COST AND EFFICIENCY PERFORMANCE OF AUTOMOBILE ENGINE PLANTS

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Abstract

This paper analyzes the basic performance of 27 automobile engine lines operated by 18 companies on three continents, based on questionnaire data gathered in 1995. A composite cost comprising labor and amortization of capital, accounting for downtime, is used to compare plant performance. We find that performance varies widely, even after eliminating differences in number of cylinders, number of engine varieties, scheduled utilization, and currency translation effects on wages. Cost drivers comprise number of workers, capital invested, and efficiency (fraction of scheduled time actually used for production). The drivers are in turn driven by external factors out of the plant's control and internal factors that are under its control to some degree. About half the variance in cost is due to the external factors, such as number of cylinders, utilization of scheduled time, and number of variants of engine made (the last loosely related to age of the engine family). Internal factors include work in process inventory (strongly) and age of the workers (somewhat). Scheduled downtime is driven largely by number of variants while unscheduled downtime is driven partly by the age of the family. A cost of variety is calculated for block machining. Statistical analyses show that increasing the square root of the number of variant blocks by one adds $4.92 to the composite cost per block, $15 million extra investment, 9 additional workers and -4% operating efficiency. Opportunities for substituting capital for labor and vice versa are also calculated.

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Keywords: automobile engine plants, automation uptime, staffing

I. Introduction

A. Background

The International Motor Vehicle Program's (IMVP) current research efforts examine five broad areas in the industry: Product Development; Supplier Relations; Manufacturing, Organization and Human Resources; Distribution; and Environmental Issues. Within Manufacturing, the IMVP has studied the productivity of assembly plants for nearly a decade.[Roos et al, MacDuffie, et al] In 1993 the program launched studies of two other important value-adding segments of automobile production: stamping plants [Roth] and engine plants. These new studies broaden the reach of the program by including capital-intensive operations that feed assembly plants and are sometimes directly integrated into them. Company and plant personnel have many opinions about the impact of product variety, the effect of different currency values, and the proper amount of autonomy that plants ought to have. This study is the first to provide detailed quantitative information about these issues. By contrast, data available in the public domain or from consultants cover fewer aspects of plant operations and performance or are not normalized with respect to standard operations or work content of the engine.

This study was conducted during the period June, 1994 to June 1997, and includes data from 27 engine families made in 18 plants on three continents, or about a quarter of all engine families world-wide. Ten companies took part in the study and contributed questions to the questionnaire. The study's phases were as follows: June, 1994- December, 1994: formulation of the questionnaire in consultation with the participants; December, 94 - December, 95: gathering and correcting data; March, 1995 - June 1995: first phase of data analysis; June, 1995 - June 1996: second phase of data analysis; June, 1996 - June, 1997: third phase of data analysis. Details of the study's methods and results may be found in [Peschard].

B. Literature Review

Specific studies of engine plant performance are few. These plants present an unusual combination of large fixed cost in the machining departments and large variable costs in the assembly departments. The conflicting demands of these kinds of cost structures are well known. While product variety is generally assumed to be a driver of cost, data are hard to come by and the assumptions are not always borne out. [MacDuffie et al] found that in auto assembly plants, some kinds of variety increase costs or decrease labor productivity but other kinds of variety do not. They found that plants with higher variety could have higher productivity if they adopted a particular set of management and human resource policies. In busy plants with many hard working machines, preventive maintenance is often performed at the expense of production time, another well-known source of tension. [Somers and Gupta] found that one engine plant was able to increase uptime overall by a combination of preventive maintenance policies including a well-trained work force and use of opportunistic preventive maintenance during periods when the line was down for repairs. [Mueller and Purcell] found that European auto manufacturers were all adopting similar policies that form what they call the "productivity improvement wheel," a combination of human resource policies, new technology, and decentralized management. A basic human resources issue is the amount and kind of support workers needed by particular kinds of industries. [Ward et al] found from national census data that industries with specialized technologies needed more support personnel per unit of direct production workers.

The present paper provides data on a number of these issues and is unique either in the kind of plant, number of plants, or quantitative tradeoffs explored.

C. Methodology

The study was carried out using a mail questionnaire and follow-up visits or clarifications by fax. The questionnaire contained three parts:

1. <u>Basic information about the plant, its operating schedule, number of parts and engines produced per shift, number of employees performing standard activities, and daily schedule of work and break periods.</u> The concept of "standard

activities" was borrowed from the IMVP Assembly Plant Study. The purpose is to count the same activities in every plant, eliminating differences such as whether a plant makes its own cylinder heads (a standard activity), its own pistons (not a standard activity), and so on.

2. <u>A series of questions applicable to an individual engine family made at the plant</u>. These questions were answered individually for each engine family made at the plant. An engine family is defined as all engines having the same number of cylinders and the same distance between cylinder centerlines. These questions include history of the family, descriptions of the family members currently being made, part count, complexity of operations, cost distributions among parts, labor, capital, and other costs, number of workers involved in standard activities, statistics about the shops (number of machines, shop area, investment in equipment, distribution of operating and down time, and number of automated operations.

3. <u>Questions on a variety of topics related to human resources, logistics and inventories, maintenance procedures, production technologies (including how equipment is obtained), quality, information systems, accounting practices, and recent improvement efforts</u>. Of particular interest in this section are questions concerning length of supply lines, selective assembly, and patterns of involvement of plant personnel in plant design activities.

No attempt was made to define a "standard engine." Instead, data were gathered and analyzed separately based on the number of cylinders (4, 5, 6, or 8 in our sample). Regressions, discussed below, indicate that the number of cylinders explains a large part of the variation in manpower and cost per engine, confirming our decision to treat different cylinder numbers separately.

Responses to the questionnaire were analyzed directly in order to obtain a picture of typical plant operations. Regressions were then calculated on engine block machining in order to determine what correlations might be found. For this dataset, a composite cost was calculated, based on combining labor and equipment depreciation, scaled for scheduled utilization and uptime. Utilization and uptime are defined in Section IV. The costs and their correlates were divided into those directly under the control of the plant, such as age of the plant, work-in-progress inventory (WIP), and age of the workers, and those determined elsewhere, such as factors inherent in the design of the engine, the number of variants in one family, and scheduled utilization. Of course, plant and worker age are not altogether under the control of the plant, but they are local to the plant.

Other analyses were conducted in order to determine root causes for certain performance results, such as downtime, and to see if certain hypotheses (for example, does increasing variety in a plant increase the cost of making engines there) are true.

D. Summary of Findings

1. General Findings

- Engines are complex systems, typically containing 350 to 450 parts. Their cost to final assembly plants ranges from $600 to $2000. Most of the key parts are made by suppliers. Generally, engines are robust, and a properly maintained plant with a well-trained and motivated workforce can make high quality engines regardless of many daily inconveniences and local problems.

- Engine plants are generally treated as captive suppliers. In most cases, plant managers and supervisors feel a lack of control over the factors that most affect the plant: plant design, plant equipment choice, engine design, number of engine variants, and production schedules.

- Engine plants differ greatly from assembly plants, having a lot of costly capital equipment that is heavily stressed. Good cooperation and institutional learning by the workforce are important for keeping this equipment up and running and making good parts.

- There is very wide variation in engine plant performance, whether measured according to total person-hours required per engine, amount of capital required per engine, amount of inventory, or percent uptime of equipment.

- Plant performance depends in complex ways on the engine's design, the age of the plant and of its workers, the design of the machines, and the number of different varieties of engine made. However, performance variations between plants that make similar engines are larger than most of these individual effects can account for.

- Engine plants that manage - or are forced to manage - based on a single metric, such as hours per engine, may be forced to make ill-advised tradeoffs between labor and capital.

- Plant design and operating philosophies differ widely, with two identifiable camps distinguished by whether the plant's owner directly controls a machinery vendor or not. Those that do (such as Toyota and Honda) generally have smaller, more manageable plants with fewer workers. There is some anecdotal evidence that they operate their plants according to principles and beliefs that are essentially unknown at other companies.

- The engine plant itself is responsible for only about 25% of the cost of an engine. This amount is about equally split between labor costs, capital depreciation, and all miscellaneous costs (mainly consumables and scrap). The other 75% is purchased raw materials (25%) or finished parts and subassemblies (50%). Therefore, to understand engine costs requires broadening the unit of analysis beyond the plant to include engine design and the performance of suppliers, topics that are beyond the scope of this study.

- Suppliers not only provide half of the cost of an engine via value-adding finished parts and assemblies, but these parts embody most of the advanced technologies of engines (such as turbochargers, emission controls, fuel injectors, electronic timing, and fuel valving). In some cases the suppliers control the technology through patents or know-how. One could say that the engine plants make mostly mature technology items and assemble the engine. The interface region between the new and mature technologies is the cylinder head, which may be said to be a battleground for control between the assemblers and the suppliers.

• Put another way, engine plants make on the order of 5 to 7 of the 450 parts in a typical engine and devote half to three quarters of their capital and floor space to making them.

2. Detailed Findings from a Focused Statistical Analysis of Block Machining Lines

The following findings apply to block machining lines and are supported by statistically significant correlations at the 0.05 level or better:

• The type of engine (number of cylinders), the level of variety (measured as the square root of the number of variants) and the level of equipment utilization contribute close to half of the variation in cost-performance across the plants in our sample.

• Work-in-Process (WIP) inventory appears to be a significant determinant of performance and is closely associated with cost. Also, it is positively correlated with the number of workers and the amount of investment required. Moreover, the level of WIP inventory seems to be determined in part by the level of variety, which suggests that part of the influence of variety on performance takes its effect through a higher level of inventory.

• Older plants are associated with lower efficiency and higher cost per block. The number of machines on the block line is an important determinant of the number of workers but does not have a visible effect on investment, efficiency, or cost. Flowtime through the shop is positively correlated with total downtime ($p = 0.011$ for the block line). However, contrary to expectations based on interviews with plant personnel, cycle time of machines does not seem to affect either scheduled or unscheduled downtime. Other factors such as the use of Total Productive Maintenance programs and the level of cumulative production do not appear to have a significant effect on performance in our sample.

• Of the labor conditions we examined, more absenteeism and higher worker age are associated with lower efficiency and higher cost per block. The existence of incentive programs and number of hours of training per workers did not yield any statistically significant results.

- Finally, we examined the trade-offs between the factors that directly affect performance: the number of workers, investment and efficiency. We find that there are some visible trade-offs among the “resources” in our sample: workers can be replaced by investment, and workers can be added to the lines in order to improve efficiency. In some plants we observed what appear to be counter-productive reductions in indirect maintenance workers, with adverse effects on uptime. In other plants, we found direct workers being assigned many formerly indirect tasks, such as tool setting and maintenance, with resulting increases in uptime.

3. Findings Determined from Data Applicable to Various Aspects of Plant Operation

Data were obtained on uptime of machining lines. Downtime was divided into scheduled (such as tool changes and fixture changes), unscheduled (resulting from breakdowns), and employee break time. The following conclusions are supported at the 0.1 level or better:

- The number of unique engines in a family correlates positively with the age of the engine family ($p = 0.11$). This confirms statements made to us by many engine plant personnel, some of whom referred to "creeping variety" as their main long term problem. Engine plants cost a lot and must be operated for many years in order to pay for themselves. Plants in our sample average 12 years old, $\sigma=9$.) The result is that engine families tend to last a long time, and many changes and additions are made over the years. This makes engine plants fundamentally different from assembly plants, which are rebuilt every 5 to 7 years, and stamping plants, which can accommodate new panel designs by using new, relatively inexpensive dies in the same relatively expensive presses.

- *Scheduled* downtime is positively correlated with the number of different varieties of items being made. For example, scheduled downtime on the block, head, and crank machining lines correlates positively with number of different kinds of blocks, heads, and cranks respectively. A stronger correlation on the block line is obtained with the sum of the number of bores and strokes made (p = 0.007). A reasonable explanation is that different varieties require different cutting tools and/or fixtures to be installed in the machines, requiring them to be shut down at predictable times.

- *Unscheduled* downtime correlates positively with total flowtime for heads and cranks through their respective machine shops. The sum of scheduled and unscheduled downtime correlates with flow time even better: for heads p = 0.03, for cranks p = 0.06, and for blocks p = 0.011. One possible explanation is that longer flowtimes are associated with larger shops, for which it takes longer to transport people or equipment from place to place.

- *Unscheduled* downtime is also positively correlated with the age of the engine family (p = 0.08). Presumably this is due to the increased age of the machinery. Electrical failures occur more frequently early in a line's life, and mechanical failures tend to dominate as a line ages.

- *Unscheduled* downtime in block (p = 0.07), crank (p = 0.09), and head (p = 0.05) machining also correlates positively with the fraction of workers in the respective shops that do non-production tasks. A possible explanation is that when a breakdown occurs in a shop with mostly production workers, it is they who either fix the breakdown or start repairs without delay. In either case, this saves time waiting for a non-production crew to arrive. A broader explanation is that one team is responsible for all the necessary tasks in a shop, learns them well, and takes total ownership of their shop.

- Reported hours/engine correlates positively with square meter area of shops. One possible explanation is that larger shops require more people to cover them.

II. Plant Operating Data and Analyses

A. Definition Of Metrics

In order to properly measure the performance of an engine plant, it is necessary to appreciate the different pressures on its management and employees. They must balance the costs of labor and capital and must do so under conditions in which many of the determining decisions have been made elsewhere by others. Figure 1 shows that only 25% of the cost of an engine is determined inside the engine plant itself. The design of the engine determines the difficulty of machining and assembling it, and the performance of suppliers contributes greatly to cost and schedule performance. To try to determine what is under the control of the plant and to see how different plants respond, we have defined four metrics of performance.

Figure 1. Cost Distribution of a Typical Engine

1. Labor Productivity

Labor productivity is defined as the number of actual employee hours per year, including breaks and sick time, required to perform the following standard activities, per engine produced by the plant on average over a year: machining of “the 5 Cs” (Cylinder block, crank shaft, cam shaft, cylinder head, connecting rod), accomplishing head subassembly and piston/ connecting rods subassembly; basic assembly of engine; final assembly and dressing; and hot test. From the questionnaire replies, we calculated the metric "hours per engine" and compared it with the plant's own estimate of the same thing. In many questions, we distinguished between the number of workers assigned production tasks (production workers, PW) and the total number of workers (total workers, TW) assigned to a line.

2. Capital Productivity

Capital productivity measures the amount of capital that is invested in a plant or line per unit of capacity. This is expected to capture the differences between heavily automated plants that require a lot of investment, and more manual lines which may require less investment.

3. Efficiency Of Plant Use

The efficiency of a line reflects the fraction of the parts that could theoretically be produced at full capacity compared to the number that are actually produced. We calculated the efficiency of a line as the ratio of the actual average production rate (jobs per hour) and the theoretical capacity of the line. We also defined “uptime” as another measure of the “efficiency”. Uptime is the time that is scheduled for production, including overtime, minus the time when the line is stopped for either scheduled or unscheduled downtime. The ratio of uptime over available time serves as a measure of the ability of a plant to keep the lines running when they are intended to be.

4. Cost Performance

While single-factor productivity measures are useful to the extent that they permit simple comparisons across plants, they do not fully capture overall productivity. In order to obtain a measure that better captures overall productivity, it is necessary to use a measure that integrates all the relevant inputs (labor, capital, materials, energy...).

Based on the measure of total factor productivity (TFP) proposed by [Chew, Bresnahan, and Clark (1990)], we may construct a typical measure of the following form:

$$TFP_i = [\ (value_X \times \ sum\ (C_{Xj}\ .\ X_{ij}) + (value_Y \times \ sum\ (C_{Yj}\ .\ Y_{ij})]\ /\ [\ (number\ of\ worker\ hours \times wage\ +$$
$$investment\ \times cost\ of\ capital\ +\ energy\ cost\ +\ materials\ cost];$$

where X and Y would be two main types of products, $value_X$ and $value_Y$ would be monetary values assigned to product X and Y, and C_{xj} would be a complexity factor assigned to each product subtype.

In our study, as in Chew et al, we only included labor and capital in our measure. Moreover, we have treated each plant as if it produced only one type, or family, of engines. Since the effect of product complexity is one of the issues that we are trying to examine, we have excluded the complexity factor from our measure and analyzed complexity separately using number of cylinders as a proxy.

The result is the following total factor cost formulation:

$$cost_i = (TW_i \times wage_i \times util._i + invest_i \times capital\_cost) / (cap_i \times eff_i \times util_i) \qquad (eq.\ 1)$$

where $cost_i$ is the calculated cost per unit at plant i;

$wage_i$ is the total cost to plant i for an average worker (based on local labor cost -- wages and benefits -- converted to 1996 US dollars);

TW_i is the total number of workers involved in standard activities;

$util_i$ is the utilization rate calculated as the share of total hours that are made available for production, where we considered that the total number of hours is 24 hours per day, 7 days a week.

$invest_i$ is the total investment (in US dollars) in standard activities departments;

$capital\_cost$ is the cost of capital charged to the investment per unit of time. In this case, the value used was $capital\_cost = 10\%$ / year = 0.00114% per hour, considering 24 hours per day, 365 days per year.

cap_i is the capacity in jobs per hour (JPH), calculated as the inverse of the nominal cycle time. For example, if a line's nominal cycle time is 30 seconds, then

$$cap_i = 30 \text{ seconds per unit} \times 3600 \text{ s / hour} = 120 \text{ units per hour;}$$

eff_i is the efficiency of plant i, or the relevant line in plant i, measured as the fraction of capacity that is achieved during the time available for production, thus,

$$eff_i = \text{actual production of good parts (JPH) / capacity (JPH)}$$

B. Data On Manpower and Time Per Engine

As documented in [Roos, et al], IMVP researchers found during the late 1980's that Japanese automotive companies' vehicle assembly operations were significantly more productive than those of American and European firms. More recent studies of vehicle assembly plants, however, seem to point at a strong process of convergence. The best American and European plants seem to match the levels of labor productivity of the best Japanese plants. Our results for labor productivity seem to confirm this: as shown in Figure 2, we have not found any significant regional differences, and the best plants in each region reach similar levels of productivity. In addition, variation in labor productivity within regions seems to be far greater than that across regions. Note that among our sample of 27 families, six are made at "transplants" (plants whose owning company headquarters are in a different country). The owning companies are in the US, Japan, and Europe. Anecdotal observation indicates that none of these owning companies has much difficulty imposing its operating philosophy on its distant plant.

Figure 2. Hours Per Engine for All Types, Separated by Geographic Region

The number of cylinders is likely to affect the labor productivity of a plant: the more cylinders, the more operations that need to be performed and the more parts that need to be assembled and thus the more labor will be required. Our labor productivity data confirm this hypothesis to a certain extent. On average, as shown in Figure 3, engine plants producing 4 cylinder engines require 1/3 less labor per unit than plants producing larger engines. Significantly, there are plants that can produce large engines with far less labor than some plants can produce small engines.

Figure 3. Hours Per Engine for All Geographic Regions Based on Number of Cylinders

The most striking thing about Figures 2 and 3 is the wide range of labor productivity across plants in the same regions making engines of similar complexity.

C. Data On Required Investment

Total investment should include all investments in equipment and installation as well as upgrades to the line. However, since it requires accurate information on the amounts and times of investment, which are hard to obtain, we have relied on each plant's estimate of the value of their line if they had to purchase it again. Gathering this information accurately and in a comparable way has been particularly complicated for a variety of reasons: plants seem to have used different methods for calculating the value of their investment, some plants refurbished old equipment from another plant making investment figures look very small, currency fluctuations and time value of money have been difficult to adjust because of a lack of information about amounts and dates of investments, etc. Figure 4 shows the results for capital investment per unit of capacity for the departments performing the standard activities.

Given the uncertainty in our data, we have watched the popular press for new engine plant announcements, which often state the planned capacity, investment, and employment. Such information is also subject to uncertainty, of course. For six plants giving values for all three items, hours per engine ranged from 1.4 to 9.8 (average 5.04) and for 12 plants giving only investment and capacity, the investment per capacity per shift ranged from $180,000 to $825,000 (average $481,691), all similar to our results. While we cannot identify individual plants, we can say that company and regional patterns in the popular press items are similar to those in our data.

Figure 4. Investment Per Unit of Capacity for Individual Lines and Total.

D. Data On Uptime And Its Implications

Companies were asked to report their uptime and downtime in three categories: employee break time during which the line was stopped, unscheduled downtime (for tool breakage or machine repair), and scheduled downtime (tool change, fixture change, or scheduled maintenance). From these data, companies calculated and reported their net uptime. Since companies were also asked to report the number of cycles that resulted in good parts, we have a check on the uptime data. In general, the correspondence is good, but the lack of really good correspondence is cause for concern. In some cases there were errors which we corrected. In other cases it emerged that plant personnel were not in the habit of calculating uptime, much less sorting downtime into scheduled and unscheduled. This apparent inattention to such presumably vital data indicates that plant personnel either do not realize the connection between uptime and overall cost, or else management at headquarters do not realize it and therefore neither demand that such data be recorded nor set targets for uptime. When targets are set, they are in the vicinity of 80%. Eighty five percent net uptime is considered hard to beat in any industry, whether the line is manual or mechanized.

Figure 5 shows data for block machining lines, where we have made an effort to remove errors. The wide spread of net uptimes is significant. This divergence is not explained by any of the following factors: number of cylinders, choice of machining cycle time, amount of employee training (hrs/yr), years that total productive maintenance (TPM) has been in effect (usually less than 3 years), or the degree to which capacity is being utilized. Even more striking is the fact that uptime in crank and head machining correlates excellently with uptime in block machining. (Figure 6)

A possible explanation for the similarity of uptimes in these shops is that all shops in a plant operate at the rate needed to make the parts required. Since each engine needs one block, one crank and (for I's) one head, and since the plant presumably was built with balanced capacity in all machining lines, if a plant needs only 75% of the block line's capacity, then it should need only 75% of the crank and head lines' capacity. But we find statistically that there is no correlation between uptime and percent capacity utilization, indicating that plants with low uptime make up their production needs by operating for longer hours. This suggests in turn that the similarity of uptimes across lines in the same plant is the result of management's efforts (when uptime is high) or management's neglect (when uptime is low).

Figure 5. Distribution of Uptime and Downtime in Engine Block Machining lines.

Figure 6. Correlation between Uptimes in Block, Crank and Head Machining.

E. Data On Cost Performance

Cost performance was analyzed carefully for block machining lines after special efforts were made together with the plants to remove errors from this section of the dataset. The complete set of analyses may be found in [Peschard]. Some significant results are reported here.

Using equation (1), a cost to machine a block was calculated for each family. The results are shown in Figure 7. As can be seen, there is an enormous variation in terms of cost-performance that cannot be explained by size of engine, number of variants, scheduled utilization, or local currency valuations.

Figure 7. Distribution of cost per unit calculated for block machining lines.

1. Effect of External Factors

Capacity utilization (fraction of 24 hours/day. 7 days/week that is scheduled) may affect cost-performance in two ways. First, the obvious effect, as capacity utilization increases, the capital cost of the engine plant can be distributed over a higher number of units. This effect is more significant the larger the share of capital cost in total cost. Second, utilization may have an effect on the efficiency of the lines. As people at one of the plants we visited suggested, running an engine plant on three shifts limits the time available for maintenance, which may lead to more frequent stops for machine failures and thus a lower efficiency. On average, the level of utilization in our sample was 55%, with a minimum of 27% and a maximum of 85%. As a point of comparison, a plant which operates 2 eight-hour shifts, 5 days a week would have a utilization level of 48%.

The complexity of the engine affects the performance of the plant because a more complex engine requires more operations, more machines, thus more people and investment. A more complex engine may also require more complex operations which may be slower and may cause more machine or tool failures. Elements which could contribute to the complexity of the product in block machining include the number of cylinders, the number of holes, the complexity of the machining operations required, or the tolerances necessary. In this study, however, we have focused only on the number of cylinders to capture the effects of complexity of the blocks.

At one of the plants, for example, we were told that one of the main reasons for having lower than average productivity was that the engine was difficult to manufacture. After the engine had been introduced in that plant, the design of the engine was improved using the experiences of this plant and the redesigned engine was introduced at a different plant. The plant producing the re-designed engine requires many less operations and approximately half the amount of labor of the original plant.

Variety in the products has been pointed at as an important reason for differences in productivity by various study participants. The more variants, the more often a line will need to stop for tool and fixture changes and adjustments, and the more investment may be necessary to provide flexibility to handle different products. Different technology choices may respond differently to variety, but we expect in any case to see a visible cost disadvantage associated with increased variety.

Using ordinary-least-squares regression, we estimated the effect of these variables on the calculated cost per block. The model that we used in the regression was as follows:

$$\text{Model 1: } cost = A_0 + A_1\ utilization + A_2\ cylinders + A_3\ square\ root\ variants$$

where *cost* is the measure of cost-performance constructed for blocks as defined in equation 1;

utilization is the measure of capacity utilization as used in equation 1 for the construction of the measure of cost-performance;

cylinders is the number of cylinders, which in this case we use as a proxy for product complexity; and

square root variants is the square root of the number of variants of cylinder blocks which is used as a proxy for product variety. The square root form was used to allow for a diminishing effect of variants. After testing various functional forms of the number of variants, we found that the square root form had the best fit in most of our regressions, so we selected to use this form throughout the study.

A1, *A2,* and *A3* are the coefficients for utilization, cylinders, and variants respectively estimated by the regression on cost.

We selected an almost linear model in order to make the results more intuitive: what is the effect of each additional cylinder, of more variants. For example, each additional cylinder is associated with an increase of *A2* in cost.

The results from the regression are shown in Table 1. The three variables show the expected signs. A one percentage point increase in the level of utilization is associated with a reduction in cost per block of $0.448, significant at the 1% level. On average, each additional cylinder adds $5.37 to the cost of producing a block, significant at the 1% level. Increasing the square root of number of variants by 1 -- or increasing the number of variants from 1 to 4, or from 4 to 9 for example -- is associated with an increase in cost of $4.92 per block, significant at the 7% level.

Table 1: Effect of utilization, complexity, and variants on cost-performance

Dependent Variable: Independent Variable:	Change in cost per block per unit of change in the independent variable calculated from eq. 2.2
Intercept	22.8
	1.43 *
number of cylinders	$5.37
	2.68 ***
square root number of variants	$4.92
	1.54 *
utilization, %	-$0.448
	-2.80 ***
R Square	0.46

Note: The number in italics is the t-statistic corresponding to the coefficient. Asterisks are used to show the significance of each variable: * means that the probability of sign error is between 5% and 10%, ** between 1% and 5%, and *** below 1%.

The value of R^2 of 0.46 suggests that nearly half of the variance in cost can be attributed to these variables. (This fact is shown another way in Figure 7.) This would mean that half of the variation in cost-performance comes from factors which are not controlled by the plants: the level of utilization, the variety of products, and the level of complexity are generally determined by the demand that a company places on each plant, and by the design of the engine.

2. Effect of Internal Factors: Work in Process Inventory (WIP)

Work-in-process inventory (WIP) has been identified as one of the main elements of manufacturing performance. Part of the success of the “lean” production system has been attributed to the strict focus on reducing WIP.

WIP implies the existence of an unproductive capital investment. On average, the engine plants in our sample hold about $22 million in inventory, $7 million of which consist of WIP. The distribution of total value of inventory is shown in Figure 8. Assuming a cost of capital of 15% per year and a production volume of 300,000 per year, $7 million in inventory would increase the cost of an engine by $3.50.

Figure 8. Distribution of Value of Inventory in Engine Plants

As shown in Figure 9, a typical block line carries two shifts of WIP inventory.

Figure 9. Level of WIP inventory on block machining lines - histogram

In addition, WIP requires additional labor for handling and quality control. The data from our sample seems to confirm these hypotheses: more WIP is significantly associated with more support workers and with more investment.

We used ordinary least squares regressions to analyze the effect of WIP on performance by including the number of shifts of WIP in the block machining lines into our regression model. As shown in Table 2, one additional shift worth of WIP inventory in the block machining line is associated with 1.7 more total workers per shift. But WIP was not significantly associated with production workers, so we can presume that it is associated with 1.7 additional support workers, which may be in charge of the extra handling and control required. Also, one additional shift of WIP inventory is associated with an additional investment of $2.9 million, which may take the form of extra equipment necessary in order to deal with it.

As shown in Table 2, each additional shift of block WIP inventory is associated with a $1.93 higher cost per unit (significant beyond the 1% level). When compared to the results from Table 1, we see that including WIP in the model decreases the relevance of the number of variants both in magnitude of the coefficient (from 4.92 to 2.67) and in significance (the t-statistic goes from 1.54 to 0.92). This may suggest that WIP is associated with more variety, which is investigated below. However, given that the R^2 increases from 0.464 to 0.640 when WIP is included, we have concluded that the effect of WIP is not limited to the effect of variety: WIP significantly contributes to explaining the variation in cost-performance across plants.

In Table 2, we can also notice that WIP is not significantly associated with efficiency, which may suggest that two confronting effects balance each other. On one hand, more WIP may occur as a consequence of an unbalanced system with a lot of breakdowns in some part of the line, so WIP would tend to be associated with lower efficiency. On the other hand, WIP could be expected to be associated with higher efficiency since it may prevent certain disruptions of the entire line when one of the machines breaks down.

We then used ordinary least-squares regression to investigate the factors that may lead to high WIP. As shown in Table 3, the two factors most closely associated with WIP are utilization and variety. Each percentage point increase in the level of capacity utilization is associated with 0.07 shifts of additional WIP inventory. Also, increasing the square root of the number of variants by one unit (for example, going from 1 to 4 variants or from 4 to 9) is associated with adding 1.28 shifts of WIP inventory. Both coefficients are only slightly significant and have a probability of sign error close to 10%.

Table 2: Effect of WIP on performance of block lines

Dependent Variable: Independent Variable:	Cost	TW / shift	PW / shift	investment	efficiency
Intercept	22.16	-72.54	-25.07	-83.14	0.805
	1.38 *	*-2.69* ***	*-1.36**	*-2.07* **	*3.89* ***
cylinders	5.14	7.571	2.595	10.757	-0.014
	2.91 ***	*2.55* ***	*1.28*	*2.43* **	*-0.62*
sqrt variants	2.67	6.489	5.269	3.30	-0.012
	0.92	*1.33* *	*1.59**	*0.46*	*-0.33*
utilization	-0.604	0.358	0.306	-0.542	0.298
	-4.07 ***	*1.44* *	*1.81***	*-1.46* *	*1.56* *
cap. JPH	0.072	0.301	0.066	1.091	-0.0013
	1.05	*2.63* ***	*0.84*	*6.34* ***	*-1.54* *
WIP, number of shifts	**1.932**	**1.737**	**0.183**	**2.914**	**-0.004**
	2.99* **	***1.60* ***	***0.25***	***1.80* ****	***-0.54***
R Square	0.640	0.520	0.320	0.696	0.180

Note: The number in italics is the t-statistic corresponding to the coefficient. Asterisks are used to show the significance of each variable: * means that the probability of sign error is between 5% and 10%, ** between 1% and 5%, and *** below 1%.

Table 3: Effect of utilization, complexity, and variants on Work-in-Process inventory.

Dependent Variable: Independent Variable:	WIP inventory in block line
Intercept	-2.43
	-0.44
cylinders	0.239
	0.39
sqrt variants	1.277
	*1.33 **
utilization	0.070
	*1.44 **
cap. JPH	0.014
	-0.62
R Square	0.18

Note: The number in italics is the t-statistic corresponding to the coefficient. Asterisks are used to show the significance of each variable: * means that the probability of sign error is between 5% and 10%, ** between 1% and 5%, and *** below 1%.

F. Summary

Table 4 summarizes the results of all our statistical analyses. Figure 10 graphically displays the most important pairwise and multiple regression relationships found in our study.

Table 4: Summary of statistical analysis

Dependent Variable: Independent Variable	cost	PW per shift	TW per shift	investment	efficiency
External factors					
• number of cylinders	+++	++	+++	++	-
• number of variants	+	++	++	+	-
• level of utilization	---	0	++	++	+
• capacity	0	++	++	++	--
Internal Factors					
• WIP inventory	+++	0	++	++	0
Equipment Policies					
• plant involvement	0	++	++	0	0
• age of plant	+	0	0	0	--
• age of line	0	0	0	--	--
• cumulative production	0	0	0	0	0
• number of cutting machines	0	++	++	0	0
• number of years of TPM	0	0	0	0	0
Labor Policies					
• absenteeism	+	0	0	0	--
• age of workers	++	0	0	0	--
• worker turnover rate	0	0	0	0	0
• training	0	0	0	0	0
• incentive programs	0	0	0	0	0

Note: +++ / --- mean that the variables are positively / negatively correlated, with a probability of sign error below 1%; ++ / -- between 1% and 5%; and + / - between 5% and 10%.

Figure 10. Graphical Summary of Factors Affecting Engine Plant Performance. (Based mainly on data for block machining lines)

III. Resource Substitution

Given that our measure of cost-performance (equation 1) is actually constructed from efficiency, investment, and the number of workers, together with capacity and utilization as well as local wages, it is logical that variation in cost can be explained by variation in these variables. However, it remains to be understood how each of these variables affects cost-performance. In order to quantify such effects, we used our cost function from equation 1 to calculate the change in cost per unit (called the marginal cost) that would arise from a unit change in each of our factors: workers, investment and efficiency.

The marginal cost per unit of a worker is a function of wage, as well as the level of capacity and efficiency. Based on eq(1), the marginal cost per unit of adding one worker is (partial derivative):

$$MC^{unit}_{workers} = wage \,/\, (capacity \,.\, efficiency) \qquad (eq.\ 2)$$

Similarly, the marginal cost per unit of adding a million dollars of investment, and of losing one percentage point in efficiency are:

$$MC^{unit}_{investment} = (\$1\ M \,.\, capital\_cost) \,/\, (capacity \,.\, efficiency \,.\, utilization\ ) \qquad (eq.\ 3)$$

and

$$MC^{unit}_{eff} = -\,[(wage \,.\, \#\ workers) \,/\, (cap \,.\, eff^{2})\ ] - \ [(\ inv \,.\, capital\_cost) \,/\, (cap \,.\, util \,.\, eff^{2}\ )] \qquad (eq.\ 4)$$

As shown in Table 5, each additional worker per shift adds on average $0.31 to the unit production cost of a cylinder block (based on equations 2 to 4 and using the local labor cost corresponding to each plant converted to $US).

Table 5: Marginal cost of workers, efficiency and investment (based on equations 2 to 4 used on the data in our sample)

Marginal cost of:	average	lowest	highest
Workers	$0.31	$.03	$1.01
Efficiency	$0.44	$0.15	$1.05
Investment	$0.30	$0.17	$0.72

These results can also be read as:

If we could... while holding all else the same (on average)...	***we would save***
cut one worker per shift	*$0.31 per unit*

improve efficiency by one percentage point	*$0.44 per unit*
reduce investment required by $1 million	*$0.30 per unit*

The question that immediately follows these results is how to reduce the work force, or improve efficiency, or reduce the investment. One possible path is to substitute resources for one another.

By substituting resources, we may for example be able to reduce the number of workers by adding investment in machinery. Or we may improve efficiency by adding workers to make sure the line stays up. Would these substitutions make sense? In order to resolve these questions through a benefit/cost analysis, we would need to know both the marginal costs of the “resources” (investment, workers, efficiency) and the rate at which we may be able to substitute a resource for another: the marginal rate of substitution.

Given the complexities of an engine plant, it is not possible to construct a measure of the marginal rate of substitution. On the factory floor, certain substitutions are possible, such as the choice whether to automate certain operations, or the decision of how many people to put in charge of operating and maintaining the machines. Moreover, most substitutions can not be multiplied or divided: being able to substitute an automatic station for one worker does not necessarily mean we can replace 10 stations with 10 workers, or half for half. Understanding these limitations of any estimate of a marginal rate of substitution, we looked at our regression results for some insight into the tradeoffs among our resources.

1. Workers vs. Investment

We had formulated the hypothesis that it is possible to a certain extent to substitute workers for investment, so we expected to see a negative correlation between the number of workers and investment. This hypothesis was confirmed with the negative coefficient found for the investment in the regression for the number of workers [Peschard, Table 3.2, p 48]. One million dollars of additional investment is associated with between 0.16 and 0.24 less production workers (PW), and 0.13 less workers total (TW). The association with PW is also more significant than that with TW: the probabilities of sign error in the estimation of the coefficient are below 1% and above 10% for PW and TW respectively. This result makes sense to the extent that investment replaces operators (PW) so we can expect the relationship with PW to be more direct and thus yield more significant results.

Moreover, while additional investment in automation may reduce the need for operators, it may increase the need for indirect workers. In fact, automation such as robots for loading and unloading blocks into and out of the line, or to maintain buffer levels generally requires a lot of attention and maintenance, and thus more indirect workers. During various plant visits we were told stories of this type of automation being particularly unreliable, and at least in one case, the plant personnel simply stopped using a robot to load blocks into the line because they were not able to make it work appropriately.

2. Efficiency vs. Workers and Investment

We expected the number of workers to be positively correlated with efficiency, based on the hypothesis that if more people are available to work on the machines, the more likely they would be to keep the machines up and the less time it would take to fix machines or to change tools. The regression results in [Peschard, Table 3.3, p 50] seem to confirm this hypothesis. Both the number of production workers and total workers are positively correlated with efficiency: One additional production worker (PW) is associated with an increase in efficiency of 0.5 percentage point while one additional total worker (TW) is associated with a 0.28 percentage point increase in efficiency. Even though regressions do not imply a causality link but a mere association, this association, significant beyond 5% (probability of sign error is less than 5% for the calculated coefficients) may serve to illustrate that reducing the number of workers may have a negative effect on efficiency.

Investment is also positively correlated to efficiency. An additional million dollars in investment is associated with an improvement in efficiency of between 0.16 and 0.26 percentage points (significant at 5% level). This may suggest that incremental investments may help to improve efficiency. Perhaps, efficiency can be increased by investing in more flexibility such as to reduce the time to change tools or to change variants, or in better controls to make it easier to monitor the machines and diagnose problems.

The relationships we have found can be summarized in Tables 6 and 7.

Table 6. Summary of Substitution Effects

A change of... **(holding all else the same)**	**increases cost per unit by ...**	**and is associated with...**		
+ $1 M USD investment	$0.30	-0.14 production workers (PW)	- 0.13 total workers (TW)	+ 0.2 percent points higher efficiency
+1 Production worker	$0.31		+0.5 percent points higher efficiency	
+1 Total worker	$0.31		+0.28 percent points higher efficiency	
- 1 percentage point efficiency	$0.44			

Table 7. Summary of Differential Cost Impacts

A change of...	**increases cost per unit by...**	**and is associated with...**	**(holding the other characteristics the same)**	
+1 cylinder	$5.37	+$14 million investment	+9 workers	-5% efficiency
+1 sqrt variants	$4.92	+$15 million investment	+9 workers	-4% efficiency
-1% utilization	$0.45		-0.4 workers	-0.2% efficiency

IV. Conclusions

A. There is a lot of variation in performance across plants.

The one feature shared by all measures of performance investigated was the existence of substantial variation from plant to plant. The ratio of highest to lowest cost-performance is 6 to 1, the ratio of highest to lowest hours per engine was approximately 3 to 1, and that of highest to lowest capital productivity was estimated in the order of 4 to 1. Yet much variability remains after many overt differences between plants or their engines are removed from the data. Differences in product design, part count, and management practices are possible sources for this variability.

B. Plants have remarkably little control over cost-performance.

Three quarters of the cost of an engine consists of purchased parts and components. These items are the responsibility of some centralized department which negotiates with suppliers. Thus, the largest share of cost does not depend on the management of an engine plant. Other important factors, such as operating schedules and number of engine and part varieties, negatively impact performance and are not under the plant's control.

C. Increased variety definitely increases cost

Statistically verifiable evidence suggests that increased variety increases costs in several ways: increasing scheduled downtime, increasing WIP, and increasing the number of workers needed.

C. Work-in-Process Inventory is a good indicator of performance

As in other studies, our statistical analysis attributed to WIP inventory a significant explanatory value. It is not clear which way the causal relationship goes: does good performance allow plants to have low WIP, or is it low WIP that allows plants to improve performance? As discussed above, it is probably a combination of both, and this association may suggest that plants that have focused more on lowering WIP have achieved better results.

Moreover, WIP inventory appeared to be a principal mechanism through which variety hurts performance: more variety is associated with more WIP, which in turn is correlated with poorer performance.

D. Labor policies and TPM

While we expected that certain policies such as Total Productive Maintenance or Quality teams would have strong effects on performance of plants, our hypothesis was not supported by our data. However, it seems noticeable that all plants are adopting similar practices and policies with the same objectives: it seems that unlike the substantial difference in approaches between “mass” and “lean” production systems revealed in [Roos, et al], all plants in our sample on a first look seem to be following similar approaches.

E. Substitution of resources

Even in block machining shops, where transfer lines are used by most plants, certain substitutions among resources seem possible. Equipment could be utilized more effectively by investing in more flexible machines that may make changeovers quicker and reduce the labor required. Also, additional workers can be devoted to the maintenance of a line in order to reduce the downtime and thus increase efficiency. This topic is treated in [Peschard].

Given that such substitutions are available, if plants are evaluated by some metric which focuses only on certain resources, they would have a somewhat metric-driven incentive to substitute certain resources for others, which may lead to a non-optimal results such as excess investment and lack of people. For this reason, single-factor measures may have adverse effects on a plant.

F. Cost of Variety

No one at any plant we visited could tell us how to calculate the cost of adding a variant to the currently produced family of engines, leaving plant personnel unable to explain the anecdotally believed negative impact to the rest of the company. In this paper, a statistical method was used to estimate cost of variety on block machining lines. The impact is substantial and verifiable statistically. This method could be extended to cover variety impacts elsewhere in the plant.

There is much more to be learned about engine plants, and engine plants can improve their operations. However, the opportunity to make major changes occurs only rarely. Too often, auto manufacturers do not take the time to consider their options carefully, but instead design their plants unsystematically and/or leave the responsibility for plant and line design to vendors. This and other topics are the subject of another paper.

V. Acknowledgements

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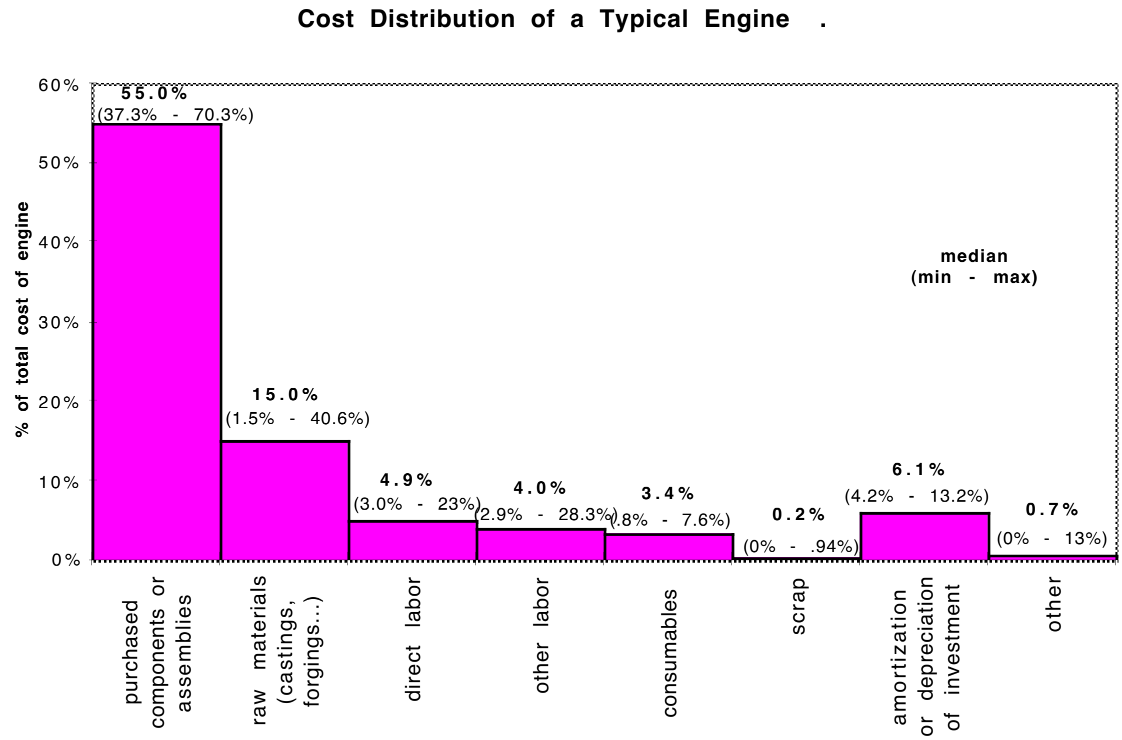


Figure 1. Cost Distribution of a Typical Engine

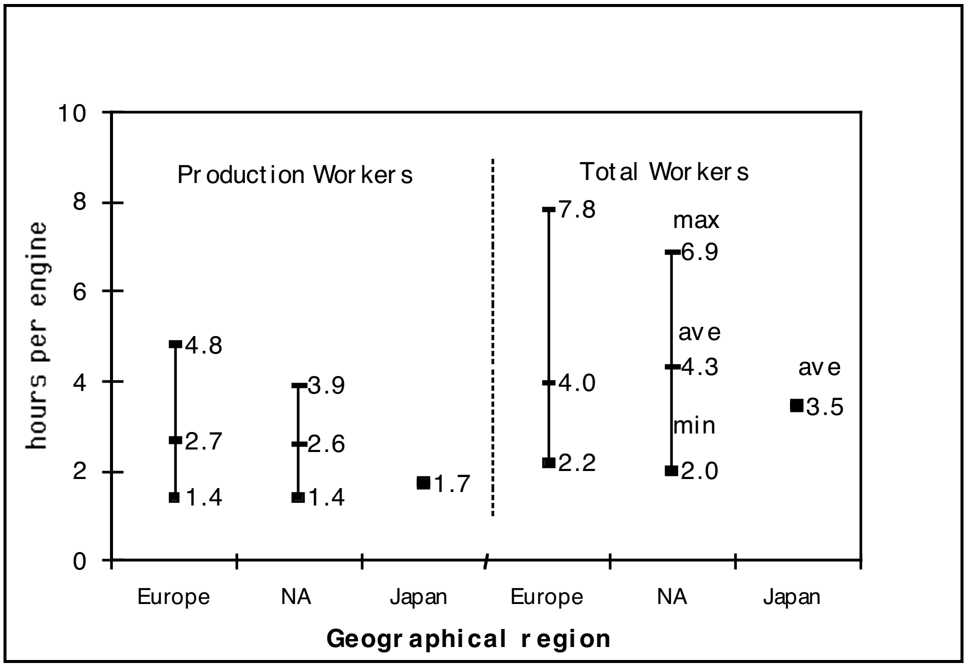


Figure 2. Hours Per Engine for All Types, Separated by Geographic Region

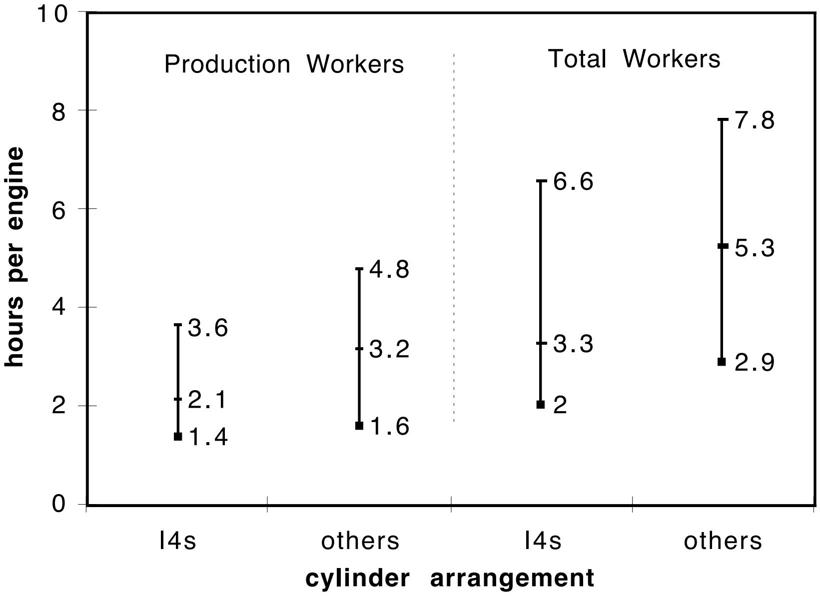


Figure 3. Hours Per Engine for All Geographic Regions Based on Number of Cylinders

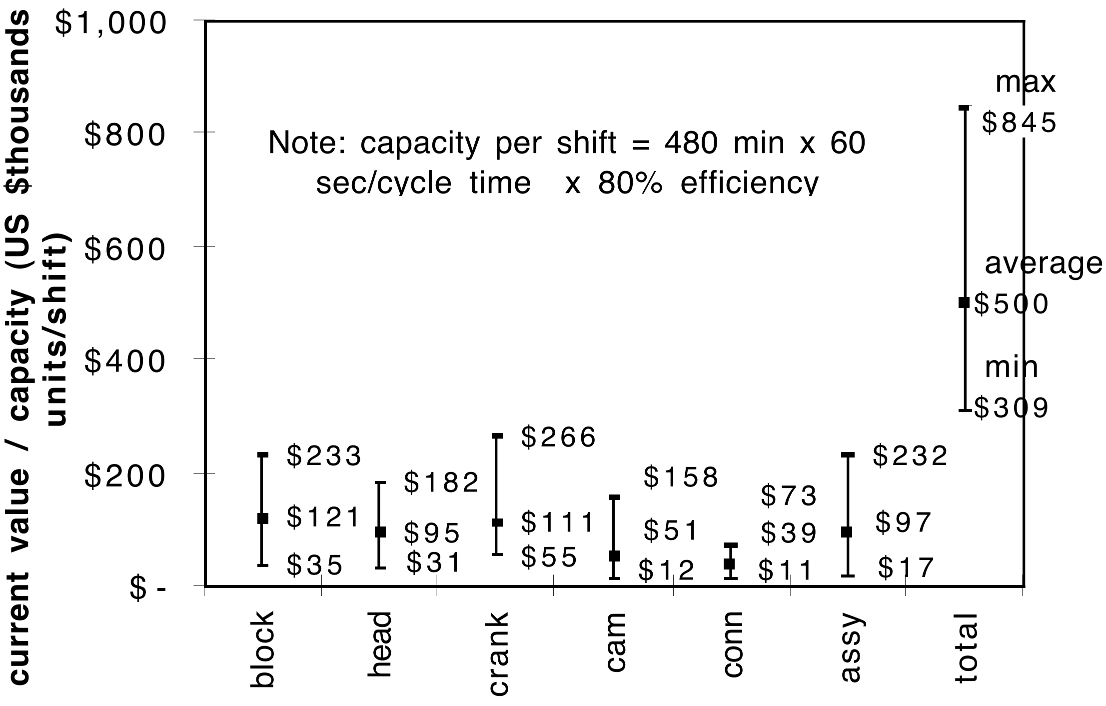


Figure 4. Investment Per Unit of Capacity for Individual Lines and Total.

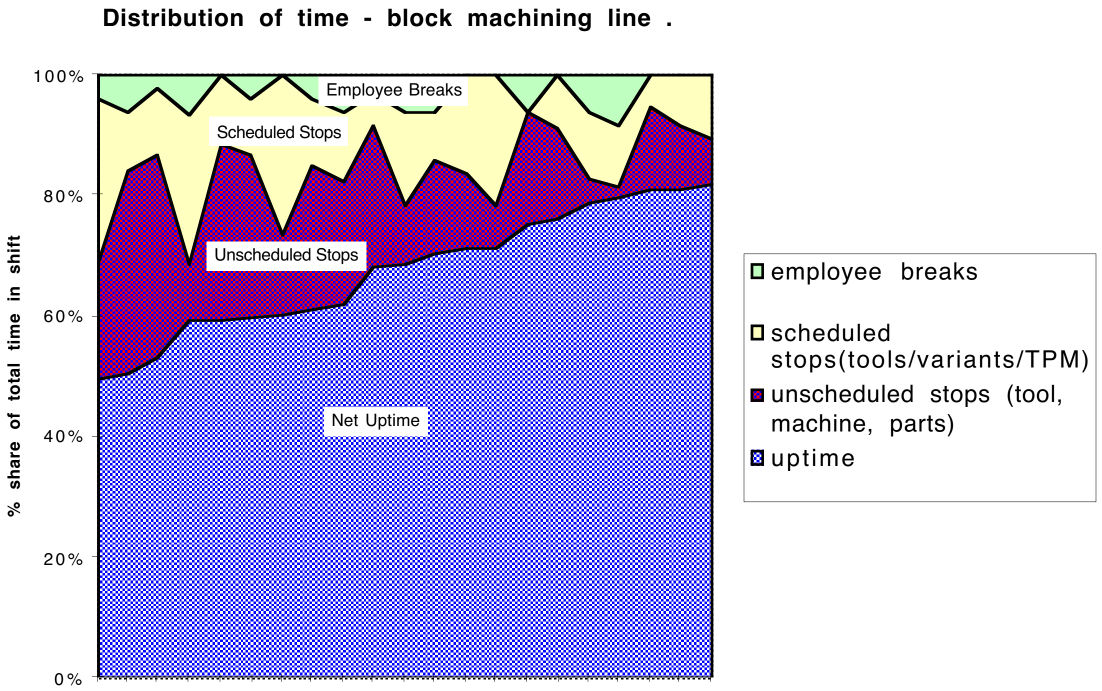


Figure 5. Distribution of Uptime and Downtime in 21 Engine Block Machining Lines.

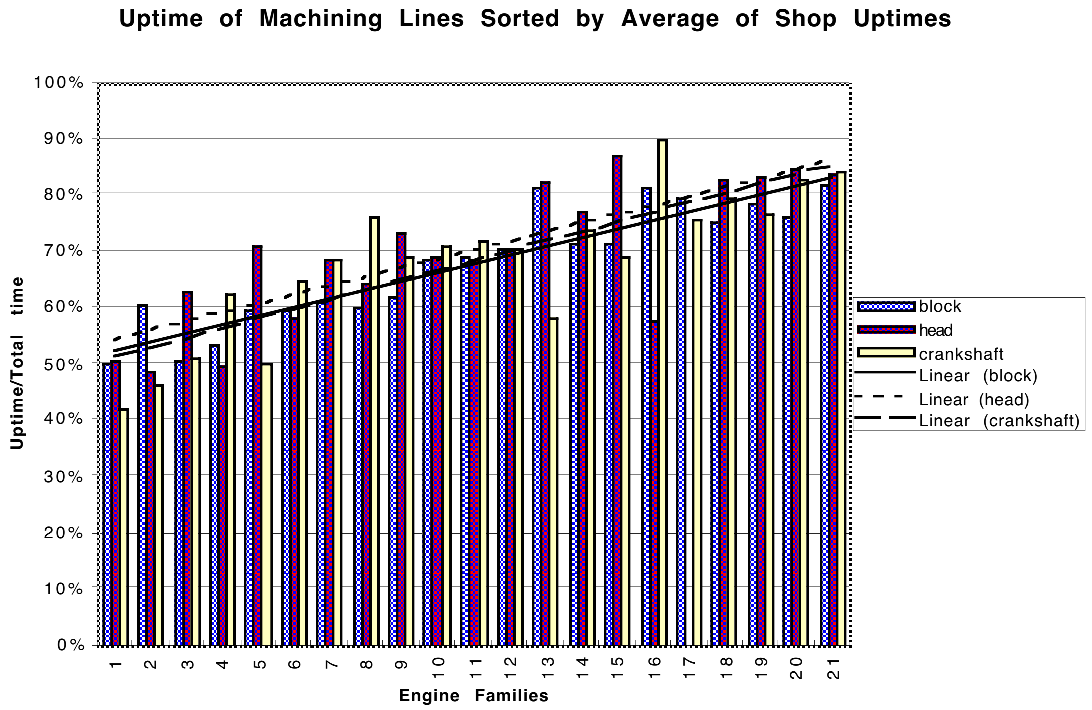


Figure 6. Correlation between Uptimes in Block, Crank and Head Machining.

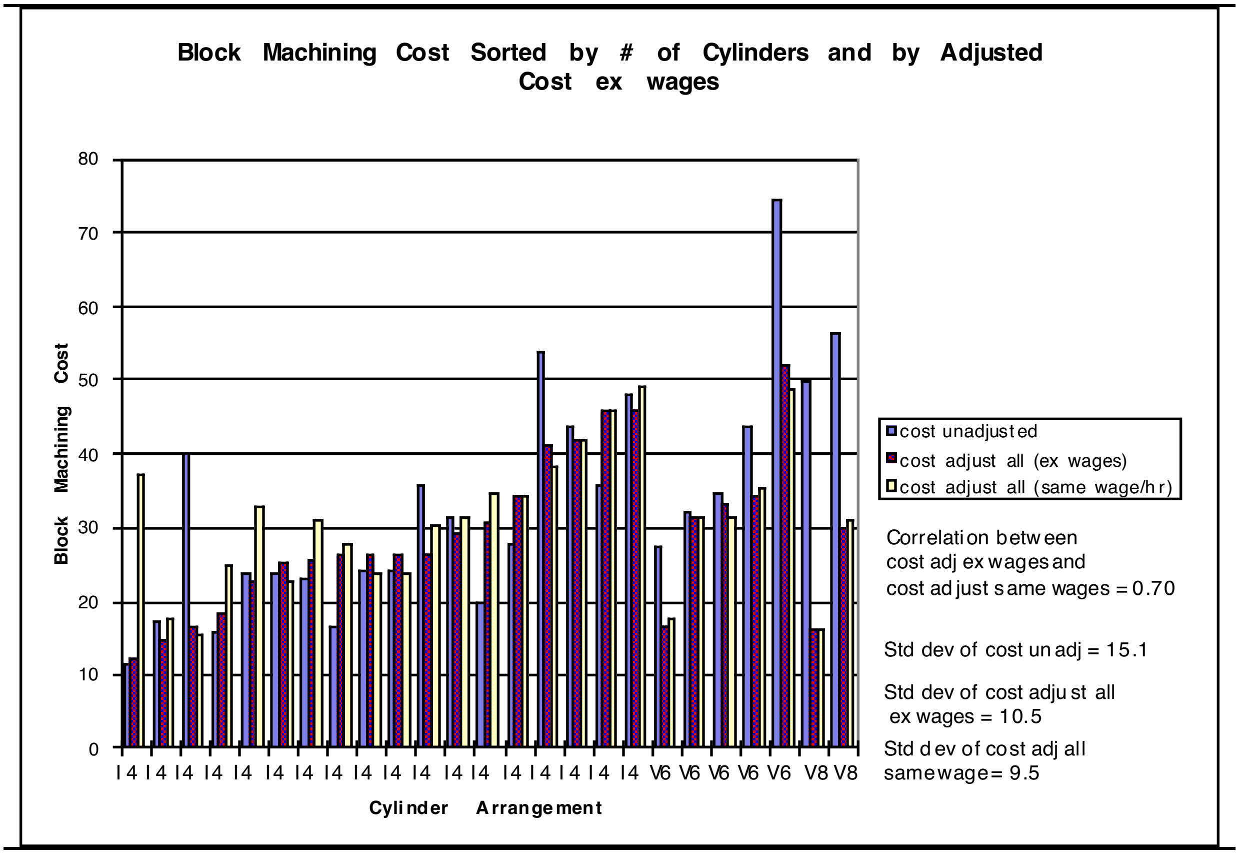
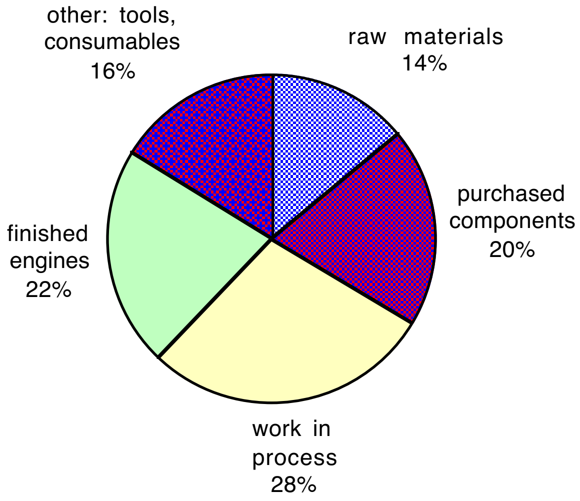


Figure 7. Distribution of cost per unit calculated for block machining lines. *Unadjusted cost* is calculated from eq(1). *Adjusted cost ex wages* is calculated by averaging number of cylinders, utilization, and variants, then adjusting the cost of each block using the coefficients in Model 1. *Adjusted cost same wage/hr* assumes each plant pays $25/hr.



Average total inventory = $22 million

Figure 8. Distribution of Value of Inventory in Engine Plants

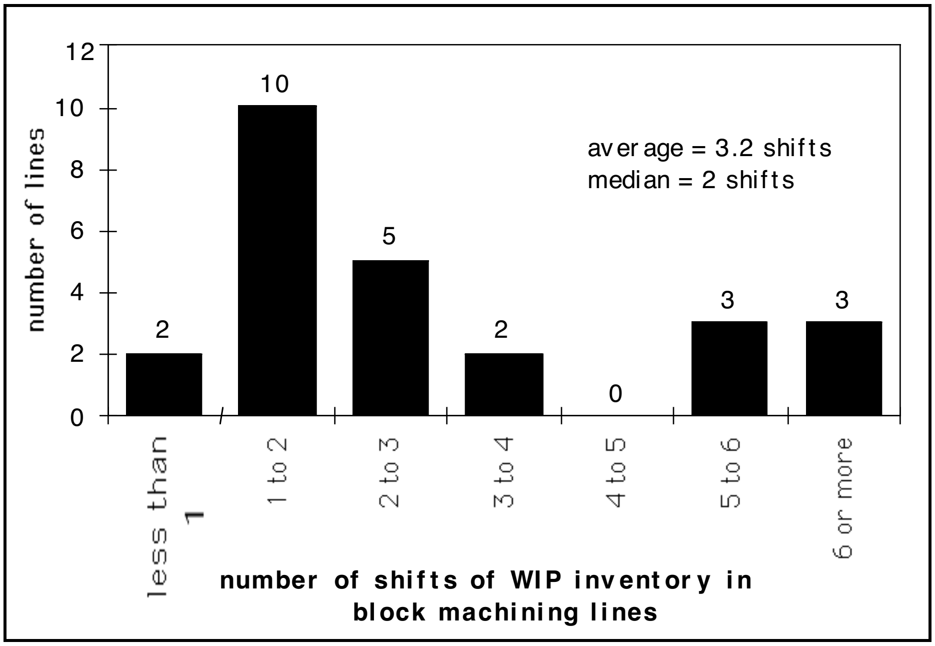


Figure 9. Level of WIP inventory on block machining lines

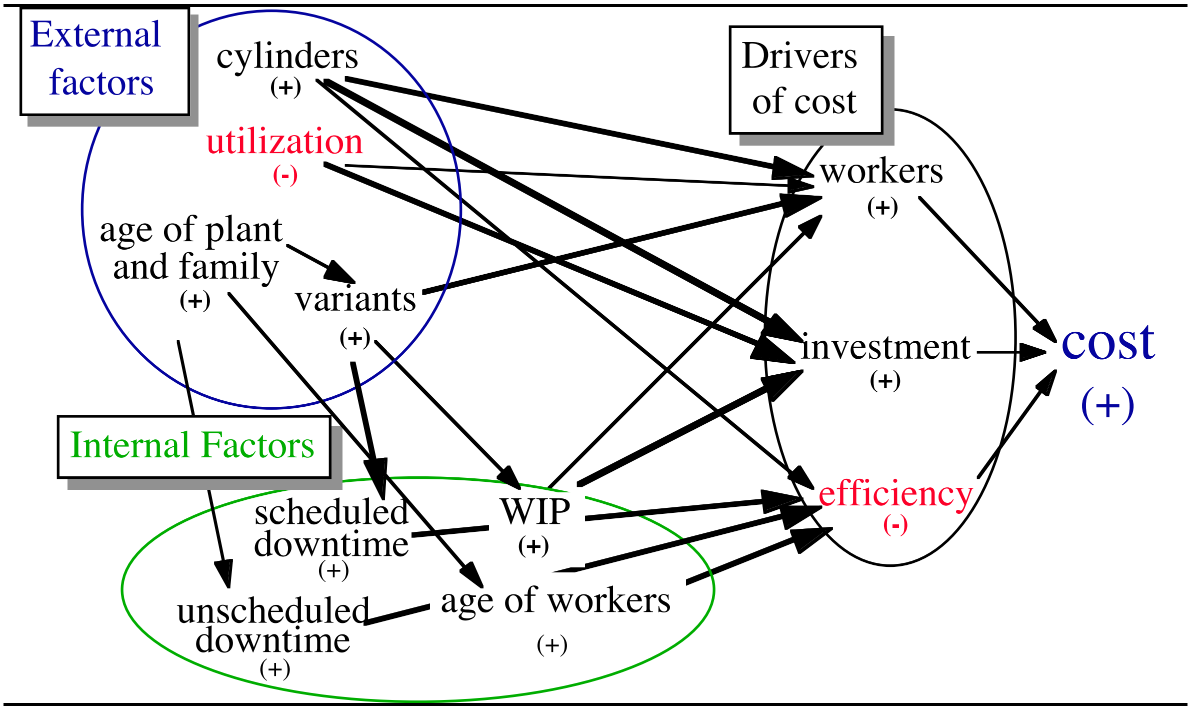


Figure 10. Graphical Summary of Factors Affecting Engine Plant Performance. (Based mostly on data for block machining lines) Thicker arrows indicate stronger statistical significance.