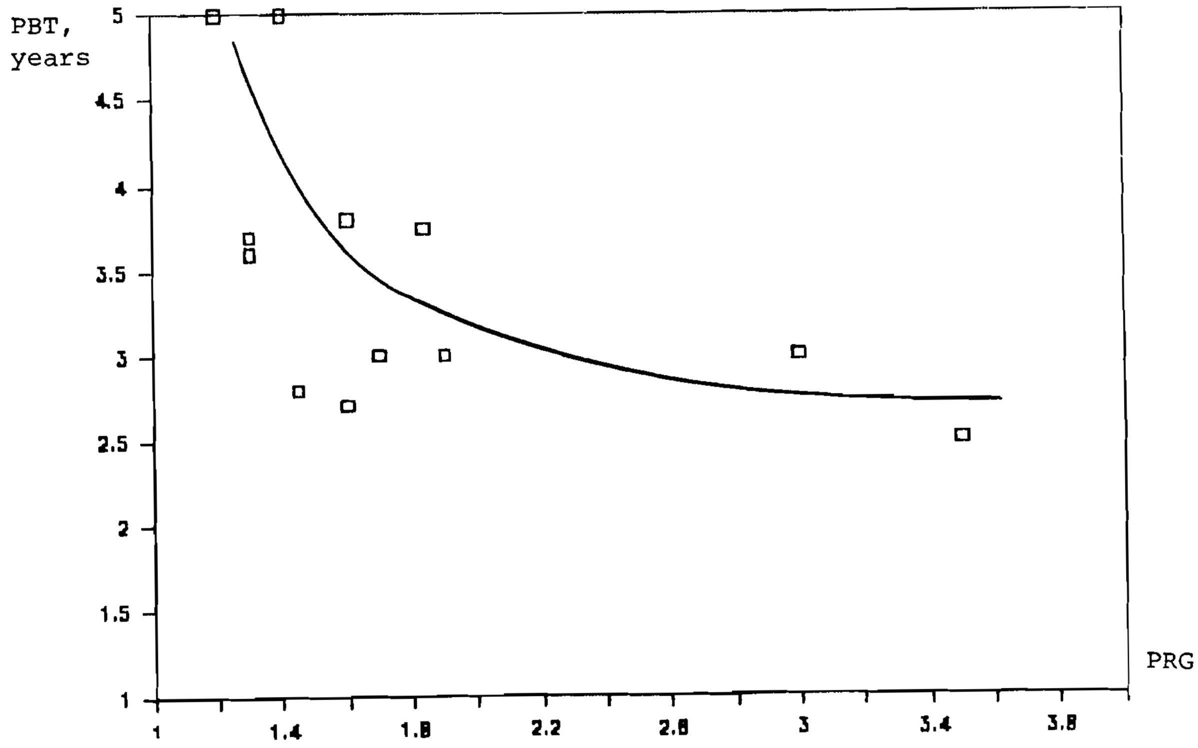
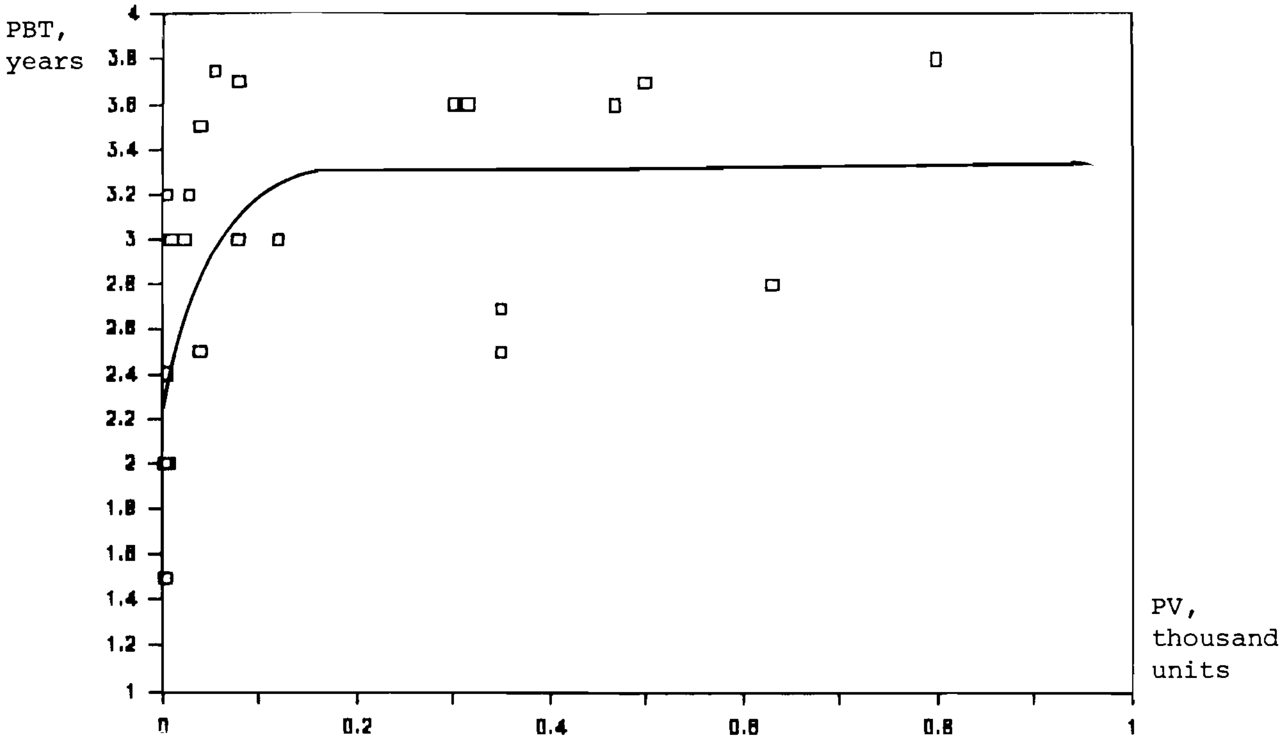


Figure 62. Pay-back time (PBT) over productivity growth (PRG)



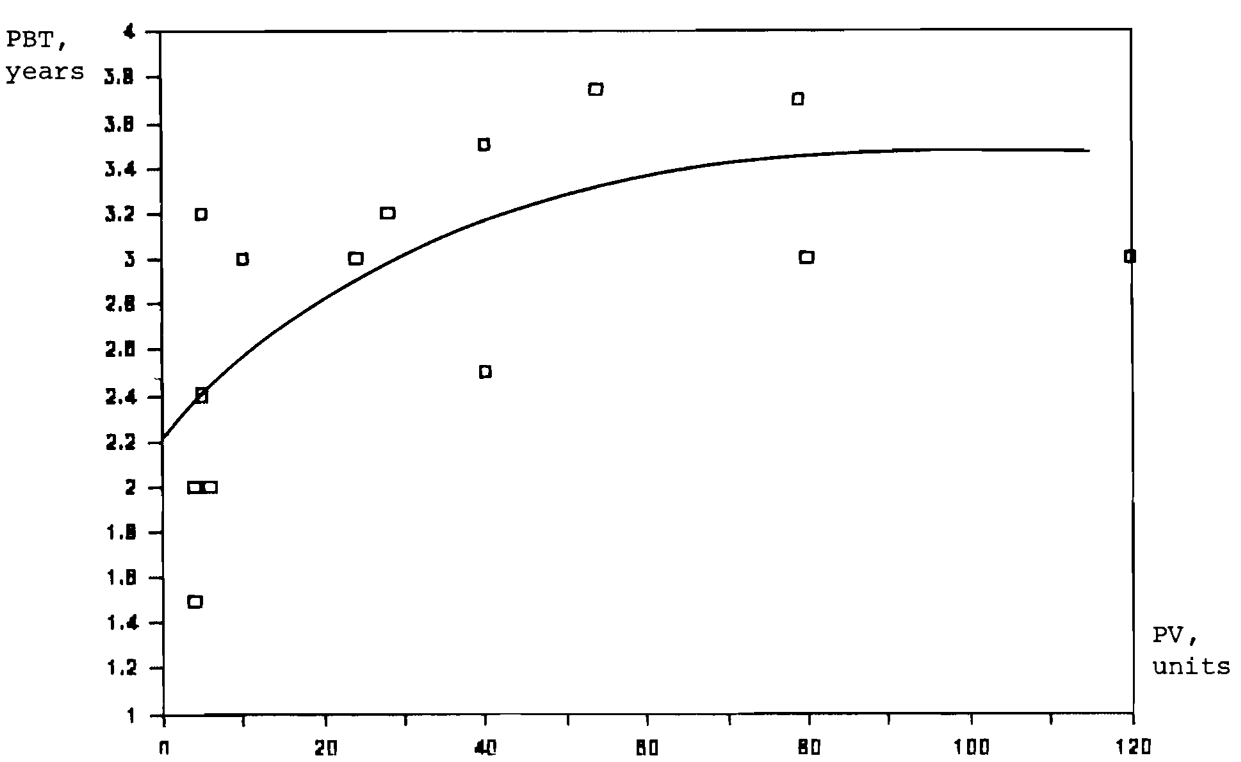


Figure 63. Pay-back time (PBT) over number of product variants (PV).

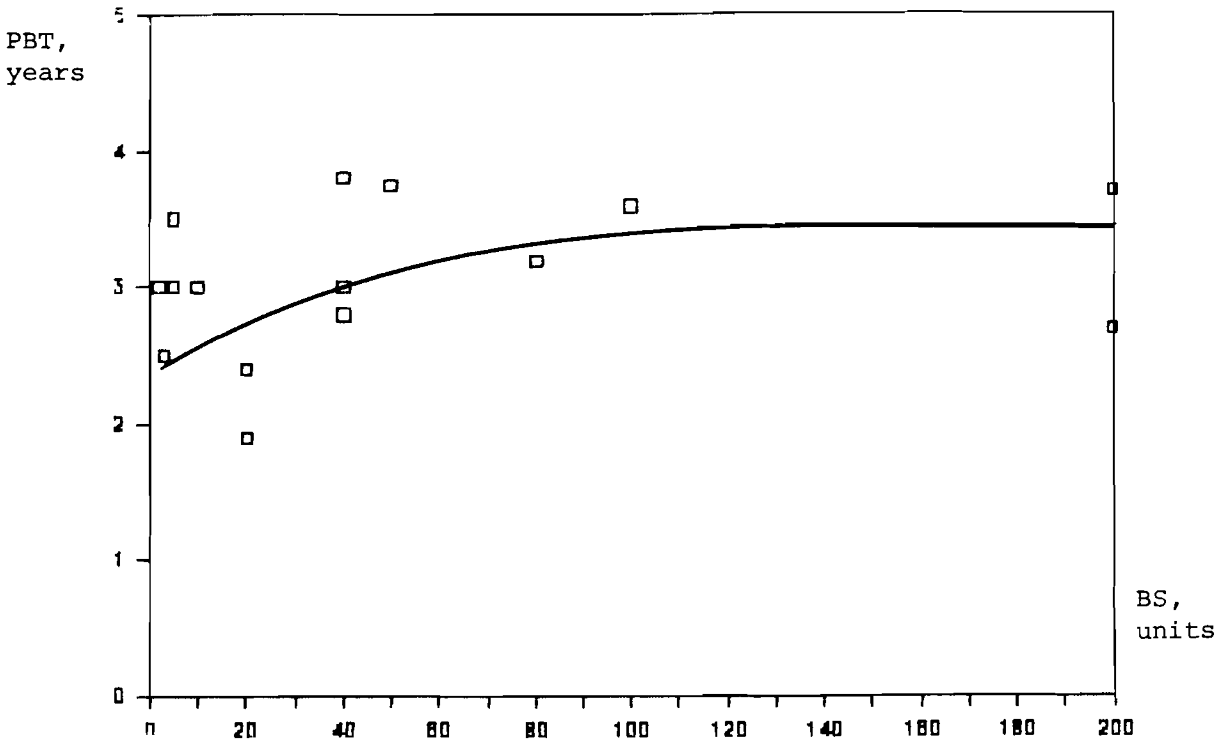


Figure 64. Pay-back time (PBT) over batch size (BS).

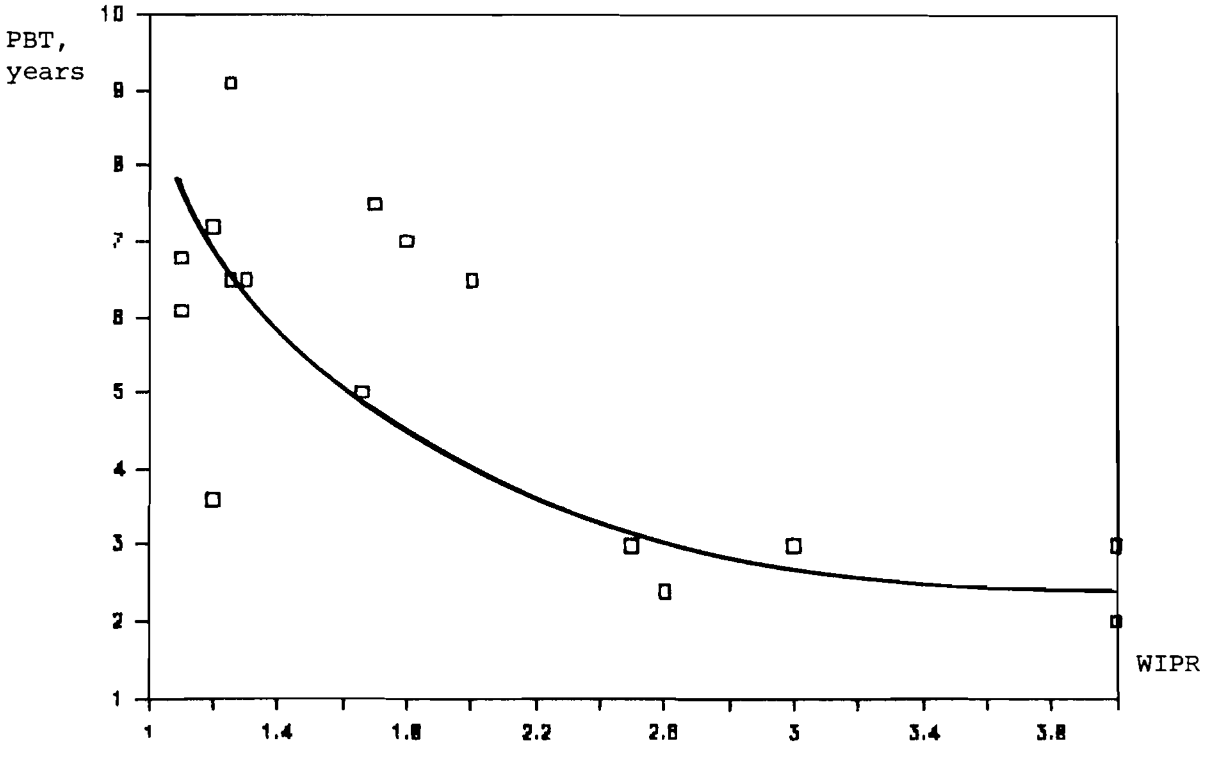


Figure 65. Pay-back time (PBT) over work-in-progress reduction (WIPR).

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.

	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

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