Manufacturing Performance in Automotive Engine Plants

Daniel Whitney and Guillermo Peschard

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International Motor Vehicle Program
Working Paper
April 1996

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Abstract

In 1994, the International Motor Vehicle Program launched the Engine Plant Study with the goal of analyzing the drivers of performance in engine manufacturing. We have collected data from 18 plants worldwide and have found that there is a very large variation in performance across plants. Half of the variation seems to be attributable to factors that do not fall under the direct control of the plant such as the characteristics of the engine, the level of product variety, or the level of capacity utilization. Moreover, we found some statistically significant relations among workers, investment, and efficiency, which reinforces the idea that automotive companies should not put so much emphasis on labor productivity, and that these tradeoffs should be taken into account when making decisions about plant design.

> *"When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you can not measure it ... your knowledge is of a meager and unsatisfactory kind"* - Lord Kelvin

Background

The International Motor Vehicle Program (IMVP) Engine Plant Study was launched in the Summer of 1994 with the goal of advancing the understanding of the drivers of performance in automotive engine manufacturing. Based on a series of discussions with people from the auto companies and with other researchers in the group, we decided to follow a methodology similar to that used on the IMVP assembly plant study, and we created a questionnaire. We defined a set of standard activities in order to be able to compare results across plants, and we made extensive use of an internal questionnaire prepared by GM Europe to guide our search.

Until now, 10 companies have participated in the study. 18 engine plants have responded to our questionnaire, and we have followed-up with visits to most of them. Preliminary data were presented at the Annual IMVP Sponsors Conference in Toronto, Canada, in June 1996, and further results will be presented at the 1996 Sponsors Conference in Brazil in June.

1. Objective

The objectives of the study have been the following: to create a base of knowledge of engine production, to develop a way to measure performance, to analyze how various factors lead to differences in performance, and finally, to develop guidelines or recommendations that may serve to improve performance.

First, we needed to create a base of knowledge of engine production. We have learned that while people understand well what constitutes good performance in certain areas of the value chain of the auto industry, other links in the chain seem more obscure. For example, there is a good base of knowledge about vehicle assembly operations, or product development; on the other hand, there is significantly less documented knowledge about engine production. For this reason, the starting point in this study was to create such a base, in order to learn who manufactures engines, where, and, most important, how.

Second, we needed to develop a way to measure performance so that we could evaluate and compare results across different plants. We first looked at some traditional single-factor productivity measures such as the labor hours per engine in order to obtain a first look into the performance of plants. Then, we turned to measures which would integrate the various factors of performance in order to better capture overall productivity, and based on the principles of Total Factor Productivity, we developed a measure of cost-performance for our plants.

Third, once we had developed a measure of performance, we had to analyze how various factors led to differences in performance across plants. We decided to trace various factors that affect performance in different ways:

- The **complexity of the product**, in terms the number of cylinders, the number of parts, and the manufacturability of the design of the engine;
- **Product variety**;
- **Capacity utilization**;
- **Efficiency** of the lines, in terms of the number of good parts that were produced divided by the number of parts that could be produced theoretically;
- **number of people**; and
- **total investment.**

In addition to analyzing the contribution of these factors to the differences in performance, we were interested in finding how these factors are related to each other. For example, how does the efficiency of the line relate to the number of workers? Is it possible to improve efficiency by adding workers? If so, is the gain in efficiency worth the increased labor cost? What is the trade-off between the number of workers and the investment required.

2. Data

In order to perform our analysis, we have gathered data in three ways: through questionnaires, plant visits, and through discussions and interviews with people from the industry.

Initially, a broad questionnaire was created in order to gather information about various aspects of engine plants: their operations, equipment, workers, policies, and products, as well as their results in terms of quality, productivity, etc. As we progressed in our analysis, we have narrowed the focus of the study and created a second version of the questionnaire which concentrates on a few key indicators. In addition, given the enormous complexity of the operations of an engine plant, we decided to concentrate on studying the block machining lines, in order to gain a deeper understanding under a narrower focus.

Until now, we have gathered information from 18 engine plants, nearly one fifth of all major engine production facilities worldwide. This sample includes 27 different engine families, and 25 separate block machining lines. 15 of the engine families consist of I4 engines, 5 of I5 or I6, 5 V6, and 2 V8. Moreover, half of the eighteen plants in the sample are located in Europe, seven are located in North America (Canada, Mexico, and the U.S.), and two in Japan.

Figure 2.1: Distribution of sample by cylinder arrangement

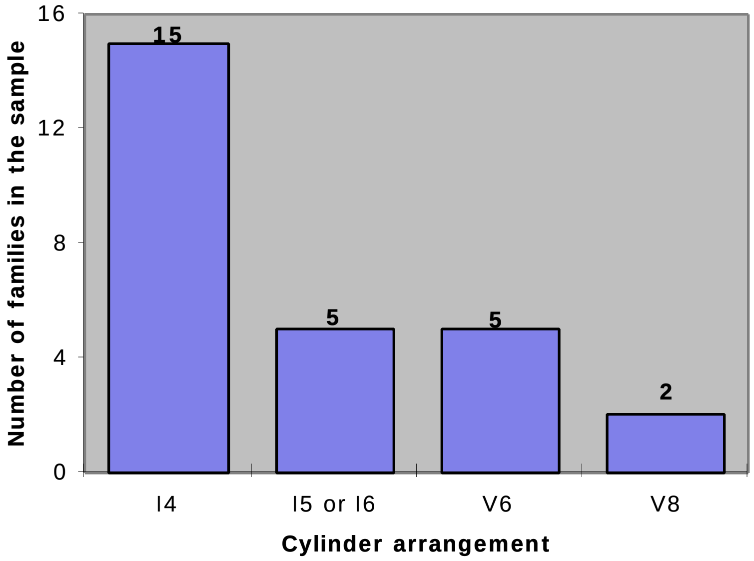
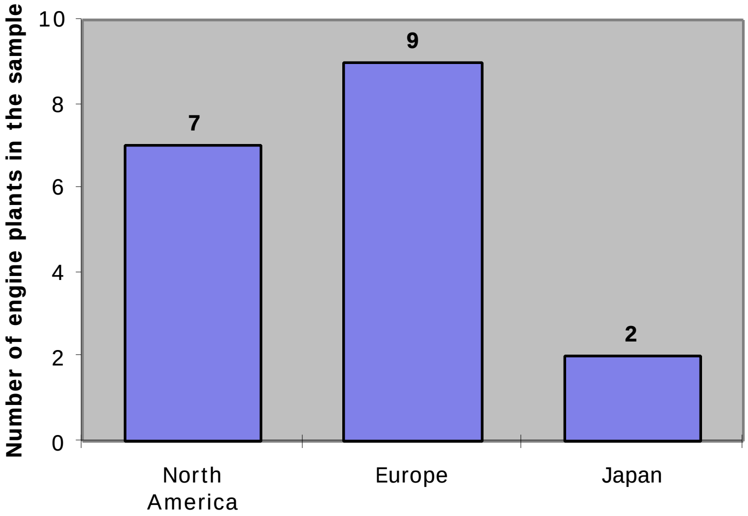


Figure 2.2: Distribution of sample by geographical location



We have complemented the data gathered through the questionnaires by conducting follow-up visits to 12 of the 18 plants that have filled out a questionnaire. These visits have provided us with a better understanding of the data from the plants and to gather additional information. In addition, we have visited several other plants that have not participated with a questionnaire yet.

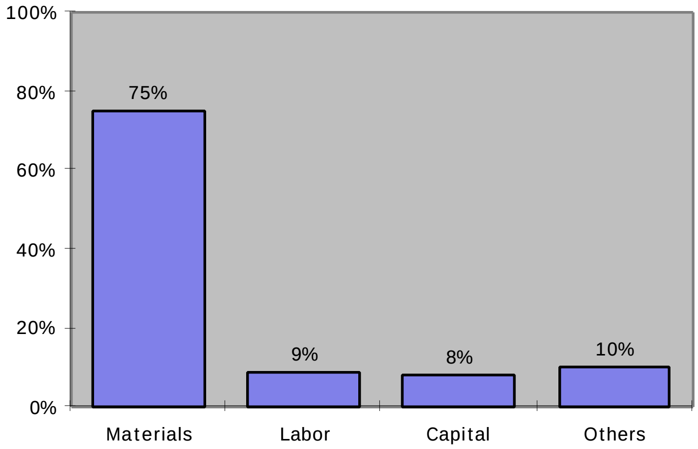
3. Measures of Performance

a. What is performance?

Traditionally, there are three general dimensions of performance in a manufacturing environment: cost, quality, and service (timeliness, reliability, flexibility...). For the purposes of this study, performance in terms of service has been considered less relevant than that in terms of cost and quality. In fact, the engine plant has relatively little variety in terms of the clients that it serves (typically between 1 and 3 vehicle assembly plants within the corporation), and in terms of the orders that it has to serve (there is relatively little fluctuation over time in terms of the quantity and the composition of the engines ordered), so we may consider that engine plants are generally able to supply the right combination of engines to the right customer at the right time. Performance in terms of quality is important, however, there seems to be more variation in terms of cost than in terms of quality, so our study has focused on measuring cost-performance, or "productivity": the ability of a plant to turn inputs into outputs in the most cost-effective manner. In addition, we have not been able to collect comparable information about quality, so quality issues have not yet been included in the study.

If we analyze the cost structure of an engine, we will discover that nearly 3/4 of the cost comes from purchased components and raw materials. As a result, purchasing and logistics activities are a critical component of cost-performance of engine plants. However, given that such activities are often not under the control of the engine plants, we have focused on labor and capital, which are the components of the cost which may be more directly linked to the operations of the engine plant, and which typically account for 9 and 8 percent of the cost of the engine, respectively.

Figure 3.1: Distribution of cost of an engine



b. Single-factor measures of productivity

In order to get a first look at the data from the engine plants, we calculated some basic single-factor productivity measures: labor productivity, efficiency of the lines, and capital investment required.

Labor productivity

We measured labor productivity as the number of worker hours per engine produced. We defined three types of workers: production workers, support workers, and administrative workers.

- Production workers operate machines, assemble parts on the engine, feed conveyors or machines, load and unload lines, and perform some basic preventive maintenance.
- Support workers include those who handle material, repair and maintain machines and equipment, supervise workers, sharpen tools, and control quality.
- Administrative workers include those in production planning, industrial engineering, logistics, etc.

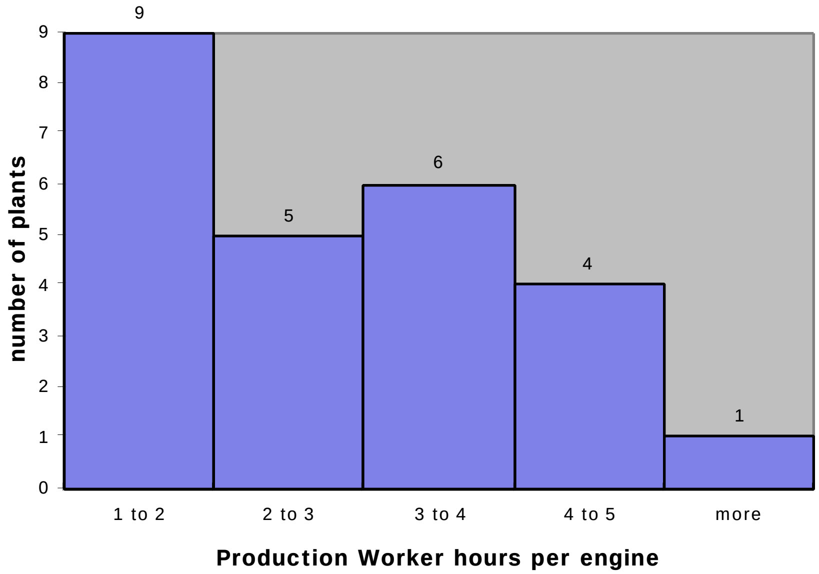
In order to ensure that the data from each plant represent the same series of activities, we have focused on the work-force dedicated to a set of standard activities, which include the machining of block, head, crankshaft, camshaft and connecting rods, as well as the assembly, dressing and testing of the engine.

The hours per engine results are summarized on Table 3.1. We made separate calculations for productivity of production workers (as defined above) and that for all workers (production, support, and administrative workers together). Also, we compared the hours per engine data that we were provided by the plants on the questionnaire with our calculations as a way to check for mistakes. Generally, the data reported matched the data calculated fairly well. Figure 3.1 displays the distribution of the results for labor productivity in our sample.

Table 3.1: Labor productivity results

	Production worker hours per engine	**Total worker** hours per engine
hours per engine **reported**	2.7 average 1.4 minimum	4.8 average 2.4 minimum
hours per engine **calculated** from standard activities	2.8 average 1.4 minimum	4.5 average 2.2 minimum

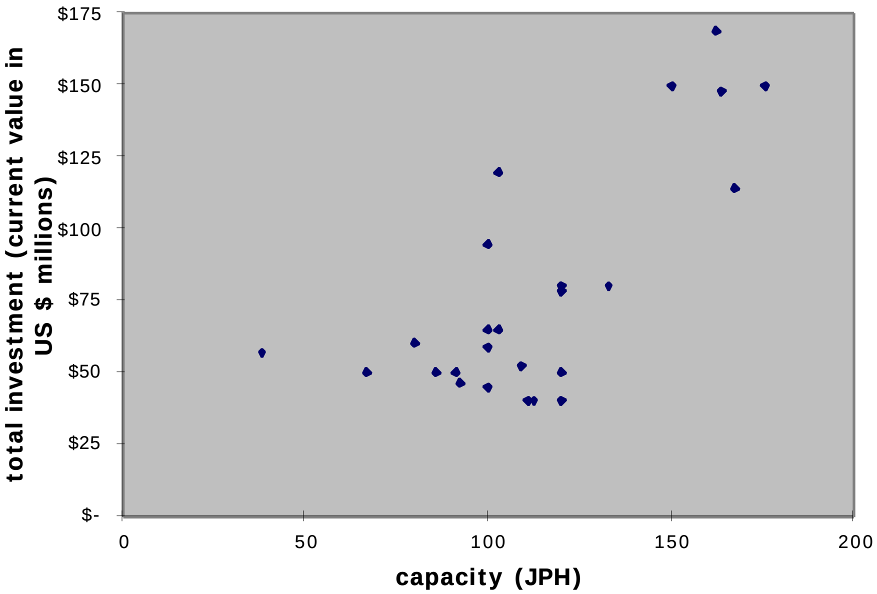
Figure 3.2: Hours per engine results - distribution



Capital productivity

We calculated capital productivity as the amount of total investment per unit of capacity (in jobs per hour, JPH). In order to obtain more comparable results, we focused on the block line: the total investment on the block line per unit of capacity (JPH). The results are shown on figure 3.3. Obtaining comparable and accurate information for total investment 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 3.3: Capital productivity of block machining lines



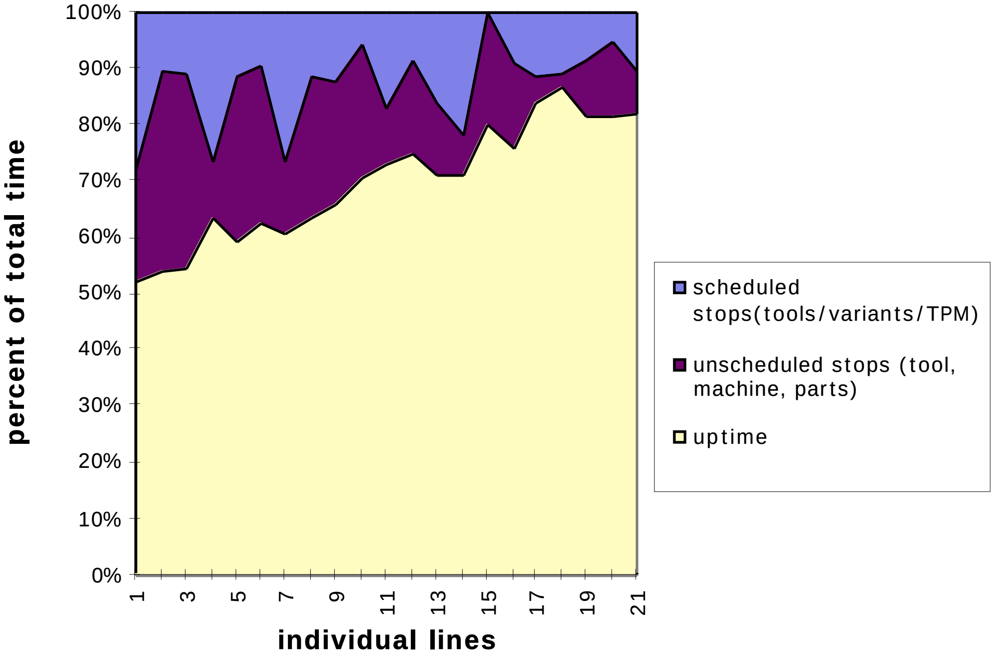
Efficiency of block lines

We calculated the efficiency of the lines as the ratio of the actual average production rate per unit of time (jobs per hour) over the theoretical capacity of the line. This measure should correspond to the "uptime" of a line: the percent of the total time (that the line was supposed to be operating) that was spent producing good pieces.

efficiency = average production rate (JPH) / capacity (JPH)

We have calculated the average production rate by dividing the number of parts produced during a period of time over the total number of hours that the lines were available for operation, including overtime. One of the main difficulties in calculating efficiency has been that it has been hard in certain cases to obtain reliable measures of the total number of hours worked. Figure 3.4 below summarizes our results for our efficiency calculations for the block machining lines in our sample in terms of the efficiency or uptime as well as the distribution in downtime between scheduled and non-scheduled stops. On average, block machining lines have a 65% efficiency, and the downtime is typically split about equally between scheduled and unscheduled stops.

Figure 3.4: Efficiency of block machining lines



c. Cost-function as a measure of 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...).

A typical measure of Total Factor Productivity, similar to that constructed, for example, by Chew, Bresnahan, and Clark (1990), could take the following form,

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

where X and Y would be two main types of products, like engines and transmissions, or meals and setups in the case of Chew et al. Each type of product would have various subtypes distinguished by the subscript j. Thus X_{ij}, would represent the number of units of product X, subtype j produced at plant i, for example the number of V8 engines produced in plant i. $value_X$ and $value_Y$ would be monetary values assigned to product X and Y in order to weigh the two types of output relative to each other.

C_{xj} would be a complexity factor assigned to each product subtype. V8 engines may thus be assigned a different complexity factor form V6 or I4 engines.

In our study, like in Chew et al, we only included labor and capital in our measure. Moreover, given that we have treated each plant as if it each produced only one type, or family, of engines (for plants that produce more than one family, we have separated each engine family as a separate plant), an alternative measure of TFP could take the form,

$$TFP_i = (value_X\, C_{Xj} \,.\, X_{ij}) / (\text{number of worker hours x wage + investment x cost of capital})$$

Since the effect of product complexity is one of the issues that we are trying to examine, we may exclude the complexity factor from our measure and analyze complexity afterwards. In addition, since we do not need to weigh engines against any other type of product (such as transmissions or axles), we may exclude $value_X$ from our measure, which results in a measure of the form:

$$TFP_i = X_{ij} / (\text{number of worker hours x wage + investment x cost of capital})$$

with units of engines per dollar.

In order to make such measure more intuitive, we have used its inverse, or cost per unit, which we adopted as our measure of cost-performance:

$$cost = (\text{\# of workers per shift x wage + capital invested x cost of capital}) / \text{\# of engines produced}$$

We rearranged the equation by making the unit of time one hour, so the formula we have used to calculate cost performance is the following,

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

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 wages;

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 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 per unit of time, units per hour (JPH) in this case, calculated as the inverse of the theoretical cycle time. For example, if the plant's theoretical cycle time is 30 seconds, then

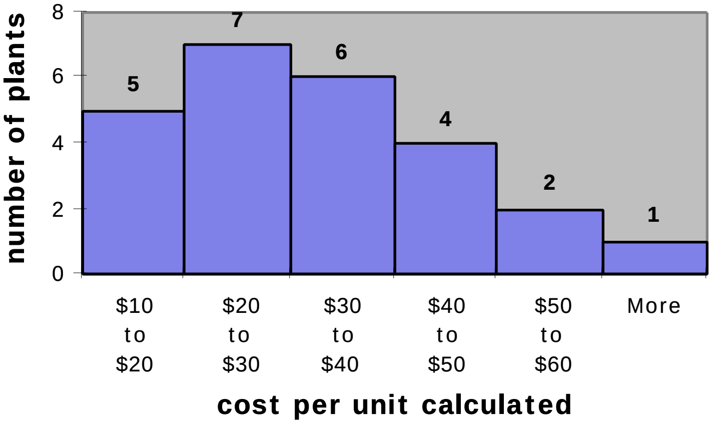
cap_i *= 30 seconds per unit x 3600 s / hour = 120 units per hour;*

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

eff_i *= actual production of good parts (JPH) / capacity (JPH)*

By applying this measure to our sample, we calculated the cost per unit for the block machining line. As can be seen on the chart, there is an enormous variation in terms of cost-performance. The ratio between the highest and lowest values is in the order of 6:1, with an average of $33.12 per unit and a standard deviation of $15 per unit.

Figure 3.5: Distribution of cost per block calculated



4. Tracing the drivers of performance

a. Where does the variation in cost-performance come from?

In tracing the sources of variation, we looked first at some of the factors which are not under the direct control of the plant: the level of capacity utilization, the complexity of the engine, and the level of variety.

Capacity utilization 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. We calculated capacity utilization as the percent of total time (24 hours a day, seven days a week) that is made available for production, including overtime. 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 may affect the performance of the plant to the extent that 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 have a higher probability of machine or tool failure. Elements which could contribute to the complexity of the product in block machining may include the number of cylinders, the number of holes, the complexity of the machining operations required, or the tolerances necessary. 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 the difficulties this plant had faced and the new 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. Until now, however, we have focused only on the number of cylinders in order to capture the effects of the most obvious indicator of complexity.

Variety in the products has been pointed at as an important reason for differences in productivity by various participants in our study. Product variety requires changeovers from one type of product to another. The more variants, the more often a line will need to stop for tool 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 unit. The results from the regression are shown in Table 4.1. The three variables show the expected signs. Utilization is negatively correlated to cost: A one percentage point increase in the level of utilization is associated with a reduction in cost per unit of $0.448. This suggests that if one of the plants has below average utilization levels of, for example 35%, cost per unit can be reduced by nearly $10 by raising utilization to the average of 55%. The number of cylinders has a positive effect on cost, significant to a 1% level. On average, each additional cylinder adds $5.37 to the cost of production of a block. Also, the number of variants shows a positive correlation with cost. 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 unit. 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. This finding is analyzed further in the next subsection.

The correlations with utilization rate and cylinders seems to be fairly strong, the probability of sign error is below 1%. The association with the number of variants is slightly weaker, but it is still significant: the probability of sign error is 7%.

Table 4.1: Effect of utilization, complexity, and variants on cost-performance
Dependent variable: cost per unit calculated from equation 1.

Independent Variables	Estimated Coefficient	t-statistic	Probability of sign error
Intercept	22.8	1.43	0.083
level of utilization	-0.448	-2.80	0.005
number of cylinders	5.37	2.68	0.007
square root of number of variants	4.92	1.54	0.069
$R^2 = 0.464$			

Another important result in this regression is the value of R^2 of 0.46, which suggests that nearly half of the variance in cost can be attributed to these variables. 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.

In order to obtain a deeper understanding of how these variables affect cost-performance, and what accounts for the other half of variation, we pursued our analysis by examining what drives the factors that determine cost-performance: number of workers, investment, and efficiency.

b. Explaining variation in number of workers, investment, and efficiency

We used ordinary-least-squares regressions to study the variation in number of workers, investment, efficiency. The results are shown in Tables 4.2 and 4.3.

Table 4.2: Explaining variation of the number of production workers (PW), and the total number of workers (TW)

Dependent Variable:	TW / shift	TW / shift	TW / shift	PW / shift	PW / shift	PW / shift
Independent Variable:						
Intercept	-124.22	-126.79	-76.770	-68.14	-25.517	-69.606
	*-2.90 ****	*-2.92****	*-2.75***	*-2.68****	*-1.43**	*-2.71****
cylinders	9.831	10.083	7.986	4.777	2.639	4.92
	*2.85****	*2.88****	*2.60****	*2.33***	*1.34**	*2.38***
sqrt variants	10.409	11.407	8.706	7.366	5.503	7.936
	*2.08***	*2.27***	*1.80***	*2.48***	*1.78**	*2.68****
utilization	0.332		0.480	0.190	0.319	
	1.25		*1.95***	*1.21*	*2.03***	
cap. JPH	0.453	0.542	0.276	0.273	0.063	0.324
	*2.29***	*2.89****	*2.34***	*2.33***	*0.84*	*-2.92****
investment	-0.103	-0.138		-0.145		-0.164
	-0.84	*-1.14*		*-1.99***		*-2.29***
efficiency	0.448	0.594		0.336		0.419
	*1.39**	*1.95***		*1.76***		*2.33***
R Square	0.51	0.47	0.46	0.48	0.32	0.43

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%.

Impact of the number of cylinders

From Table 4.2, we can see that the number of cylinders shows the signs that we expected: the more cylinders, the more operations you require, and thus the more people you need, the more capital needs to be invested, and to a lesser extent, the harder it will be keep efficiency high. The magnitude of these effects is less clear. Each additional cylinder is associated with somewhere between 2 and 5 more production workers, or between 8 and 10 more “total workers”. From Table 4.3, we learn that the effect of the number of cylinders on investment appears to be more certain:

each additional cylinder is associated with an increase in investment of between $11 and $16 million dollars, which would suggest, for example, that a block machining line that produces V6 engines is expected to be up to $30 million more expensive than a similar line which produces I4 engines. This result makes sense to the extent that I4 lines include on average 15 cutting machines, while V6 lines include 20.5: the extra equipment is necessary to perform the additional operations that a larger engine requires. Finally, the number of cylinders also appears to be associated with a lower efficiency. On average, we would expect a line to be close to 5 percentage points more inefficient for each additional cylinder, thus a line which produces V6 engines would be expected to be 10 percentage points more inefficient than one which produces I4 engines.

We tested various functional forms of cylinders, such as the square root and the exponential of the number of cylinders, in order to investigate the "shape" of the effect of cylinders: Is the effect of the number of cylinders diminishing, constant, or increasing? The exponential form yielded poorer fits than the plain number of cylinders in the regressions for workers, investment and efficiency; while the square root form showed only slightly better fits than the plain number of cylinders. We concluded that effect of cylinders may be slightly diminishing: the difference in expected performance between a V8 and a V6 is somewhat smaller than that between a V6 and an I4. However, given that fits were almost as good, in the name of simplicity we decided to stick to the plain number of cylinders for the rest of our regressions.

Table 4.3: Explaining the variation of investment and efficiency

Dependent Variable: Independent Variable:	Investment	Investment	Investment	efficiency	efficiency
Intercept	-105.00 *-1.98***	-208.97 *-2.48***	-224.04 *-3.18****	81.60 *4.03****	111.50 *4.52****
cylinders	11.233 *1.92***	15.571 *2.25***	16.142 *2.84****	-1.52 *-0.68*	-4.678 *-1.75***
sqrt variants	8.720 *0.94*	13.565 *1.36**	17.467 *1.90***	-1.79 *-0.51*	-4.777 *-1.29*
utilization	-0.275 *-0.58*	-0.347 *-0.67*	-0.163 *-0.34*	0.266 *1.49**	0.198 *1.06*
cap. JPH	1.152 *5.14*	1.373 *5.04****	1.368 *6.14***	-0.13 *-1.51**	-0.335 *-2.48***
investment					0.127 *1.55**
TW per shift		-0.366 *-0.84*			0.216 *1.39**
PW per shift			-1.242 *-1.99***		
efficiency		93.004 *1.55**	107.041 *1.94***		
R Square	0.578	0.631	0.686	0.167	0.317

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%.

Impact of the number of variants

The regression results showed that the number of variants is also correlated with more workers, more investment, and lower efficiency. Increasing the square root of the number of variants (for example, increasing the number of variants from 1 to 4 or from 4 to 9) is associated with adding between 5 and 8 production workers, or 8 and 10 workers total to the block line, increasing the investment required by $13 to $17 million, and reducing the efficiency of the line by just under 5 percentage points.

As for cylinders, we used the regressions to investigate the “shape” of the impact of variety: does the number of variants have a diminishing, constant or increasing effect on performance? We tried various functional forms of the number of variants in the regressions such as the plain number of variants, its square root, and its exponential. The results showed that we obtained a significantly better fit in all regressions with the square root than with the plain number of variants, and that the exponential form yielded a much poorer fit. We concluded that variety does have a visible effect on cost-performance, and moreover, this effect appears to be diminishing with the number of variants.

Impact of the level of utilization

The level of utilization did not appear to have a significant effect on either efficiency or investment. The number of workers is only significantly associated to the level utilization as long as we do not add investment or efficiency to the regression. When significant, an additional percent unit in the level of utilization is associated with an increase of .32 production workers or .48 total workers. This may suggest that an average plant which increases its level of utilization by 24 percentage points by adding one 8 hour shift, five days a week, may expect an increase in the workforce of near 8 production workers, and 11 workers total. Perhaps the additional people would have to take care of maintaining the machines and changing tools during the shift. Even though our regressions do not imply any causality link, this association may illustrate the concern of certain plants that working at a higher level of capacity utilization (like running three shifts per day) is more demanding on a plant’s resources.

In addition, utilization has a relatively weak positive correlation with efficiency. On a first interpretation, this may seem to contradict the hypothesis that was suggested by some plants that high utilization made it more difficult to keep efficiency high. Perhaps, this phenomenon can be caused by a more indirect relationship between utilization and efficiency: it may be that plants that run at high utilization face a strong demand and are more pressed to increase their throughput, thus these plants may be more ready to devote more resources (including more workers) to keep the lines up, which could result in a higher efficiency.

Impact of Capacity

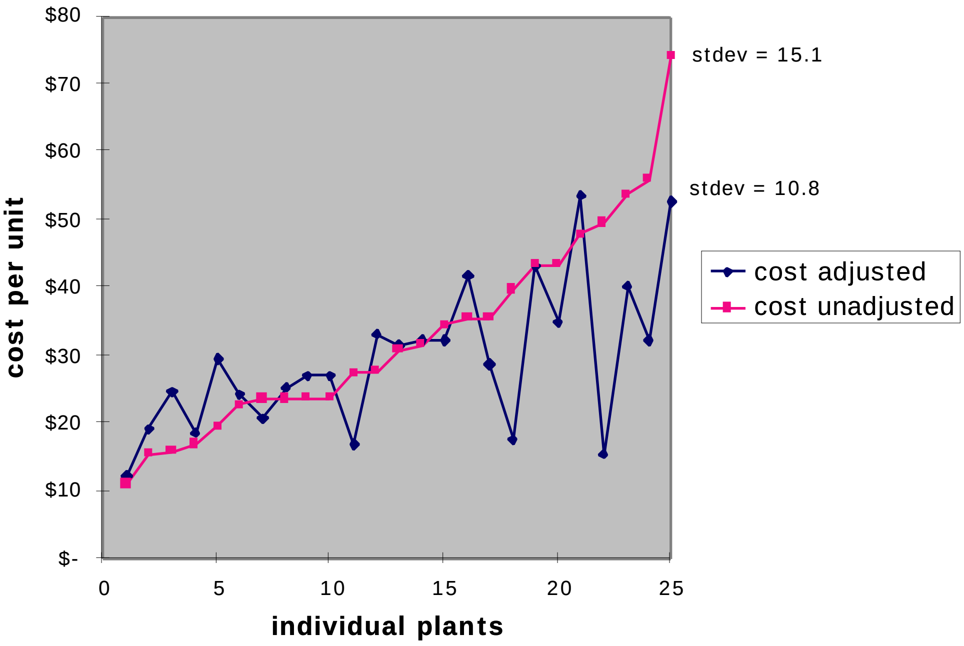
In most of our regressions, capacity came out as a significant explanatory variable. The signs of its coefficients make intuitive sense: higher capacity is associated with a higher number of workers, a larger investment, and a lower efficiency. Our regression results relate each additional unit per hour of capacity to .45 additional total workers, or .27 production workers. This may be explained in part because a higher capacity is also associated with more machines, which would require more workers. In addition, as the capacity increases, tool changes may become more frequent and thus require more labor. An additional unit per hour of capacity is also associated with an increase in the value of the line of $1.15 million, which again could be explained by the additional machines which may be required to handle the additional capacity, or perhaps more expensive equipment is necessary to run at faster speeds. Finally, the additional unit of capacity per shift is also related to a reduction in efficiency of 0.33 percentage points. This finding may illustrate an effect that has been explained to us at some of our visits: faster machines require tools that need to be replaced more often, and may have a higher probability of tool or machine failure, which may bring about a penalty in terms of efficiency.

c. Adjusting for cylinders, variants, and level of utilization

Having traced the effect of cylinders, variants, utilization, and capacity on efficiency, workers, and investment, we continued by adjusting the latter three factors for the first three variables. Using the coefficients from the regression results from Tables 4.2, we adjusted the total number of workers per shift (TW) for utilization, cylinders and variants, such as to calculate how many workers we would expect to see at each plant if it produced an engine with the average number of cylinders, the average number of variants, at an average rate of utilization. Similarly, we adjusted efficiency and investment for the number of cylinders and variants using the coefficients from our regression results shown on Table 4.3. Given that utilization was not a significant explanatory variable for either efficiency or investment, the latter were not adjusted for utilization.

Using these adjusted values for workers, efficiency and investment, we calculated an adjusted cost per unit using the same formula as before. As an additional adjustment, the rate of utilization was set at the average level for all plants for this calculation. The adjusted cost shows less variation than the unadjusted cost. In fact, the standard deviation of adjusted cost is $10.50 while that for unadjusted cost was $15. This difference in standard deviation implies that by adjusting cost per unit for utilization, cylinders and variants, we reduced total variance by 49%, which corresponds almost exactly to our previous finding in section (4.a) that 47% of variance in cost could be explained by these three variables. Moreover, these adjustments can be performed individually for each of the three variables in order to isolate their effects. Adjusting for utilization only, the variance in cost falls by 29%, while adjusting just for the number of cylinders would reduce variance by 12%. On the contrary, adjusting only for the number of variants increases variance by 36% instead of decreasing it.

Figure 4.1: Cost adjusted vs. unadjusted



d. Effect of efficiency, investment and workers on cost per unit

Given that our measure of cost-performance is actually constructed from efficiency, investment, and the number of workers, together with capacity and utilization as well as local wages (from cost formula in section 3), 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 that would arise from a unit change in each of our factors: workers, investment and efficiency.

Each additional worker per shift adds on average $0.31 to the unit cost of an engine. This marginal cost per unit of a worker is a function of wage, as well as the level of capacity and efficiency. Based on our cost function in section 3, the marginal cost per unit of adding one worker would take the form (partial derivative):

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

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

$MC^{unit}_{investment} = (\$1\ M \,.\, cost\ of\ capital) / (capacity \,.\, efficiency \,.\, utilization\ )$

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

Table 4.4: Marginal cost of workers, efficiency and investment

Marginal cost of:	Average	Min	Max
Workers	$0.31	$.03	$1.01
Efficiency	$0.44	$0.15	$1.05
Investment	$0.30	$0.17	$0.72

The summary of the values of these marginal costs are shown on Table 4.4. These results can also be read as:

If we could... while holding all else the same	***we would save (on average)...***
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.

Substitution of resources - Tradeoffs between workers, investment, efficiency

By substituting resources, we may for example be able to reduce the number of workers by adding investment for automation. Or we may improve efficiency by adding workers to make sure the line stays up. Would these substitutions make sense? Would the additional cost of extra investment be justified by the savings in labor? Would the benefit of improving efficiency exceed the cost of the extra workers? 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 for 10 workers, or half for half. Understanding these limitations of any estimation of a marginal rate of substitution, we looked at our regression results for some insight into the tradeoffs among our resources.

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 in Table 4.2. 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 substitutes operators, direct workers, 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, which is the type of automation where substitutions may be possible in a block machining line, 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. In sum, it seems understandable that investment is clearly associated with less operators while the association with total workers is much less clear: does the reduced number of operators offset the increased number of indirect workers?

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 Table 4.2 seem to confirm this hypothesis. Both the number of production workers and total workers are positively correlated with efficiency: One additional production worker is associated with an increase in efficiency of half a percentage point, while one additional worker total (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, these associations, 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 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 as follows:

A change of… **(holding all else the same)**	**increases cost per unit by …**	**and is associated with…**		
+ $1 M USD investment	$0.30	-.2 production workers (PW)	- .13 total workers (TW)	+ .2 percent points higher efficiency
+1 Production worker	$0.31		+.5 percent points higher efficiency	
+1 Total worker	$0.31		+.28 percent points higher efficiency	
- 1 percentage point lower efficiency	$0.44			

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 percent points lower efficiency
+1 sqrt variants	$4.92	+ $15 million investment	+ 9 workers	-4 percent points lower efficiency
-1 percent point utilization	$0.45		- 0.4 workers	- 0.2 percent points lower efficiency

5. Conclusions

- **There is a lot of variation in performance across plants.** A good share of this variation seems to be explained by factors beyond the control of the plants, but the remaining variation seems to suggest that there must be ways to improve performance through better management.

- **Engine plants have remarkably little control over their overall performance**. First, three quarters of the cost of an engine consists of purchased parts and materials, so the manufacturing practices of plants can only affect approximately one quarter of the cost. Second, half of the variation in performance seems to be attributable to factors that fall outside of the control of an engine plant: engine characteristics, product variety, and level of utilization.
- **Evaluating plants** based on measures of productivities that do not capture overall performance may lead to a deterioration in performance. For example, many companies still evaluate their plants based mainly on their labor productivity, which makes reducing the workforce one of the main objectives. Leaving aside social considerations for the consequences of such decisions, on purely financial terms these incentives may lead to non-optimal performance. In fact, when substitutions of resources are available, it may be possible to improve the productivity of one resource at the expense of lower productivity of other resources. In order to optimize the overall performance of a plant, it is thus necessary to take into account all of the resources. Performance should be assessed by tracking a measure that is designed to cover all the main components of performance.
- **The design of a plant** should take into account its effect on cost performance. Through discussions with people at engine plants, we have been told that the tradeoffs between workers, investment, and efficiency are not taken into account when making decisions about the design of the plant. Given that during the design phase of a plant it is more possible than ever to make substitutions among resources, conscious choices should be made based on the tradeoffs among resources in order to optimize performance.

We are still working on analyzing more relationships in our data. We are looking at other issues such as:

- the degree of involvement of the plant personnel in the process of design of a line and its consequence on performance
- the effect of programs such as Total Productive Maintenance on the efficiency of the lines
- the effect of various practices regarding the handling of inventory and relationships with suppliers
- the effect of various human resource management practices.