VOICES FROM ENGINE PLANTS

by

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Abstract

Statistical results from a survey of automobile engine plant performance are combined with quotes from interviews and anecdotal observations by the researchers to create a picture of the realities of designing engines and planning and operating engine plants. Topics covered include emerging organizational and managerial techniques, manufacturing tolerances, the effects of increasing product variety on production efficiency, modern casting methods, hot testing and its inability to predict problems in the field, plant design and its effect on operating personnel, and the emerging power of large vendors of sophisticated components and systems.

Background

In 1993 the International Motor Vehicle Program launched an extensive survey of automobile engine plant productivity. This study was conducted during the period June, 1994 to June 1997,[1] 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.[2] A summary and interpretation of the statistical results pertaining to cost and productivityappears in [Whitney et al] while details of the study's methods may be found in [Peschard].

The present paper differs from [Whitney et al] by attempting to capture more anecdotally how engine plants come into being and what it is like to operate them on a daily basis. Each section of the paper begins with quotes

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[1] 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

[2] The questionnaire is based on that of the IMVP Assembly Plant Study and borrows certain formats and questions from one developed by Opel. Contributions and advice from these sources are gratefully acknowledged.

from various people that the researchers interviewed in the course of the study. These quotes capture and motivate the topic of the section, which comprises both anecdotal observations and statistical support from the original survey.

Automobile Engines and Engine Plants

Engines and engine plants are both very complex and technically challenging. An engine plant can cost between $500 million and $1 billion and take two to four years to design and build. It may have 300 to 1000 employees and produce 200,000 to 700,000 engines per year depending on how many distinct engine lines are made in the plant and how many shifts it operates. An engine family comprises engines that have the same cylinder bore spacing, regardless of any other differences. As discussed below, a given manufacturing line (comprising machining, assembly, and test) makes only one family, although several families may be made in the same plant.

Figure 1 shows the parts of a typical 4 cylinder engine and notes that only a few of the most important machined parts (the “5 C’s” comprising cylinder block, cylinder head, crank shaft, cam shaft, and connecting rod) are made at typical engine plants. Almost all the others are produced at other plants and the vast majority are purchased from suppliers. Some implications of this are discussed later in the paper.

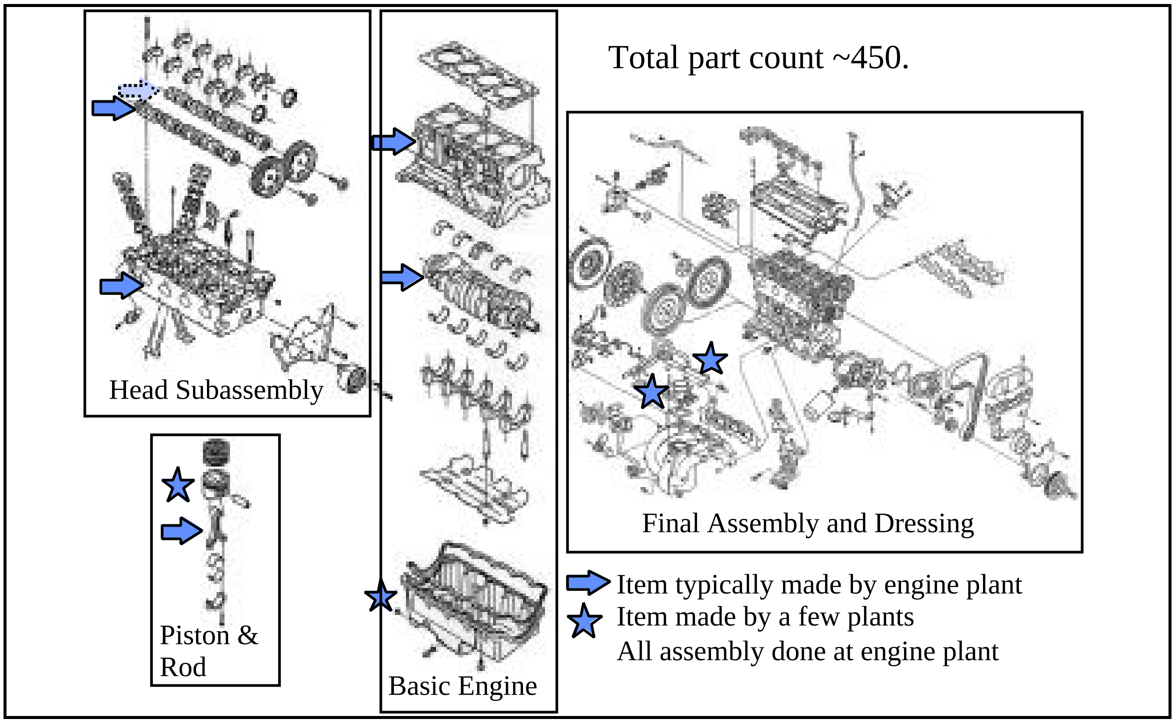

Figure 1. Main Parts of a Typical In-line 4 Cylinder Engine (Courtesy Ford Motor Co.) Note how few of the parts are made at the engine plant.

Relations Between the Plant and Central Headquarters

It appears in practice that engine plants are treated as captive suppliers that must live within the constraints of decisions made elsewhere and often without their participation. The most visible issues are design changes (large and small) and equipment acquisition policies. In fact, interviews revealed that companies have tried several approaches ranging from tight central administration to allowing plants considerable autonomy in such things as choosing suppliers and acquiring equipment. No convergence on such issues has emerged and apparently each approach has its pitfalls.

Some companies take a product focus and force disruptive changes onto the plants. Companies whose plants have more autonomy or companies that take a larger role in providing equipment from internal sources have a stronger process focus and may see the benefit of protecting the plants from the largest disruptions. But market pressure to change engines is strong, and the cost of completely rebuilding a plant is prohibitive, so the most likely scenario is that disruptions will continue regardless of whether the headquarters appreciates their effects or not.

At one company the plants had had autonomy for many years and central control had only recently been reasserted. One result was that there was no central history of equipment acquisition, capital expenditures by plants, or effectiveness of different policies, practices, or vendors. Headquarters remedies included establishing tri-monthly meetings of plant supervisors to exchange information.

Going into this study, we assumed that labor and equipment productivity were the main foci of management at the plants. Our report [Whitney et al] evaluates plants according to such criteria. Independent consultants such as Harbour and Associates publish hours/engine data as well as similar data for assembly plants, apparently creating pressure on plants to adhere to such metrics. Our data indicate that plants are measured rather differently. The overwhelming majority of plants in our survey report that the prime financial measure imposed on them is variance from budget; inventory level is the second, and none other (such as cost of capital, sales growth, etc.) comes close. The overwhelming majority of plants report that the prime non-financial measure is product quality followed by safety and delivery performance. Labor productivity is next, followed far behind by things like equipment productivity, manufacturing flexibility, schedule performance, and material yield.

Yet plant personnel themselves give the following items the highest importance for future plant improvements (in decreasing order of the number of plants that ranked this as “very important”): productive time of machines, flexibility of factory, more engines for less investment, indirect labor cost, direct labor cost, and material flow flexibility. Items ranked “not very important" included replacing direct workers with machines and making more engines in less space. It is interesting to note that

· plants strongly desiring to build more engines in less space already are statistically verifiably[3] *more* space-efficient than plants which rate this need as "somewhat" or "not very" important

· plants that strongly desire to increase the flexibility of the factory, the individual machines, and the material flow currently face statistically verifiably *less* variety than plants which rate this need as only "somewhat important"

Clearly the concerns of higher management who set financial and non-financial measures differ sharply from the concerns of those who must operate the plant every day.

Technology Trends and Their Effect on the Plants

A study by [Doi] of engine development and technology trends states that new engine designs and new engine technology adoption are highly correlated with a car firm's market share growth. Additionally, his interviews with engine product planners revealed two avenues to increased engine performance and two types of company strategy: one can relatively easily improve performance (measured as horsepower per liter of displacement) by adding items to the outside of the block. These items include highly integrated ones like entirely new heads or highly discrete ones like electronic fuel injection and turbochargers, which are provided by suppliers and simply bolt on the outside. Without incurring large in-house development efforts, the company can target specific market segments with focused engines. The impact on the engine plant of adopting such changes is primarily organizational, requiring management of a huge variety of parts and engine models, and leading to possible increases in overhead costs and assembly errors. Table 1 gives a sense of the variety.

Item	**Quantity**
Engine varieties	80
Exhaust manifolds	15
Blocks	11
Clutches and flywheels	10
Intake manifolds	25
Crankcase gas circulation pipes	5
Finished heads	10
Dipsticks	8
Water pump gaskets	7

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[3] Via Student's T test.

Table 1. Number of Different Kinds of Selected Items in 1995 for an I4 Engine First Made in 1972

The alternate strategy is to alter the configuration of the block itself, totally redesigning it or changing its displacement, with consequent changes to rod and crank design.[4] These changes permit the company to offer a nearly continuous range of engine performance, but their adoption causes huge in-house product development activity and major impacts on the machining departments. Once a new block is introduced, at the cost of $0.5 to $1.0 billion, there is enormous incentive to achieve additional improvements by altering the block in many seemingly small ways, again with major impacts on the machining departments.

In either case, engine plants must absorb a constant stream of changes with technical, organizational, or both kinds of impacts. This fact, almost more than any other, is statistically and anecdotally related to a wide range of production problems, losses in plant capacity and performance, and management preoccupations. This paper deals with many of these issues.

Methods Used in this Study

Our survey [Whitney et al] concluded that while engines of a specific type (say in-line 4 cylinder models with cast iron blocks) are similar, the performance, along a variety of testable measures, of plants that make similar engines differs very widely. Statistically verifiable causes include the age of the plant and its workers, the floor area of the plant in relation to its production capacity, and the number of unique engines in a given family, also called product variety.[5]

Yet these statistics do not completely capture life in an engine plant. In addition to obtaining statistical data, we visited 17 plants and held extensive semi-structured interviews lasting one to three days with design engineers and plant personnel. We also spent a day visiting a small but innovative manufacturer of engine plant machining equipment. Our hosts and study participants were quite open and frank with us, showing us what they were proud of and admitting where their problems were. We found definite regional differences and distinct company styles. In most companies, the principals felt they were doing things the right way and were constantly improving. It falls to us researchers to note the differences that nevertheless

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[4] Displacement equals number of cylinders times cylinder bore times stroke. The simplest way to increase displacement is to add cylinders, requiring a totally new block and machining line. It is simpler to increase the bore, but good horsepower and fuel economy require that bore be about 90% of stroke. At some point, larger bore requires larger stroke, requiring changes to block, crank, and rod.

[5] At some companies, “complexity” is the term used to refer to product variety.

exist and to wonder if all our hosts can be right when their methods and results differ so much.[6]

The sections of the paper that follow deal with the following topics:

- Different Methods for Operating a Plant
- Tolerances and Selective Assembly
- The Effect of Product Variety on Production Operations
- Near Net Shape Casting and Machining Efficiency
- Hot Testing and Engine Quality
- Plant Design and Equipment Acquisition Policies
- One Person's Story of Designing and Installing a New Machining Line
- Repair and Maintenance Policies and Downtime
- The Growing Power of System Suppliers

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[6] Some of these differences can be expected to narrow, due in part to the appearance of our statistical study but also due to the fact that many of the participating companies now voluntarily cross benchmark with each other.

Different Methods of Operating an Engine Plant

"We've had *teams/TQM/reduction of indirects/process unification/you name it* for 2 years." - Many people at many engine plants. (Process unification means that managers of all direct activities and indirect services needed in one area report to that area's manager rather than to specialty area supervisors.)

Almost without exception, the plants we visited and studied statistically have adopted various new organizational and operating practices very recently, in some cases only in the year prior to our visit. This puts them far behind assembly plants in this regard. Plant personnel think the new methods are helpful: Line workers with more responsibility for their machines and tools respond faster when there are breakdowns. Plants that organize horizontally along the flow of the manufacturing process solve problems faster than plants organized vertically, where each department reports separately to the plant manager. Line workers organized into teams and given more responsibility take increased “ownership” of their shop. Line workers who also must go get the parts they need from the previous stage of production do not complain about lack of parts.

Yet our statistical data detect almost no correlation between adoption of these practices and important performance measures such as hours per engine or uptime of machines. The only strong correlation we found was that employees who are given more training per year submit more suggestions. A medium correlation found was that block, head, and crank machining lines with fewer non-production workers had lower unscheduled downtime. A possible explanation is that when production workers are given a wider range of responsibilities, they take ownership, learn more skills, and contribute to repairing their machines or in some other way shorten the downtime.

The lack of correlation of these organizational policies with hard performance statistics reflects two factors: First, engine plants generally do not do a good job of recording downtime and further do not segregate scheduled downtime (such as preventive maintenance and employee breaks) from unscheduled downtime (machine failures and tool breakage) even though this distinction is one of the principles of Total Productive Maintenance. For example, only 7 of 15 plants responding said they regularly tracked downtime and only 5 display it where workers can see it. Plants that display downtime data where line workers can see them do not have statistically verifiably better downtime performance. Second, the statistically verifiable correlations to downtime (age of the engine family, flowtime of parts through the shop, number of different bores and strokes in the family - itself correlated with age of family) reported in [Whitney et al] are consequences of engine, plant, design, or marketing decisions taken elsewhere in the company. Whether or not these correlations are known to plant personnel, we found among many a feeling that their destiny was controlled elsewhere and that they were tied to a massive and largely viscous set of equipment and responsibilities. Significant exceptions to these conditions are discussed elsewhere in this paper.

Tolerances and Selective Assembly

"Tolerances are a never-ending discussion. We are just starting to try relating tolerances to performance needs. It is driven by the process people who need to save money. If they didn't press for this, the designers would just copy last year's tolerances." - Engine designer.

"They select parts the way resistors are made." - Engine plant production manager, speaking disparagingly of a competitor.

"We had to open the cylinder bore tolerances to create three select classes because the piston vendor could not hold his diameter closely enough." - Block machining area manager.

Designers know that closer running clearances improve engine performance, reducing noise and wear. Production people and equipment designers know that closer clearances and interchangeable parts require tighter tolerances on individual parts, and these in turn require more expensive machines, more frequent tool changes and inspections, and increased scrap or rework. Only one company told us that it was aware of systematic studies of what clearances and tolerances are really needed to obtain a given level of performance, and this work was being conducted by an independent engine design consultancy. Other firms tighten tolerances when they feel the necessity or loosen them on a trial and error basis until a problem occurs, after which the trend is reversed.

When a manufacturing process cannot economically deliver the required tolerance, selective assembly is used. This quite practical and effective method selects pairs of parts which by prior measurement are known to achieve the desired clearance.[7]

Companies generally disagree over what levels of tolerance and clearance are necessary, and have adopted selective assembly in no consistent pattern. Some have invested in equipment that can make the parts to the required tolerance. In the case of crankshaft bearings, this can be as small as 6μ, or 0.00015 inch. Another company conducted a Taguchi experiment and concluded that a simple design change, and not closer running clearances, accomplished a major reduction in noise.[8] Table 2 shows the pattern of adoption of selective assembly by the plants in our study.

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[7] If the desired clearance between parts A and B, x - y, is intended to be less than z, an interchangeable process creates A with nearly the correct x and B with nearly the correct y, which can be costly. A selective process looks for A's and B's whose respective x and y together satisfy $x - y < z$. The respective x's and y's can range relatively widely, lowering the cost.

[8] Ironically, the design change was actually a reversion to a previous design that was abandoned to save money before its ability to reduce noise was understood. The experiments verified the effectiveness of the original design.

	% of plants doing selective assembly	median number of classes	average size of each class
cylinder bore diameter	60%	3	10.7 microns
piston diameter	67%	3.5	10.6 microns
crankshaft main bearing diameter	47%	2	8.1 microns
crankshaft crank bearing diameter	20%	2	13.3 microns
block main bearing diameter	40%	2.5	7.4 microns
connecting rod crank bearing diameter	20%	3	8.0 microns
piston pin diameter	33%	3	5.9 microns
connecting rod weight	53%	19	4.0 grams
piston weight	7%	3	2.0 grams

Table 2. Patterns of Selective Assembly at 14 Surveyed Engine Plants. Two other plants did not use selective assembly at all. Selective assembly sorts the parts into classes according to some dimension, such as a diameter. All parts having dimensions that fall within a range equal to the class size are put in the same class. Thus, for example, cylinder bores might emerge from machining with diameters falling in a range of 30µ from smallest to largest. These might be sorted into three classes with a range of 10µ each. The fact that the median number of classes for the parts in this table is about three indicates that the desired tolerances for these parts are about three times tighter than the processes making them can deliver economically at the plants that practice selective assembly. Plants that do not practice selective assembly either control their processes to tighter tolerances, or have found other ways to achieve the desired performance, or do not strive for such tight tolerances.

The Effects of Product Variety on Production Operations

"They [a Japanese competitor] drive complexity out so the factory can focus on making production efficient." - Central Headquarters production operations chief.

"We spend a long time error-proofing our operations. When a new version arrives, we spend more time than money absorbing it. But the product design people have promised us that they won't exceed our current capabilities." - Plant assistant manager. "

"We suffer from creeping variety. Maybe we will slowly cook like the frog." - Central operations chief.

"I have tried for years to calculate the cost of adding a new variant but I'm about to give up." - Composite of quotes from several people.

"Every summer we modify the plant for the new varieties. Every September we suffer an increase in breakdowns." - Plant operating manager

"Our strategy was to optimize this plant for one variety of engine. Within a year, new versions began to arrive. Now (10 years later) we have a mess." - Central office staff member who designed the original plant.

"Our WIP and changeover problems are the fault of the unions." - Plant operations chief who later agreed that the problems were due to product variety and not the unions.

If anything concerns engine plant operating personnel, it is the variety of engines that they manufacture. Operating people in all types of manufacturing complain about this, but is it really true that variety has negative effects on performance? If so, what effects can we measure?

The quotes above point us in some interesting directions but in fact our studies show that while plant people complain, they have remarkably little accurate information about how or whether variety affects their operations. Sometimes, they miss the effect altogether and blame variety-induced problems on other causes entirely.

The history of most engine plants is one of increasing variety over time. This is borne out by the data in Figure 2, which shows some correlation between the age of engine families and the number of unique engines in the family.

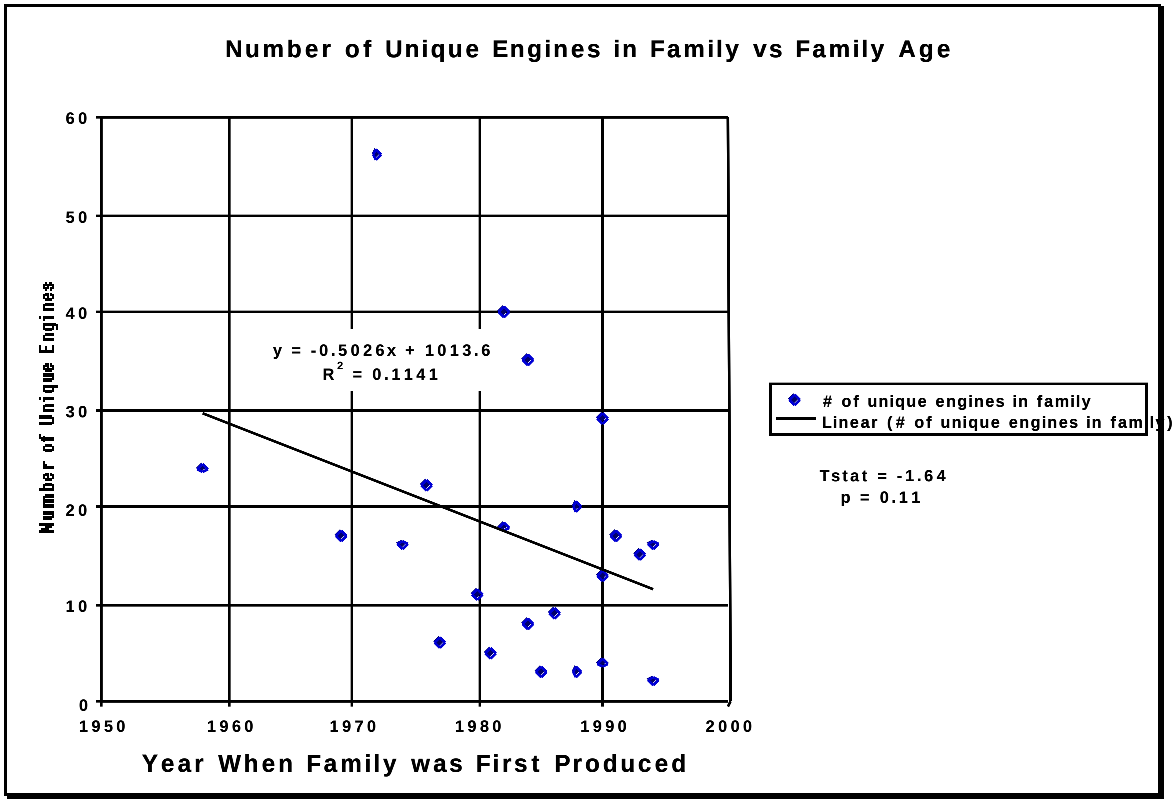

Figure 2. Number of Unique Engines in a Family vs Age of Family. This chart supports the feeling of “creeping variety” reported by plant personnel.

This effect makes sense, because engine plants represent a huge investment and a long time in construction and ramp-up. Engines themselves represent huge time and cost investments. Incrementally it is much faster and cheaper to introduce modifications and additions to the family (keeping cylinder spacing the same). These additions can add part choices during final assembly and dressing or they can add tool and fixture change time during machining.

There are strong indications that variety interrupts the flow of production and reduces the effective capacity of the plant. It does this by increasing the downtime. We asked the plants to report downtime in two broad categories: scheduled and unscheduled. We were able to get accurate data for block machining lines, with the following results. Figure 3 shows that if we measure block variety by the number of different bores and strokes, each of which can require different cutters and fixtures, we find a very strong correlation between variety and *scheduled* downtime, the kind we can reasonably associate with tool and fixture changeovers.

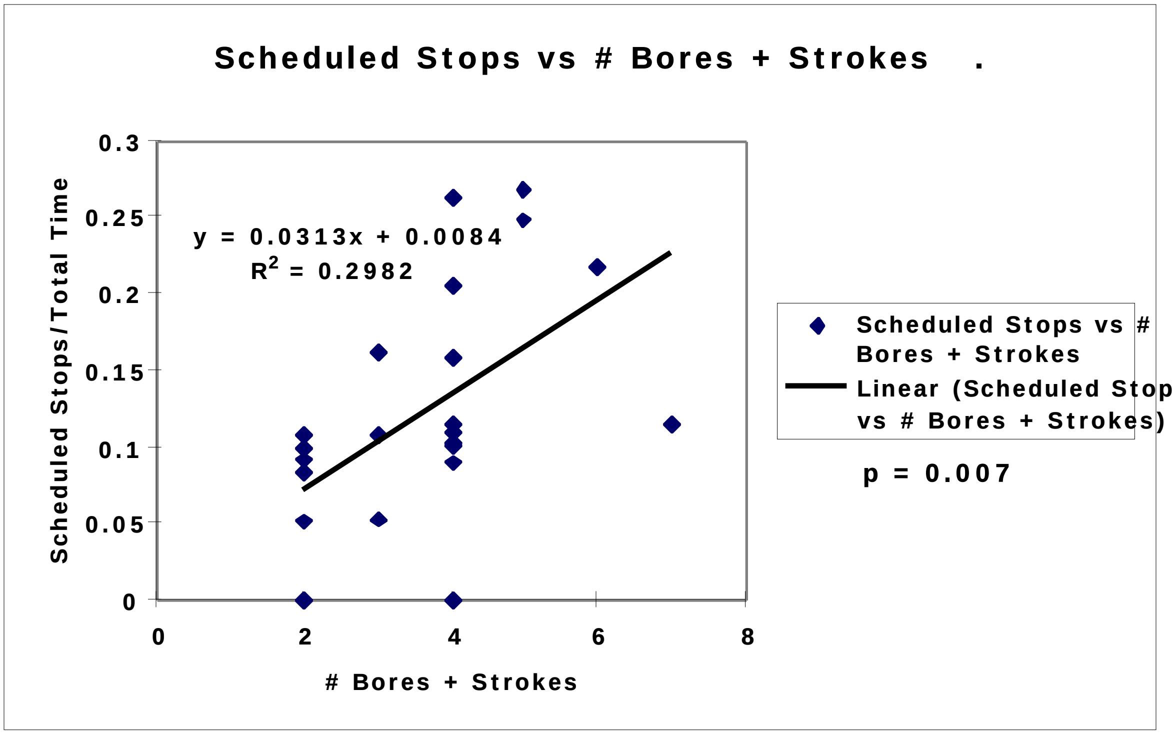

Figure 3. Scheduled Stops in block Machining vs Variety of Blocks Measured by the Total Number of Bores Plus Strokes

On the other hand, if we look at unscheduled downtime, typically caused by breakdowns, we can see from Figure 4 that this is fairly strongly correlated with the age of the family, although the latter is also associated naturally with the age of the plant itself.

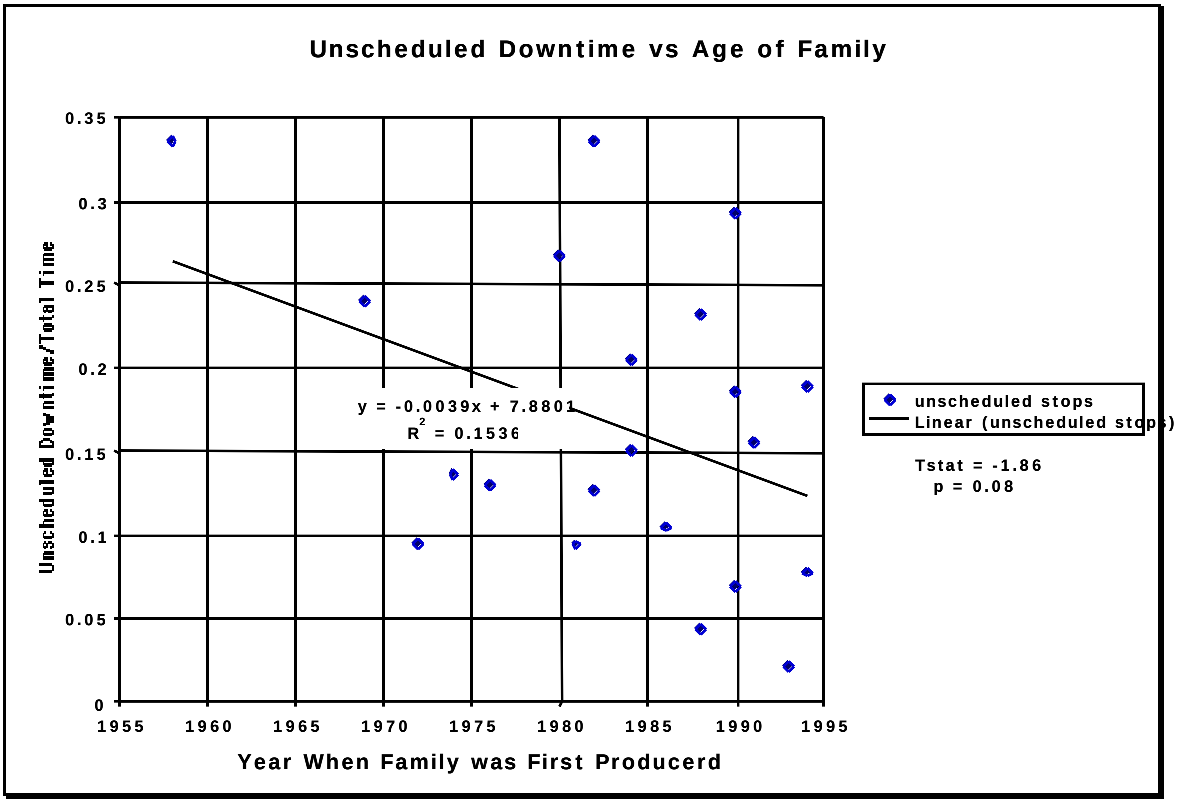

Figure 4. Unscheduled Downtime in Block Machining vs Age of Engine Family

Figures 3 and 4 indicate that some of the plant personnel quoted above are correct. In addition, in [Whitney et al] we calculated that each additional square root[9] of additional block types was associated with $4.92 increased cost,[10] $15 million in investment, 9 additional workers, and -4% efficiency (uptime). Thus the negative effects of variety are real and statistically verifiable.

Figure 5 indicates that design changes arise from many sources, of which the vast majority are outside the plant. Only a few of these can be classified as major upgrades or additions to the family. This is indicated by the fact that twice to three times as many plants report changes arriving monthly as arriving either weekly or annually. Fax is the overwhelming medium of communication, followed by computerized text. Only rarely are two dimensional or three dimensional CAD data transmitted.

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[9] Different functions of variety were tested, and the square root of the number of varieties consistently gave better correlations than linear or square. Square root is a function with decreasing second derivative, indicating that plants can absorb additional variety more easily than the first increment of variety.

[10] The average block is estimated to cost $33 to machine, counting amortization of machinery, but the range is quite large. I4s comprise about 2/3 of the blocks in this sample.

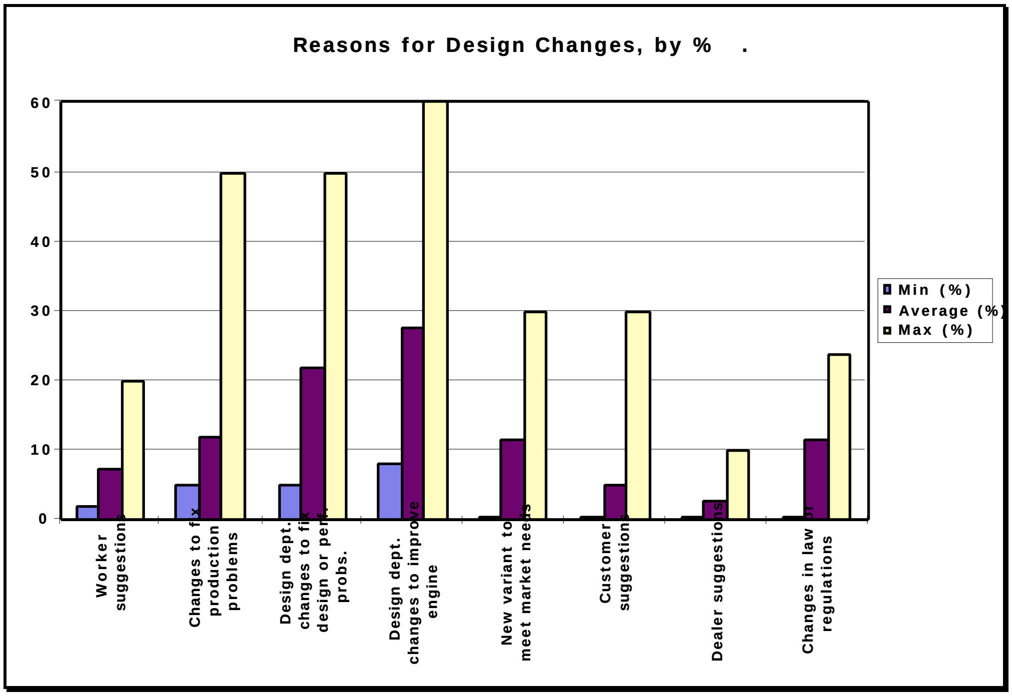

Figure 5. Reasons for Design Changes. The averages add to 100%.

Near Net Shape Casting and Machining Efficiency

> "Our chip removal system carries away 45 lbs of chips from each block." - Plant production supervisor, V-8 engines.

The raw iron casting for a V-8 weighs about 200 pounds, so 45 pounds is 22%. This is a lot of metal to cast on and then cut off. The person quoted was proud of his chip management system but his statement prompted us to ask in our questionnaire for the weight of blocks and heads before and after machining. Behind this question lie many issues. As time passes, casting methods get better: are any trends visible in the data? For the past several years, designers have sought to reduce the weight of engines having a given horsepower: have they succeeded?

Most plants make a family with a variety of different displacements, such as 1.6, 1.8 and 2.0 liter I4's. This is done by machining the same raw block casting to different cylinder bore diameters, and occasionally by using a taller block to accommodate a longer stroke. One result of this is that lower displacement engines weigh more than they need to because they carry the extra metal around the cylinder that is just bored away on higher displacement engines.

One way to eliminate this excess metal is to make lower displacement engines from blocks that have their cylinders closer together. No one does this, for the simple reason that many dimensions and features of the block would thereby change, not only bore spacing. Making all the cutting machines adjustable along these many dimensions would be very expensive, and no one presently does it. Making unique machining departments for each displacement engine would also be prohibitively expensive since there would be too few engines of each displacement to justify the expense.

It has been suggested that if the pressure to reduce the weight intensifies, one result could be that independent engine makers could emerge. These would collect business at each displacement value until an economical amount had been booked, and then build a special plant for that displacement. So far, even though many companies buy limited amounts of engines from each other, there are no independent car engine makers, although there are several independent truck engine makers. [See Sfazir, Artzner and Whitney for a detailed discussion of possible future trends in engine manufacture.] Most car firms still feel that engine design and manufacture is a core competence and are loath to give it up.

Figure 6 indicates that there has been a trend toward less percent material removed from both blocks and heads over the past 25 years, regardless of whether iron or aluminum are used. More interesting, there is some correlation between the percent removed from the head and the block of the same engine, even though most blocks are iron and most heads are aluminum, and casting methods are quite different for the two materials. Finally, we can detect a trend toward aluminum over the years, first for heads and more recently for blocks.

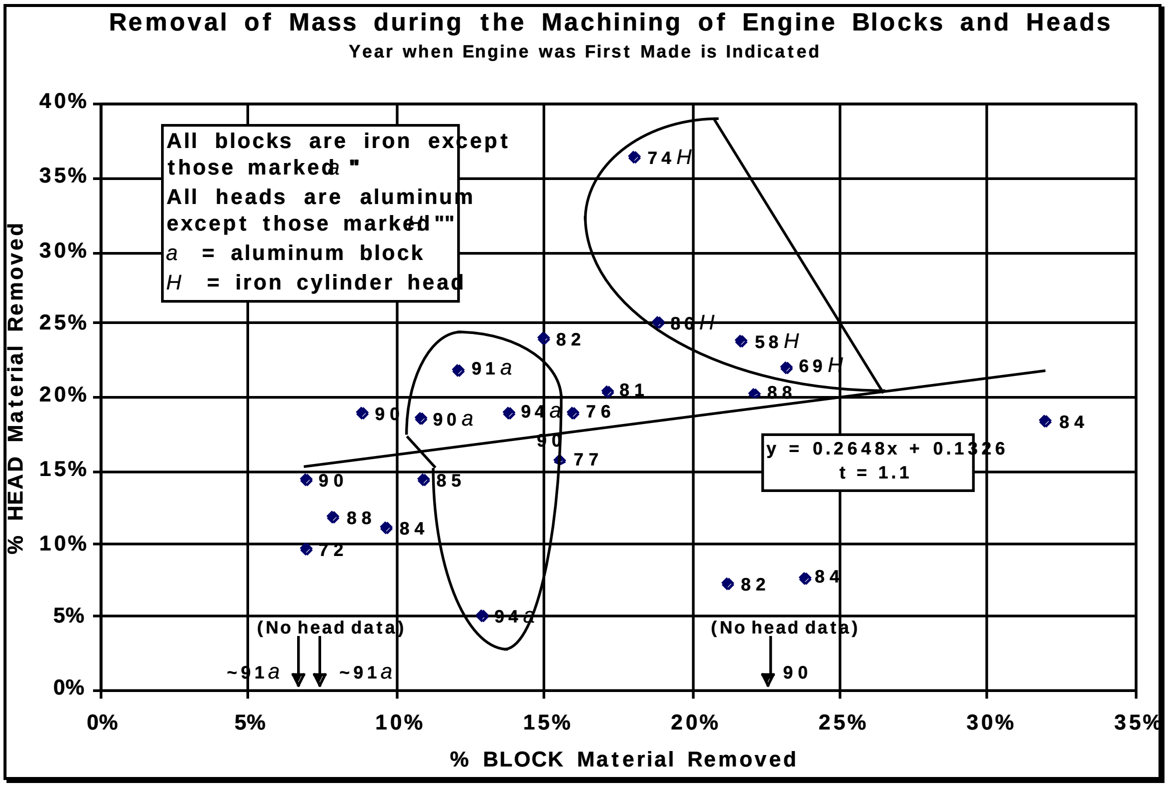

Figure 6. Relations Between Percent Metal Removed from Heads and Blocks, Comparing Materials, Date When Engine Was First Made

Figures 7 and 8 indicate that there are definite penalties related to removing a larger percentage of material from blocks: more cutting heads and a larger shop. Both of these imply increased investment and (as shown elsewhere) more downtime.

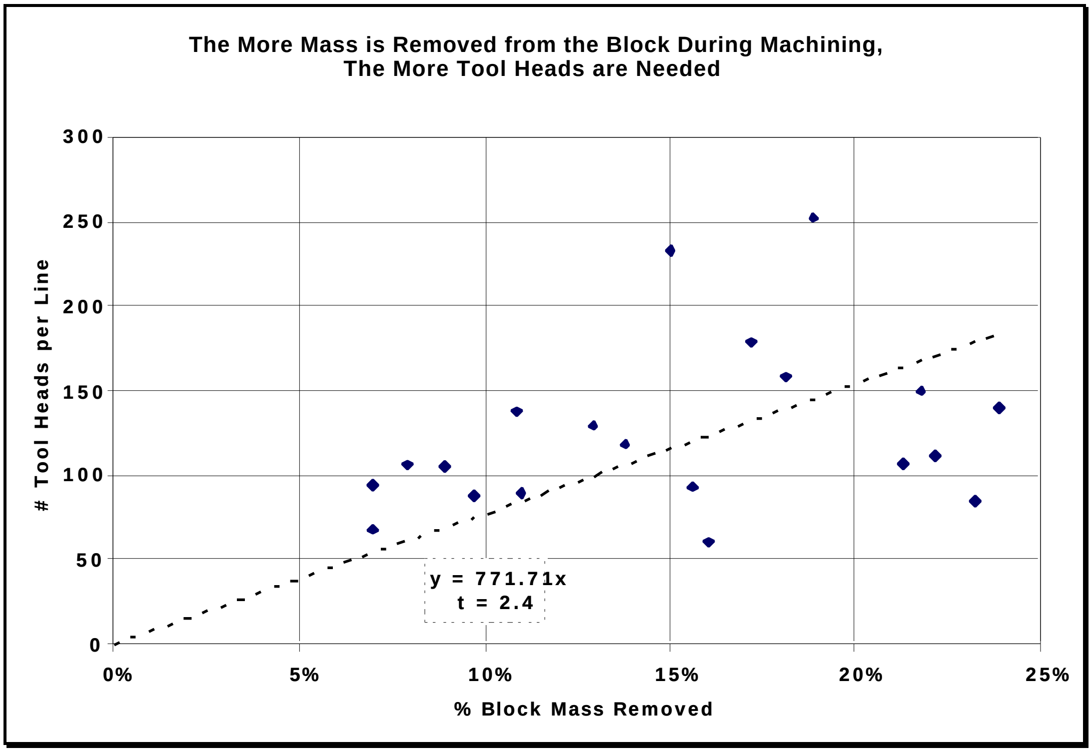

Figure 7. More Percent Material Removed from Blocks Requires More Machine Cutting Heads, Implying a More Costly Shop

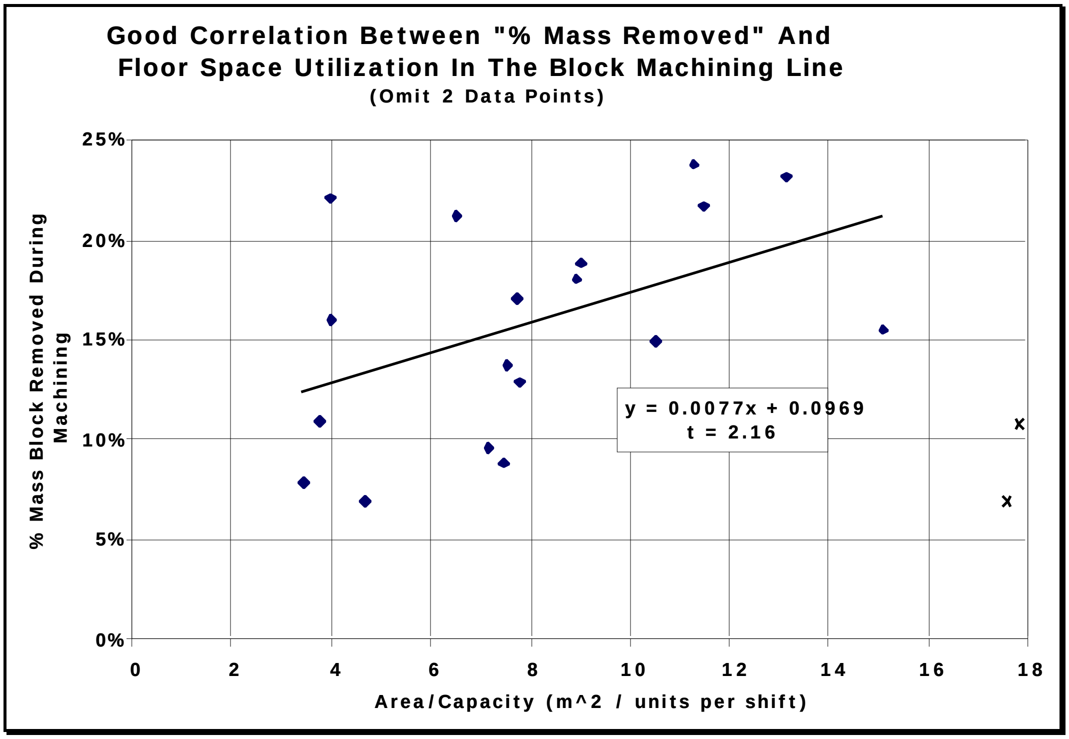

Figure 8. More Percent Mass Removed from the Block Means a Larger Shop for a Given Capacity.

Hot Testing and Engine Quality

> "We have error-proofed our processes and have many in-process tests. So we just cold test the final engine. Hot testers make their own errors." - Assembly area manager of plant that cold tests only.

Most engine plants were designed by people who do not agree with this statement, which was made by someone whose plant did not participate in our statistical study. Without exception, the participating plants hot test some or all of their engines. What is surprising is that these tests, while they find some errors, do not predict any subsequent reliability or durability data.

There appears, first of all, to be little agreement over how long a hot test should last, except if the block is aluminum, in which case a long test is used to find porosity. See Figure 9. Second, test duration does not correlate with the fraction of engines in which problems are detected.

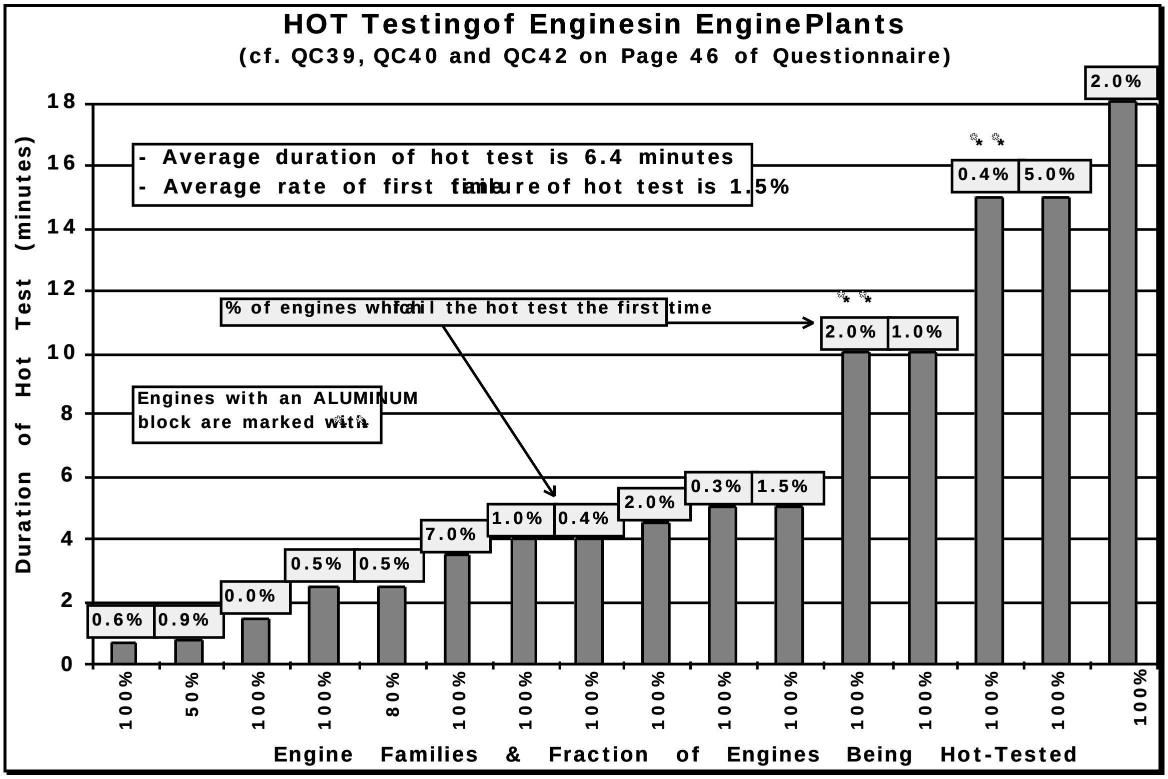

Figure 9. Duration of Hot Tests in Engine Plants. Most plants test all the engines but test duration varies widely, as does the percent of engines that pass the first time.

More distressing is the fact that testing, regardless of duration, apparently finds only immediate problems, probably infant mortality of components married to the outside of the engine or assembly errors that cause obvious leaks or electrical problems. Our data indicate that a longer test has no increased ability to prevent problems such as engines returned from the assembly plant, customer complaints after three months, or complaints after 12 months. See Figure 10. Complaints after three months reliably predict complaints after 12, however, as shown in Figure 11. European, Japanese, and North American production sites have statistically verifiably different rates of complaints after both 3 and 12 months. In spite of our finding that hot test duration does not help to find problems that occur after 3 or 12 months, the trend in recent plant designs has been to lengthen hot tests from a typical 2 - 4 minutes for plants last refurbished in the 1965-75 period to a typical 2 - 18 minute range in the 1980-92 period.

Figures 9-11 indicate that the kind of problems detected by hot test are different from those that reveal themselves after three or twelve months, although in quantity the last two are related in a given engine family. Plant personnel feel that complaints within the first three months are due to engine plant problems while those that occur later are due to engine design. Two simple models were tested to see how they fit the data in Figure 11. The first model assumes that complaints arrive at a fixed rate for the entire year, indicating that there is no change in their causes during that time. We find that for North America the rate is 5.3 complaints per thousand engines per month, while for Europe the rate is 31.9. If we assume that complaints arrive at a rate R1 for the first three months and R2 for the last 9, then for North America the results are R1 = 10, R2 = 7.77, while for Europe the results are R1 = 66.6 and R2 = 49.8. There is some consistency in these results because 31.9/5.3 = 6.02, 66.6/10 = 6.66, and 49.8/7.77 = 6.41, indicating that European engines generate about 6 times as many complaints per thousand engines per month as North American engines do, regardless of which model we use to calculate this ratio. Also, R2/R1 = about 0.75 for both Europe and North America, indicating that there is a consistent difference between the number of complaints after three months and after 12 regardless of region. These calculations suggest that the two-rate model is more likely to be correct, but a strong conclusion is not possible due to the limited size of the sample.

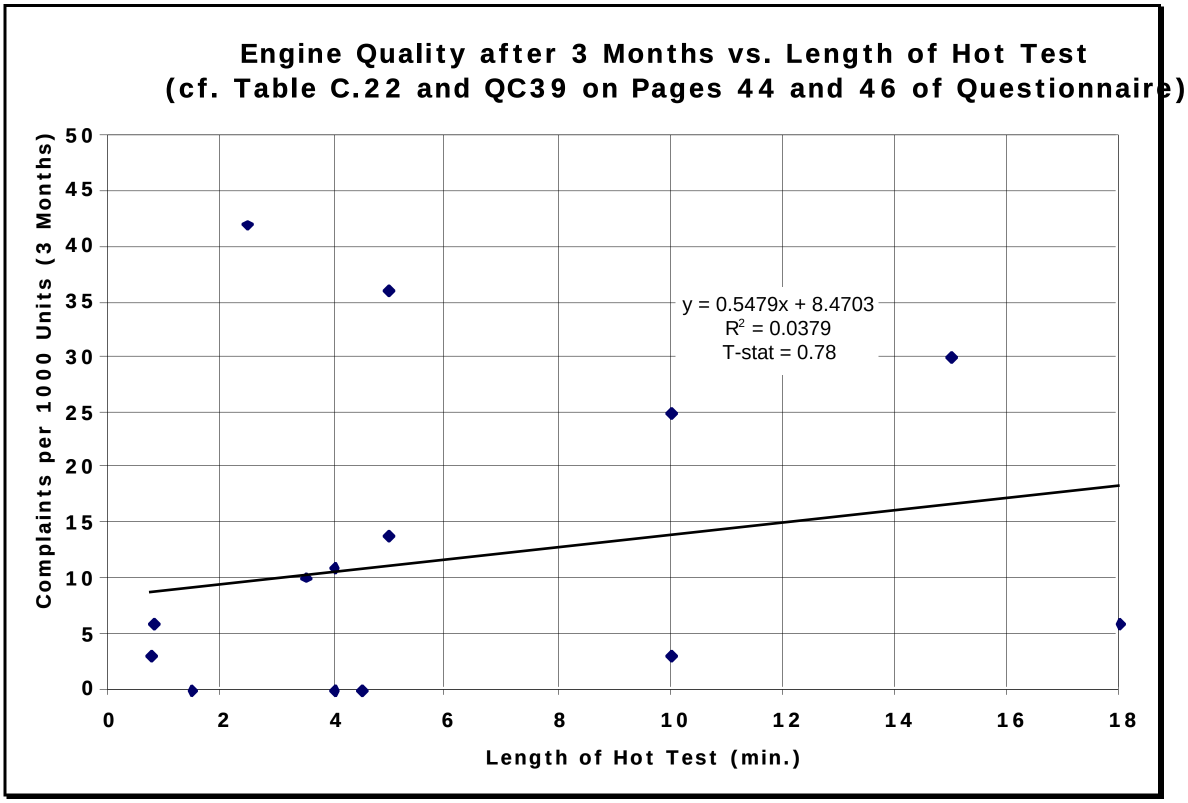

Figure 10. Complaints per Thousand After Three Months in Service vs Duration of Hot test. Complaints after 12 months show similar lack of correlation with hot test duration.

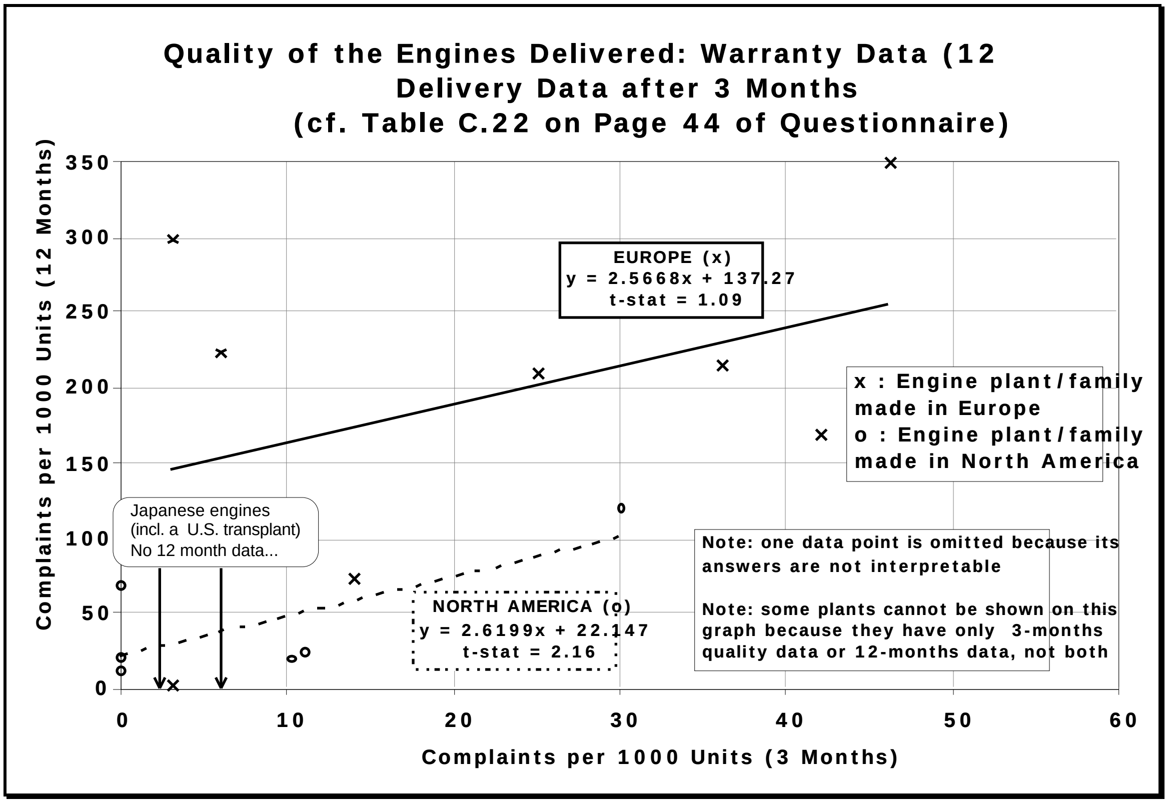

Figure 11. Complaints per Thousand After Three Months Reliably Predicts Complaints per Thousand after Twelve Months. Also shown in this graph is the statistically verified finding (via Student's T-test) that European engines receive about six times as many complaints per thousand after both three and twelve months as North American engines, although the sample may be too small for a strong conclusion.

Plant Design and Equipment Decision Processes

“Someone goes to a machine tool show. Next thing we know, a lot of fancy machines start showing up.” - Machining area supervisor speaking of central headquarters staff.

"Is there a competitive advantage to be gained from the machines? Well, we and our competitors all buy our machines from the same few vendors. If someone has a good idea, it flashes through the industry in about a year. So what difference can the machines make?" - European central operations manager.

"Those Honda machines are wimps, not nearly stiff enough." - European operations manager.

"We can't buy engine plant machines as good as Honda has." - American operations manager.

"We try out new machines here in Japan for a year. If our people can operate and maintain them, we try them out for another year in Ohio. If they pass that test, then we make them available to other companies through Honda Engineering." -Honda spokesman. (This effectively keeps Honda three years ahead of anyone who buys from Honda Engineering.)

"Engine designs are really refined, using lots of finite element calculations. No such refinement can be seen in the machines. The vendors just add iron hoping to make them stiff." - Plant assistant manager.

"Purchasing thinks we should let the vendors do everything. But we find their quality control is lacking. Most of them can't critique our specs, and those that can help themselves in the process." - Central strategy staff member, car components division.

“Vendors don’t do a good job of proving out their lines before installing them.” Headquarters operations staff engineer, components division.

"We spent two years at headquarters designing our lines, selecting vendors, redoing their process plans, saving big money." - Block machining area manager.

"You can't do kaizen on a black box." - European central planning staff member.

Three quotes from a machining area manager at an engine plant whose parent car company has a machine tool subsidiary and in-house equipment design departments that provide machining and assembly lines:

1. "What's the advantage of small machines? Big machines block your view of the andons."

2. "You don't see any people? To find the people, follow the andons."

3. "How did we get [vendor Y] to give us small machines? With difficulty!" "Are they stiff enough? The issue is natural frequency, the ratio of stiffness to mass. That controls surface finish. Small machines certainly can have high natural frequency, maybe more easily than large machines."

Companies fall into two groups regarding their reliance on vendors for engine plant equipment. In by far the larger group, companies prepare the specifications for manufacturing or assembly lines, participate to varying degrees in detailed design, but generally leave line and equipment design, system integration, and installation to vendors. In the smaller group, companies have engine equipment subsidiaries or sister companies with whom they work to develop the lines. The differences between plants belonging to companies in each group can often be seen easily by a visitor. Companies that own an engine equipment supplier have

- smaller plants
- smaller variety of equipment suppliers
- smaller departments containing...
- smaller machines
- fewer employees per unit of production capacity

The individual quoted at the end of the box at the head of this section displayed complete understanding of the decisions that led to the design of his shops and the operating methods used there. “Big machines block your view of the andons” is not the answer one would expect, but it makes perfect sense. The five attributes of his plant are not accidental but in fact depend on each other in a systematic way. It would appear that this plant operates according to principles that are basically unknown at other plants we visited. Since vendors apparently want to provide big machines (possibly they carry larger profit margins), these principles depend heavily on controlling the machine vendor so that small machines are obtained, something that one gets “with difficulty” from an independent vendor.

An extreme example is provided by assembly lines for cylinder heads. Heads are small and contain very small parts. However, only in one plant did we see correspondingly small assembly machines. They were about the size of a large card table. Each machine did a single task, as is typical, such as placing four valves in the head. At other plants, machines with corresponding tasks were the size of small cars themselves. At the extreme, we observed machines the size of small houses, equipped with huge robots hung upside down from the ceiling. Imagine how difficult it must be to service such huge machines compared with servicing machines that sit on a small table. The small machines were built by the machinery division of the same company, while vendors provided the machines at all the other plants.

Table 3 shows that plant personnel are not greatly satisfied by the properties of the machines in their shops. Higher satisfaction can be clearly traced to the methods used to obtain machines and the degree of involvement the plants have in vendor and/or equipment choice, as shown by Figure 12.

Desirable properties of machines (cf. Table C.18)	**Level of satisfaction & number of instances**			
	Very Satisfied	**Satisfied**	**Not Satisfied**	**No answer**
Delivers required tolerances	*****	********	**	
Breakdowns are easy to diagnose	****	******	*****	
Is easy to switch from one variant to another	***	***	********	*
Has standard electronic interface	***	********	****	
Has open software	*	*******	*****	**
Has standard user interface	*	*********	*****	
Is very rigid	*	*******	*****	**
Has automatic resetting of tools	**	*******	****	**
Has software source code available		*************	*	**
Has our own proprietary electronic interface	*	*****	****	*****
Is small	*	******	*******	*
Can easily be moved to a new location		******	******	***

Table 3. Level of Satisfaction with Machines, Ranked by Decreasing Importance of the Listed Properties. Evidently, plant personnel are not too satisfied, regardless of the importance.

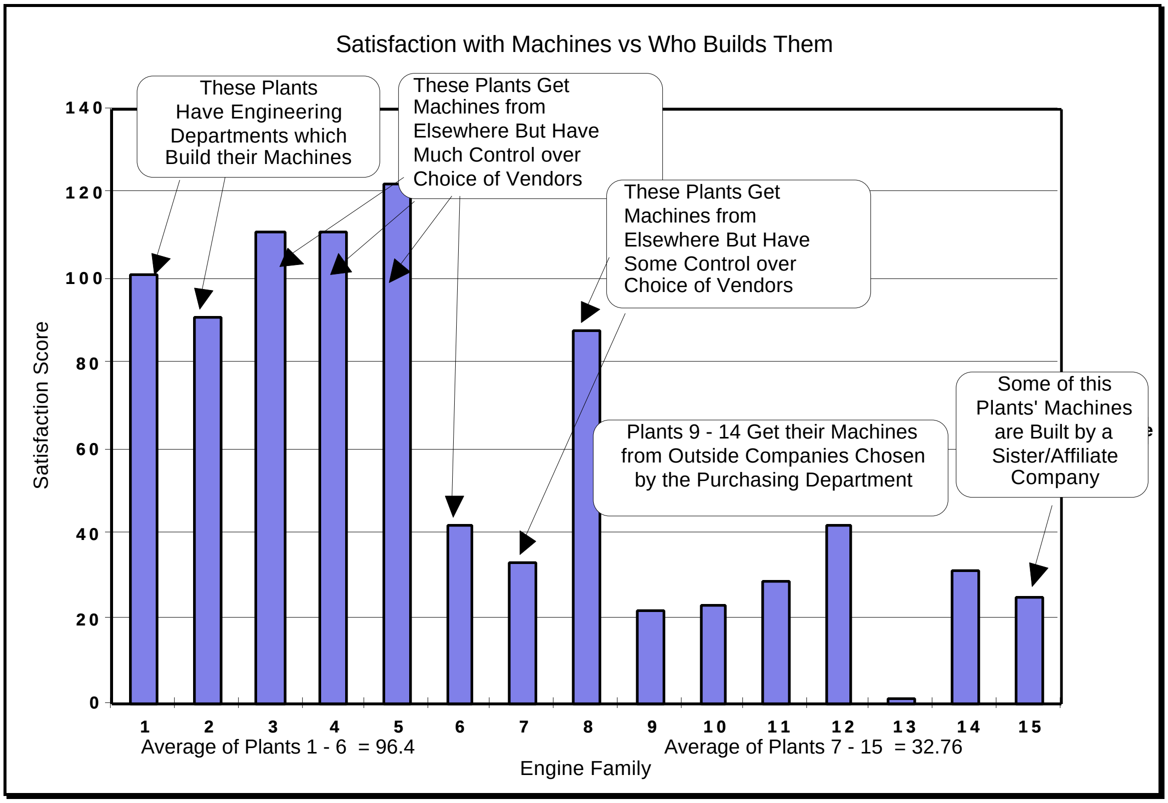

Figure 12. Plants That Get their Equipment from In-house Engineering Departments or Which Have a Lot of Control over Choice of Equipment Vendor are Much More Satisfied with the Machines. The score sums the product of each property's importance rank and plant satisfaction with it. The maximum possible score is 156. Plants 7 and 10 did not answer all the questions, artificially lowering their scores.

Figure 13 compares the sequence of events involved in creating an engine plant.

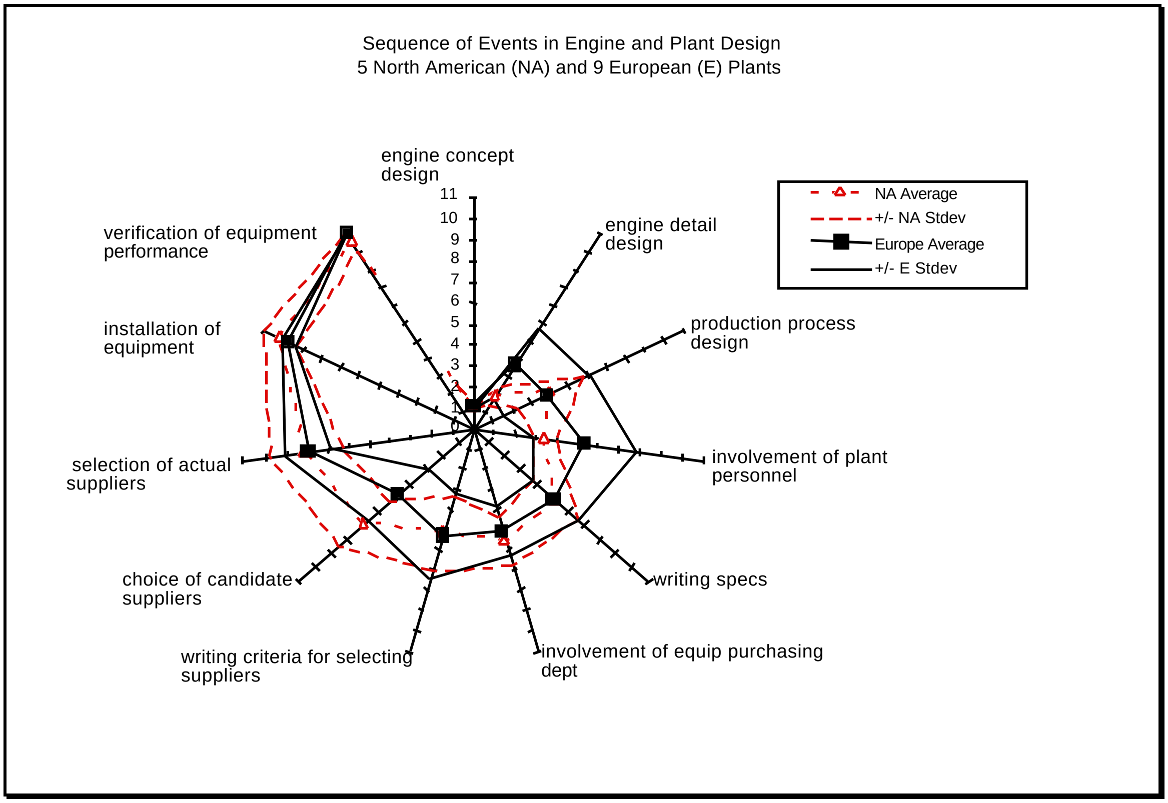

Figure 13. Main Events in Creating an Engine Plant, Plotted in Typical Sequence. Step 1 is always first, step 11 always last, but intervening steps are done in different sequences in Europe and North America. For example, North American plant personnel are on average involved at step 4 (ranging from step 3 to step 5) whereas on average European personnel are involved at step 6 (ranging from step 3 to step 8).

Figure 13 reveals several differences in European and North American practice. Europeans are in less agreement about the sequence of the early steps, as indicated by the wider ± 1σ range in when the nominally second, third, and fourth steps are done. On the other hand, North Americans are in less agreement about the later steps. Notably, North American plant personnel are involved earlier in the process than most of the Europeans. This difference is reflected in Figure 12, where many of the more satisfied plants are in North America.

One Person's Story of Designing and Installing a New Machining Line

"We don't pay enough attention to how our hardware decisions affect manpower needs." - Plant manager.

"Each department is designed as a separate unit, usually by a different vendor. No one designs the whole system. When it doesn't work, they blame it on poor communication and call us." - Central office operations analyst.

Note: The following quotes are from people at the same company, who all know each other and discuss these issues regularly.

"I've run lines with 30 second cycle times and gotten 1000 blocks per shift, and I've run lines with 20 second cycle times and still gotten 1000 blocks per shift." - Block line area manager who designed his own line and specified 30 seconds. (Theoretical capacity at 30s for 8 hours is 960 blocks; at 20s, 1440.)

"We tend to flog our machines. They [Japanese competitor] will build a second line to raise capacity but we try to shorten the cycle." - Composite of two quotes: a central office operations chief and an assistant plant manager at the same company.

The block line manager quoted above gave us a complete history of the development of his line. More than most people of his rank at his or any company, he took charge of the line's design. The approximate time line is shown in Figure 14. This manager spent two years at headquarters selecting candidate vendors, discussing the new engine with its designers, preparing bid packages, and selecting the winning vendor, plus redoing the winner's design as described below.

The engine was a slight redesign of an existing engine made at another distant plant, so one possibility would have been to copy the existing line. The vendor who built that line bid exactly this. Another would have been to copy the line that was being replaced. Another vendor bid this. The first vendor won because he reused more existing process engineering and thus had a lower bid. However, the line manager made the following changes:

1. reduced the line speed so that the cycle time was 30 seconds instead of 21 - for this he had to get permission of both the plant manager and the engine operations manager at headquarters

2. chose low cutting speeds compatible with a slower line speed, permitting the use of low cost tool bits

3. designed combination cutting tools to create multiple surfaces in one operation, saving tool heads

4. put multiple spindles on the same head, further reducing tool head count

5. used other means to further reduce the size or number of machines

The result was that the original bid of 18 machines at $38 million fell to 10 machines at $20 million.

His objective in lowering the line speed and cutting speeds was to permit the tools to last two shifts, preventing the need to stop the line during production to change tools. He is satisfied that he achieved this goal, and he is one of only a few in the company who believes this is the correct strategy. However, it appears from the data that cycle times in othr plants are chosen to meet basic production rhythms, and they range between 20 and 40 seconds.

Our statistical study also showed that choice of cycle time is not correlated with uptime or scheduled or unscheduled downtime. This fact could indeed reveal a weakness of the statistical analysis rather than a denial of the conclusions reached by this block line manager, because there is no doubt that he can run two shifts without changing tools due to normal wear. He accomplishes this in part by using numerically controlled tool wear compensation, a practice we did not take account of in our questionnaire.

He also benchmarked in-process measuring methods before specifying the kind he wanted. He and his people redid all the tolerance analyses done by both the vendor and the existing engine's builders, finding and removing many errors. He also specified noise shields and large observation windows on the machines. The shop is one of the quietest we visited, and all the information given here was imparted in normal speaking voice while walking around the shop. "It's hard to get people to work in a block machining department but people want to work with me because we have such a nice shop."

This company had previously allowed its engine plants considerable autonomy, so this much participation by a line manager was not necessarily new. What was new in his experience was the close working relationships he had with engine designers, builders of the existing engine, builders of other engines, and the vendor. He feels he has the best block line in the company.

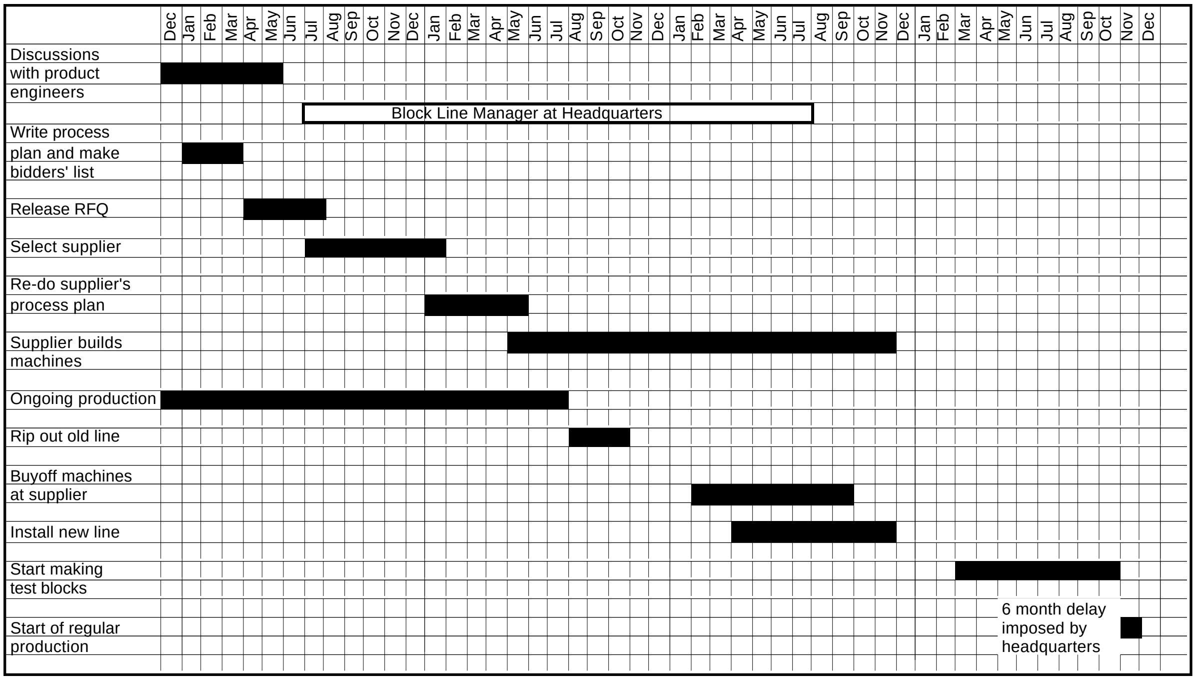

Figure 14. Schedule of Creation of an Engine Block Machining Line

Repair and Maintenance Policies and Downtime

"We have to be able to fix the machines. There's no hope of getting the vendor here in time." - Block line area manager.

"Once we install the machines and check them out, we never hear from the customer again." - President of machine tool vendor.

“We make 13 kinds of blocks. Demand is so high and the time required to switch from one kind of block to another takes so much time that we run 3 shifts 6.5 out of 7 days. We don’t have time for preventive maintenance.” Said in slightly different words at several plants.

Engine plant equipment is arguably the most complex of any in the automotive supply chain. Keeping it running is clearly a top concern of plant management. Yet it is not clear that plants have converged on the right means for achieving this goal. There is some evidence, as indicated by the quotes above, that there is limited communication between equipment vendors and the users of the machines once they are installed. In some cases, as noted elsewhere in this paper, there is limited communication during plant design, with statistically measurable improvements when communication is stronger.

Our data support these views. By a wide margin, plants report that they train their own maintenance personnel to perform preventive maintenance and repairs to machines. The rest of the plants rely on the vendor to train plant personnel for these tasks. In second place are plants that utilize regular production workers for preventive maintenance; it is rare that production workers are relied on for repairs. A few plants rely on outside contractors or, more rarely, the suppliers themselves, for these services.

Our data show that mechanical and electrical breakdowns are by far the most frequent, accounting for about 70% of all breakdowns. Tool breakage accounts for 13% or less. As plants age, however, hydraulic breakdowns increase in frequency. Statistical analysis reveals that no single type of breakdown can be cited as the prime cause of downtime in any major department. This result means that the plants basically face a continuous and random series of breakdowns. None of the following were found to have any correlation with uptime or downtime: how many years TPM had been in effect, fraction of machines covered by TPM, hours per week devoted to preventive maintenance, the fraction of available calendar time that the machines are operated, the amount of training given to employees, or whether the plant was unionized.[11] More study is required to explain the

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[11] In fact, some of our data indicate that more intensive TPM-related activities are weakly associated with *more* unscheduled downtime, a result we do not think is reliable.

wide variation (50% to 85%) in reported uptime and its approximately uniform distribution across this range [Whitney et al].

The Growing Power of System Suppliers

"If we give away a whole system like the head, what do we have left?" - Central design staff member.

"We have to keep mastery of the whole chain." - Central strategy chief

"The 5 C's *are* the engine." - Central design staff member.

"We get parts from 214 vendors." - Assembly area manager. (A typical engine has about 450 parts.)

Three quotes from people at the same company:

1. "The car's quality comes from the interaction of systems. ABS is the gateway to customized ride quality and handling. The vendors already have control of these technologies and we need to get them back." - Car systems engineer.

2. "ABS is just a black box that stops the car. That systems engineer is really an empire builder." - Young manager.

3. "We have NOT lost control to the vendors. We do the system engineering and tell the vendors what to do!" - Central design staff manager's angry response.

The following two quotes are from *Ward's Engine and Automotive Technology Report:*

The view from Bosch of the same topic, commenting on its purchase of Allied Signal's brake components business to augment its ABS controller line: "We already have the ability to control fuel injection and transmissions, and bringing in the brake piece gives us the actual stopping power. So it should lead to even greater systems." [Ward's 3/15/96]

A similar view from Varity/Kelsey -Hayes: "The answer is integration. If braking was all brake by wire and electronic brake management could do, they would never see the light of day. The true advantage ... comes from the fact that they allow full integration of the increasingly sophisticated extensions of ABS, traction control, and yaw control." [Ward's 9/15/96]

Engine plants typically make only five of the approximately 450 parts in an engine. On a cost basis, plants obtain 75% of the engine from outside the plant, of which 25% is raw castings and forgings while 50% is complete parts and assemblies. In some sense, the "5 C's" represent the core of the engine but in another sense they represent the aboriginal portion of it, while much of the purchased portion contains the most advanced technology: turbo or superchargers, electronic controllers, emission controls, fuel injection and associated electronics, sensors, and so on. According to [Doi] these advanced items are responsible for by far the majority of recent improvements in HP/liter.

An example is provided by a recently announced intake system from Siemens. See Figure 15. This is an innovative polymer unit that contains a number of previously separate items (intake manifold, throttle body, fuel rails and injectors, etc.). It even has its own gasket. One takes it out of the box and bolts it onto the engine. An intake manifold from VDO reported in Ward's [3/1/97] comprises manifold, air intake sensor, and control logic. Once upon a time intake manifolds could be used as door stops. Now they are computers that have air running through them.

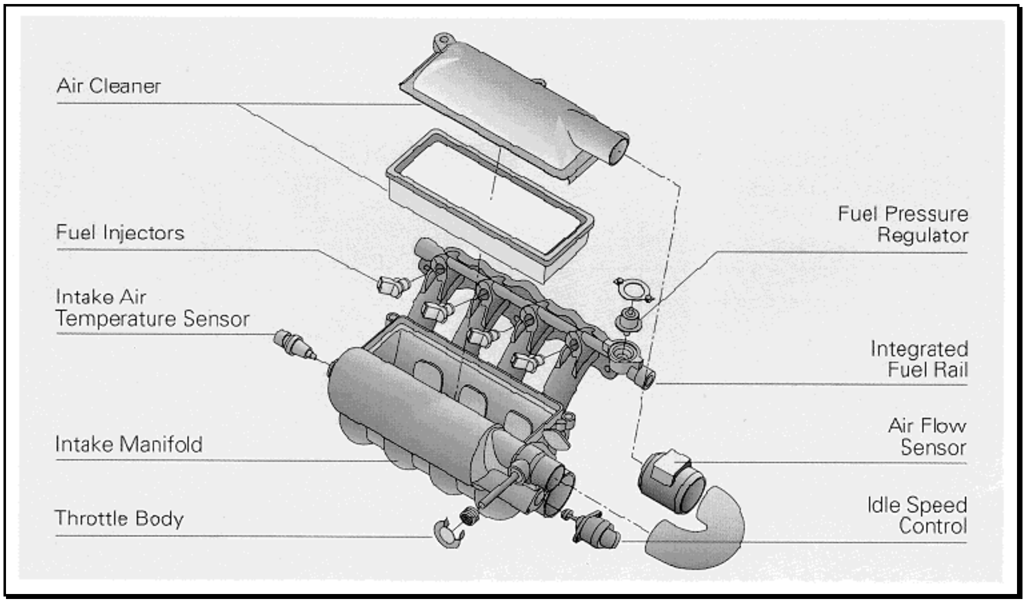

Figure 15. Integrated Air/Fuel Intake System from Siemens.

Car firms are dependent for production technology knowledge as well as engine technology. Eleven plants identified 29 "critical casting, machining, assembly and testing technologies that give engines high performance and quality." Examples include bore honing, aluminum cylinder heads, three different cam hardening processes, laser welding, and in-line testing capability. Only four of these items were obtained in-house or from an affiliated company.

As more and more of the engine, whether measured by cost or technological content, is obtained from outside the engine plant, it is tempting to conclude that the engine plant itself has lost most of the control of both its costs and its technologies to outside entities. This certainly means that the engine plant itself is too small to be a unit of analysis for researchers seeking to relate these larger issues to either engine plant performance or engine performance.

One can always argue, as the angry design staff person did, that the one who writes the specifications retains control. But technology advances, and control of knowledge can pass from one entity to another. One can lose the ability to write a competent specification if one lacks practice at making the item or integrating it with others. More insidious is the trend identified by the system engineer who foresees vendors accumulating power through integration of knowledge of several systems that in the future will work together to deliver a new level of quality. ABS can be seen as part of an as yet undeclared “chassis system,” which would likely include programmable suspension and steering, perhaps even sensing of road conditions and interconnections to the engine/transmission control system. Detailed proprietary knowledge of ABS algorithms already resides with suppliers, although there is no necessary barrier to car firms seeking to recapture it. The cost of re-entry nevertheless increases as time goes on. As suppliers buy each other they obtain knowledge of related systems and create the ability to integrate them. An impregnable barrier could be the result. The system suppliers clearly recognize this and several observers said that in their opinion the car firms have not. A discussion of the strategic implications of outsourcing of product and process technology may be found in [Fine and Whitney].

Engines represent a crucial battleground in this arena. The region below the head-block interface clearly belongs to the car firms, with the exception of piston rings, which are highly proprietary. The region outside the head, containing most of the recent technological advances, may belong to the suppliers. The head itself is probably still contested ground. The first quote at the top of this section reflects one car firm’s fear about this region.

Conclusions

Engines and the plants that produce them contain high concentrations of the most advanced technology in the auto industry. The plants are under a variety of strong external pressures, and both the hourly and salaried personnel are under considerable stress. Whether one looks at production, design, or supply constraints, the plants have remarkably little control over these pressures. The consequences of rapid technological change are also evident in the engines and plants. Power may be passing to a few adept system suppliers who see a path to control by means of system integration.

If the internal combustion engine is eventually replaced by a radically different technology, the situation will undoubtedly change and entirely new players may gain control. Nevertheless, manufacture of automobile prime movers will still be a high-tech, high-stress undertaking.

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